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Assessment of rapid impact compaction for transportation infrastructure applications

Peter J. Becker
Iowa State University

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Assessment of rapid impact compaction for transportation infrastructure applications

by

Peter J. Becker

A thesis submitted to the graduate faculty

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Geotechnical Engineering)

Program of Study Committee:
David J. White, Major Professor
Jeramy Ashlock
Charles Jahren

Iowa State University

Ames, Iowa

2011

This work is dedicated to
my wife, Rita, and my son, Montgomery

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LIST OF SYMBOLS

Symbol	**Description**	**Units**
AE	Applied energy	(tonne-m)/m^2
$C + C_0$	Sill	—
C_0	Nugget effect	—
C_{DPI}	DPI to $DPI_{7.2kPa}$ correction factor	—
C_N	SPT correction factor for overburden pressure	—
CPT	Cone penetration test	—
C_c	Coefficient of curvature	—
C_u	Coefficient of uniformity	—
D	Compaction depth	m; ft
Dr	Relative density	%
DDC	Deep dynamic compaction	—
d_A	Diameter of RIC anvil	m
DPI	Dynamic penetration index	mm/blow
$DPI_{7.2kPa}$	Dynamic penetration index at 7.2 kPa confining pressure	mm/blow
c'	Drained cohesion	kPa; psf
e_{max}	Void ratio of soil in loosest state	—
e_{min}	Void ratio of soil in densest state	—
f	Frequency	Hz
G_S	Specific gravity	—
H	Drop height	m
h	Separation distance	m, ft
N	Number of blows/hammer drops	—
n	Empirical coefficient	—
n(h)	number of data pairs h unit apart	—
P	Number of passes	—
p	slope of the line	—
p_a	Atmospheric pressure	kPa; psf
PMT	Pressuremeter test	—

PPV	Peak particle velocity	mm/s; in/s
QA	Quality assurance	—
QC	Quality Control	—
RIC	Rapid impact compaction	—
S	Impact point spacing	m
SEM	Scanning electron microscope	—
SPT	Standard penetration test	—
SPT-N_{60}	Standard penetration number, corrected to 60% energy	bpf; blow/0.3 m
W	Mass of drop weight	tonne; ton
W_A	Mass of RIC anvil	tonne
w	Moisture content	%
w_{opt}	Optimum moisture content	%
$z(x_i)$	Measurement taken at location x	—
a	Range	—
γ	Semivariogram	—
γ_t	Total unit weight	kN/m^3; pcf
γ_d	Dry unit weight	kN/m^3; pcf
$\gamma_{d,max}$	Maximum dry unit weight	kN/m^3; pcf
γ_w	Unit weight of water	kN/m^3; pcf
$\hat{\gamma}$	Experimental estimate of variogram function	—
Φ'	Drained angle of internal friction	degrees
ρ_d	Dry density of soil being tested	kN/m^3; pcf
$\rho_{d,max}$	Dry density of soil in densest state	kN/m^3; pcf
$\rho_{d,min}$	Dry density of soil in loosest state	kN/m^3; pcf
σ	Standard deviation	—
σ'	Effective stress	kPa; psf
$\sigma_{D,S}$	Simulated dynamic normal stress	kPa; psf
σ_0'	Effective overburden pressure	kPa; psf
τ_f	Shear strength	kPa; psf

ABSTRACT

Despite being identified as a geoconstruction technology applicable to transportation infrastructure applications, rapid impact compaction (RIC) has yet to be utilized on a transportation infrastructure project. Both technical and nontechnical obstacles, such as a lack of performance data, have impeded the introduction of RIC into the transportation sector. Each obstacle requires mitigation before RIC can be incorporated into the transportation sector. The goal of this research was to evaluate RIC for civil engineering applications in the transportation sector and mitigate the obstacles impeding the use of RIC within the transportation sector. The objectives that were sought to achieve this goal include expanding the RIC knowledge base; presenting a detailed case history of a commercial RIC project; and assessing the applicability of RIC's design, QC/QA, and specification procedures to transportation infrastructure projects. RIC is a well established technique within the commercial sector. An ample amount of commercial case histories and data pertaining to RIC performance, induced vibrations, and cost are currently in existence. The current procedures for design, QC/QA, and specification within the commercial sector will require improvement before application to transportation infrastructure projects. This research has addressed each of the obstacles preventing use of RIC within the transportation sector and has either partially or fully mitigated each obstacle. Additional future strategies for partially mitigated obstacles have been proposed. With fewer obstacles and a greater knowledge base, transportation agencies will have greater confidence in employing RIC for transportation projects.

CHAPTER 1. INTRODUCTION

This chapter is arranged in four sections: problem statement, research goals and objectives, research benefits and significance, and arrangement of the thesis.

Problem Statement

Geoconstruction technologies consist of methods such as ground improvement, grouting, compaction, soil stabilization, etc. Despite existing for decades and being readily available, many geoconstruction technologies have had little exposure in transportation infrastructure projects. Transportation agencies have not been able to take full advantage of the benefits these technologies provide due to a variety of both technical and nontechnical obstacles (Berg et al. 2008).

A geoconstruction technology with great potential for transportation infrastructure projects is rapid impact compaction (RIC). RIC is a method of soil compaction that utilizes successive impact blows to densify loose soil.

Since as early as 2003, RIC has been identified as a technology capable of being effectively utilized by transportations agencies within the United States (Dumas et al., 2003). Dumas et al. (2003) proposed applications including the stabilization of weak embankment foundations and the rapid construction of embankments using thick compaction lifts.

Despite the promising outlook on RIC’s contributions to the transportation infrastructure within the United States, it has yet to be used on any transportation infrastructure projects. According to Berg et al. (2008), the significant barriers preventing wider use of RIC in the transportation sector include:

- lack of simple, comprehensive, reliable, and nonproprietary analysis and design procedures;
- lack of established engineering parameters and/or performance criteria;
- lack of easy-to-use tools for selecting technology;
- lack of long-term performance data;
- environmental impacts of RIC (i.e. vibrations);
- performance uncertainty; and
- lack of accessible case histories.

Research Goal and Objectives

The main goal of this research was to evaluate RIC for civil engineering applications in the transportation sector and mitigate the obstacles impeding the use of RIC within the transportation sector. Three objectives were sought to meet this goal:

1. develop an expanded RIC knowledge base from published material and information gathered from RIC contractors;
2. present a detailed case history of an commercial RIC project; and
3. assess the applicability of RIC's design procedures, quality control procedures, quality assurance procedures, and specification procedures to transportation infrastructure projects.

Research Benefits and Significance

The most important results of this research will be the elimination of the some of the previously mentioned obstacles preventing RIC's usage in transportation infrastructure projects. RIC obstacles identified by Berg et al. (2008) include. With fewer obstacles and a greater knowledge base, transportation agencies will have greater confidence in employing RIC for transportation projects. Transportation agencies will be able to capitalize on the capabilities incurred by RIC.

Arrangement of the Thesis

Chapter 2 is a review of literature concerning RIC as well as the aspects that complement RIC and this research. Chapter 3 summarizes the current state of RIC practice in for commercial construction applications. Chapter 4 discusses the test methods and materials used in this research. Chapter 5 presents the results and subsequent analysis of this research. Chapter 6 introduces assessments of RIC for transportation applications. Chapter 7, the final chapter, outlines the conclusions of the research and suggests recommendations for future research.

CHAPTER 2. BACKGROUND

This chapter provides background information regarding rapid impact compaction, deep dynamic compaction, cohesionless soil compaction, and geostatistical analysis. Information on theory and practice for each section has been presented.

Rapid Impact Compaction

A typical solution to poor ground conditions encountered in foundation soils (e.g., low bearing strength or high compressibility) is to simply replace the unfavorable soils. This method, known as overexcavation and replacement, involves the removal of unsuitable soils and the subsequent replacement with more suitable fill material. The fill material can be the same excavated material recompacted to a satisfactory state or a select fill material transported from outside of the project site. Because of economic reasons, excavation and replacement depths are practically limited to approximately 2 m (7 ft) below the ground surface (Elias et al. 2006; Greenfield and Shen 1992; USACE 1999).

Since excavation and replacement is unfeasible at deeper depths, alternative solutions for the improvement of unstable foundation soils have been implemented. Rapid impact compaction (RIC) is one such solution.

RIC is an alternative to overexcavation and replacement. RIC is a compaction method that uses impact forces to density loose, granular soils (Allen 1996; Braithwaite and du Preez 1996; BRE 2003; Kristiansen and Davies 2004; Miller 2005; SAICE 2006; Serridge and Synac 2006; Simpson et al. 2008; Watts and Charles 1993; Woodward 2005). This process has been called by other names including low energy dynamic compaction (Allen 1996; Merrifield and Davies 2000; Merrifield et al. 1998; Parvizi 1999, 2006, 2009; Parvizi and Merrifield 2000) and high speed dynamic compaction (Neilson et al. 1998).

The RIC device is mounted to the front end of a hydraulic excavator and comprises a hydraulic piling hammer, an anvil, and a data acquisition system, as shown in Figure 1. The hydraulic piling hammer drops a weight [7 tonnes (7.5 tons) typical] from a height of up to 1.2 m (4 ft) onto a 1.5 m (5 ft) diameter circular anvil. As the hammer impacts the anvil, potential energy is transferred through the anvil and into the underlying soil and is translated into compactive energy. BRE (2003) and Serridge and Synac (2006) reasoned that the initial blows create a dense soil plug immediately beneath the anvil and, as additional blows are applied to the soil, the plug is advanced deeper thereby compacting more deeply underlying soil.

RIC is a more cost effective ground improvement solution relative to other techniques (Braithwaite and du Preez 1997; SAICE 2006; Kristiansen and Davies 2004). BRE (2003) provided an example specification for RIC.

Specialty contractors supply the RIC equipment; however there is no patent on either the RIC method or the RIC equipment (Dumas et al. 2003).

RIC has been effectively used in different civil engineering applications:

- Compacting loose granular soils and miscellaneous fills to increase bearing capacity and stiffness (e.g., Allen 1996; Braithwaite and du Preez 1997; Serridge and Synac 2006; Watts and Charles 1993);
- Compacting granular backfill material in lifts of approximately 3 m (10 ft) thick (Allen 1996);
- Mitigating liquefaction potential (e.g., Kristiansen and Davies 2003, 2004; Serridge and Synac 2006; Simpson et al. 2008); and
- Reducing the collapse potential of metastable soils (Serridge and Synac 2006).

Previous case histories (Appendix G) (Braithwaite and du Preez 1997; BRE 2003, Kristiansen and Davies 2004; Serridge and Synac 2006; Watts and Charles 1993) have reported that compaction depths range from 2 to 9 m (7 to 30 ft). Compaction depths depend on these factors:

- the properties of the soil such as soil classification, degree of saturation, initial relative density, permeability, and drainage path length (BRE 2003; Kristiansen and Davies 2006; Merrifield et al. 1998);
- the weight of the hammer and its drop height (energy per blow) (Merrifield et al. 1998); and
- The number of blows per impact point and the spacing of the impact points over the area being treated (applied energy) (BRE 2003; Merrifield 1998).

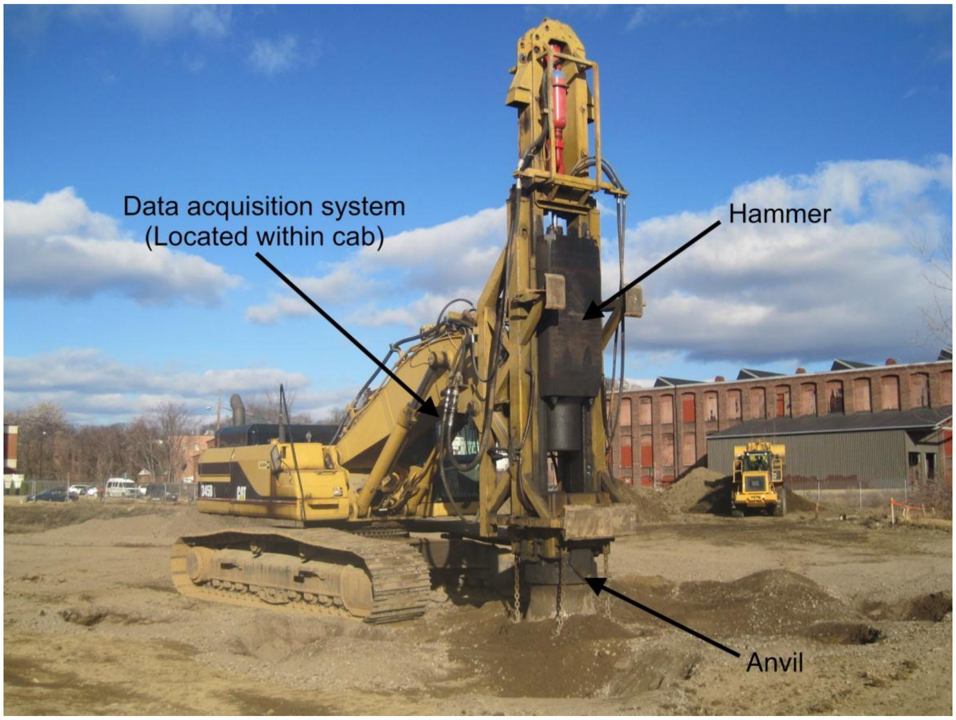


Figure 1. A typical RIC unit

RIC History

RIC was first conceived in the United Kingdom during the early 1990s as a method of rapidly repairing airfield runways following bomb damage (Allen 1996; SAICE 2006; Serridge and Synac 2006, Watts and Charles 1993). This method, as described in Faun Trackway (2009a, 2009b, 2011) comprises overexcavating bomb craters to sound material and subsequently backfilling the craters with select backfill. The fill is then compacted with an RIC unit and overlain with an aluminum mat for temporary take off and landing of military aircraft.

Watts and Charles (1993) applied RIC to civil engineering applications by evaluating the technique as a method of in situ soil compaction. They evaluated RIC by measuring compaction depth and degree of compaction (i.e., resulting strength) at different field trials. Additional RIC field evaluations have been performed since then (Allen 1996; Braithwaite and du Preez 1997; Kristiansen and Davies 2003, 2004; Serridge and Synac 2006; Simpson et al. 2008; Tara and Wilson 2004).

Although the majority of studies into RIC have involved field investigations, laboratory modeling of the RIC method utilizing a geotechnical centrifuge has been performed (Merrifield et al. 1998; Merrifield and Davies 2000; Parvizi 1999; Parvizi 1999; Parvizi 2006; Parvizi 2009; Parvizi and Merrifield 2000).

RIC Design

The engineer designs an RIC treatment program with the objective of attaining a specified soil strength to a certain depth following compaction.

The compaction depth that can be achieved using RIC is approximated for different soil types using Table 1 (BRE 2003). Table 2 (SAICE 2006) can be used if the RIC unit is equipped with a hammer weighing 9 tonnes (10 tons).

Regardless of soil type, impact points from the RIC method are positioned based on one of three impact point layouts:

- An arc pattern with the RIC unit acting as the center of the arc (Figure 2) (Braithwaite and du Preez 1997; BRE 2003);
- A 6 m by 6 m (20 ft by 20 ft) square pattern with 13 impact points within the layout area (Figure 3) (BRE 2003; Kristiansen and Davies 2004; SAICE 2006; Simpson et al. 2008); or
- A triangular pattern (BRE 2003).

The required number of blows per compaction point is calculated from the compaction point spacing and a predetermined applied energy. Typical applied energies for different soil types are presented in Table 1.

The resulting degree of compaction is typically determined from a *compaction trial*. As part of the *compaction trial*, the RIC contractor compacts a portion of the proposed project site. Following the *compaction trial*, verification tests [e.g., standard penetration test (SPT), cone penetration test (CPT), etc.] are performed on the compacted soil and compared to any pre-compaction tests. If the verification tests prove to have attained the desired soil strength to the specified depth below the ground surface, then the RIC method is deemed suitable for the entire project site. (Kristiansen and Davies 2003; Kristiansen and Davies 2004; Serridge and Synac 2006; Simpson et al. 2006; Woodward 2005).

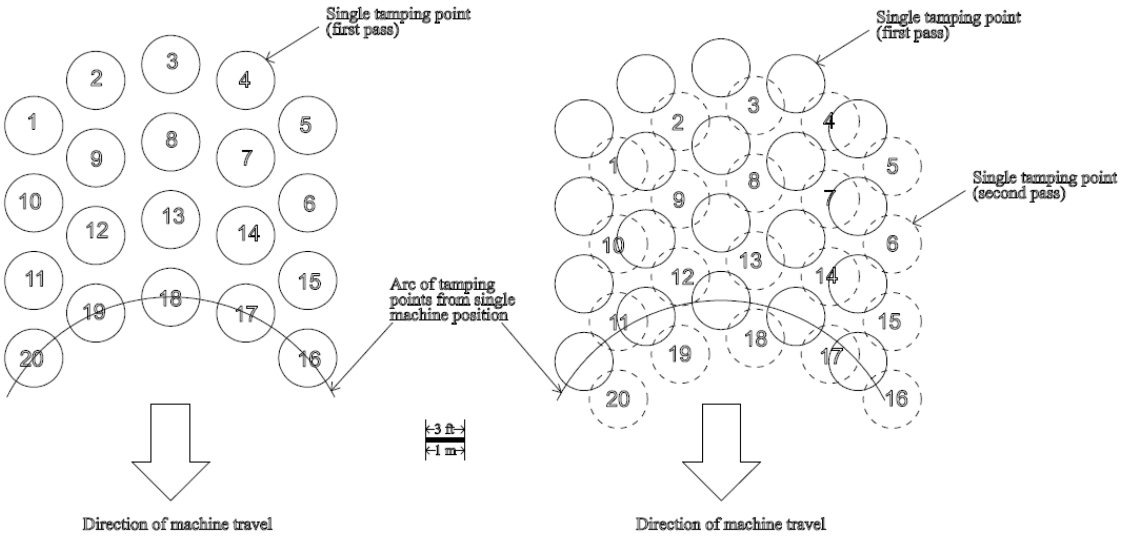
The resulting soil strength in terms of SPT N-value following RIC can also be approximated using Table 2 if the RIC unit is equipped with a hammer weighing 9 tonnes (10 tons) (SAICE 2006).

Table 1. Typical compaction depths with RIC (from BRE 2003)

Ground Type	Applied Energy (tonne-m/m^2)	Compaction Depth (m)
Loose building waste	150	4.0
Ash fill	150	3.5
Select granular fill	150	4.0
Sandy silt and silty sand	80 and 190	2.0 and 3.0

Table 2. Results of RIC using unit equipped with 9 tonne (10 ton) hammer (from SAICE 2006)

Soil type	Typical SPT N value following compaction (bpf)	Typical maximum compaction depth (m)
Sand	20–30	6
Silty sand	15	4.5
Sandy silt	10–15	3.5–4.5
Miscellaneous fill	>10	3–5



(a) Primary treatment pass

(b) Secondary treatment pass

Figure 2. Arc pattern impact point layout (from Braithwaite and du Preez 1997)

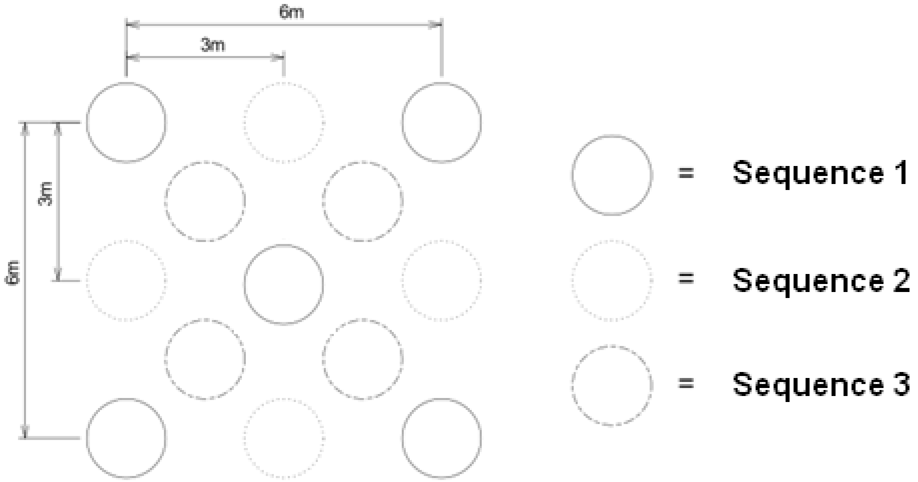


Figure 3. Impact point square layout (SAICE 2006)

RIC Quality Control and Quality Assurance

During the RIC process, the RIC contractor performs quality control by utilizing a data acquisition system built into the RIC unit. The data acquisition system (Figure 4) displays operating parameters for each impact point during compaction including:

- The total number of blows;
- The total energy input;
- The set (deflection in mm per blow); and
- The total depth of penetration of the anvil.

The operating parameters monitored by the data acquisition system are used as cutoff criteria for each impact point. Cutoff criteria are determined based on observations from the *compaction trial* and include a maximum number of blows, a minimum final set, or a maximum total depth of penetration. When any of the operating parameters reaches a specified cutoff criterion, an alarm is triggered and the RIC unit is moved to the next impact point. If a cutoff criterion fails to be achieved at an impact point, then the underlying soil or fill is likely to contain material that does not respond well to RIC such as a boulder or a thick clay deposit (BRE 2003; Kristiansen and Davies 2006; SAICE 2006; Serridge and Synac 2006; Simpson et al. 2008; Watts and Charles 1993).

Both Allen (1996) and Neilson et al. (1998) proposed methods to monitor the stiffness of the compacted soil as blows from the RIC unit are applied. Although these methods have been successfully demonstrated, they have not yet been incorporated into the RIC data acquisition system.

A party independent of the RIC contractor performs quality assurance (QA) testing following compaction of the entire project site. The results of the QA testing verify whether or not the RIC program achieved the specified degree of compaction to the necessary depth below the ground surface. Different in situ testing methods are used with penetration tests (e.g., SPT, CPT, etc.) as the most common (Braithwaite and du Preez 1997; BRE 2003; Krisitansen and Davies 2003, 2004; SAICE 2006; Serridge and Synac 2006; Simpson et al. 2008, Watts and Charles 1993). Other less common verification tests include geophysical techniques (BRE 2003; Serridge and Synac 2006) and plate load tests (Braithwaite and du Preez 1997; Serridge and Synac 2006).

Figure 4. RIC data acquisition system (from Rapid Impact Compactors, Ltd 2004)

RIC Induced Vibrations

Ground vibrations are a product of RIC and because vibrations can cause damage to existing structures, RIC should only be used if there are particle velocities less than or equal to 51 mm/s (2 in/s) (Nichols et al. 1971) at existing structures. Siskind et al. (1980)

concluded that vibration damage is dependent upon not only particle velocities but the frequency of ground vibrations as well. For ground vibrations with frequencies greater than 40 Hz, a maximum allowable particle velocity for all existing structures is 51 mm/s (2 in/s). Dry walled and plaster walled structures are more susceptible to vibration damage when vibration frequencies are below 40 Hz. To prevent cracks from developing in such structure types, maximum allowable particle velocities in lower frequency vibrations must be calculated in accordance with Siskind et al. (1980) (Figure 5).

Allen (1996) and Tara and Wilson (2004) studied the magnitude of vibrations (peak particle velocities) produced by the RIC unit as a function of scaled distance (energy per blow per square root of distance from the compactor). RIC unit-induced vibrations are generally smaller in magnitude than the vibrations produced by DDC, however they are greater in magnitude in terms of scaled distance. Tara and Wilson (2004) suggested that the higher vibrations in terms of scaled distance were the result of a higher efficiency of compactive energy transfer from the anvil always maintaining contact with the ground. Allen (1996) noted that typical vibration frequencies with RIC range from 9 to 15 Hz.

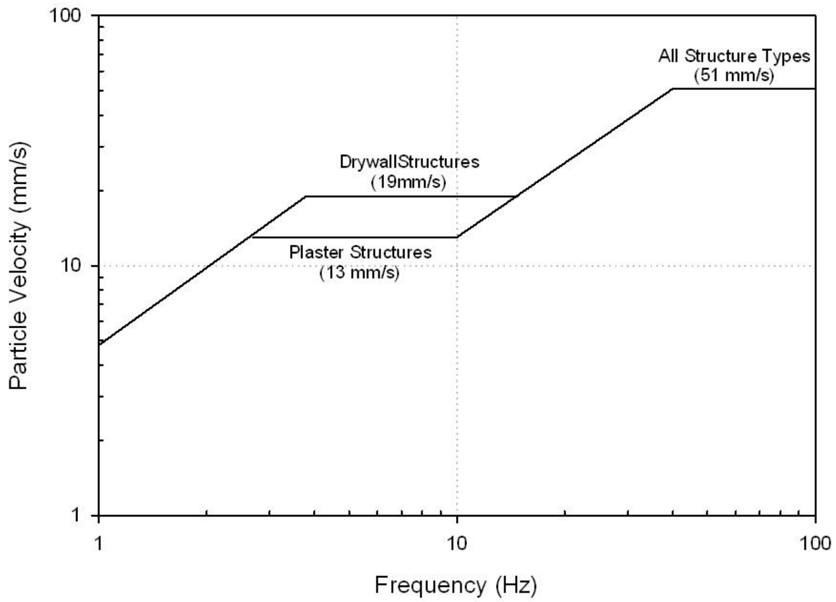


Figure 5. Safe vibration levels for existing structures (from Siskind et al. 1980)

Deep Dynamic Compaction

RIC is analogous to deep dynamic compaction (DDC), therefore a background on DDC is provided.

DDC Background

Lukas (1986) defines DDC as the “densification of soil deposits by means of repeatedly dropping a heavy weight onto the ground surface.” A standard crawler crane is generally used to lift and release the weight (Figure 6). Weights typically range from 5.4 to 27.2 tonnes (6.0 to 30.0 tons) and drop heights typically range from 12.2 to 30.5 m (40.0 to 100 ft) (Lukas 1995). DDC has been called by other names including heavy tamping, dynamic consolidation, and pounding (Mitchell 1981).

Reported by Lukas (1995), DDC has been used to improve different types of weak ground deposits including:

- loose, naturally occurring soils (e.g., alluvial soils);
- landfill deposits;
- building rubble and construction debris deposits;
- strip mine spoil;
- partially saturated clay fill deposits;
- metastable soils (i.e., loess);
- formations where large voids are present (i.e., karst terrane);
- liquefaction susceptible loose sands and silts; and
- nuclear waste.

Although DDC emerged as a compaction method in 1969 (Menard and Broise 1975), the concept of compacting soil by dropping a heavy weight has existed since the age of the Roman Empire (Kerisel 1985). Pre-modern DDC emerged during the 1930s from field studies performed in Germany (Loos 1936) and the United States (Corps of Engineers 1938). In 1969, Louis Menard developed the technique into its present state as a method of deep densification (Menard and Broise 1975).

DDC induced compaction for partly saturated soils is governed by the expulsion of air voids within the soil mass, similar to conventional compaction theory (Mitchell 1981; Elias et al. 2006). However for saturated soils, Menard (1975), Menard and Broise (1975), and

Gambin (1979) theorized that soil improvement from DDC results from a four mechanism process:

1. compression of air-filled "micro-bubbles";
2. liquefaction following repeated impacts and subsequent particle rearrangement;
3. increased permeability from the development of vertical radial tension cracks at each impact point; and
4. thixotropic recovery.

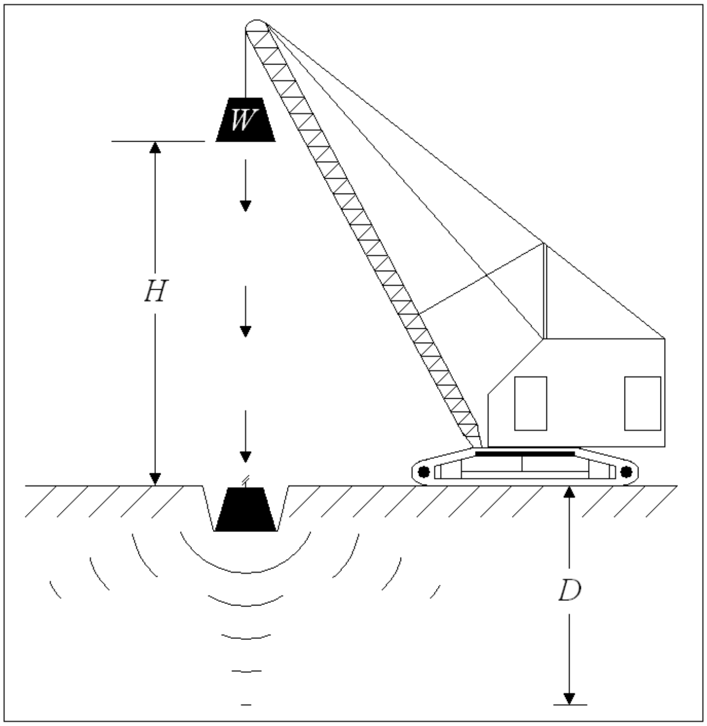


Figure 6. Deep Dynamic Compaction (DDC)

DDC Compaction Depth

From Menard and Broise (1975), Leonards et al. (1980), and Mayne et al. (1984), DDC compaction depth is a function of drop weight mass, drop height, and an empirical coefficient [Equation (1)].

$$D = n(WH)^{1/2} \tag{1}$$

where:

D = compaction depth in meters

W = mass of drop weight in tonnes

H = drop height in meters

n = empirical coefficient ($0.3 < n < 0.8$; $n = 0.5$ typical)

According to Lukas (1992), the empirical coefficient, n, accounts for factors including:

- cable drag;
- type and characteristics of deposit being compacted (e.g., soil type and degree of saturation);
- contact pressure of the drop weight; and
- the presence of energy absorbing layers (i.e., interbedded clay layer).

Because the capacity and maximum drop height of standard cranes are limited to 18.1 to 20 tonnes (20 to 22 tons) and 20 to 30 m (66 to 98 ft), respectively; compaction depths are practically limited to 10 to 12 m (33 to 39 ft) (Lukas 1986). When deeper compaction depths are required, specialty lifting equipment must be used such as the Menard Tripod (Gambin 1979).

DDC Degree of Compaction

DDC densifies the soil mass and this, in turn, improves soil shear strength and reduces compressibility. The resulting soil strength is typically linked to the degree of compaction. Degree of compaction from DDC is typically inferred from in situ test properties such as the standard penetration test (SPT) N-value, the cone penetration test (CPT) tip resistance, or the pressuremeter test (PMT) limit pressure. Degree of compaction upper bounds in terms of different in situ tests for multiple soil types are shown in Table 3 (Elias et al. 2006).

In order to achieve the specified degree of compaction, a sufficient amount of energy (applied energy) must be applied during DDC. The applied energy is generally given as the average energy applied over the entire area and can be calculated with equation (2) (Lukas 1995).

$$AE = \frac{(N)(W)(H)(P)}{(S)^2} \tag{2}$$

where:

AE = applied energy in tonne-m/m^2

N = number of drops at each impact point location

W = mass of drop weight in tonnes

H = drop height in m

P = number of passes

S = impact point spacing in m

Typical ranges of unit applied energy (applied energy per unit depth) for different soil types are shown in Table 4. The applied energy at the surface of the deposit can be obtained by multiplying the unit applied energy by the compaction depth (Lukas 1995).

Table 3. Upper bound in situ test values after DDC (from Elias et al. 2006)

Soil Type	Maximum Test Values		
	Standard Penetration Resistance (blows/300mm)	Static Cone Tip Resistance (MPa)	Pressuremeter Limit Pressure (MPa)
Pervious coarse-grained soil: sands and gravel	30–50	19–29	1.9–2.4
Semipervious soil:			
sandy silts	25–35	13–17	1.4–1.9
silts and clayey silts	20–35	10–13	1.0–1.4
Partially saturated impervious deposits: Clay fill and mine spoil	20–40*	N/A	1.0–1.9
Landfills	15–40*	N/A	0.5–1.0

**Higher test values may occur because of larger particles in the soil mass*

Table 4. Typical ranges of unit applied energy (from Lukas 1995)

Soil Type	Unit Applied Energy (kJ/m3)
Pervious coarse-grained soil	200–250
Semipervious fine-grained soils and clay fills above the water table	250–300
Land Fills	600–1100

DDC Vibrations

To determine whether or not threshold vibration levels will be exceeded during DDC, the particle velocities that will develop should be predicted before construction (Figure 7). Figure 7 presents peak particle velocity as a function of scaled distance for different soil types. The scaled distance incorporates the energy imparted into the ground from a single drop into the distance from the point of impact to the point of concern. Peak particle velocity is therefore a function of soil type, distance from the source, and the energy per blow (mass of drop weight and drop height) (Lukas 1995).

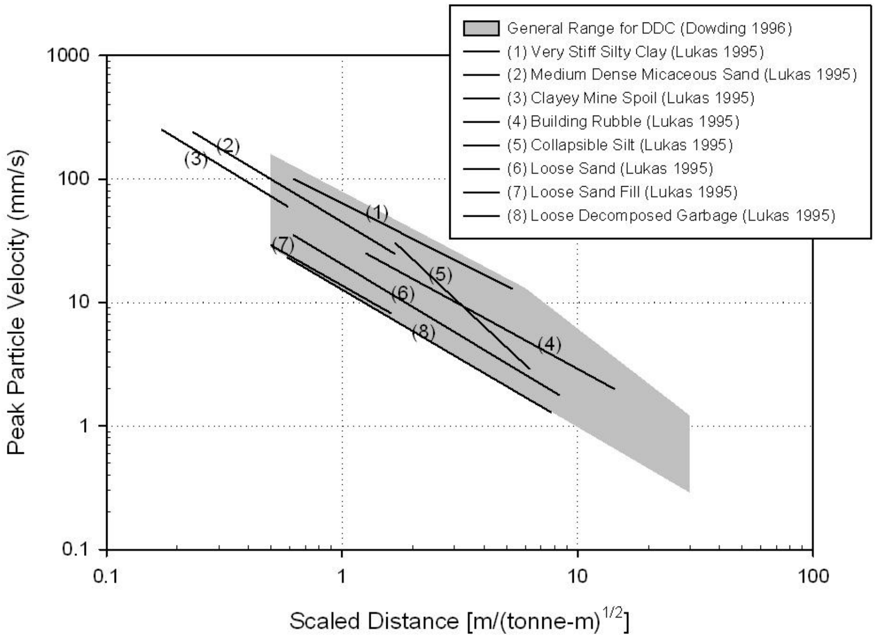


Figure 7. Peak particle velocity versus scaled distance for DDC (from Lukas 1995; Dowding 1996)

DDC Cost

According to Elias et al. (2006), the unit cost (including equipment mobilization) for DDC generally ranges from \$8–\$25/m^2 (\$0.75–\$2.30/SF). Projects requiring heavier drop weights cost more due to the requirement of larger cranes to support the larger drop weights. DDC projects typically have high equipment mobilization costs so relatively large areas have to be treated [greater than 10,000 m^2 (108,000 SF)] before the method becomes economic (Broms 1991).

Basic Principles of Soil Compaction

Soil compaction is the process by which a mass of soil consisting of solid soil particles, air, and water is reduced in volume by the momentary application of loads (e.g., rolling, tamping, etc.). Compaction generally increases its shear strength, decreases its compressibility, and decreases its permeability (Hilf 1991).

General relationships between soil type, moisture content, density (unit weight) and compactive effort are predictable. The compacted dry density generally increases as the moisture content increases (Figure 8). Beyond a certain moisture content (the optimum moisture content), any increase in the moisture content tends to reduce the dry density. The dry density at the optimum moisture content is defined as the maximum dry density.

Proctor (1933) first theorized that this relationship was caused by water lubricating the soil particles thereby reducing the energy needed to force the particles together. Excessive amounts of moisture would produce smaller dry densities because the space that would have been occupied by the soil particles would then be taken up by water. Research has shown, however, that soil compaction is rather complex and depends on, not only on soil lubrication, but capillary suction pressure, hysteresis, pore air pressure, pore water pressure, permeability, surface phenomena, and osmotic pressures as well (Hilf 1991).

As shown in Figure 8, different soil types have different dry density-moisture content compaction curves. A bell shaped curve is indicative of a clayey soil. Sandy soils tend to first have a decrease in dry density as moisture content increases and then have an increase in dry density to a maximum value with further increase of moisture content. This phenomenon is known as bulking. Bulking in sands occurs at relatively low moisture contents (approximately 5%) where small capillary stresses in the partially saturated soil tend to resist the compactive effort (Hilf 1991).

As the compactive effort is increased, the maximum dry density is increased while the optimum moisture content is decreased (Figure 9).

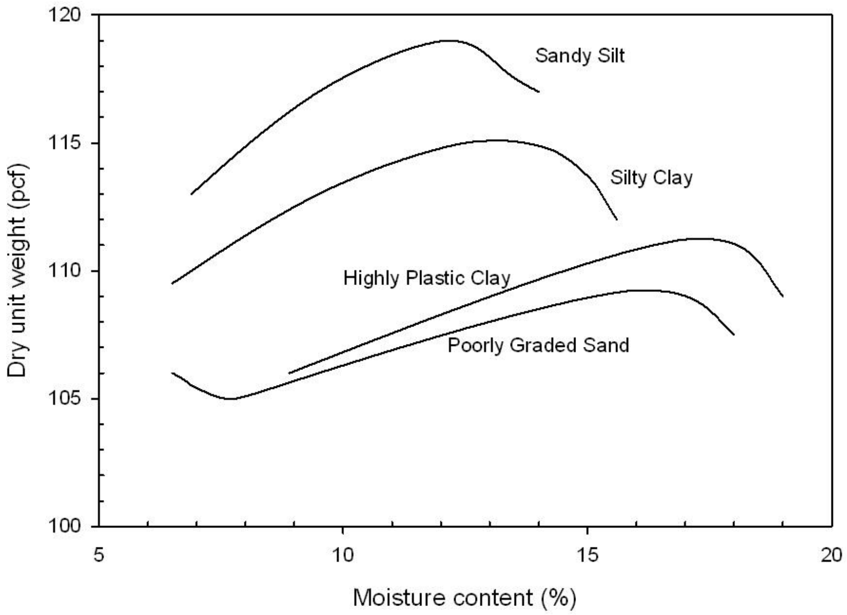


Figure 8. Typical compaction curves for different for different soil types compacted in accordance with ASTM D698 (from Das 2006)

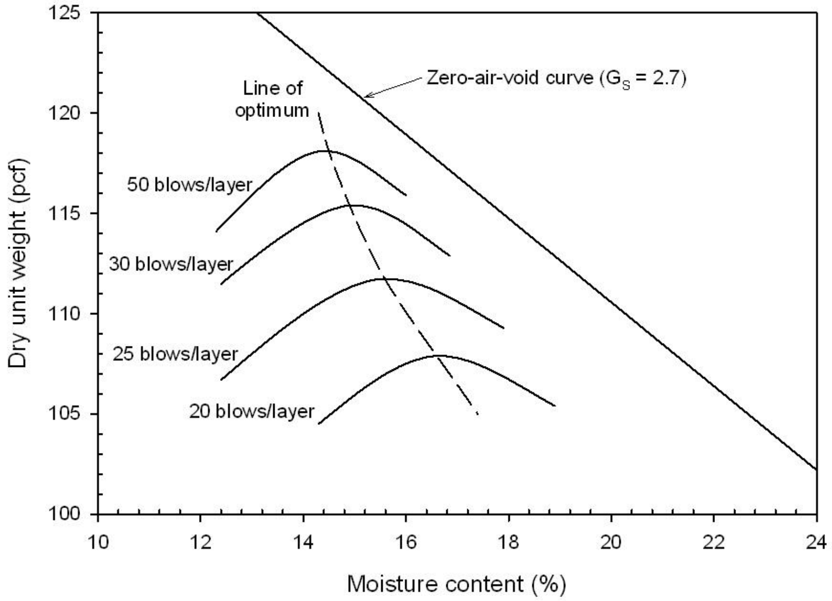


Figure 9. Effect of compactive effort using standard Proctor hammer on the compaction of a sandy clay (from Das 2006)

Compaction of Cohesionless Soils

Cohesionless soils are relatively clean sands and gravels that remain pervious even when well compacted. As a result, compaction curves for cohesionless soils can be less defined compared to cohesive soils. Contrary to the conventional compaction curve, cohesionless soils obtain high dry densities when the soil is either completely dry or saturated with somewhat lower dry densities (i.e., bulking) when the soil is partially saturated (Hilf 1991).

Since the traditional compaction curve is not typically applicable, relative density is the preferred compaction criterion. Introduced by Terzaghi (1925), relative density is defined by equation (3):

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{3}$$

where:

D_r = relative density in %

e_{max} = void ratio of the soil in its loosest state

e = void ratio of the soil being tested

e_{min} = void ratio of the soil in its densest state

Relative density can be expressed in terms of dry density as well [equation (4)]:

$$D_r = \frac{\rho_{d,max}(\rho_d - \rho_{d,min})}{\rho_d(\gamma_{d,max} - \rho_{d,min})} \tag{4}$$

where:

D_r = relative density in %

$\rho_{d,max}$ = dry density of the soil in its densest state

$\rho_{d,min}$ = dry density of the soil in its loosest state

ρ_d = dry density of the soil being tested

Das (2007) describes cohesionless soil deposits as being very loose, loose, medium, dense, or very dense based on relative density (Table 5).

Relative density in situ can be predicted from the standard penetration test N_{60} value (Table 6).

Compactibility is a measurement of how easily soils can be compacted. Compactibilty is calculated from equation (5) (Terzaghi 1925).

$$F = \frac{e_{max} - e_{min}}{e_{min}} \tag{5}$$

where:

F = compactibility

e_{max} = void ratio of the soil in its loosest state

e_{min} = void ratio of the soil in its densest state

A large value of compactibilty is indicative of a large increase in density upon introduction of compactive energy. It is a function of grading, grain size distribution, particle shape, and surface texture. The value can range from about 0.6 for poorly-graded sands to about 2.3 for well-graded gravels (Hilf 1991).

In most earthwork specifications, the contractor must achieve a field dry density relative to the maximum dry unit weight (relative compaction) determined from either ASTM D698 or ASTM D1557 (Das 2008). Relative compaction is defined in equation (6).

$$R = \frac{\gamma_d}{\gamma_{d,max}} \times 100 \qquad (6)$$

where:

R = relative compaction

γ_d = dry density of the soil being tested

$\gamma_{d,max}$ = dry density of the soil in its densest state (ASTM D698; ASTM D1557)

Although most transportation agencies prefer using the concept of relative compaction when specifying compaction, relative density is still the preferred compaction criterion. Lee and Singh (1971) therefore provided a correlation between relative compaction and relative density (equation 7).

$$R = 80 + 0.2D_r \qquad (7)$$

where:

R = relative compaction

D_r = relative density

Table 5. Description of cohesionless soil deposits based on relative density (from Das 2006)

Relative Density (D_r)	**Description of soil deposit**
0–15%	Very loose
15–50%	Loose
50–70%	Medium
70–85%	Dense
85–100%	Very Dense

Table 6. Relative density of sands according to results of standard penetration test (from Terzaghi et al. 1996)

SPT-N_{60}	Relative Density
0–4	Very Loose
4–10	Loose
10–30	Medium
30–50	Dense
>50	Very dense

Shear Strength of Compacted Cohesionless Soils

The Mohr-Coulomb failure criterion (Figure 10) is a commonly used model to describe the shear strength of soil. This model is defined as in equation (8):

$$\tau_f = c' + \sigma' tan\phi' \qquad (8)$$

where:

τ_f = shear strength

c' = drained cohesion

σ' = effective stress

ϕ' = drained angle of internal friction

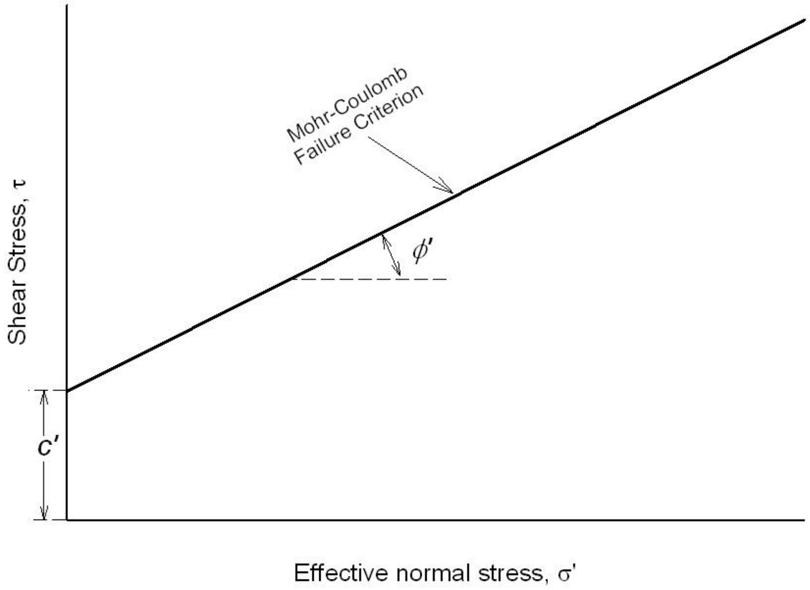


Figure 10. The Mohr-Coulomb Failure Criterion

Since cohesionless soils have negligible drained cohesions, the drained angle of internal friction is the governing parameter in the shear strength of cohesionless soils. With no drained cohesion, the shear strength of cohesionless soils at low normal stresses (confining pressures) is quite low.

Parameters that affect the shear strength of cohesionless soils include:

- particle size and distribution;
- particle shape (i.e., angularity);
- particle hardness; and
- particle stiffness (Mitchell and Soga 2005).

Loose sands and gravels are known to have less resistance to shear than the same soils in a dense state. Relative density is directly proportional to drained angle of internal friction (Hilf 1991).

The shear strength of cohesionless soils is highly dependent on confining pressure. To determine shear strength parameters in situ, raw data should be corrected to correspond to a standard confining pressure. In the case of the standard penetration test (SPT) for example, the N-value is corrected by multiplying it by a correction factor. Correction factors have been proposed by Liao and Whitman (1986) [equation (9)] and Skempton (1986) [equation (10)].

$$C_N = \left[\frac{1}{\left(\frac{\sigma'_0}{p_a}\right)}\right]^{0.5} \tag{9}$$

where:

C_N = correction factor
σ'_0 = effective overburden pressure (confining pressure)
p_a = atmospheric pressure

$$C_N = \frac{2}{1+\left(\frac{\sigma'_0}{p_a}\right)} \tag{10}$$

where:

C_N = correction factor
σ'_0 = effective overburden pressure (confining pressure)
p_a = atmospheric pressure

GeoStatistical Analysis

Olea (1999) defines geostatistics as “a collection of numerical techniques that deal with the characterization of spatial attributes, employing primary random models in a manner similar to the way in which time series analysis characterizes temporal data.”

The Semivariogram $\gamma(h)$ is used to describe spatial relationships in earth science applications (e.g., Vennapusa et al. 2010; Iqbal et al. 2005). As cited in Vennapusa et al. (2010), Isaaks and Srivastava (1989) define the semivariogram as one-half of the average squared differences between data values that are separated at a distance h. If the semivariogram calculation is repeated for as many different values of *h* as the sample will support, then the result can be graphically presented as the experimental semivariogram plot (Figure 11).

From Olea (2006), the mathematical expression to estimate the experimental semivariogram is [equation (11)]:

$$\hat{\gamma}(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2 \qquad (11)$$

where:

$z(x_i)$ = measurement taken at location x_i

$n(h)$ = number of data pairs h units apart in the direction of the vector

$\hat{\gamma}$ = experimental estimate of the underlying variogram function γ

A semivariogram plot is summarized by three characteristics, which include the range (a), the sill (C_0+C), and the nugget effect (C_0) (Isaaks and Srivastava, 1989). The range is described as the separation distance at which the semivariogram plateaus. The sill is the value of the semivariogram plateau. According to Srivastava (1996), a semivariogram (which is one-half of the variogram) generally has a sill that is approximately equal to the variance of the data. The nugget effect is described as a discontinuity at the origin of the semivariogram. Although the value of the nugget effect at a separation distance of zero is strictly equal to zero, factors such as sampling error or very short scale variability may cause sample values separated by extremely short distances to be quite dissimilar (Vennapusa et al. 2010).

The major purpose of fitting a theoretical model to the experimental semivariogram is to give an algebraic formula for the relationship between values at specified distances (Vennapusa et al. 2010). Commonly used theoretical semivariogram models are presented in Table 7 [equations (12), (13), (14), (15), (16), (17), (18). (19) ,(20)].

Table 7. Commonly used theoretical semivariogram models (from Vennapusa et al. 2010)

Model Name	Mathematical Expression	
Linear	$\gamma(0) = 0$ $\gamma(h) = nC_0 + ph, when\ h > 0$	(12) (13)
Spherical	$\gamma(0) = 0$ $\gamma(h) = C + C_0\left[\frac{3h}{2a} - \frac{h^3}{2a^3}\right]\ when\ 0 < h < a$ $\gamma(h) = C_0 + C, when\ h > a$	(14) (15) (16)
Exponential	$\gamma(0) = 0$ $\gamma(h) = C_0 + C\left[1 - exp\left(-\frac{h}{a}\right)\right]\ when\ h > 0$	(17) (18)
Gaussian	$\gamma(0) = 0$ $\gamma(h) = C_0 + C\left[1 - exp\left(-\frac{h^2}{a^2}\right)\right]\ when\ h > 0$	(19) (20)

Where:

γ = semivariogram
p = slope of the line
n = number of data pairs
h = separation distance
a = range
C_0 = nugget effect
$C + C_0$ = sill

Coupled with the procedure of Kriging, geostatistics can be used as a spatial prediction technique i.e. to predict values at unsampled locations based on values at sampled locations. Kriging is a stochastic interpolation procedure by which the variance of the difference between the predicted and "true" values is minimized using a semivariogram model (Krige 1951). Contour maps of the desired values can be developed from the Kriging analysis.

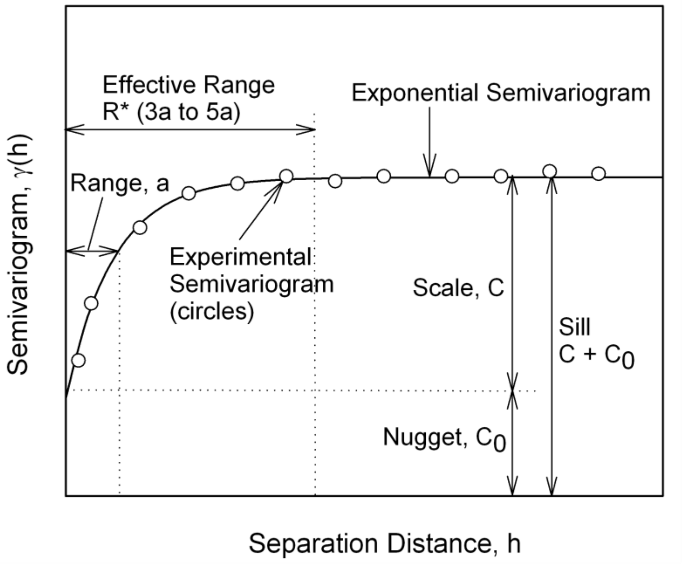


Figure 11. Typical sample semivariogram (from Vennapusa et al. 2010)

CHAPTER 3. CURRENT STATE OF PRACTICE FOR COMMERCIAL CONSTRUCTION APPLICATIONS

This chapter provides a summary of procedures and techniques for implementing rapid impact compaction in the United States. The following information presented includes design and construction procedures, case histories, results of vibration studies, and cost information. The information within this chapter was provided by GeoStructures, Inc. (Ed O'Malley, personal communication).

RIC Implementation

Four contractors have performed RIC projects in the United States:

- GeoStructures, Inc. (GeoConstructors, Inc.)
- Farrell Design-Build Companies, Inc.
- DGI-Menard, Inc.
- Hayward Baker, Inc.

Locations of reported RIC project sites are presented in Figure 12. RIC projects within the United States have exclusively involved the improvement of loose foundation soils. Project sizes have ranged from approximately 930 to 46,000 m^2 (10,000 to 500,000 SF).

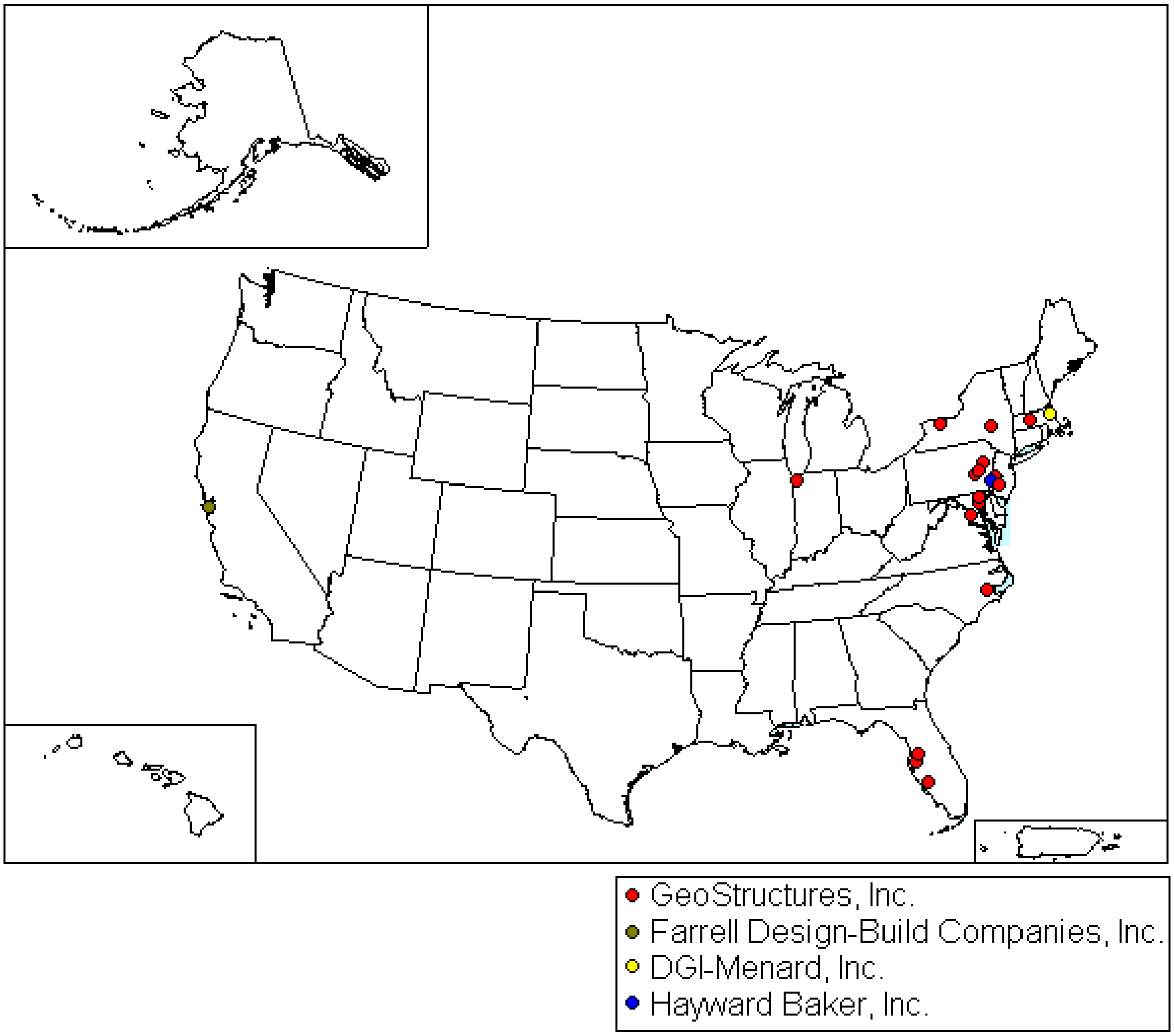


Figure 12. Reported RIC project sites in the United States

Current RIC Design and Construction Procedures

RIC design is a qualitative procedure. A client seeking soil improvement for a site contacts an RIC contractor for a consultation. Based on the site's preexisting standard penetration values (SPT-N_{60} values), soil type(s), and stratigraphy; the RIC contractor assesses whether or not RIC is capable of meeting the client's soil improvement requirements. Discussion between the client and the RIC contractor concerning the client's needs and the capability of RIC results in a minimum RIC criterion [e.g. SPT-N_{60} value of 15 to a depth of 4.6 m (15 ft)]. Following assessment and evaluation of RIC criterion and consultation with the client, the RIC contractor the RIC contractor develops a written specification and a proposed impact point layout for the site. An example specification is provided in Appendix G.

RIC contractors in the United States typically use an RIC unit equipped with a 7 tonne (7.5 ton) drop weight that can fall from a maximum height of 1.2 m (4 ft).

In the United States, RIC is nearly always produced in the same square impact point pattern (Figure 3; Chapter 2) over the entirety of the site (Figure 13). Compaction continues at each impact point until one of the following three compaction criteria is met:

- a minimum final set value (determined from *compaction trial*; usually 5 mm);
- a total penetration of 0.8 m (the limiting depth allowed by boom on RIC unit); or
- a total of 99 blows applied (the limiting readout of data acquisition system).

If the minimum set criterion is met first, then the RIC unit is moved to the next impact point. If either the total penetration criterion or the total number of blows criterion is met first, then the impact point is backfilled with a select granular fill (less than 15% fines) and the compaction process is repeated for a second pass. If compaction fails to achieve the minimum set criterion after the second pass, then the impact point is backfilled again and a third pass commences. If the RIC unit still has failed to meet the minimum set criterion after three passes, then RIC at that impact point is ended and additional improvement or overexcavation and replacement may be required. This process is repeated across the site for sequence one points, followed by sequence two points and finally sequence three points. Verification, usually by standard penetration test, concludes the RIC process.

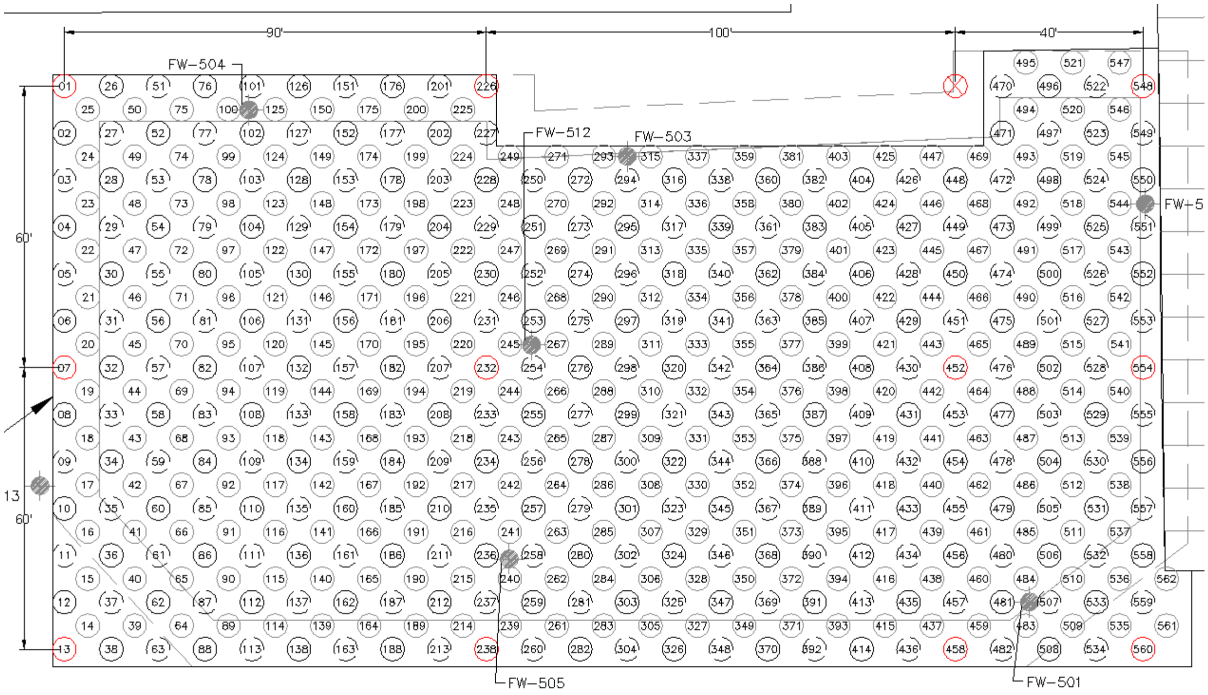


Figure 13. Example RIC impact point layout

RIC Case Histories

The following section pertains to case histories of RIC within the commercial construction sector. A total of 10 case histories are presented. Each case history has standard penetration testing (SPT) data subsequent to RIC. The majority of case histories have a general description of the project (e.g., design considerations, subsurface conditions, etc.). Relative density descriptions from SPT-N_{60} values are interpreted from Terzaghi et al. (1996). In addition, a summary table of all the case histories is provided (Table 8).

Average depths of compactions were approximated by comparing the weighted average post-compaction SPT-N_{60} values post-compaction to the weighted average pre-compaction SPT-N_{60} values. A sample spreadsheet is provided in Appendix A. The depth at which the average post-compaction SPT-N_{60} value no longer exceeds the average pre-compaction SPT-N_{60} value is the average depth of compaction.

Table 8. Summary of RIC case histories

Case History	Average Depth of Compaction	Average SPT-N60 (Weighted Average)		$\frac{\text{Post RIC SPT } N_{60}}{\text{Pre RIC SPT } N_{60}}$	Soil Type
		Pre-RIC	Post-RIC		
Philadelphia, PA	*	*	16 (medium D_R)**	*	Miscellaneous debris fill
Land O'Lakes, FL	6.5 m (21 ft)	16 (medium D_R)**	27 (medium D_R)**	1.7	Sand
Tampa, FL	5.0 m (16 ft)	11 (medium D_R)**	18 (medium D_R)**	1.6	Sand
Pasadena, MD	4.0 m (13 ft)	9 (loose D_R)**	13 (medium D_R)**	1.4	Sand (SP/SM/SP-SM)
Punta Gorda, FL	5.9 m (19.5 ft)	8 (loose D_R)**	18 (medium D_R)**	2.2	Sand
Glen Burnie, MD	4.1 m (13.5 ft)	9 (loose D_R)**	20 (medium D_R)**	2.2	Sand (SP)
Reading, PA (I)	6.5 m (21 ft)	12 (medium D_R)**	27 (medium D_R)**	2.2	Miscellaneous debris fill; Sand
Easton, PA	7.5 m (24.5 ft)	10 (loose D_R)**	18 (medium D_R)**	1.8	*
Reading, PA (II)	3.5 m (11.5 ft)	22 (medium D_R)**	23 (medium D_R)**	1.0	*
Rochester, NY	1.5 m (5 ft)	13 (medium D_R)**	11 (medium D_R)**	0.9	*

*Information not provided
**Terzaghi et al. (1996)

Philadelphia, PA

The project involved the construction of condominium units in Philadelphia, PA. The site was underlain by scattered areas of debris fills [0.6 to 2.7 m (2 to 9 ft) below the ground surface], which would have required extensive overexcavation and replacement. The debris fill comprised silty sand to sandy silt with miscellaneous debris (e.g. bricks, concrete, rock fragments, etc.). RIC was used to increase the fill's shear strength to support the 190 kPa (4 ksf) loading from the continuous wall footings. A set of six SPTs were performed following RIC to evaluate the degree of compaction (Figure 14).The post-RIC average SPT-N_{60} was 16 (medium relative density).

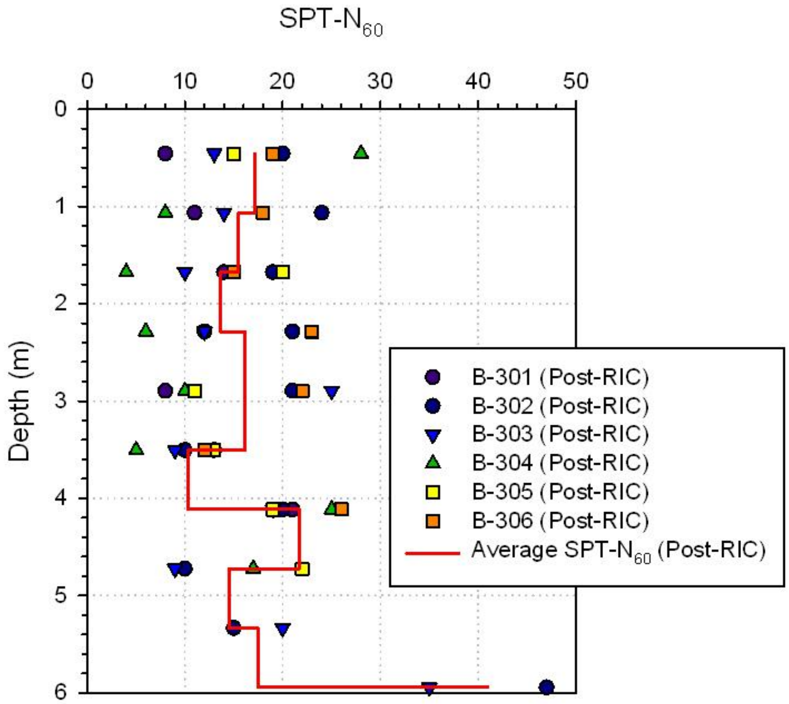


Figure 14. Post RIC SPT N_{60} values (Philadelphia, PA)

Land O'Lakes, FL

The project entailed the construction of a two-story school in Land O'Lakes, FL. The site was underlain by a 3.0 to 6.1 m (10 to 20 ft) thick deposit of loose sands. RIC was employed to improve the soils enough to support the heavily loaded [3200 kN (720 kip)] footings of the structure. Degree and depth of compaction was verified by cone penetration testing with tip resistance values converted to SPT-N_{60} values (Figure 15). The correlation used was not provided. The compaction depth was approximately 6.5 m (21 ft) and the average SPT-N_{60} value increased from 16 (medium relative density) to 27 (medium relative density).

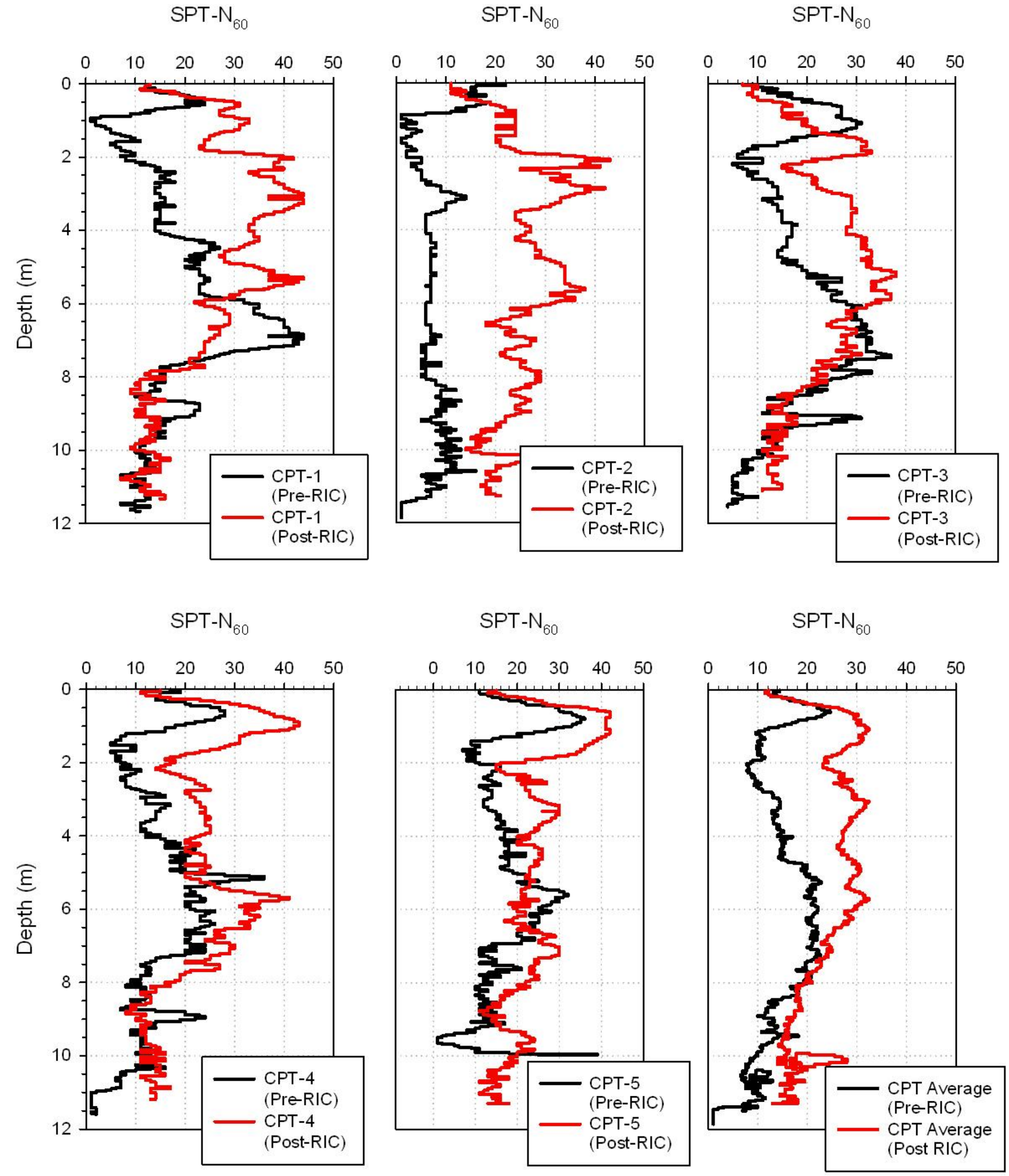


Figure 15. Comparison of pre- and post-RIC equivalent SPT-N_{60} values (Land O'Lakes, FL)

Tampa, FL

This project comprised the construction of a large tank on a site composed of loose sands. Investigations revealed that the sands were susceptible to excessive total and differential settlements. RIC was utilized to densify, thereby stabilizing the loose foundation soils. SPT-N_{60} values determined the post-RIC depth and degree of compaction (Figure 16). The compaction depth was approximately 5.0 m (16 ft) and the average SPT-N_{60} value increased from 11 (medium relative density) to 18 (medium relative density).

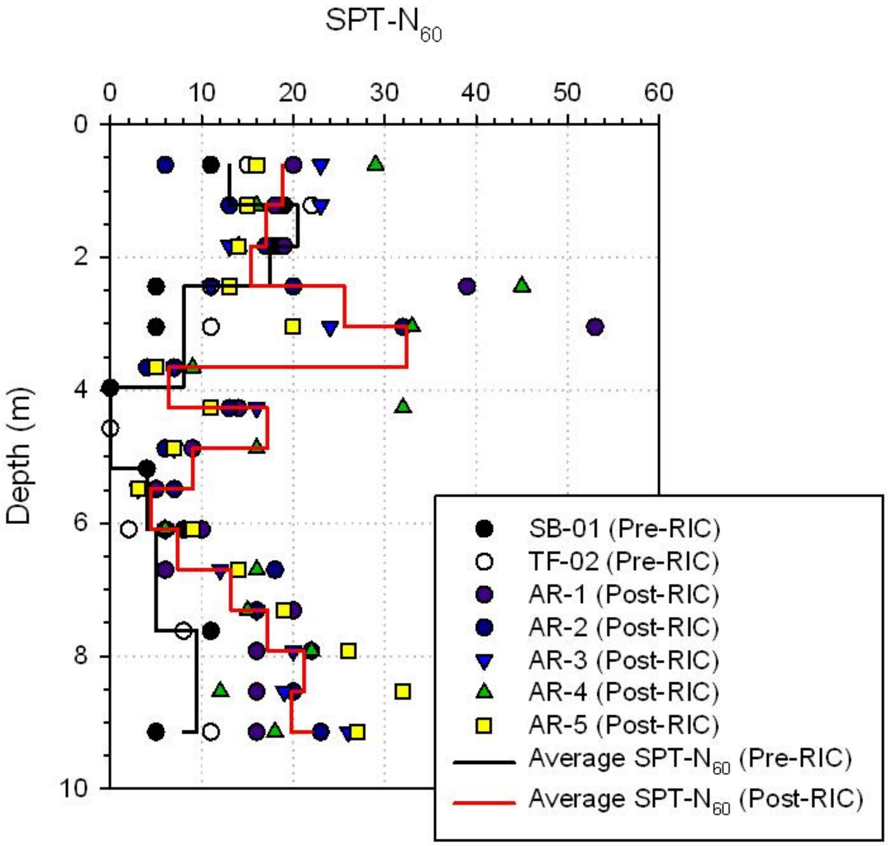


Figure 16. Comparison of pre- and post-RIC SPT-N_{60} Values (Tampa, FL)

Pasadena, MD

An elementary school was proposed for a site underlain by a loose sand deposit. The sand deposit comprised poorly graded sand (SP), silty sand (SM), and poorly graded sand with silt (SP-SM). It extended to a depth from about 1.5 to 6.1 m (5 to 20 ft) below the ground surface and overlaid a hard stratum. RIC was selected as the soil ground improvement method for the project with the SPT as the verification method. The RIC contractor was required to compact the soil such that an SPT-N_{60} value of 10 extended to 3.0 m (10 ft) below the ground surface. A comparison of before and after SPT-N_{60} values are provided in Figure 17. The compaction depth was approximately 4.0 m (13 ft) (the depth to the hard stratum) and the average SPT-N_{60} value increased from 9 (loose relative density) to 13 (medium relative density).

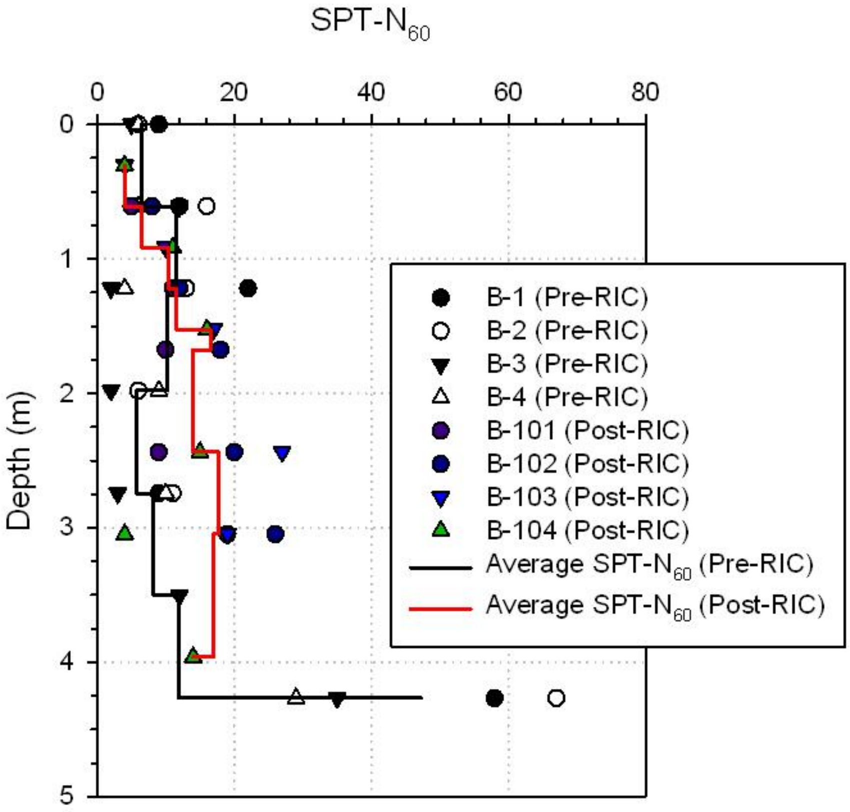


Figure 17. Comparison of pre- and post-RIC SPT-N_{60} Values (Pasadena, FL)

Punta Gorda, FL

The project consisted of the construction of a hotel in Punta Gorda, FL. The site comprised loose sands that were susceptible to excessive settlements. In order to minimize settlement of the structure, RIC was performed over the building footprint. The RIC contractor was required to achieve a 4.0 m (13 ft) deep compaction depth. SPTs verified the depth and degree of compaction (Figure 18). The compaction depth was approximately 5.9 m (19.5 ft) (end of boring) and the average SPT-N_{60} value increased from 8 (loose relative density) to 18 (medium relative density).

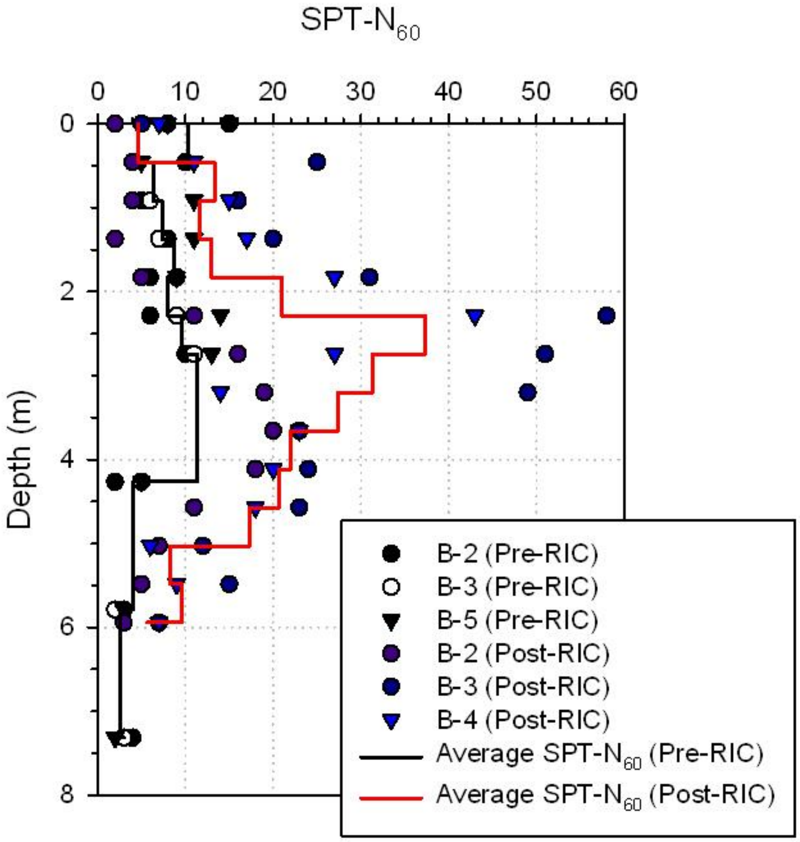


Figure 18. Comparison of pre- and post-RIC SPT-N_{60} Values (Punta Gorda, FL)

Glen Burnie, MD

This project involved the construction of an elementary school in Glen Burnie, MD. A stratum of loose sand (SP) existed from approximately 1.8 to 4.3 m (6 to 14 ft) below the ground surface. The loose sand was underlain by a layer of dense sand. An SPT-N_{60} value of 10 to a depth of 3.0 m (10 ft) was required to provide adequate support for the structure. RIC was utilized to compact the loose sand thereby increasing the SPT-N_{60} value. Comparisons of pre- and post-RIC SPT-N_{60} values are presented in Figure 19. The compaction depth was approximately 4.1 m (13.5 ft) and the average SPT-N_{60} value increased from 9 (loose relative density) to 20 (medium relative density). There was no significant improvement to approximately 1.2 to 1.5 m (4 to 5 ft) below the ground surface.

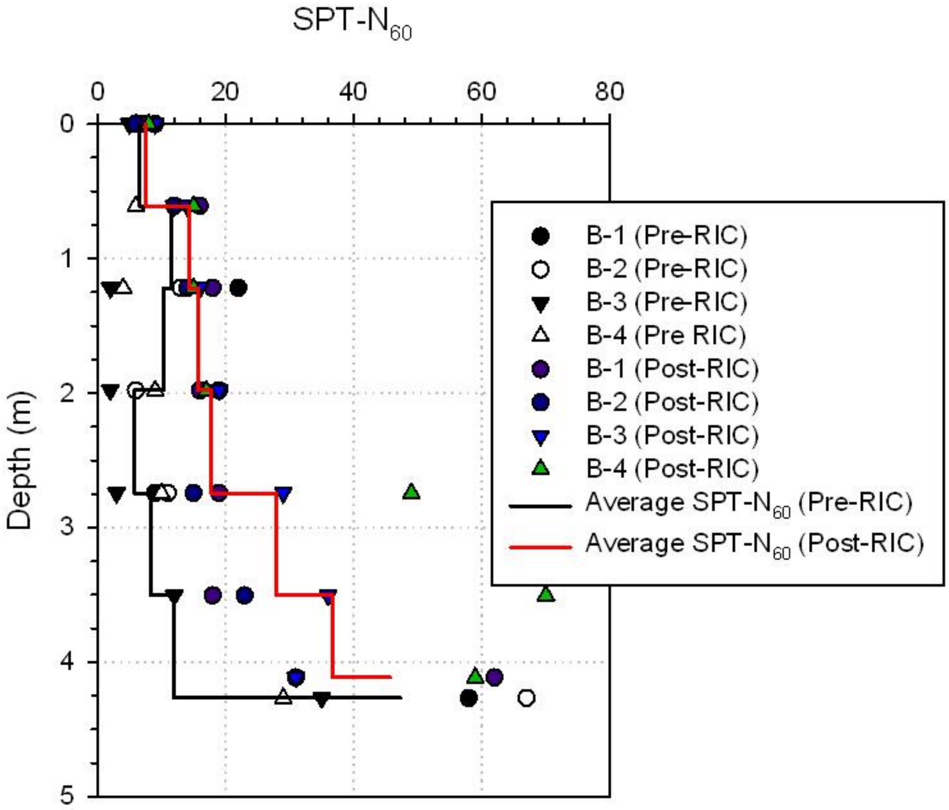


Figure 19. Comparison of pre- and post-RIC SPT-N_{60} Values (Glen Burnie, MD)

Reading, PA (I)

This project entailed the construction of a warehouse facility in Reading, PA. The site was underlain by miscellaneous fill material (on site soil, metal, brick concrete, etc.) which extended to a depth ranging from 1.8 to 6.9 m (6 to 22.5 ft). A layer consisting of fine sand with silt, clay and rock fragments existed below the miscellaneous fill. The geotechnical engineer determined that the fill was unsuitable to support the proposed construction and recommended that it be improved. RIC was utilized to compact the fill and SPTs were used to verify that the appropriate improvement had been achieved. Comparisons of the pre- and post-RIC SPT-N_{60} values are shown in Figure 20. The depth of compaction was approximately 22 ft. Post-RIC SPT-N_{60} values ranged from 20 to 40. The compaction depth was approximately 6.5 m (21 ft) and the average SPT-N_{60} value increased from 12 (medium relative density) to 27 (medium relative density).

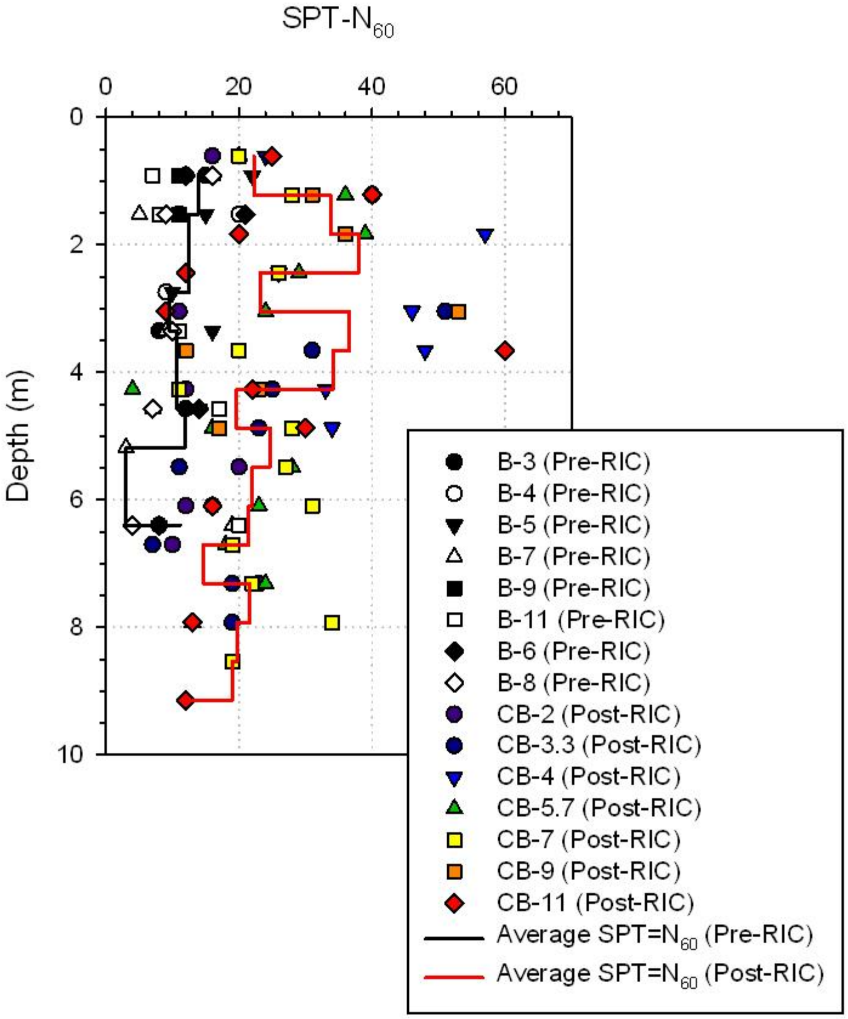


Figure 20. Comparison of pre- and post-RIC SPT-N_{60} Values [Reading, PA (I)]

Additional Projects

Three additional RIC case histories are presented in Figure 21. The information provided on these case histories was limited to the pre- and post-compaction SPT-N_{60} values. The projects are identified as Easton, PA (Figure 21a), Reading, PA (II) (Figure 21b), and Rochester, NY (Figure 21c).

In the Easton, PA case history, the compaction depth was approximately 7.5 m (24.5 ft) and the average SPT-N_{60} value increased from 10 (loose relative density) to 18 (medium relative density).

In the Reading, PA (II) case history, the compaction depth was approximately 3.5 m (11.5 ft) and the average SPT-N_{60} value increased from 22 (medium relative density) to 23 (medium relative density).

In the Rochester, NY case history, the compaction depth was approximately 1.5 m (5 ft); however because compaction loosed the topmost layer of soil the average SPT-N_{60} value decreased from 13 (medium relative density) to 11 (medium relative density). Although a description of the soil type was not provided, it is possible that the site was underlain by a material that did not respond well to RIC.

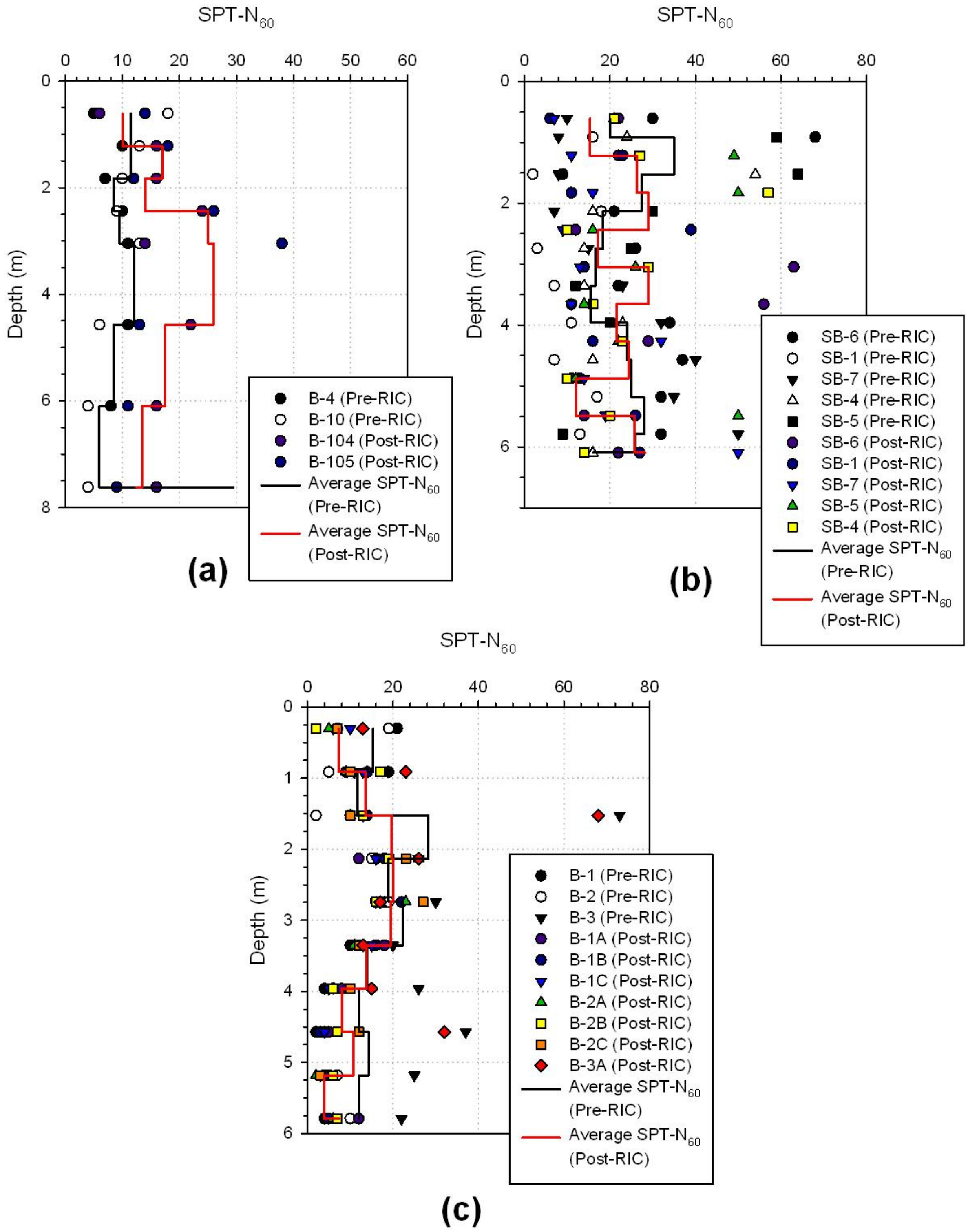


Figure 21. Comparison of pre- and post-RIC SPT-N$_{60}$ Values for (a) Easton, PA; (b) Reading, PA (II); and (c) Rochester, NY

RIC Induced Vibrations

Results of RIC induced vibration studies are provided and discussed in the following section. Project sites include those within the United States, Canada, and the United Kingdom. Peak particle velocities from the different projects with distance from the RIC unit are presented in Figure 22.

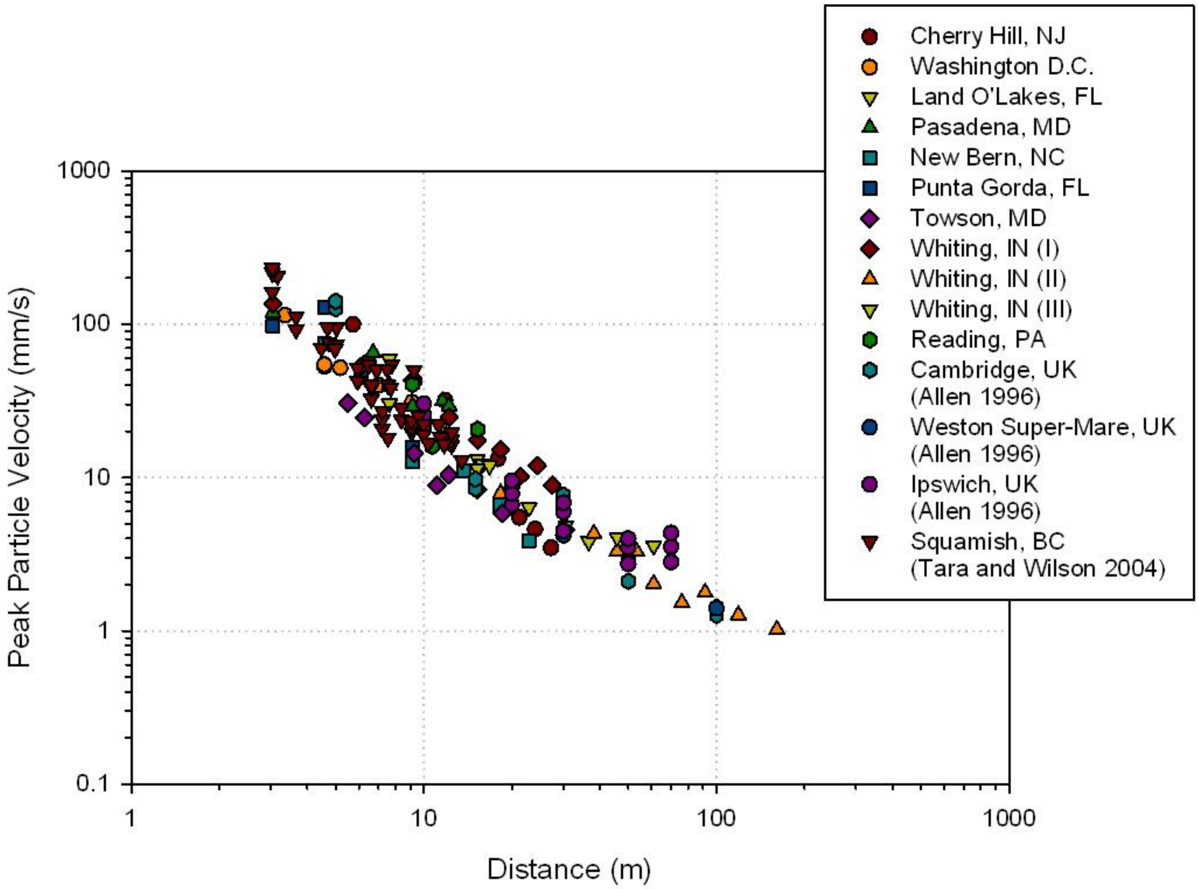


Figure 22. Peak particle velocities with distance for RIC

Since the average energy per blow for each RIC project differed, the distances from the RIC unit for each project are normalized to scaled distances (distance per square root of energy per blow) (Figure 23). Peak particle velocity and scaled distance follow an inverse power relationship.

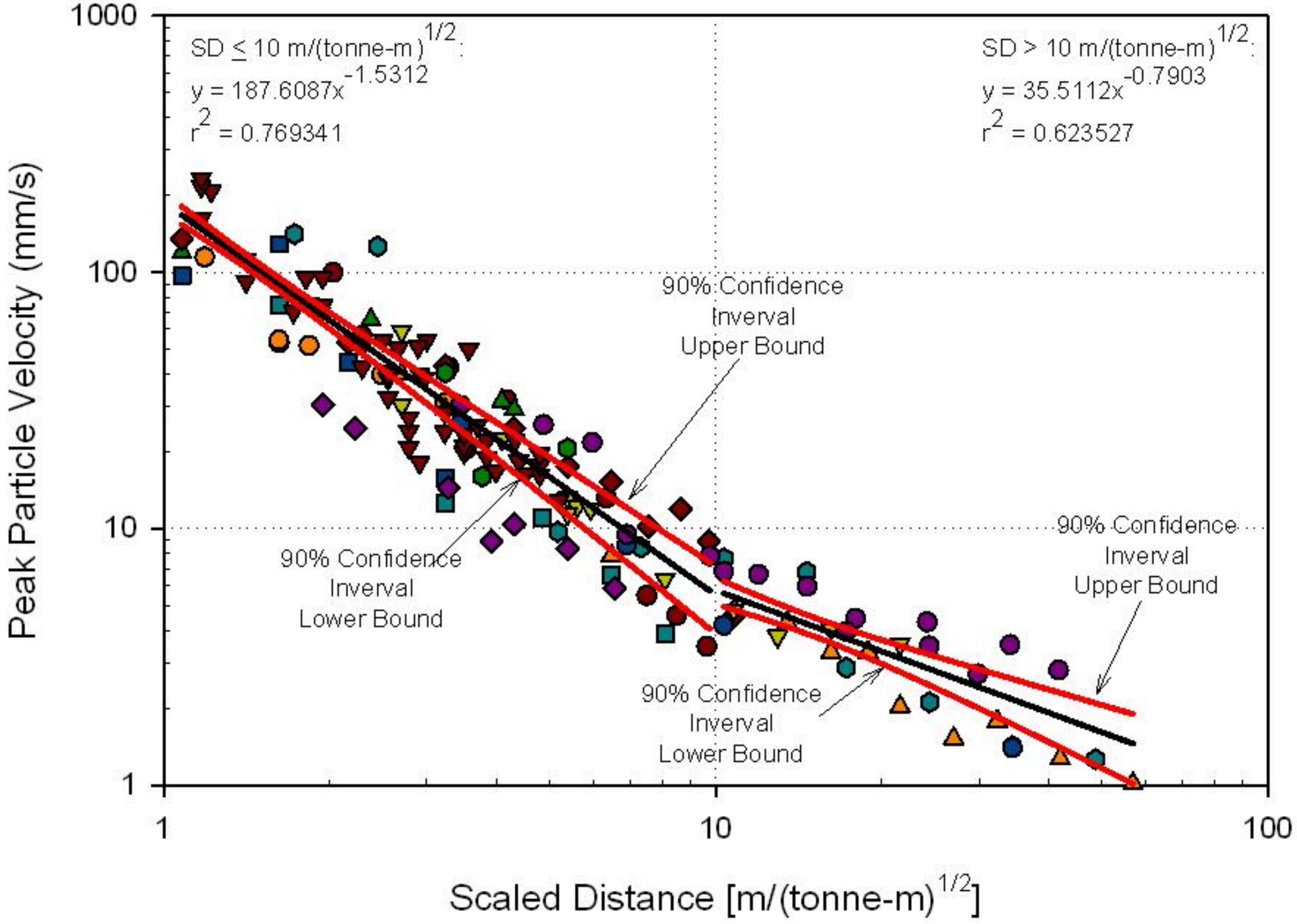


Figure 23. Relationship between peak particle velocities and scaled distance for RIC

From Figure 23, scaled distance is correlated to peak particle velocity by equations (21) and (22).

$$PPV=188SD^{-1.53} \quad [SD\leq 10\ m/(tonne\text{-}m)^{1/2}] \qquad (21)$$

where:

PPV = peak particle velocity in mm/s

SD = scaled distance in m/(tonne-m)$^{1/2}$

$$PPV=35.5SD^{-0.79} \quad [SD>10\ m/(tonne\text{-}m)^{1/2}] \qquad (22)$$

where:

PPV = peak particle velocity in mm/s

SD = scaled distance in m/(tonne-m)$^{1/2}$

A comparison between RIC and DDC induced peak particle velocities are presented in Figure 24. It is evident from Figure 24 that RIC produces greater magnitude peak particle velocities in terms of scaled distance than DDC. Tara and Wilson (2004) suggested that the higher peak particle velocities with RIC result from the RIC anvil always maintaining contact with the ground thus providing a more efficient energy transfer. Despite the greater magnitude peak particle velocities with RIC than with DDC, the safe working distance from existing structures remains typically larger with DDC since the energy per blow is greater.

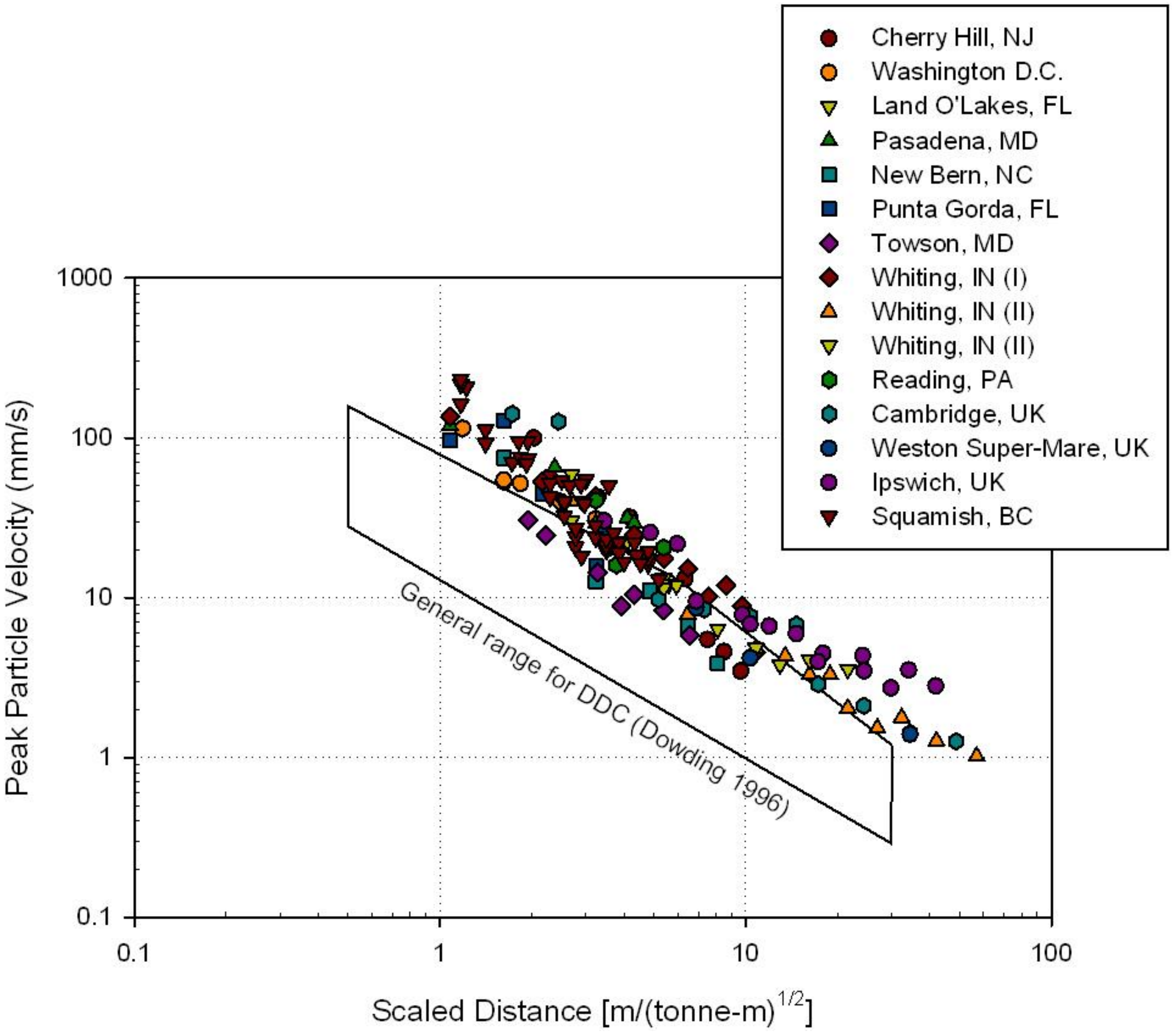


Figure 24. Comparison of RIC and DDC induced vibrations

Allen (1996) reported that the vibration frequencies produced during RIC range from 9 to 15 Hz. With guidelines from Siskind et al. (1980), peak particle velocity thresholds for RIC are presented in Table 9.

Table 9. Peak particle velocity thresholds for RIC

Structure Type	Peak Particle Velocity Threshold (mm/s)
Drywall Structures	19
Plaster Structures	13
All other Structures	51

With the upper bound of the 90% percent confidence interval for the plot of peak particle velocity and scaled distance in Figure 24, assuming a drop weight mass of 7 tonnes with a drop height of 1.2 m, maximum safe working distances for different structure types are presented in Table 10.

Table 10. Maximum safe RIC working distances for different structure types

Structure Type	Maximum safe working distance for RIC
Drywall Structures	14.5 m (47.6 ft)
Plaster Structures	19.0 m (62.3 ft)
All other Structures	7.2 m (23.6 ft)

The safe working distances provided in Table 10 only apply when site soils are similar to those analyzed in Figure 22, 23, 24. Since peak particle velocity is a function of material stiffness, safe working distances are expected to be larger for sites underlain by stiffer materials.

RIC Cost

The relationship between total RIC costs and compaction area for different projects within the United States are presented in Figure 25. It is evident from Figure 25 that total RIC cost is linearly related to compaction area and that RIC cost can be broken down to a mobilization cost (y-intercept) and unit cost (slope). RIC costs in the United States therefore are approximately:

- $37,000 mobilization

- \$9.7 per m^2 (\$0.90 per SF)

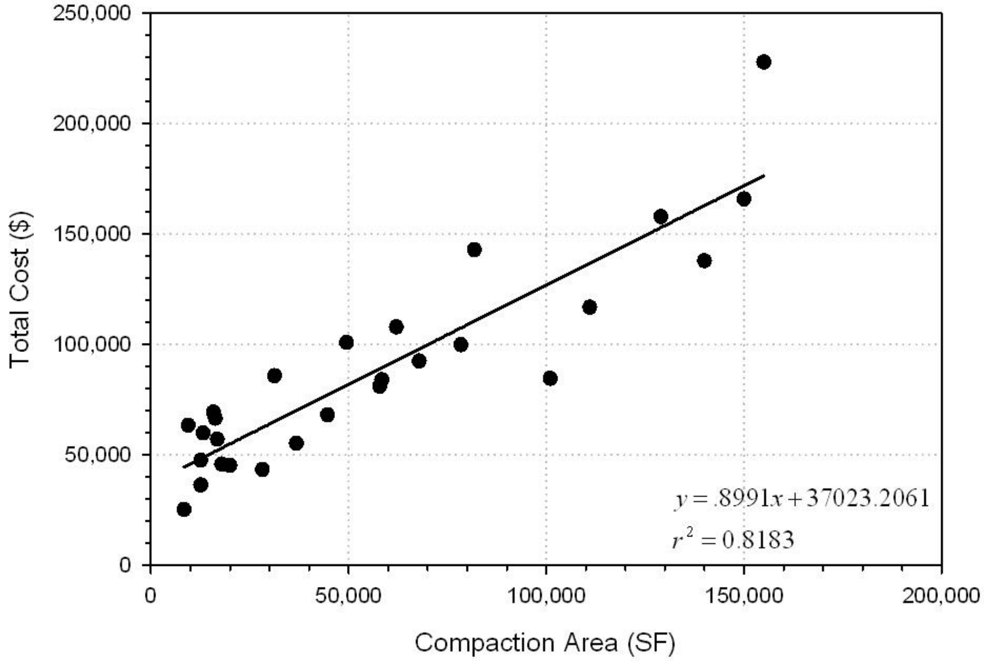


Figure 25. Relationship between total RIC cost and compaction area

RIC costs compared with DDC costs are presented in Figure 26. RIC can be economically utilized on projects with compaction areas less than 10,000 m^2 (108,000 SF) unlike with DDC. RIC total costs are comparable to DDC total costs.

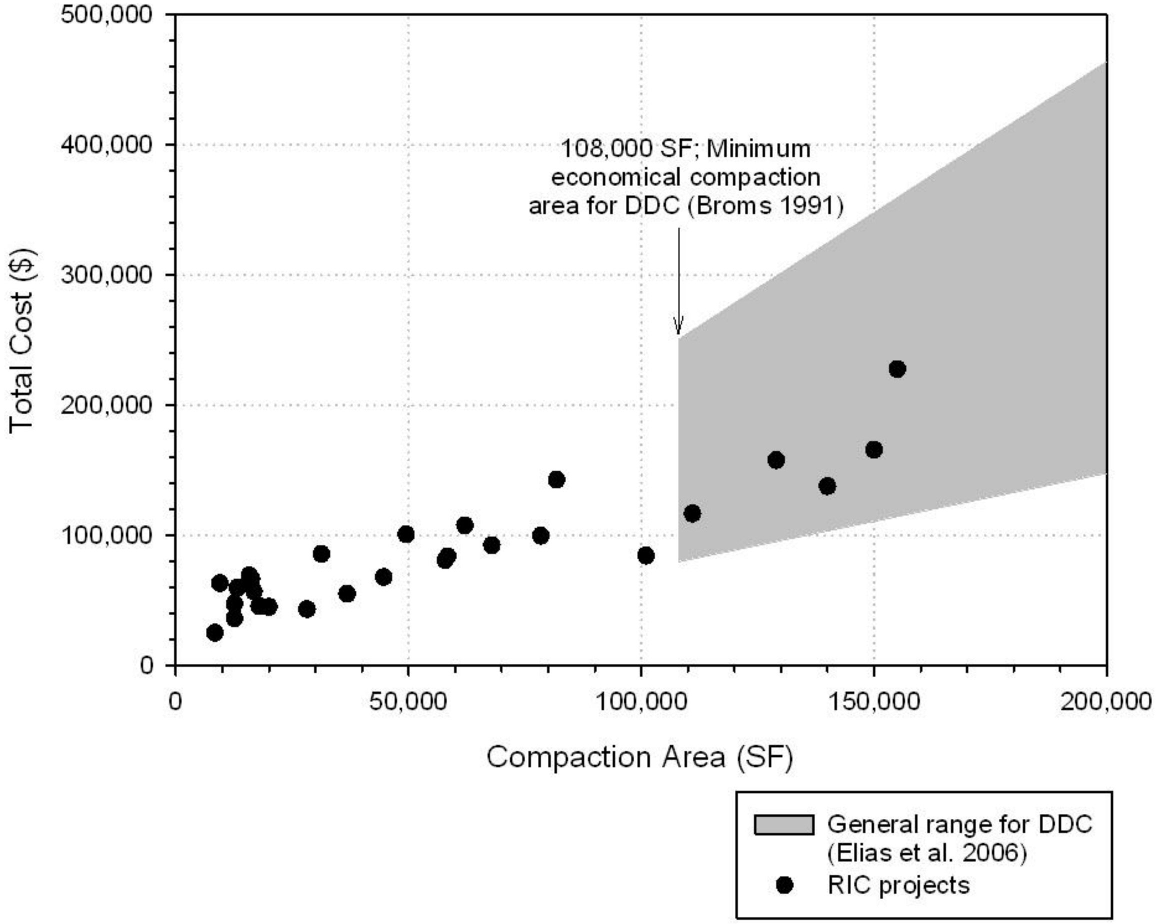


Figure 26. Comparison of RIC and DDC total costs

CHAPTER 4. TEST METHODS AND MATERIALS

This chapter summarizes the field and laboratory test methods employed in the research as well as the materials that were subjected to the testing. Test standards or detailed test procedures are provided. Materials were tested for gradations properties, strength parameters, and compaction properties.

Grain-size Analysis

ASTM D422-63(2002) *Standard Test Method for Particle-Size Analysis of Soils* was followed to conduct the grain-size distribution test. The prepared samples were divided into two portions by the No.10 sieve. Sieve analysis was performed on the portion washed and retained on No. 10 sieve and hydrometer analysis was conducted on the portion passing the No. 10 sieve using a 152 H hydrometer. After finishing the hydrometer test, the suspended material was washed through the No. 200 sieve, oven dried, and then sieved through the No. 40 and No. 100 sieves. Due to a lack of material, approximately 800 g of material was used for each sample as opposed to the standard 2000 g.

Moisture Content Analysis

Field Moisture contents were obtained in accordance with ASTM D2216-10 *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*.

Compaction Tests

Minimum Dry Unit Weight

ASTM D4254-83 *Standard Test Methods for Minimum Index Density of Soils and Calculation of Relative Density* was followed when determining the minimum dry unit weights. A 2830 cm^3 volume mold in conjunction with method A of ASTM D454-83 was used for all samples (Figure 27).

Maximum Dry Unit Weight

ASTM D4253-83 *Standard Test Methods for Maximum Index Density of Soils Using a Vibratory Table* was followed when determining the maximum dry unit weights. Oven dried samples were placed in a 2830 cm^3 (0.100 ft^3) volume mold on top of a vibratory table and subjected to 13.8 kPa (2.00 psi) surcharge pressure (Figure 28). Samples were then vibrated at 60 Hz frequency for 8 min.

Standard Proctor Test

The moisture content and dry unit weight relationships for select materials was developed by performing the standard Proctor test (Figure 29) in accordance with ASTM D698-00 *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))*. Test method A was followed. Materials were air dried and sieved through the No.4 sieve, and then moisture conditioned, in accordance with the test standards.

Figure 27. Relative density mold (ASTM D4253-83, D4254-83)

Figure 28. Relative density mold with surcharge on vibratory table (ASTM D4254-83)

Figure 29. Standard Proctor test, method A (ASTM D698-00)

Drained Direct Shear Test

In accordance with ASTM D3080-04 *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*, drained direct shear (DDS) tests (Figure 30) were performed to determine the drained shear strength parameter values. A 10,000 mm^2 (15.5 in^2) area shear box was used. Samples were compacted by tamping to near 100% relative density at their respective field moisture contents. Shearing rate was 1.0 mm/min (2.4 in/min). Before normal stress application, samples were subjected to a simulated dynamic normal stress representative of RIC. The simulated dynamic normal stress which was equal to 120 kPa (17.4 psi) was estimated from equation (23):

$$\sigma_{D,S} = \frac{2(W+W_A)}{0.25\pi {d_A}^2} \times 9.8 \qquad (23)$$

where:

$\sigma_{D,S}$ = simulated dynamic normal stress in kPa

W = mass of RIC drop weight in tonnes (7 tonnes)

W_A = mass of RIC anvil in tonnes (4 tonnes)

d_A = diameter of RIC anvil in m (1.5 m)

Figure 30. Drained direct shear test (ASTM D3080-04)

Scanning Electron Microscopy Analysis

Select samples were photographed by scanning electron microscope (SEM). The microscope used in the study was a Hitachi S2460-N variable pressure (up to 40 Pa) scanning electron microscope (Figure 31). The microscope was equipped with electron detectors for image detecting and an energy-dispersive x-ray system for both qualitative and quantitative x-ray analysis. Imagery of the samples was taken at different magnifications ranging from 25 to 1000 times magnification. X-ray analysis of the samples was performed.

Figure 31. Scanning electron microscope

Dynamic Cone Penetrometer

Dynamic cone penetrometer (DCP) tests were performed following ASTM D6951-03 *Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications*. The device consists of either an 8 kg (17.6 lb) hammer or a 4.6 kg (10.1 lb) hammer dropped at a height of 575 mm (22.6 in) (Figure 32). Dynamic penetration index (DPI) is reported from the tests with units of mm/blow, which relates to the soil strength.

Figure 32. Dynamic cone penetrometer with 8 kg hammer (ASTM D6951-03)

During this study, DCP tests were performed in the laboratory on vibratory compacted samples. The tests resulted in material specific correlations between DPI and relative density. The procedure followed for this laboratory study is as follows:

1. The specimen is batched at its respective field moisture content.
2. In accordance with ASTM D4253-83, the moist specimen is vibratory compacted in a 2830 cm^3 (0.100 ft^3) mold. In this study however, the sample is only compacted for a predetermined time (e.g., 30 sec). Compaction times depend on the characteristics of the sample being tested.
3. The vibratory compaction induced settlement is measured and the moist unit weight is computed.
4. A surcharge pressure of 7.18 kPa (150 psf) is applied to the compacted sample still inside the mold (Figure 33). The surcharge used in the study was a 95.2 mm (3.75 in) thick steel plate (Figures 34 and 35) with a 149.2 mm (5.875 in)

diameter. The steel plate had a 25.4 mm (1.0 in) diameter hole 38.1 (1.5 in) mm off center to allow for insertion of the DCP tip while still maintaining the surcharge pressure. The plate was fitted with a removal rod that allowed for easy insertion and extraction from the mold (Figure 36). A DCP equipped with a 4.6 kg (10.1 lb) hammer is inserted through the hole in the plate and a DPI profile through the sample is produced (Figure 37).

5. The DCP is extracted and the borehole left behind (Figure 38) is backfilled and lightly compacted with the same material comprising the sample already in the mold.
6. The plate is placed again on the sample although rotated so that the hole in the plate is positioned 120° away from the previous borehole(s). The DCP is inserted into the repositioned hole and an additional DPI profile is produced.
7. Steps 6 and 7 are repeated for a third DPI profile.
8. The moisture content of the sample is determined in accordance with ASTM D2216-10.
9. Steps 2 through 9 are repeated for the remaining vibratory compaction times required to generate the DPI-relative density correlation.

Figure 33. Application of surcharge pressure to sample in mold

Figure 34. Surcharge plate

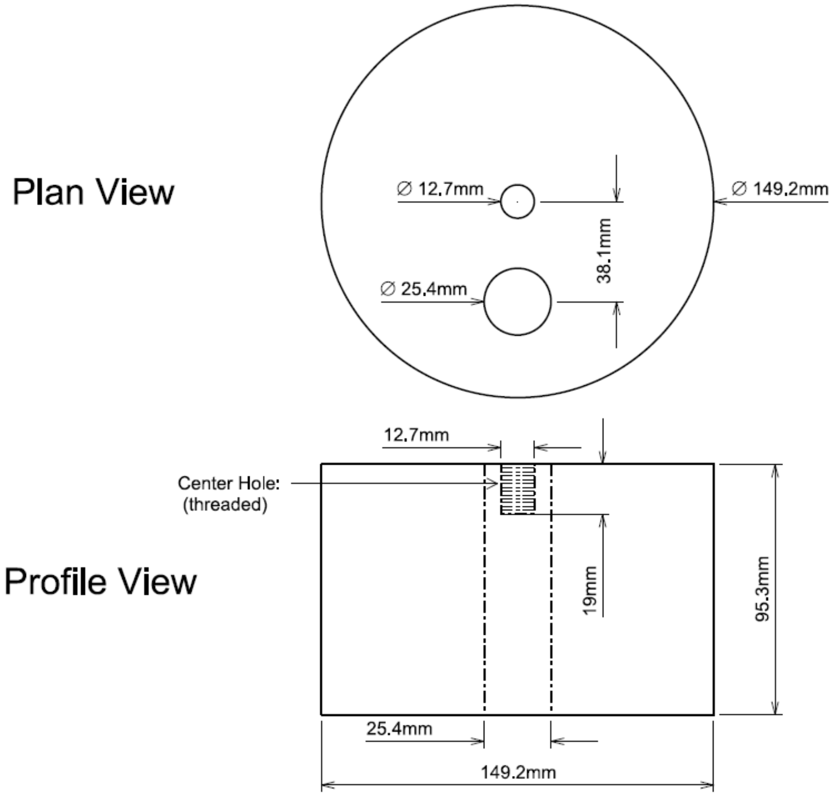


Figure 35. Surcharge plate schematic

Figure 36. Surcharge plate extraction with removal rod

Figure 37. DCP test of sample in mold (4.6 kg hammer)

Figure 38. DCP borehole through sample in mold

Materials

Springfield Fill

The Springfield Fill is a highly variable granular material. The material consisted of a mixture of sand, silt, and gravel with some trace amounts of debris (brick, coal, ash). The soil was sampled from Springfield, MA.

The performed laboratory tests included: grain-size distribution analysis, moisture content analysis, relative density test, standard Proctor test and drained direct shear (DDS) test. A summary of Springfield Fill material properties is presented in Table 11.

The material was classified as SM (silty sand) based on USCS classification and A-2-4(0) from AASHTO classification (Figure 39). The Springfield Fill sample had 33.2% fines. The coefficient of uniformity and coefficient of curvature were 27.22 and 0.89, respectively. The moisture content analysis revealed that the field moisture content was 12.0%.

From the relative density test, the minimum dry unit weight and the maximum dry density were 12.81 kN/m^3 (81.5 pcf) and 18.65 kN/m^3 (118.7 pcf), respectively (Figure 40). Assuming a specific gravity of 2.7, the Springfield Fill had a compactibilty of 1.545 [equation (5)]. The standard Proctor tests revealed a maximum dry unit weight of 18.98 kN/m^3 (120.6 pcf) with an optimum moisture content of 9.7% (Figure 41).

The DDS test revealed that, at or near maximum relative density, the drained angle of internal friction was equal to 36.0° and that the drained cohesion was equal to 15.8 kPa (330 psf) (Figure 42). Cohesion in the material was attributed to the large amount of dilation experienced during shearing. The shear stress-horizontal displacement and vertical displacement-horizontal displacement curves are provided in Figure 43.

Table 11. Summary of material properties for Springfield Fill

Parameter/Material	Springfield Fill
Material description	Silty sand
USCS	SM
AASHTO	A-2-4(0)
Fines Content (<75μm)	33.2%
Coefficient of uniformity, C_u	27.22
Coefficient of curvature, C_c	0.89
Field moisture content	12.0%
Minimum dry density, $\rho_{d,min}$	12.81 kN/m^3 (81.5 pcf)
Maximum dry density, $\rho_{d,max}$	18.65 kN/m^3 (118.7 pcf)
Specific Gravity, G_S (Assumed)	2.7
Compactibility, F	1.545
Standard Proctor maximum dry unit weight, $\gamma_{d,max}$	18.98 kN/m^3 (120.6 pcf)
Standard Proctor optimum moisture, w_{opt}	9.73%
Drained angle of internal friction, ϕ’	36.0°
Drained cohesion, c’	15.8 kPa (330 psf)

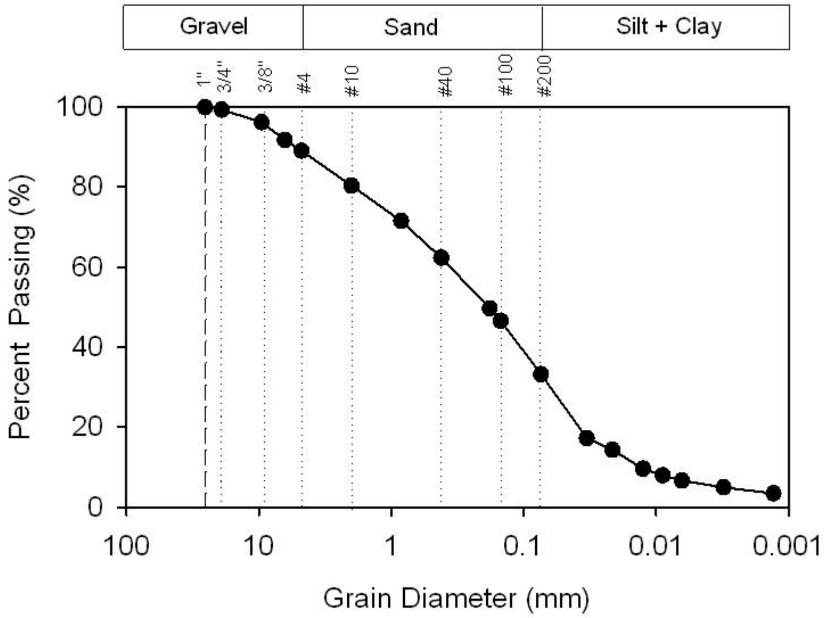


Figure 39. Grain-size distribution curve for Springfield Fill

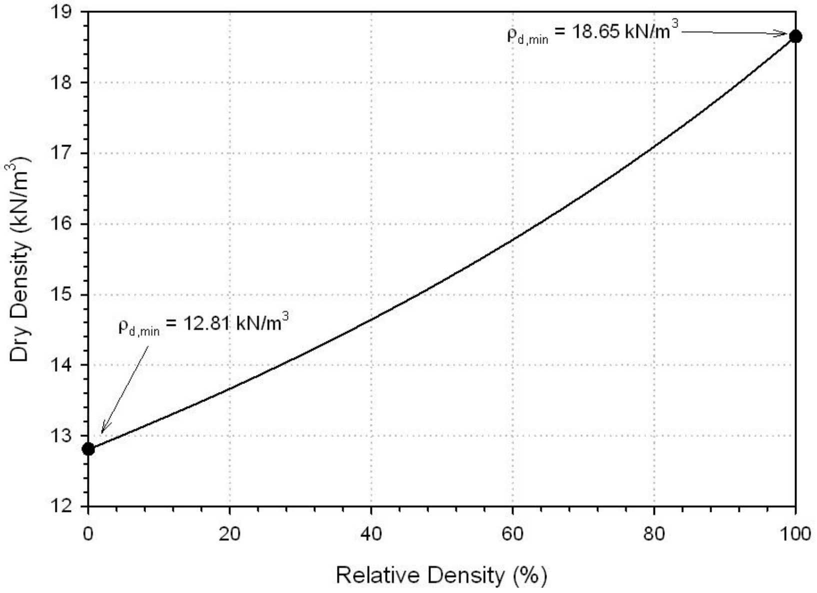


Figure 40. Dry unit weight versus relative density for Springfield Fill

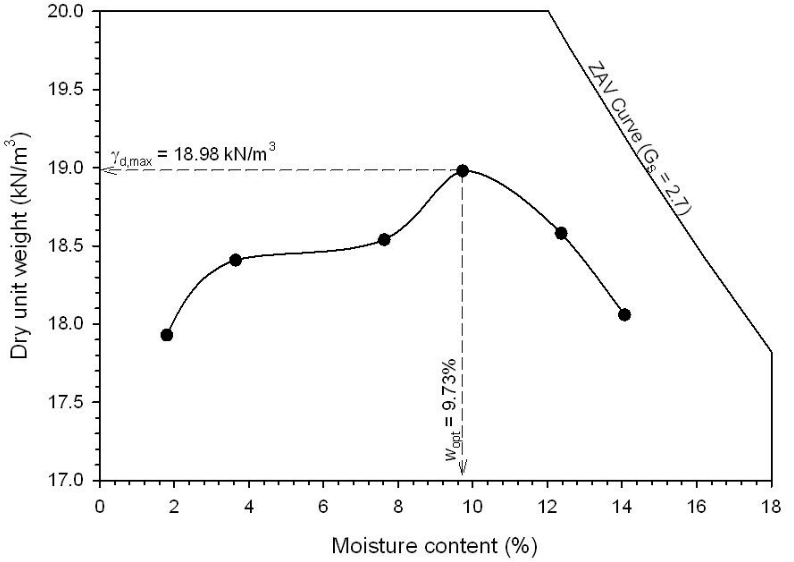


Figure 41. Standard Proctor test results for Springfield Fill

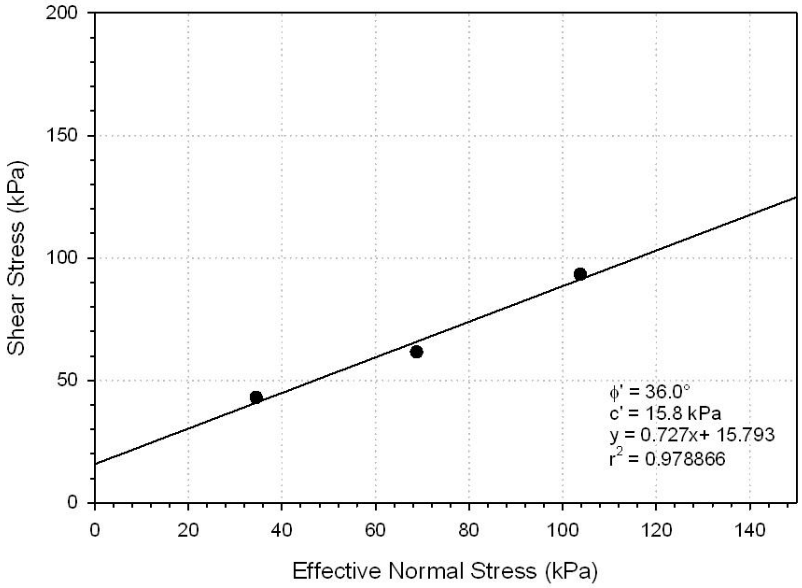


Figure 42. Mohr-coulomb failure criterion for Springfield Fill

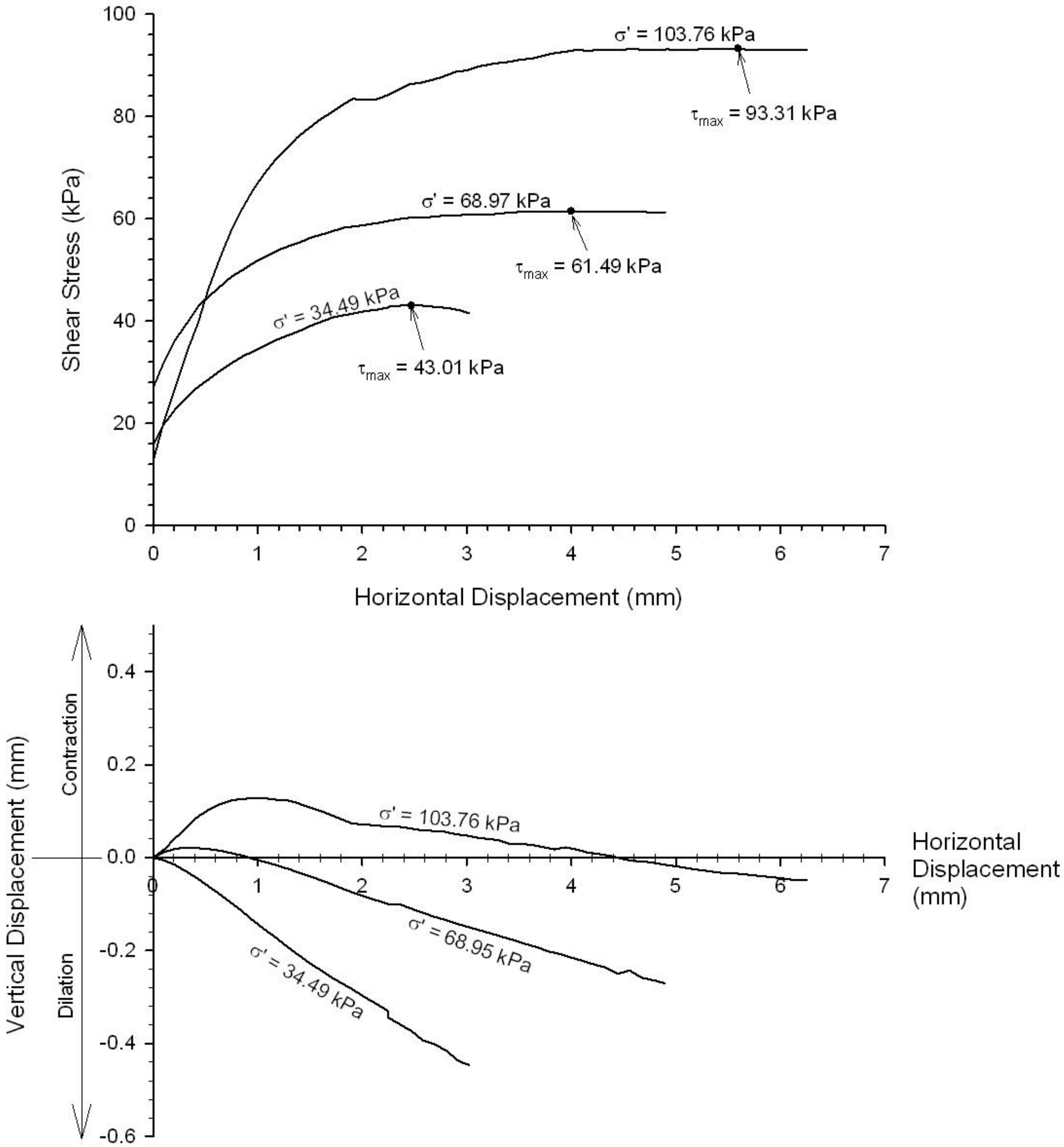


Figure 43. DDS shear stress and displacements for Springfield Fill

Hard Pack

Hard Pack is a proprietary fill material from New England. The soil is a well-graded mixture of crushed brick, stone, sand, reclaimed asphalt, concrete, etc. Hard Pack is usually used as a road bed material. The sample of Hard Pack was obtained from Springfield, MA.

The performed laboratory tests included: grain-size distribution analysis, moisture content analysis, relative density test, drained direct shear (DDS) test, and scanning electron microscopy (SEM) analysis. A summary of Hard Pack material properties is presented in Table 12.

The material was classified as SM (silty sand with gravel) based on USCS classification and A-1-b from AASHTO classification (Figure 44). The Hard pack sample had 13.2% fines. The coefficient of uniformity and coefficient of curvature were 59.74 and 1.69, respectively. The moisture content analysis revealed that the field moisture content was 11.3%.

From the relative density test, the minimum dry unit weight and the maximum dry unit weight were 15.79 kN/m^3 (100.5 pcf) and 19.50 kN/m^3 (124.1 pcf), respectively (Figure 45). Assuming a specific gravity of 2.7, Hard Pack had a compactibilty of 0.892 [equation (5)].

The DDS test revealed that, at or near maximum relative density, the drained angle of internal friction was equal to 44.7° and that the drained cohesion was equal to 29.6 kPa (620 psf) (Figure 46). Cohesion in the material was attributed to the large amount of dilation experienced during shearing. The shear stress-horizontal displacement and vertical displacement-horizontal displacement curves are provided in Figure 47.

The SEM provided imagery of the medium sized particles (0.075 to 2mm diameter) and the particle fines (smaller than 0.75 mm diameter) of the Hard Pack sample (Figures 48 and 49). It is evident from Figures 48 and 49 that Hard Pack is well graded even to particles a few microns in size and that nearly all Hard Pack particles are angular. These findings from the SEM analysis provide a reasonable explanation for the high shear strength parameters determined from the DDS. Results of the x-ray analysis from the SEM are presented in Figure 50. X-ray analysis showed the average composition to be abundant in silicon and oxygen (i.e., quartz) with lesser amounts of aluminum, magnesium, iron, zinc, sodium, titanium, lanthanum, and cerium (Appendix B). Hard Pack is therefore composed of a wide assortment of different mineral types.

Table 12. Summary of material properties for Hard Pack

Parameter/Material	Hard Pack
Material description	Silty sand with gravel
USCS	SM
AASHTO	A-1-b
Fines Content (<75μm)	13.2%
Coefficient of uniformity, C_u	59.74
Coefficient of curvature, C_c	1.69
Field moisture content	11.3%
Minimum dry density, $\rho_{d,min}$	15.79 kN/m^3 (100.5 pcf)
Maximum dry density, $\rho_{d,max}$	19.50 kN/m^3 (124.1 pcf)
Specific Gravity, G_S (Assumed)	2.7
Compactibility, F	0.891
Drained angle of internal friction, ϕ’	44.7°
Drained cohesion, c’	29.6 kPa (620 psf)

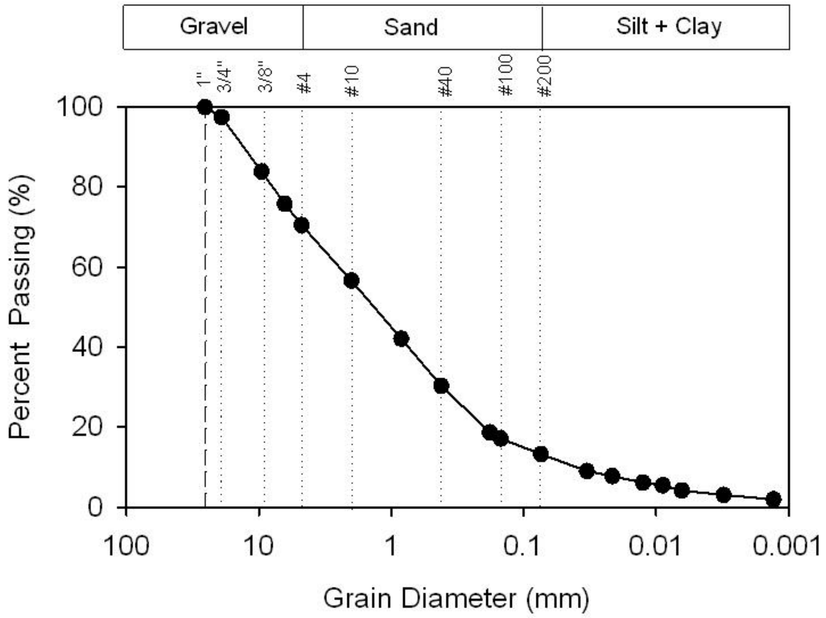


Figure 44. Grain-size distribution curve for Hard Pack

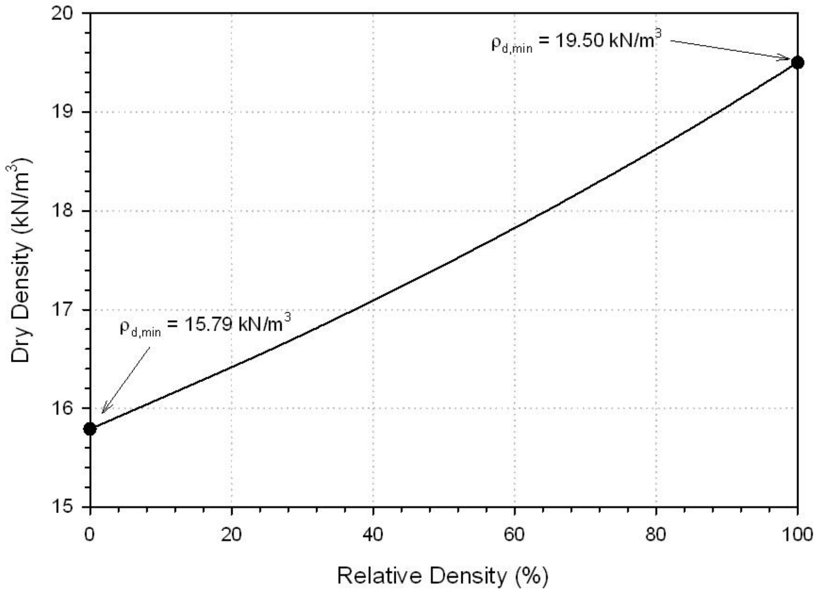


Figure 45. Dry unit weight versus relative density for Hard Pack

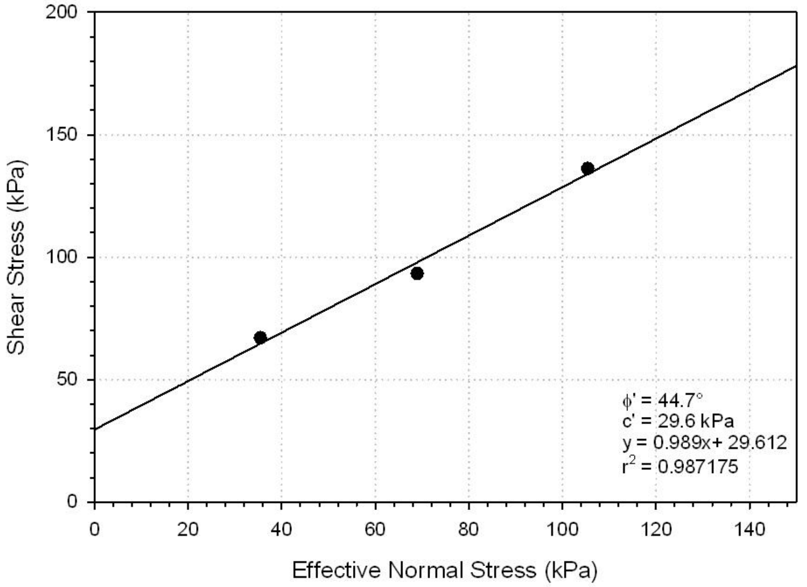


Figure 46. Mohr-coulomb failure criterion for Hard Pack

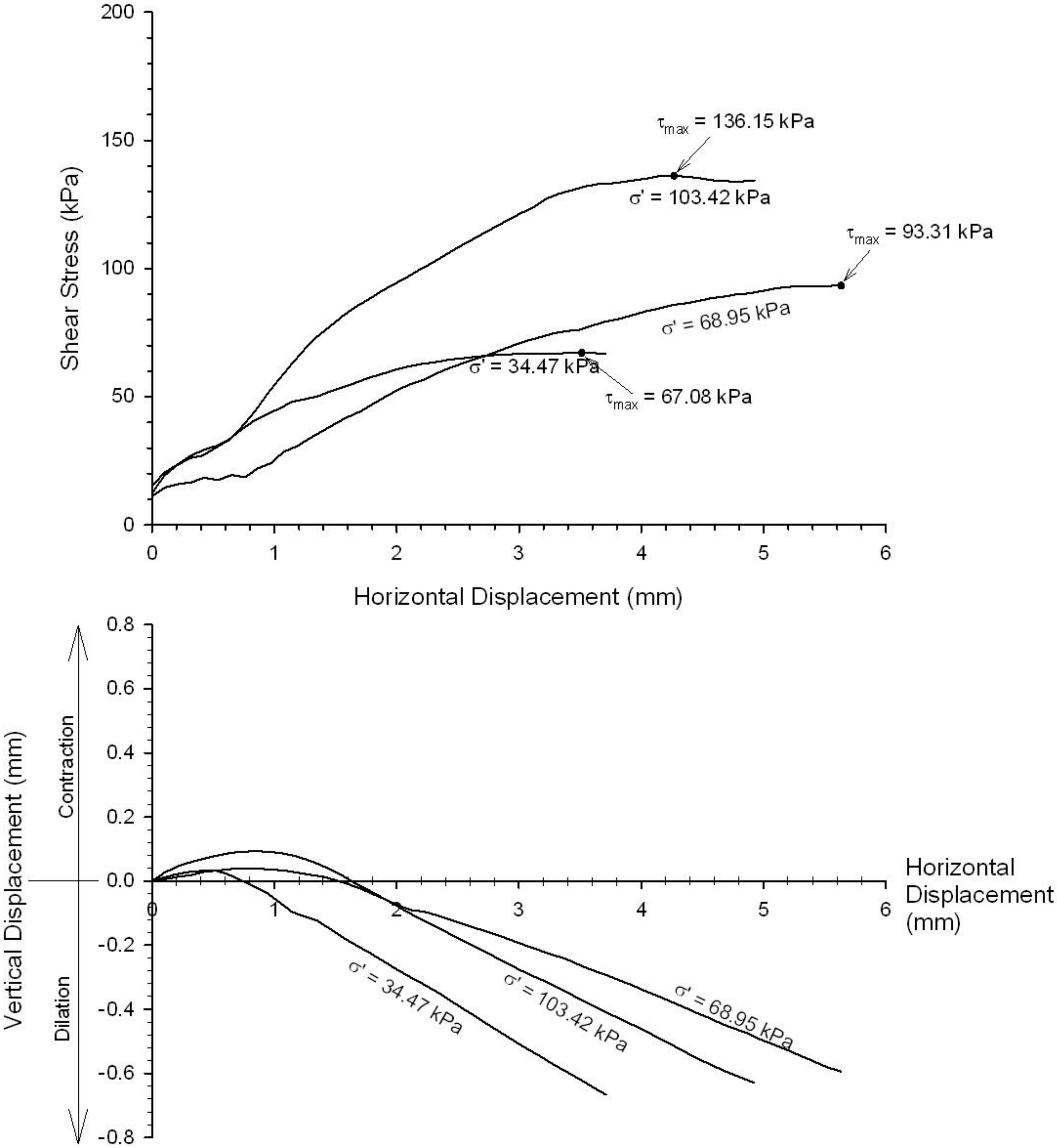


Figure 47. DDS shear stress and displacements for Hard Pack

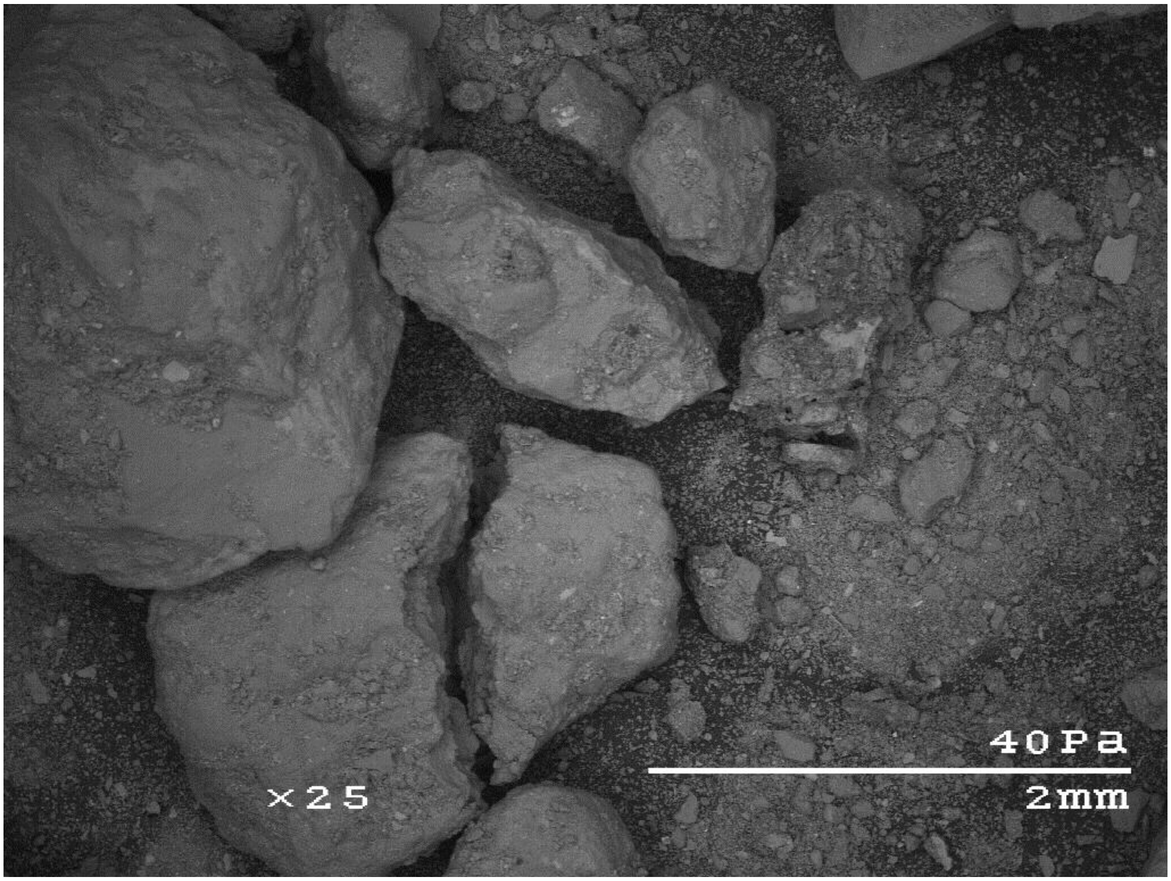


Figure 48. SEM image of medium sized Hard Pack particles at 25x magnification

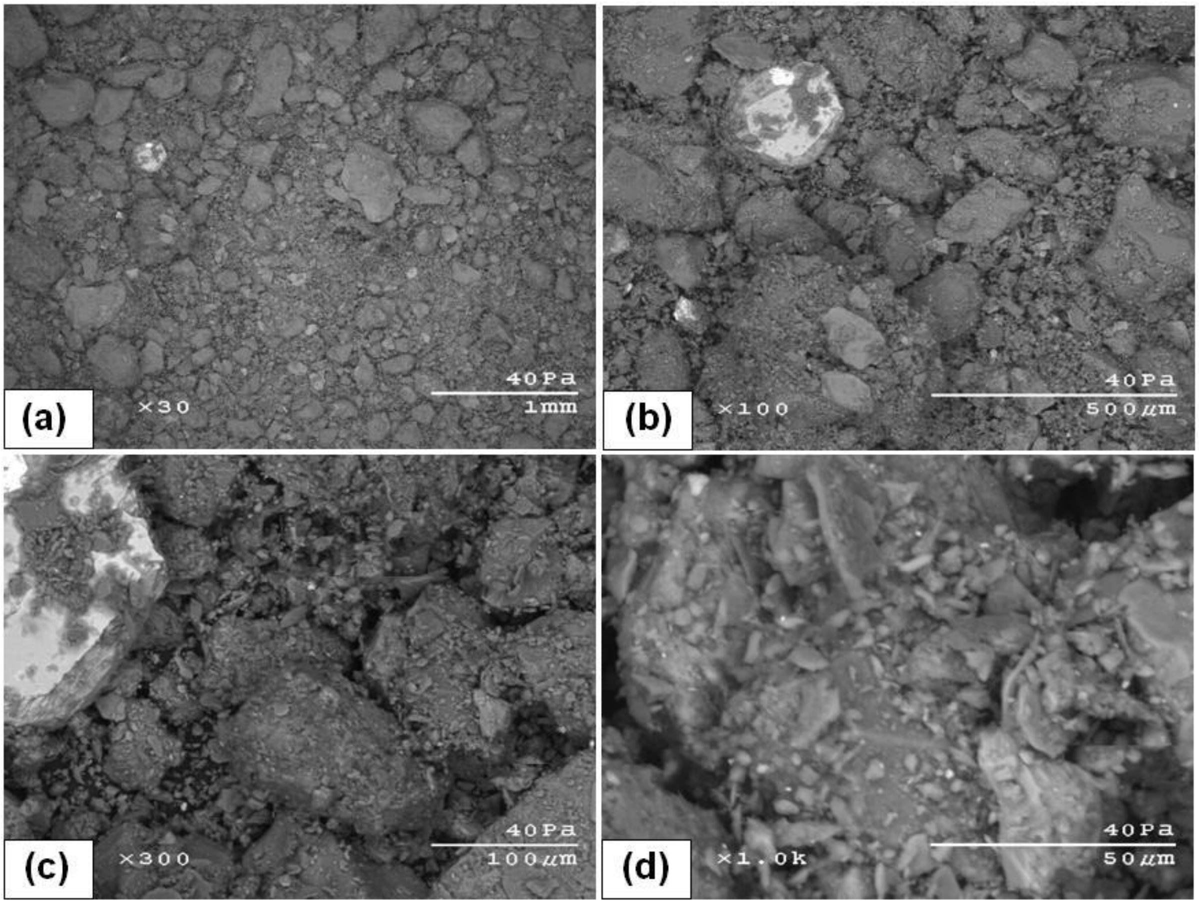


Figure 49. SEM images of Hard Pack fine particles at (a) 30x magnification; (b) 100x magnification; (c) 300x magnification; and (d) 1000x magnification

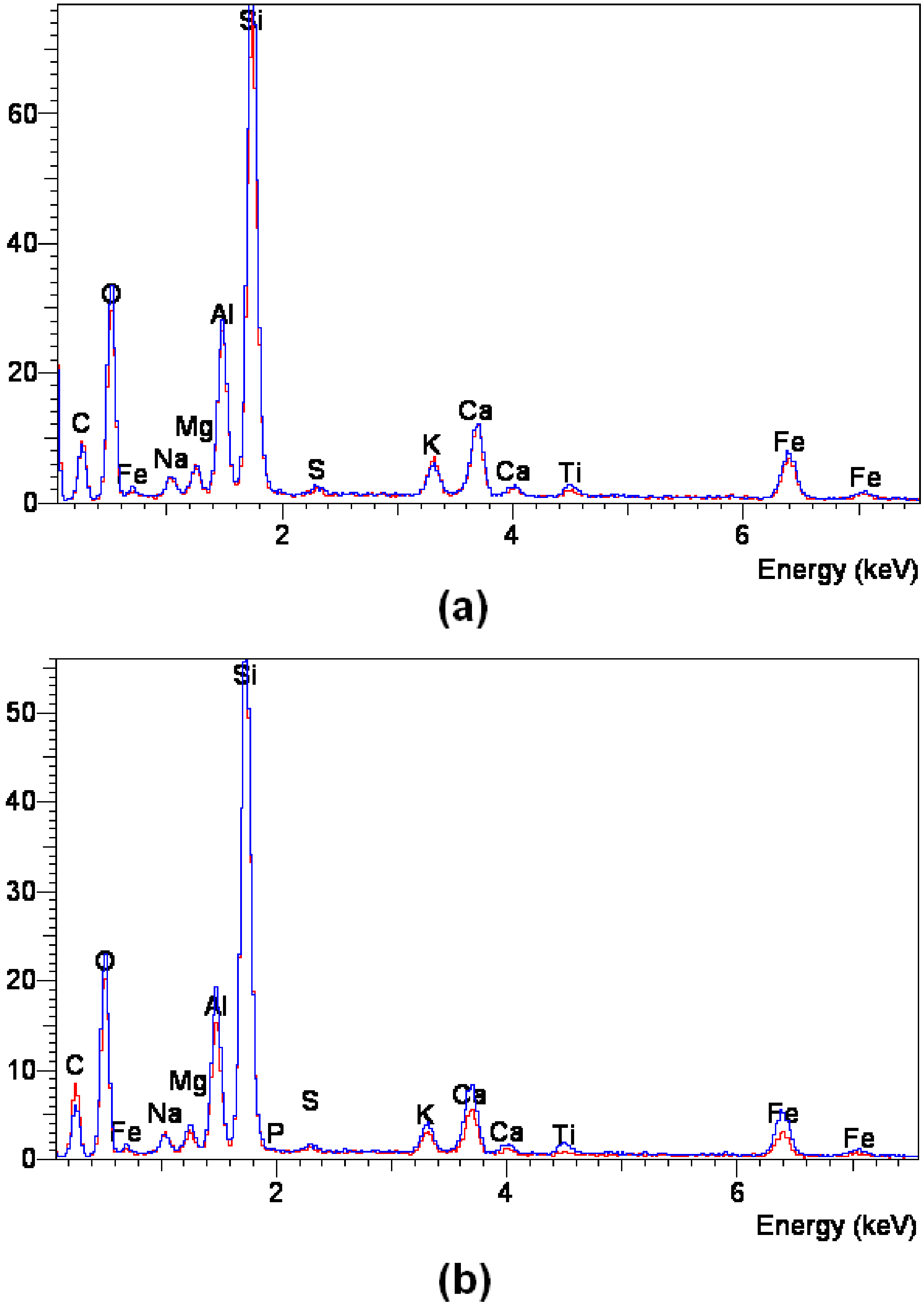


Figure 50. Results from SEM x-ray analysis on (a) Hard Pack fine particles and (b) Hard Pack medium sized particles

CHAPTER 5. RESULTS AND ANALYSIS

This chapter provides the results of a detailed case history, including field and laboratory test results. Preliminary information on the case history was obtained from Mickiewicz and Talbot (2010). Data from laboratory studies were correlated to field data and subsequently analyzed.

Case History: Springfield, MA

Project Description

Site Location

The construction of a medical office building was proposed in Springfield, MA. The site was located approximately 500 m (1500 ft) east of the Connecticut River on a former point bar deposit (Figure 51).

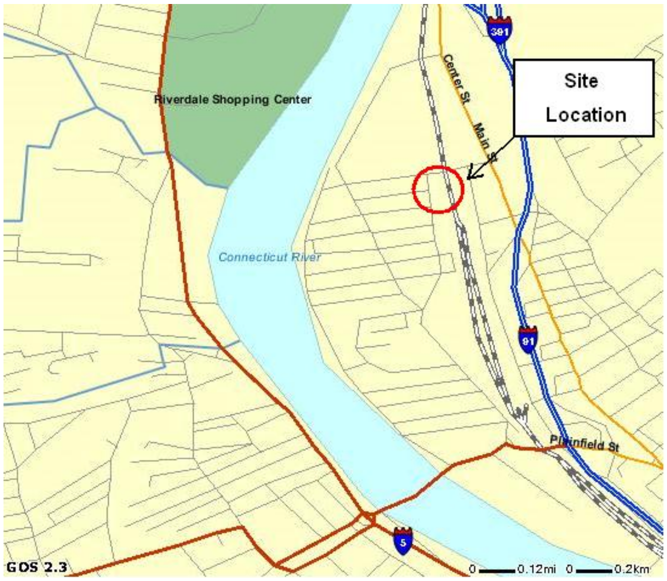


Figure 51. Location of Springfield, MA project

Structural Alternatives

Considered structural alternatives included:

- a one-story, 2300 m^2 (25000 ft^2), slab-on-grade building; and
- a two or three-story, 1300 m^2 (14000 ft^2), slab-on-grade building.

The geotechnical engineer assumed a floor load of 29 kPa (600 psf) and maximum column loads of 440 kN (100 kips) for the one-story alternative and 1100 (240 kips) for the two-story alternative.

Geotechnical Assesment

Site Investigation Program

Subsurface investigations were performed on March 19, March 20, April 9, November 30, and December 1, 2009. The investigations comprised standard penetration testing (SPT) and split spoon sampling. SPT testing and sampling was conducted beginning at the ground surface and then at 1.5 m (5 ft) intervals thereafter. All borings were advanced to 8.3 m (27 ft) below the ground level except for two which were advanced to refusal which the engineer assumed to be bedrock. Select samples were subjected to vane shear testing and pocket penetrometer testing. Boring locations within the site are shown in Figure 52.

Results of the borings in terms of SPT-N_{60} values are shown in Figure 53. Each SPT-N_{60} value profile in Figure 53 corresponds to a boring location shown in Figure 52. The average SPT-N_{60} values presented in Figure 53h were determined by calculating the mean SPT-N_{60} value for all of the borings at each split spoon sampling depth. Complete SPT-N_{60} values and standard deviations for the average profile are provided in Appendix C.

Figure 52.Boring locations within site

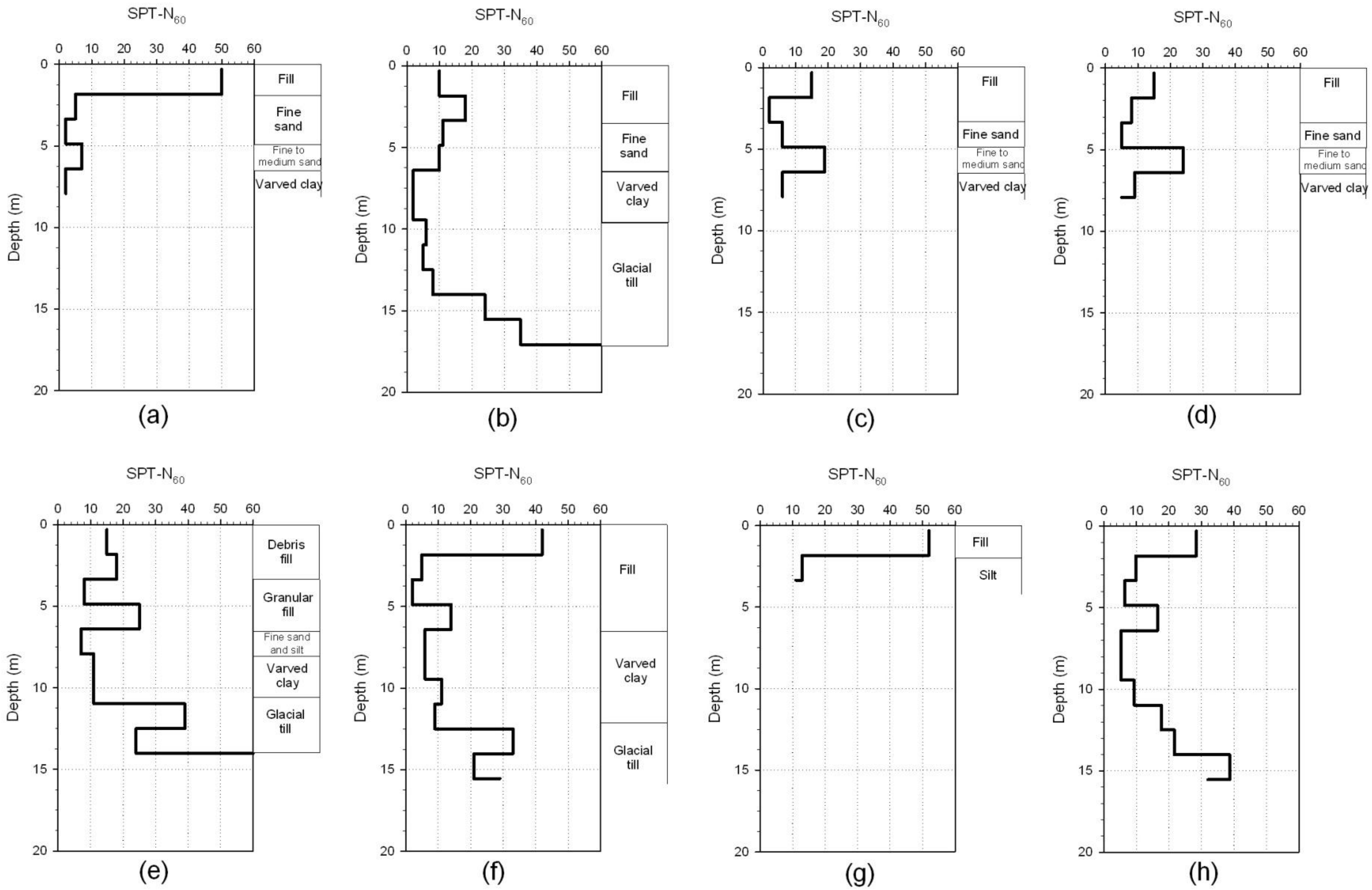


Figure 53. SPT-N_{60} values for (a) FW-501, (b) FW-503, (c) FW-504, (d) FW-505, (e) FW-511, (f) FW-512, (e) FW-513, and (h) average

Subsurface Conditions

Overburden soils consisted of Springfield Fill, alluvial deposits, varved clay, and glacial till. Bedrock underlaid the glacial till layer. Each boring encountered the ground water table at approximately 3 m (10 ft) below the ground surface at the time of drilling.

The Springfield Fill stratum ranged in thickness from approximately 1.5 to 6 m (5 to 20 ft). The fill was highly variable and was composed of a mixture of sand, silt, gravel, and miscellaneous debris (e.g., brick, crushed concrete, etc.). Generally, the fill was dense at the ground surface and looser with depth.

The alluvial deposits comprised interbedded sand and silt. According to the geotechnical engineer, the deposits ranged in density from very loose to medium dense. The majority of borings revealed that the alluvial deposits consisted of fine to medium sand underlying silty fine sand.

Immediately beneath the alluvial deposits, at a depth of approximately 6 m (20 ft) was a layer of varved clay. The varved clay varied from very soft to medium stiff throughout the site. Vane shear tests determined the undrained shear strength to range between 4.8 to 48 kPa (100 to 1000 psf). Pocket penetrometer testes determined the undrained shear strength to range between 8.6 to 120 kPa (180 to 2500 psf).

Underlying the varved clay was a 3 to 6 m (10 to 20 ft) thick stratum of glacial till. The glacial till was sufficiently overconsolidated to be not affected by the anticipated foundation loading. Underneath the glacial till was bedrock, which two different borings encountered at depths of 12 m (39 ft) and 14.3 m (47 ft) below the ground surface.

Geotechnical Recommendation

The geotechnical engineer deemed the near surface, loose, Springfield Fill as unsuitable for supporting the structure via either conventional spread footings or a structural mat. Variability of relative density within the granular fill rendered the site susceptible to differential settlement. The use of deep foundations was not an economically feasible foundation solution, given the small scale of the project. Therefore the geotechnical engineer recommended employing:

- site improvement (i.e. rapid impact compaction); and
- the on-story structure with spread footings.

RIC was required to achieve an SPT-N_{60} value of at least 15 to a 4.5 m (15 ft) depth.

RIC Program

Preparation and Construction

Clearing and grubbing of the site occurred on December 7, 2010. The earthwork contractor leveled portions of the site with Hard Pack.

The RIC unit arrived on site on December 8, 2010; distributed over three flatbed semi truck trailers (Figure 54, Figure 55, and Figure 56). The RIC was equipped with a 7 tonne (7.5 ton) hammer. With a two person crew, mobilization of the RIC unit took approximately 2 hours.

On December 8, 2010, the *compaction trial* was performed over a 6 m by 6 m (20 ft by 20 ft) area within the central portion of the site. The *compaction trial* resulted in final set cutoff criteria of 5 mm/blow. RIC compaction reference points for the entire compaction area were staked subsequent to the *compaction trial*.

Compaction of the site began on December 9, 2010 and lasted until December 29, 2010 (Figure 57). The same two person crew that assembled the RIC unit performed the compaction. One crew member operated the RIC unit while the other crew member recorded quality control (QC) data. For each pass on every point, compaction date, compaction time, final set, total penetration, and number of blows were all recorded. RIC induced vibrations were no threat to neighboring structures or utilities.

The impact points were laid out and compacted as shown in Figure 58. Each impact point received up to three passes. If the 5mm /blow final set cutoff criterion was not achieved after the first pass, then the impact point crater was backfilled and recompacted. If the final set criterion was still not achieved after the second pass, then the crater was backfilled and recompacted for a final time. The select fill used to level the site, Hard Pack, was used to backfill the craters.

Figure 54. Mobilization of hydraulic excavator

Figure 55. Mobilization of excavator back end and RIC supplies

Figure 56. Mobilization of RIC unit

Figure 57. Compaction process

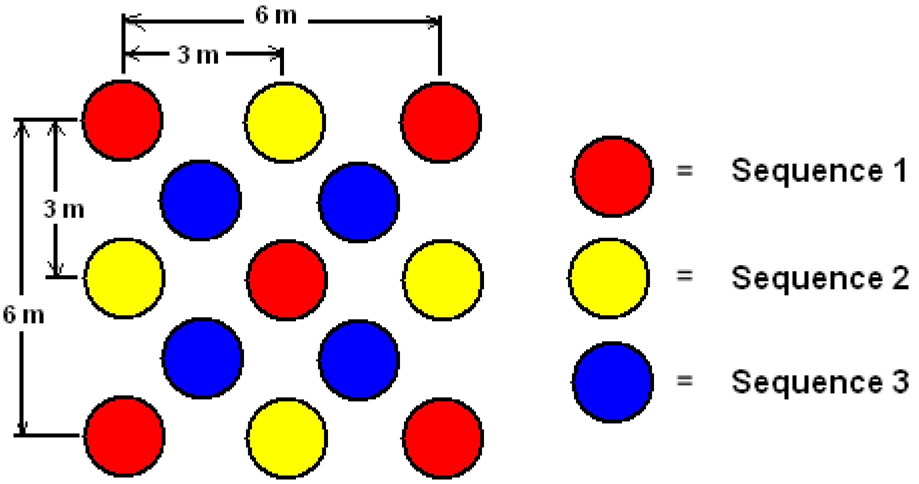


Figure 58. Impact point layout

RIC Verification

After compaction of the entire site, SPT testing advanced to 6 m (20 ft) was used to verify the resulting compaction depth and degree of compaction. Although the exact locations were not defined, SPT tests were performed near borings FW-501, FW-503, FW-504, FW-511, and FW-513 (Figure 59). SPT-N_{60} values measurements began at either 0.3 m (1 ft) or 0.6 m (2 ft) below the ground surface and continued at 0.6 m (2 ft) intervals. Borings were concluded at either 6.1 m (20 ft) or 6.4 m (21 ft) below the ground surface.

The SPT tests were performed near the pre-RIC borings and the resulting SPT-N_{60} values were compared to their pre-RIC counterparts (Figure 52). The average SPT-N_{60} values presented in Figure 59 were determined by calculating the mean SPT-N_{60} value for all of the borings at SPT-N_{60} measurement depth. Complete SPT-N_{60} values and standard deviations for the average profile are provided in Appendix C. Split spoon sampling was not performed for post-RIC borings.

Each boring comparison revealed that RIC compacted not only the surface fill layer, but the underlying alluvial deposit as well. The depth of compaction extended to the varved clay layer [approximately 5.6 m (18.5 ft)]. The resulting SPT-N_{60} values in the fill and alluvial deposit strata averaged 35. The high SPT-N_{60} values near the ground surface can be attributed to the Hard Pack material that was used to backfill impact point craters. Summary of results is presented in Table 13.

Table 13. Summary of results for Springfield, MA case history

Average Depth of Compaction	**Average SPT-N_{60} (Weighted Average)**		**$\frac{\text{Post RIC SPT } N_{60}}{\text{Pre RIC SPT } N_{60}}$**	**Soil Type**
	Pre-RIC	**Post-RIC**		
5.6 m (18.5 ft)	15 (medium D_R)**	35 (dense D_R)**	2.3	Miscellaneous granular fill (SM); alluvial silts, sands

**Terzaghi et al. (1996)

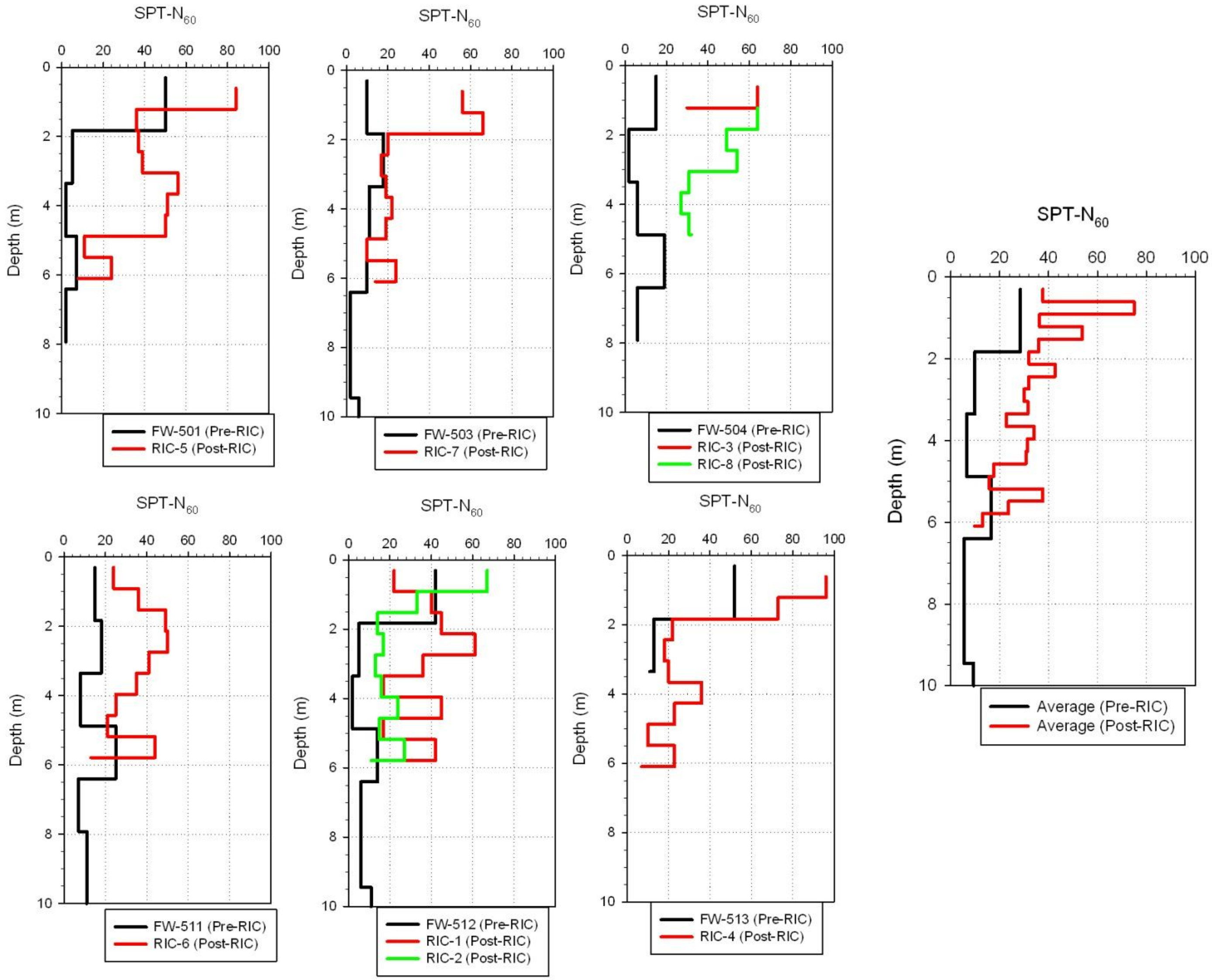


Figure 59. Comparison of pre- and post-RIC SPT-N$_{60}$ values

Field Test Results

In addition to the RIC case history, a field test was performed immediately following completion of the *compaction trial*. Results of the field trial are enclosed.

Pre-compaction Testing

A large depression existed in the northeast section of the site (Figure 60). The depression was approximately 1 m (3.3 ft) deep at its maximum depth. The depression was backfilled with Hard Pack to the same elevation of the rest of the site during the leveling of the site (Figure 61).

A DCP test was conducted through the Hard Pack stratum and into the underlying Springfield Fill resulting in the DPI profile in Figure 62. A plot of the accumulated DPI with depth (Figure 63) determined the thickness of the Hard Pack stratum to be approximately 1.1 m (3.6 ft).

Following the site preparation, the *compaction trial* was carried out over the filled in depression.

Figure 60. Depression on site prior to backfilling

Figure 61. Hard Pack placement

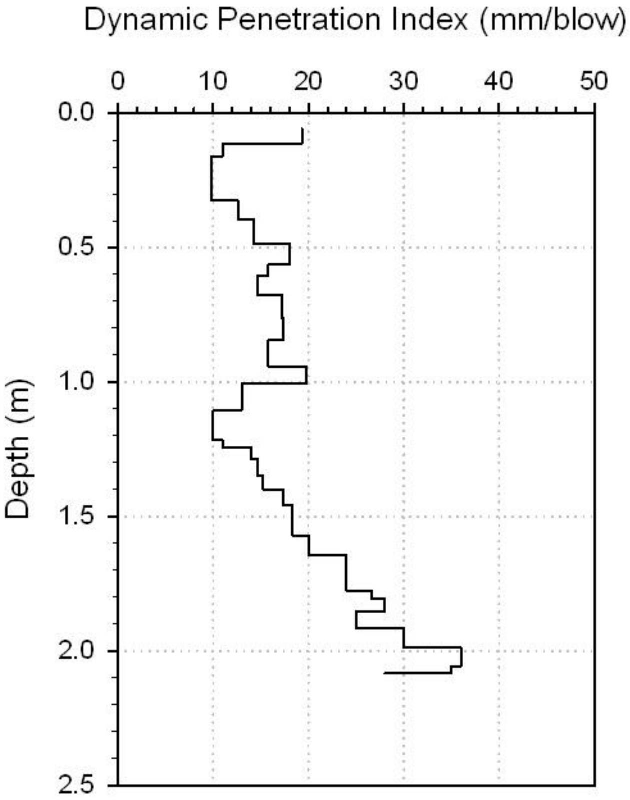


Figure 62. DPI profile before compaction

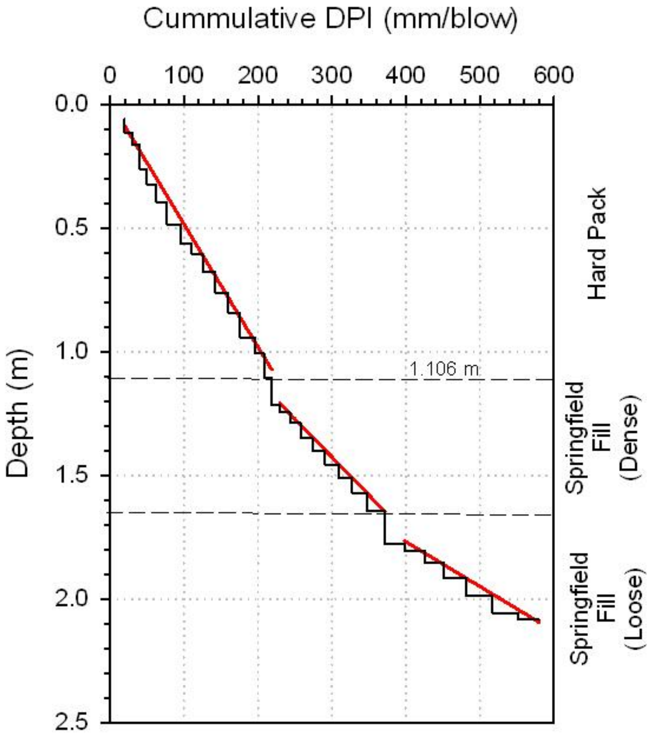


Figure 63. Cumulative DPI profile before compaction

Post-compaction Testing

Subsequent to RIC, DCP tests were performed at distances of 0 m, 1.7 m (5.6 ft), 2.3 m (7.5 ft), and 2.9 m (9.5 ft) from the center of one of the outer sequence 1 impact points (Figure 64). The impact point that was subjected to testing experienced two compaction passes. Figure 65 presents DPI profiles for each of the DCP tests. Impact point 1 left behind a crater that was approximately 2.1 m (6.9 ft) in diameter and 0.4 m (1.3 ft) deep at the center. Each DCP test comprised a stratum of Hard Pack overlying Springfield Fill. Plots of the accumulated DPI with depth (Figure 66) determined that the depth to the Springfield Fill layer ranged from 0.6 to 1.7 m (2.0 to 5.6 ft) below the ground surface. A profile view of the post-compaction Hard Pack and Springfield strata is presented in Figure 67.

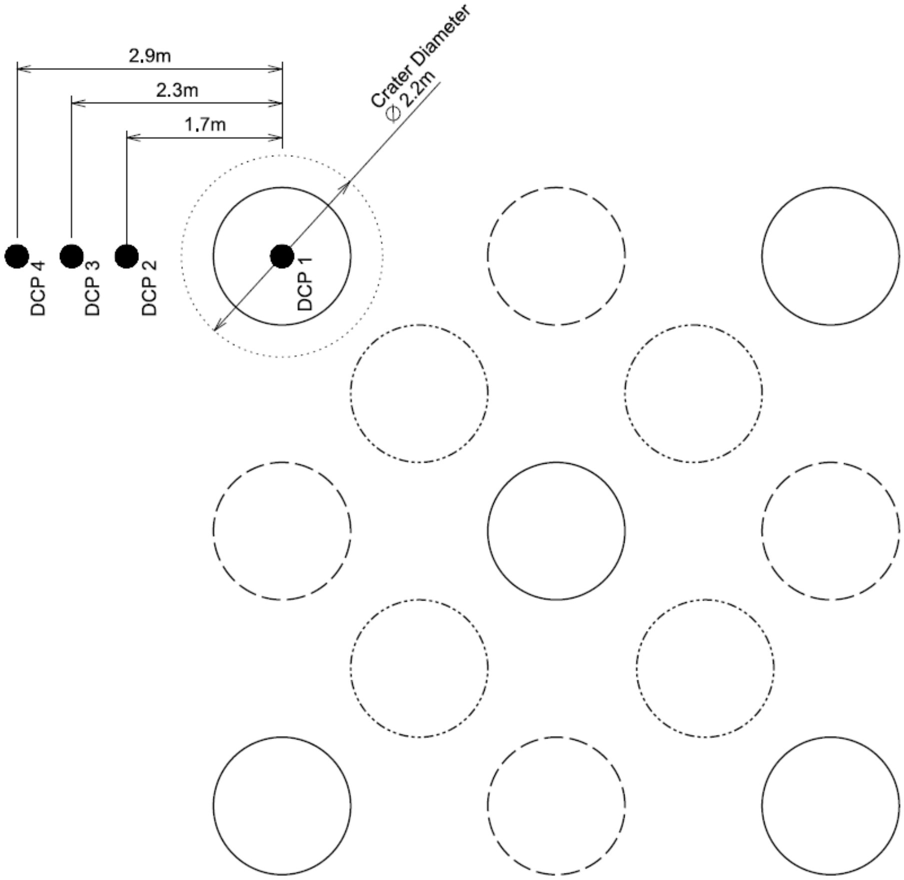


Figure 64. Locations of DCP tests relative to compaction area

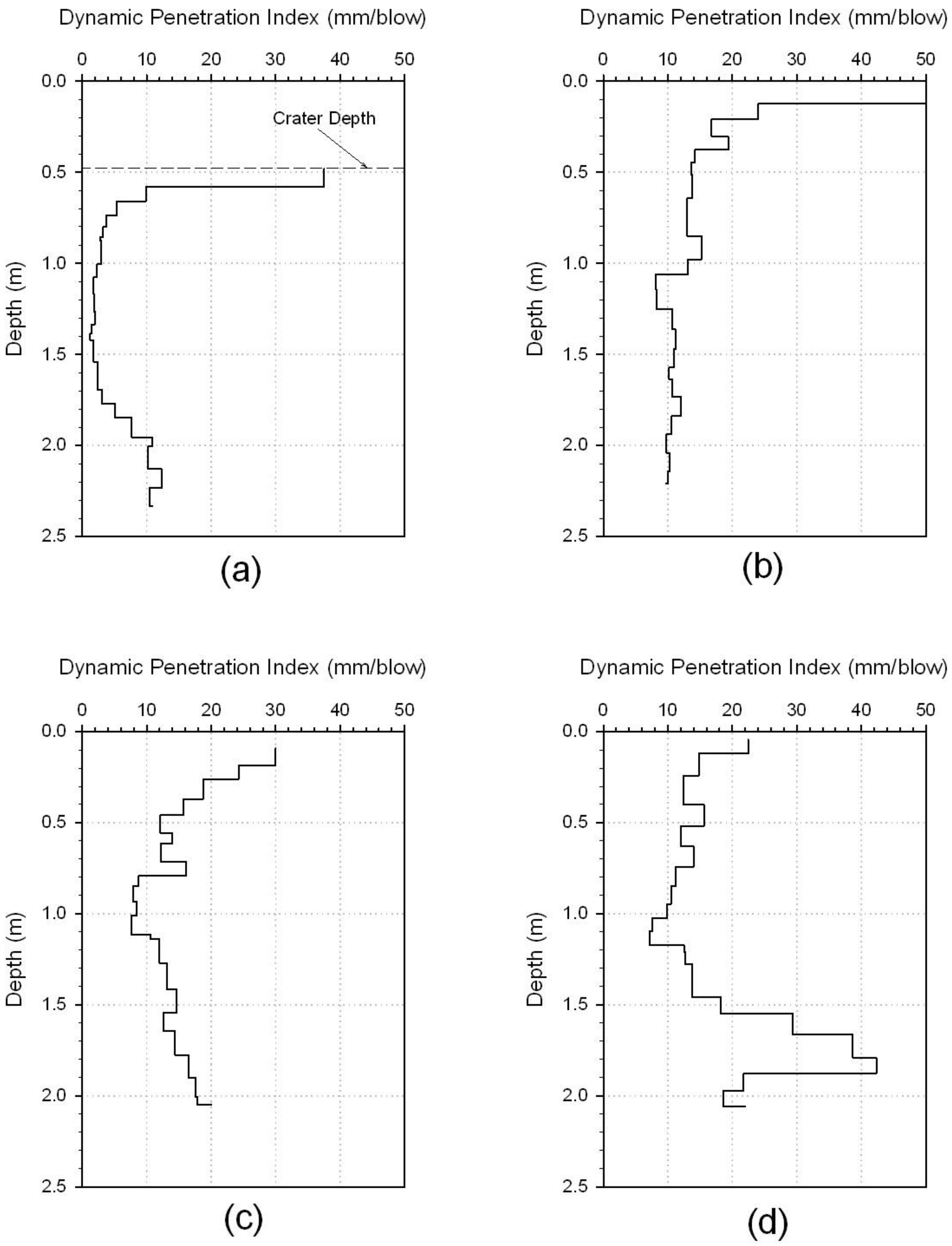


Figure 65. Post-RIC DPI profiles for (a) DCP1, (b) DCP2, (c) DCP3, and (d) DCP4

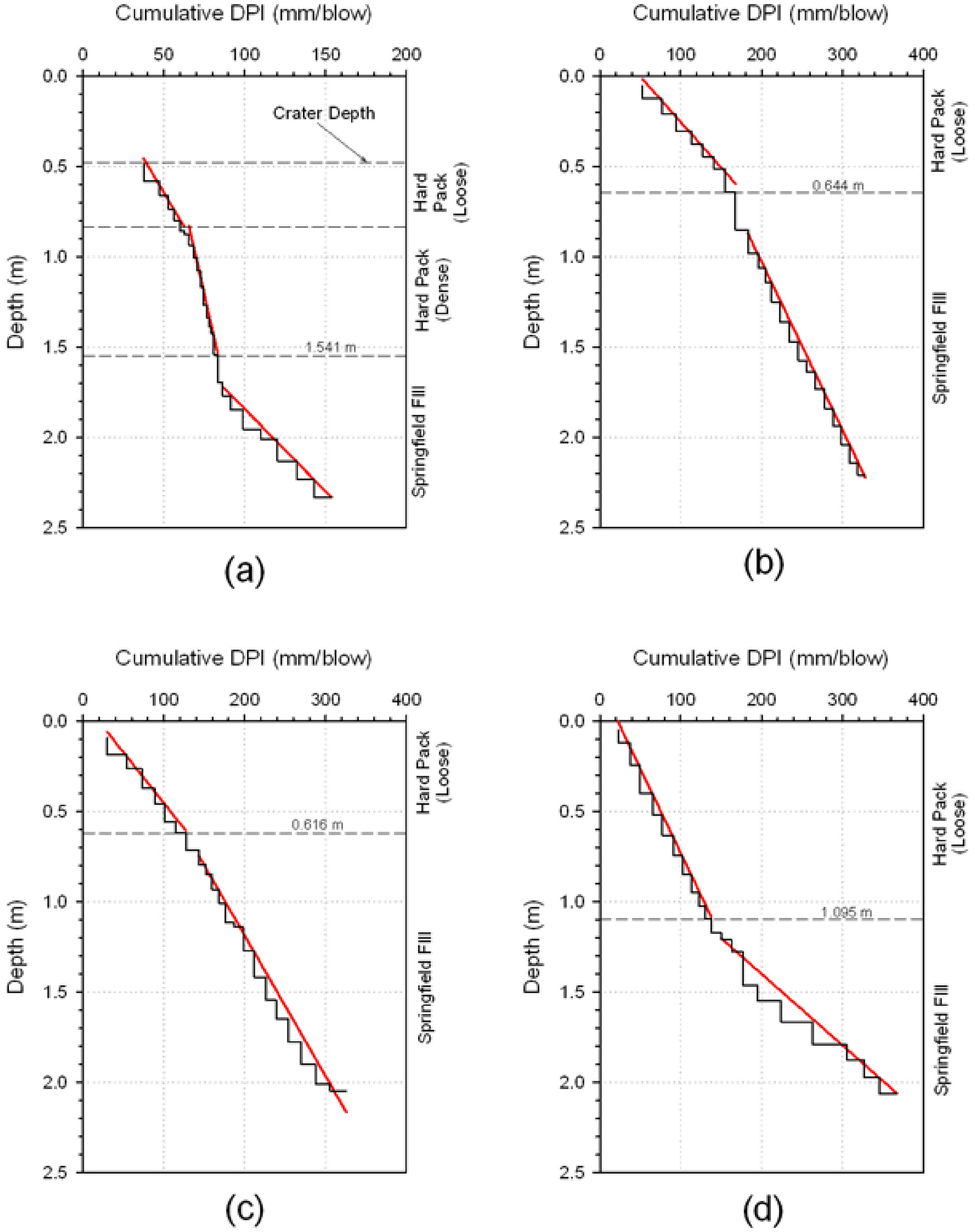


Figure 66. Cumulative DPI profiles for (a) DCP1, (b) DCP2, (c) DCP3, and (d) DCP4

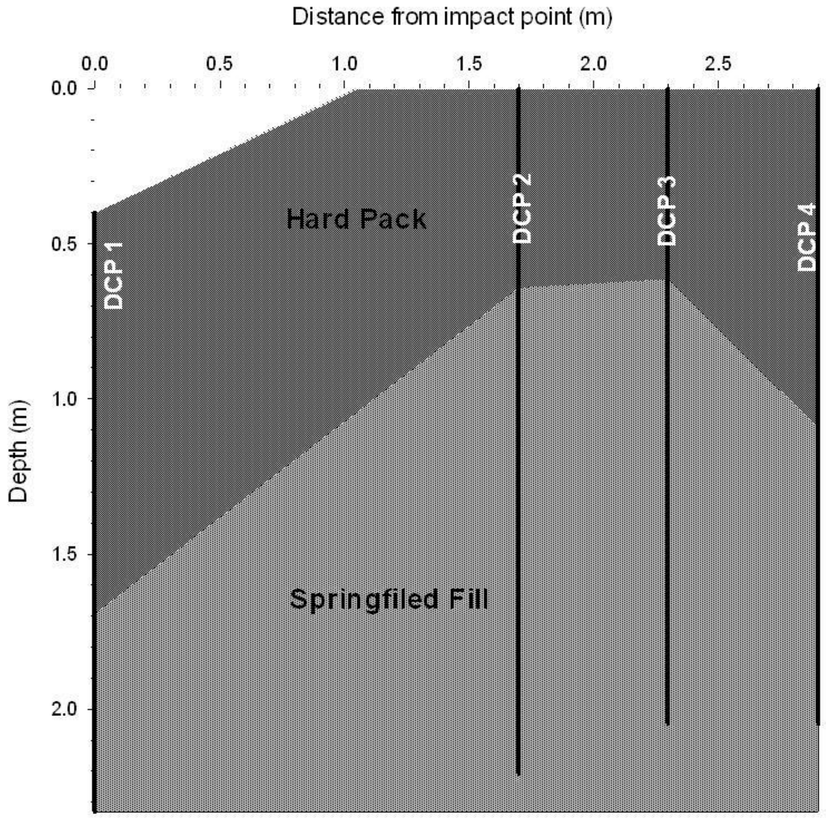


Figure 67. Post-compaction subsurface profile relative to impact point 1

Laboratory Testing

Correlation between DPI and D_r

Hard Pack and Springfield Fill samples were compacted in the laboratory and subsequently DCP tested in accordance with the procedure outlined in Chapter 5. DPI profiles (Appendix D) were generated from the DCP testing. For each profile, the DPI value at the surface is high from a localized lack of confining pressure, while the DPI values near the profile bottoms are low from the presence of the steel mold bottom. Therefore, average DPI values were approximated using only the center third of the DPI profiles. The average DPI value obtained during testing is referred to as $DPI_{7.2kPa}$, as is corresponds to 7.2 kPa (150 psf) confining pressure. A summary of the testing results are provided in Table 2.

Table 14. Results of laboratory DCP study

Material	Compaction Time (sec)	Relative Density, D_r (%)	Dynamic Penetration Index at σ' = 7.2 kPa, $DPI_{7.2kPa}$ (mm/blow)		
Hard Pack	1	20.3	36.0	42.0	40.0
	2	43.5	27.0	27.3	18.0
	3.5	55.4	24.7	24.0	20.0
	5	75.8	15.3	15.3	11.0
	15	92.0	11.5	9.2	8.4
	30	100.6	7.0	5.6	6.8
Springfield Fill	5	81.2	40.0	30.0	38.0
	15	82.4	26.0	29.0	30.0
	30	84.6	27.0	20.7	22.0
	60	90.7	16.0	17.0	15.3
	120	95.8	20.5	12.0	12.0

Figure 68 and Figure 69 show the relationships between $DPI_{7.2kPa}$ and relative density for Hard Pack and Springfield Fill, respectively. Both relationships involve the exponential decay function ($y = ae^{-bx}$). The $DPI_{7.2kPa}$ to D_r relationship for Hard Pack correlated very well ($r^2 = 0.936$). The $DPI_{7.2kPa}$–Dr relationship for Springfield Fill fit well ($r^2 = 0.660$).

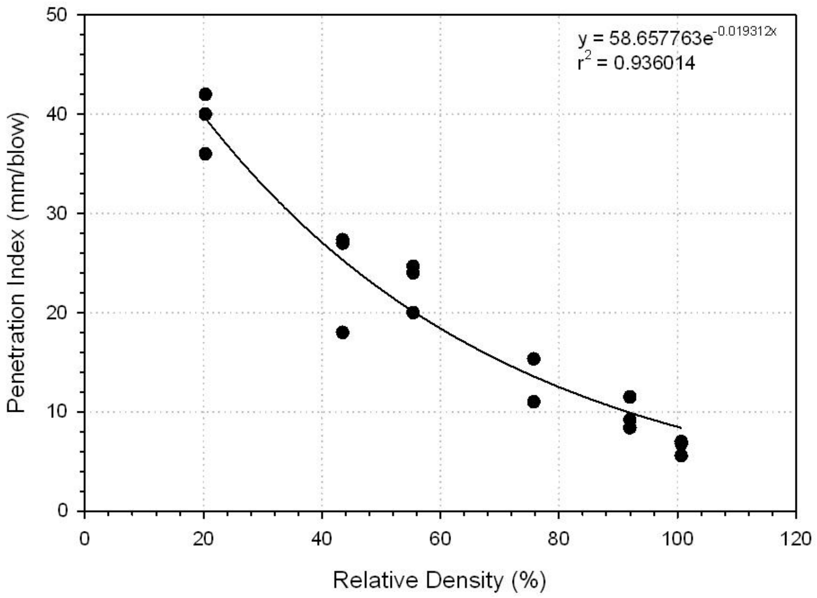


Figure 68. Relationship between relative density and DPI for Hard Pack

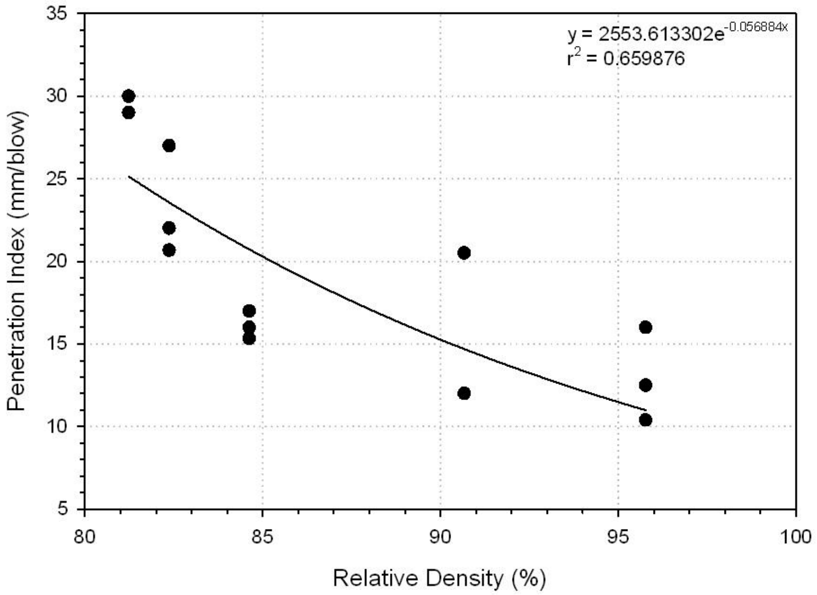


Figure 69. Relationship between relative density and DPI for Springfield Fill

Since Hard Pack has a high drained cohesion value, the shear strength, and therefore the DPI, at the low 7.2 kPa (150 psf) confining pressure is governed more so by cohesion rather than relative density. Springfield Fill however, possesses a lower drained cohesion value so the DPI at the 7.2 kPa (150 psf) confining pressure is governed more so by relative density rather than by cohesion. Thus $\text{DPI}_{7.2\text{kPa}}$ for Hard Pack is not as sensitive to relative density as Springfield Fill is.

The correlation from relative density to $\text{DPI}_{7.2\text{kPa}}$ for Hard Pack is [equation (24)]:

$$DPI_{7.2kPa} = 58.7e^{-0.0193D_r} \qquad (24)$$

where:

$DPI_{7.2kPa}$ = dynamic penetration index at 7.2 kPa (150 psf) confining pressure in mm/blow

D_r = relative density in %

Equation (24) can be rewritten in terms of relative density [equation (25)]:

$$D_r = -51.8ln\left[\frac{DPI_{7.2kPa}}{58.7}\right] \quad (25)$$

The correlation from relative density to DPI$_{7.2kPa}$ for Springfield Fill is [equation (26)]:

$$DPI_{7.2kPa} = 2550e^{-0.0569D_r} \quad (26)$$

where:

DPI$_{7.2kPa}$ = dynamic penetration index at 7.2 kPa confining pressure in mm/blow

D_r = relative density in %

Equation 3 can be rewritten in terms of relative density [equation (27)]:

$$D_r = -17.6ln\left[\frac{DPI_{7.2kPa}}{2550}\right] \quad (27)$$

Application of Laboratory Results to Field Conditions

Correlation of Field DCP Tests to D$_r$

Equation 2 and Equation 4 were applied to the DCP tests conducted in the field. Each DPI measurement in the field resulted from varying confining pressures. In order for the field DPI values to correspond to DPI values measured at 7.2 kPa (150 psf), a correction factor was applied to each field DPI measurement [equation (28)].

$$DPI_{7.2kPa} = \frac{DPI}{C_{DPI}} \quad (28)$$

where:

DPI$_{7.2kPa}$ = dynamic penetration index at 7.2 kPa (150 psf) confining pressure in mm/blow

DPI = dynamic penetration index measured in the field in mm/blow

C_{DPI} = DPI to DPI$_{7.2kPa}$ correction factor

Two different equations to calculate C$_{DPI}$ were evaluated in this study [equation (29) and equation (30)].

$$C_{DPI} = \left[\frac{1}{\frac{\sigma'_0}{7.2}}\right]^{0.5} \tag{29}$$

where:

C_{DPI} = DPI to $\text{DPI}_{7.2\text{kPa}}$ correction factor
σ'_0 = effective overburden pressure in kPa

$$C_{DPI} = \frac{2}{1+\left[\frac{\sigma'_0}{7.2}\right]} \tag{30}$$

where:

C_{DPI} = DPI to $\text{DPI}_{7.2\text{kPa}}$ correction factor
σ'_0 = effective overburden pressure in kPa

Equation (29) is based upon the corrected N_{60}-value equation from Liao and Whitman (1986) and equation (30) is based upon the corrected N_{60}-value equation from Skempton (1986).

Application of equations (25), (27), (28), (29), and (30) to both pre-RIC and post-RIC field DCP tests resulted in the relative density profiles shown in Figure 70. Using the Skempton (1986) based correction factor resulted in generally lower relative densities below a depth of approximately 1 m (3.3 ft) compared with the Liao and Whitman (1986) based correction factor (approximately 5%). The Skempton (1986) based approach is therefore more conservative. Sample calculations are provided in Appendix F.

Relative densities of up to 160% were observed in post-RIC DCP 1. This high degree of compaction is hypothesized to result from a change in the grain size distribution. From the 7 tonne (7.5 ton) hammer falling from 1.2 m (4 ft), high levels of compactive energy (82 kJ/blow) likely caused the crushing of particles and subsequent change in grain size distribution. This hypothesis could not be verified during the study as a sample of the presumably crushed material was not obtained. Lee and Singh (1971) define maximum dry density as the dry unit of a material when arranged in the most compact state possible by practical engineering methods without significantly altering the grain size distribution. The material measured by the DCP directly received compactive energy in excess of 8 MJ (5.9 x 10^6 ft-lb) which is much greater than standard engineering methods. The standard Proctor test (ASTM D698-00) and the modified Proctor test (ASTM D1557-78) impart a total compactive energy of 0.6 kJ/m^3 (12 400 ft-lb/ft^3) and 2.7 kJ/m^3 (56 000 ft-lb/ft^3), respectively. Therefore it is not unfeasible that the material could densify to that great of an extent even without significant changes in the grain size distribution. However, given the lack of data on whether or not the grain size distribution did indeed change following RIC, estimated relative densities in excess of 100% are simply be reported as ">100%."

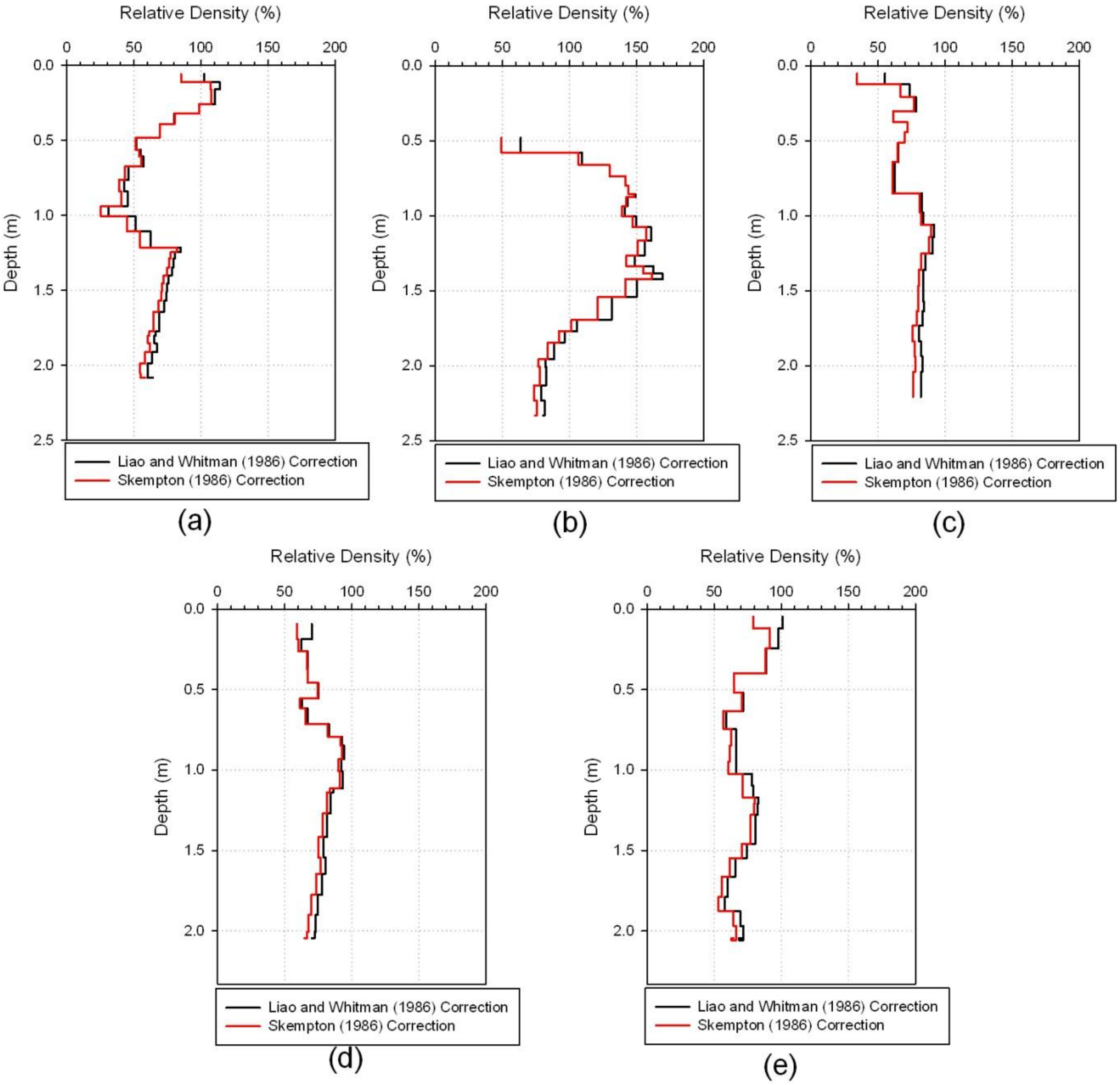


Figure 70. Correlated relative density profiles for (a) before compaction, (b) DCP1, (c) DCP2, (d) DCP3, and (e) DCP4

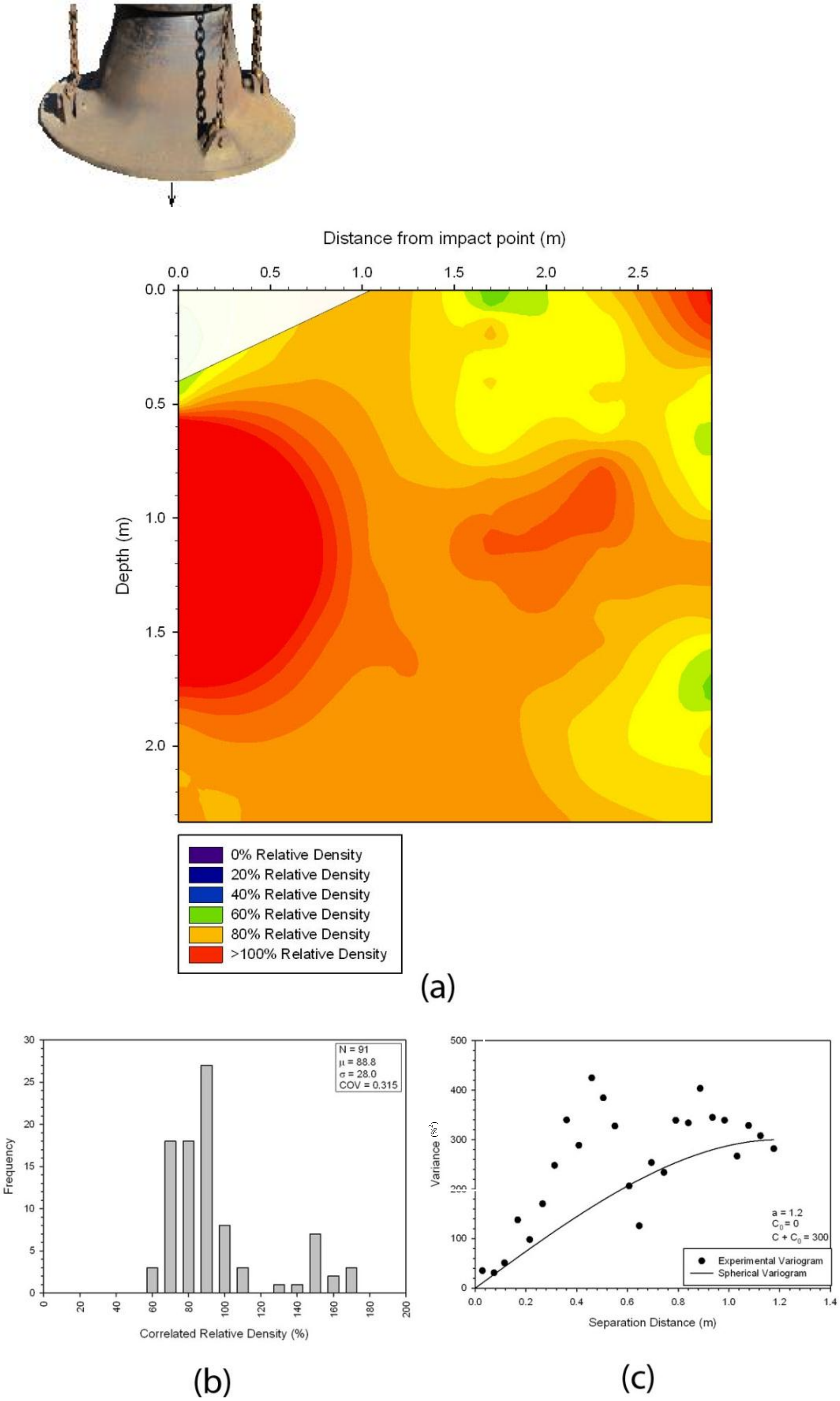
Geostatistical Analysis

Spatial Analysis of Correlated D_r

Geostatistical methods were used to analyze the correlated relative density with depth and distance from the RIC impact point. Kriged spatial contour maps, experimental semivariograms, and histograms for correlated relative density using the Liao and Whitman (1986) and Skempton (1986) based correction factors are presented in Figure 71 and Figure 72. Compared with exponential models, spherical models resulted in lower Cressie goodness fits and lower residual data means for both relative density data sets. Therefore, spherical models were used in both cases.

Figure 73 interprets and identifies the main features of the spatial analysis maps. The *soil plug* region lies immediately beneath the impact point. The region comprises material compacted to over 100% relative density. Approximately, the plug extends laterally 0.75 m (2.5 ft) and vertically downward 1.2 m (3.9 m). The very dense soil region radiates outward from *soil plug*. Approximately, the region extends both laterally and vertically downward 0.2 m (0.7 ft). The dense soil region begins tangent to the top of the dense soil region and extends downward and laterally at approximately a 45° angle with the horizontal plane. The loosened soil region lies at the ground surface. The region extends laterally approximately 2.3 m (7.5 ft) from the impact point and vertically approximately 0.3 m (1.0 ft) from the ground surface. The unaltered soil region encompasses soil that was not affected by the compaction. There is a localized dense region within the unaltered soil; however the localized dense region is the result of the interface between the Hard Pack and Springfield Fill layers. The top of the Springfield Fill layer had already been in a dense state prior to compaction.

Based on the spatial contour maps, an idealized profile of a subsurface subsequent to two RIC passes at a single impact point was developed and is presented in Figure 74.



(a)

(b)

(c)

Figure 71. Kriged spatial contour map (a), histogram (b), and variograms (c) using Liao and Whitman (1986) correction factor

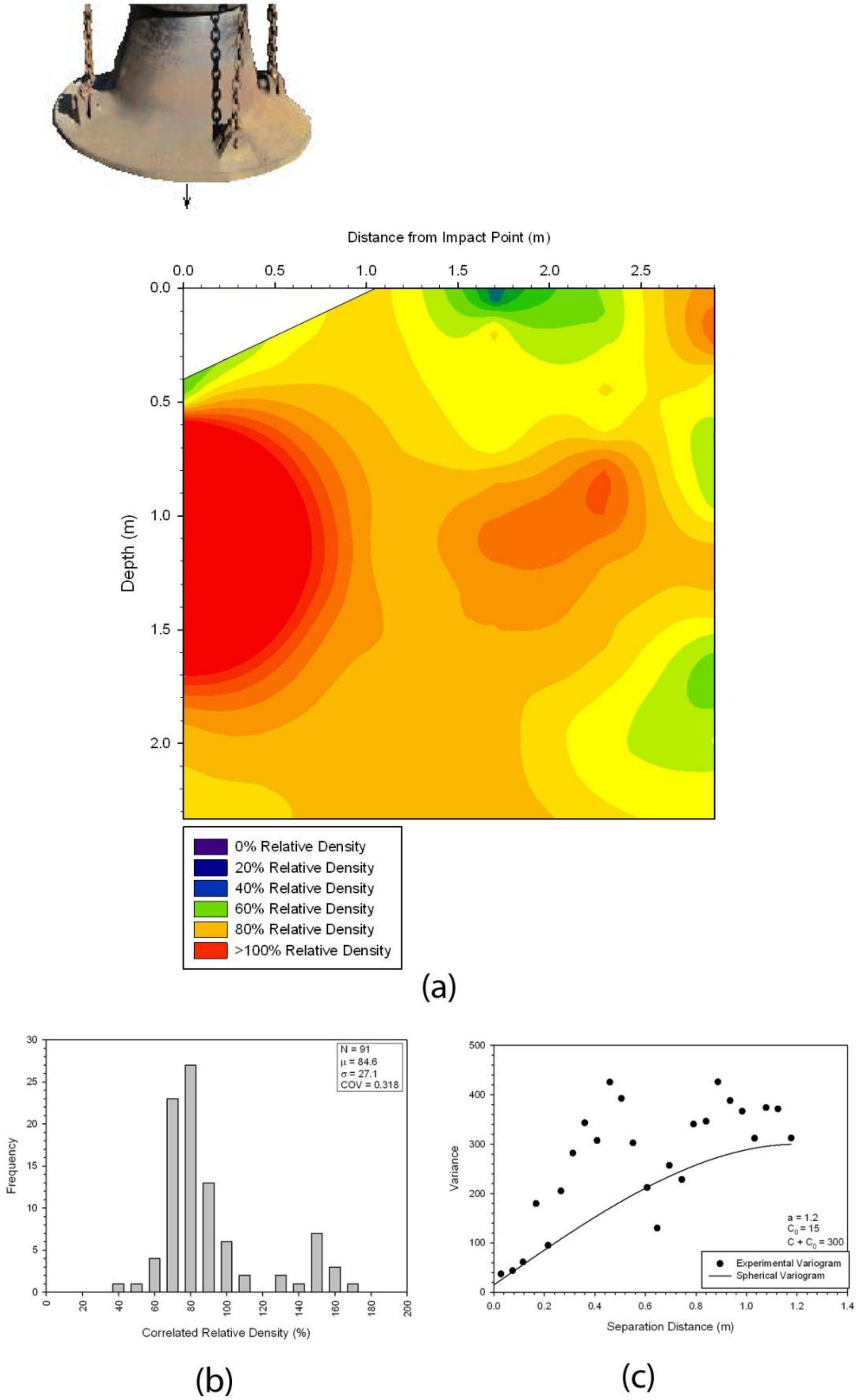


Figure 72. Kriged spatial contour map (a), histogram (b), variograms (c) using Skempton (1986) correction factor

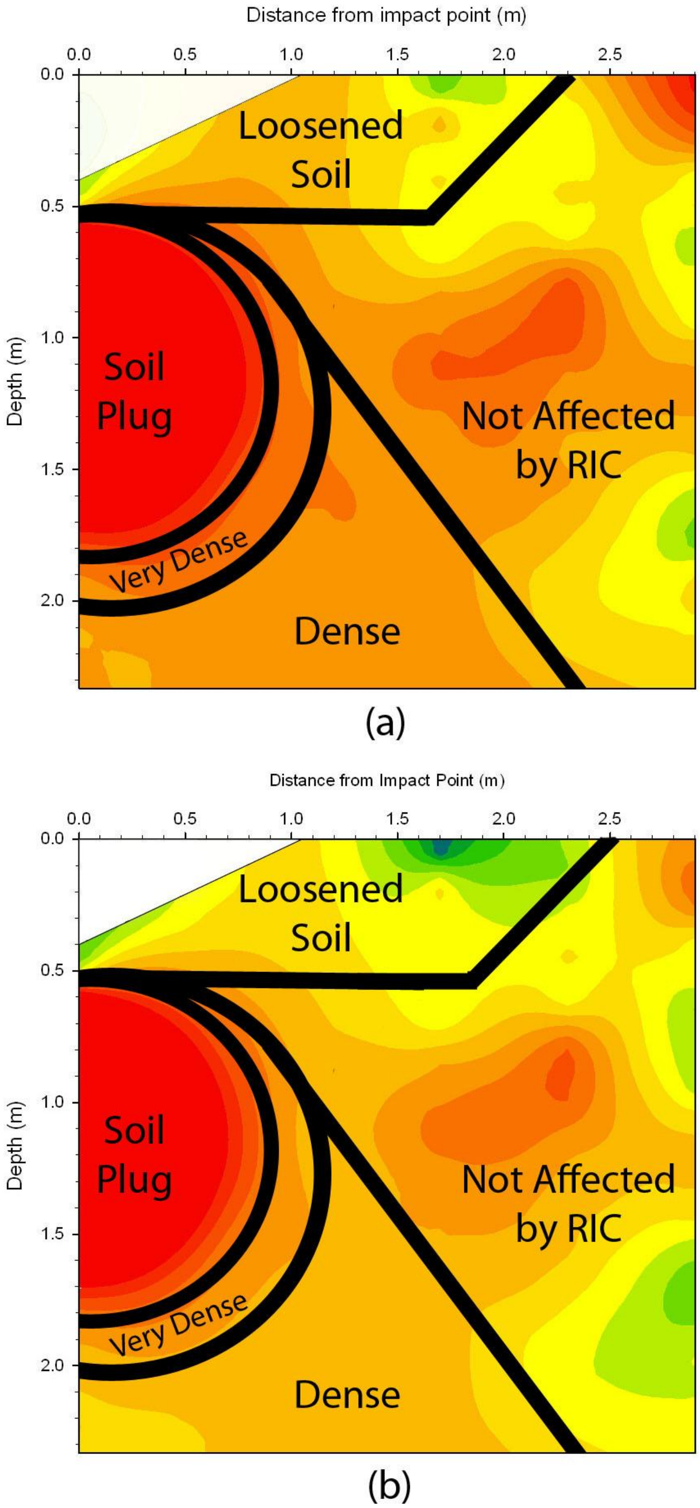


Figure 73. Interpretation of spatial map features for (a) Lioa and Whitman (1986) approach and (b) Skempton (1986) approach

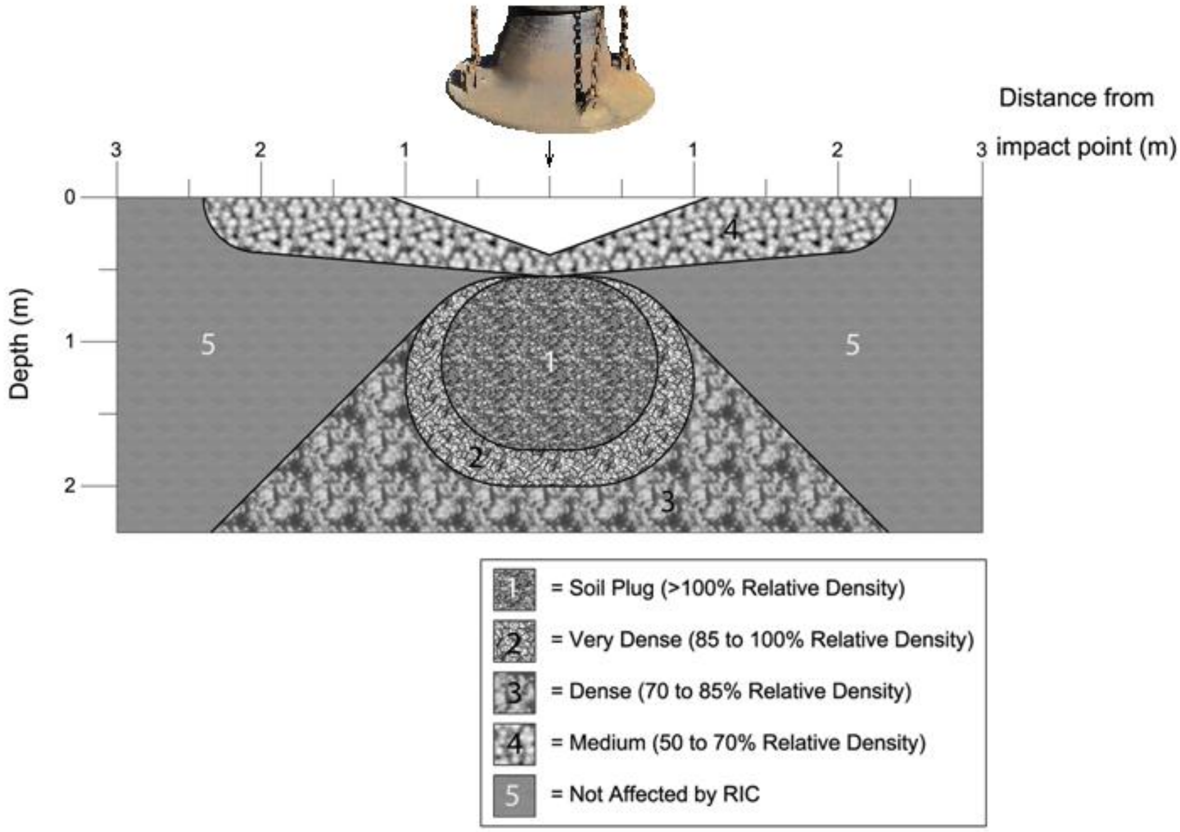


Figure 74. Idealized profile of subsurface following two RIC passes

Spatial Analysis of QC Data

Final set values recorded for each impact point were subjected to spatial analysis (Appendix E). Kriged spatial contour maps, experimental exponential variograms, and histograms are provided for the scenarios summarized in Table 1.

Figure 79 (Appendix E) reveals that spatial analysis following pass one from sequence one can be used as a diagnostic tool by showing the spatial variability of the site. Areas with high final set values (near 20 mm/blow) are indicative of “soft spots.” Soft spots can be very loose soil or clayey materials that do not respond well to RIC. The identity of the soft spots was not determined during the study. Areas with low final set values (near 5 mm/blow) are indicative of hard areas that will not require much compaction.

As additional sequences and passes are applied to the site, the final set values increase over the entire area (Appendix E). The final set values over the site converge upon

5 mm/blow and variances steadily decrease. These are demonstrative of the high levels of uniformity achieved from compaction over the entirety of the site.

Table 15. Summary of impact points analyzed to corresponding figures (Appendix E)

Figure	Impact Points Analyzed								
	Sequence 1			Sequence 2			Sequence 3		
	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3
81	✓								
82	✓	✓							
83	✓	✓	✓						
84	✓	✓	✓	✓					
85	✓	✓	✓	✓	✓				
86	✓	✓	✓	✓	✓	✓			
87	✓	✓	✓	✓	✓	✓	✓		
88	✓	✓	✓	✓	✓	✓	✓	✓	
89	✓	✓	✓	✓	✓	✓	✓	✓	✓

Rapid Impact Compaction Theory

Discrepancy with compaction depth equation

Although RIC and DDC are inherently similar geo-construction techniques, the compaction processes are quite different. RIC does not obey the compaction depth equation [equation (1), Chapter 2] for DDC. If this were the case, then compaction depth would be limited to 1.4 m (5 ft) below the ground level (assuming 7 tonne weight; 1.2 m drop height).

$$D = (0.5)[(7)(1.2)]^{1/2} = 1.4\ m$$

However it is quite evident from the spatial analysis above that compaction depth extends to at least 3 m (10 ft) below the ground surface.

Formation of the soil plug

Consistent with what was stated by BRE (2003) and Serridge and Synac (2006), RIC compacts soil by first forming the *soil plug* immediately beneath the RIC unit. Material comprising the *soil plug* is extremely dense and stiff. The *soil plug* is approximately semi ellipsoidal in shape with a diameter nearly equal in size to that of the anvil portion of the RIC unit.

Compaction of the strata underlying the soil plug

Eventually the *soil plug* becomes so stiff that it becomes a somewhat efficient energy transmitting medium. As blows are directly applied to the *soil plug*, waves of compactive energy are transmitted through the extremely stiff *soil plug* and into the soil underlying and adjacent to the *soil plug*. In accordance with what was theorized by Gambin (1979), the compaction of the soil underlying the *soil plug* occurs in two phases:

1. Transmitted compression (P) waves "shake" the soil skeleton by successively increasing and decreasing the pore water pressure until the skeleton dislocates.
2. Shear (S) waves and Raleigh (R) waves, which both have lower velocities compares with P waves (Burger et al. 2006), rearrange the dislocated grains into a denser state.

Soil plug advancement

Densification of the soil beneath the *soil plug* results in increased settlement and deeper advancement of the *soil plug*. Compaction of the soil beneath the *soil plug* induces settlement thereby resulting in deeper advancement of the *soil plug* into the soil mass. Eventually the RIC unit becomes incapable of penetrating deeper due to restrictions imposed by the excavator boom. In which case the impact point is backfilled before compaction continues, thereby increasing the size of the *soil plug*. Ultimately, advancement of the *soil plug* ceases. At this point the *soil plug* has developed sufficient frictional and end bearing resistance (i.e. densification of soil beneath *soil plug*) to prohibit further blows from advancing the *soil plug*.

CHAPTER 6. ASSESSMENT OF RIC FOR TRANSPORTATION APPLICATIONS

This chapter summarizes the assessment of RIC for transportation infrastructure applications in accordance with the SHRP2 research project. An introduction to the SHRP2 research project is provided in addition to how RIC corresponds with the project. RIC was assessed based on design procedures, QC/QA procedures, and specification procedures.

Strategic Highway Research Project 2

The United States Congress established the second Strategic Highway Research Project (SHRP2) in 2006 to address the challenges of moving people and goods efficiently and safely on the nation's highways. One of the goals of SHRP2 involves the development of design and construction methods that cause minimal disruption and produce long-lived facilities to renew the aging highway infrastructure. To achieve the goal of infrastructure renewal, numerous projects related to the design and construction of transportation infrastructure are currently being investigated.

One particular project, SHRP2 R02, entails the investigation of geotechnical solutions for soil improvement with respect to three elements:

1. construction of new embankments and roadways over areas of unstable soils;
2. widening and expansion of existing roadways and embankments, and
3. improvement and stabilization of the support beneath the pavement structure.

SHRP2 R02: Phase 1

Phase one of SHRP2 R02 identified nearly fifty geoconstruction technologies that face both technical and non-technical obstacles preventing broader and effective utilization in transportation infrastructure projects. The project tasks used to identify the technologies are provided in Table 16. One of the technologies that was identified included RIC.

According to the research done by SHRP2 R02, there are significant barriers preventing wider use of RIC. The major barriers preventing RIC usage include:

- lack of simple, comprehensive, reliable, and nonproprietary analysis and design procedures;
- lack of effective quality control and quality assurance procedures;
- lack of information on the vibrations associated with RIC; and
- lack of case histories involving RIC for use in the transportation infrastructure.

Table 16. SHRP2 R02 Phase 1 Tasks

Task 1	Identify existing and emerging geotechnical materials and systems for ground and roadway improvement for application to: 1. construction of new embankments and roadways over unstable soils; 2. rapid widening and expansion of existing roadways and embankments; and 3. improvement and stabilization of support beneath the pavement structure. In all cases, the need of the roadway or soil to carry construction loads as well as service loads is to be considered.
Task 2	Identify and discuss technical issues and project development/delivery pros and cons that need to be considered to further encourage widespread implementation of the geotechnical materials and systems identified in Task 1.
Task 3	Identify performance criteria, and existing and emerging QA/QC procedures to use with the geotechnical materials and systems identified and discussed in Tasks 1 and 2.
Task 4	Identify and discuss the non-geotechnical project-specific parameters that constrain the full utilization of the application of the identified geotechnical materials and systems.
Task 5	Assemble a panel of highway design and construction professionals and, with its help, identify the most promising methods for mitigating the non-geotechnical project-specific parameters identified and discussed in Task 4 that constrain the full utilization of the application of the geotechnical materials and systems identified in Task 1, and develop a work plan for the following activities: • Testing the effectiveness of these mitigation methods and evaluating their effectiveness • Developing a catalog of materials and systems for rapid renewal projects • Developing design procedures, QA/QC processes, and guidance for applying these geotechnical materials and systems • Developing methods for estimating the cost of their application • Developing sample guide specification for these geotechnical materials and systems.
Task 6	Develop a final report for Phase 1 detailing the work conducted in Tasks 1-5 and proposing a work plan for the tasks to be conducted in Phase 2. This report should provide: 1. searchable documentation of the identified geotechnical materials and systems addressed; 2. information on how to locate and access documentations of case histories; and 3. reference materials and other supporting documentation.

SHRP R02: Phase 2

Phase 2 of SHRP R02 involves the development of an integrated catalogue and guidance system. With the technology catalogue, one can look up a particular geoconstruction technology and instantly receive a comprehensive summary of the specified technology with respect to information such as:

- project applicability;
- soil type applicability;
- advantages and disadvantages;
- cost information;
- specifications;
- design procedures; and
- QC/QA (quality control/quality assurance) procedures.

With the guidance system, a user can specify the constraints of his or her project (i.e., required depth, soil type, etc.) and receive a short list of potentially effective geoconstruction technologies. Each geoconstruction technology output links to its respective catalogue entry. The catalogue entry for each geoconstruction technology consists of a set of documents concerning design procedures, QC and QA procedures, and specifications. The documents for RIC are enclosed in Appendix J.

The guidance system, however, is not meant to be a design procedure, only a comprehensive overview to carry out a preliminary evaluation. Currently, the selection guidance system is still in development and only comprises a logical flow chart (Figure 75 and Figure 76). Figure 75 sorts geoconstruction technologies based on application (i.e., above grade, below grade, or geotechnical pavement components). Based on the desired application, the user can specify required parameters such as soil type and depth (Figure 76).

The information used to populate the integrated catalogue and guidance system comes from a set of project tasks (Table 17).

Table 17. SHRP2 R02 Phase 2 Tasks

Task 8	Test the effectiveness of these mitigation methods approved and or amended from Phase 1, and evaluate their effectiveness.
Task 9	Develop a catalog of materials and systems for rapid renewal projects.
Task 10	Develop design procedures, QA/QC processes, and guidance for applying these geotechnical materials and systems.
Task 11	Develop methods for estimating the application costs of these geotechnical materials and systems.
Task 12	Develop sample guide specifications for these geotechnical materials and systems.
Task 13	Develop a final report for Phase 2 detailing the work conducted in Tasks 8-12.

To complete the tasks, evaluations for each geoconstruction technology were performed in regards to technology background, design methods, QC/QA procedures, and specifications. Evaluations for each technology were made using the following assessment documents:

- Comprehensive Technology Summary (CTS);
- Task 10 Assessment of Design Methods and QC/QA Procedures; and
- Task 12 Assessment of Existing Specifications.

Each geoconstruction technology has its own unique set of assessment documents. From a standard template, a CTS document, a Task 10 document, and a Task 12 document were developed for every technology.

The Comprehensive Technology Summary (CTS) is a document that contains source material for completing the SHRP2 R02 phase 2 tasks (e.g., develop design procedures, develop methods for estimating costs, develop sample specifications, etc.). The CTS document comprises:

- technology definition/description;
- technology applicability screening parameters (i.e., depth limits, soil type, etc.)
- case history database;
- summary of design procedures;
- summary of QC/QA procedures;

- cost information; and
- available specifications.

The purpose of the Task 10 document is to assess and characterize the design/analysis procedures and QC/QA methods for the geoconstruction technologies being investigated. The document relates the inputs and outputs of the design/analysis procedures to potential applications of the technology. Individual design/analysis procedures are then assessed and the technology is characterized according to the status of its respective design/analysis procedure. Objectives of QC/QA activities are related to potential applications of the technology. Published QC/QA procedures are assessed based on parameters such as accuracy, precision, adequacy of coverage, etc.

The purpose of the Task 12 document is to assess and characterize published specifications for the geoconstruction technologies being investigated. Existing specifications were characterized as method specifications, performance specifications, or performance/method specifications. A performance level (i.e., the manner in which a specification requires performance characteristics to be measured to determine project acceptance) was assigned to each existing specification. Existing specifications were assessed for factors such as completeness, constructability, and, risk allocation. Assessments on whether or not existing specifications needed to be improved before being applied to transportation projects were then made.

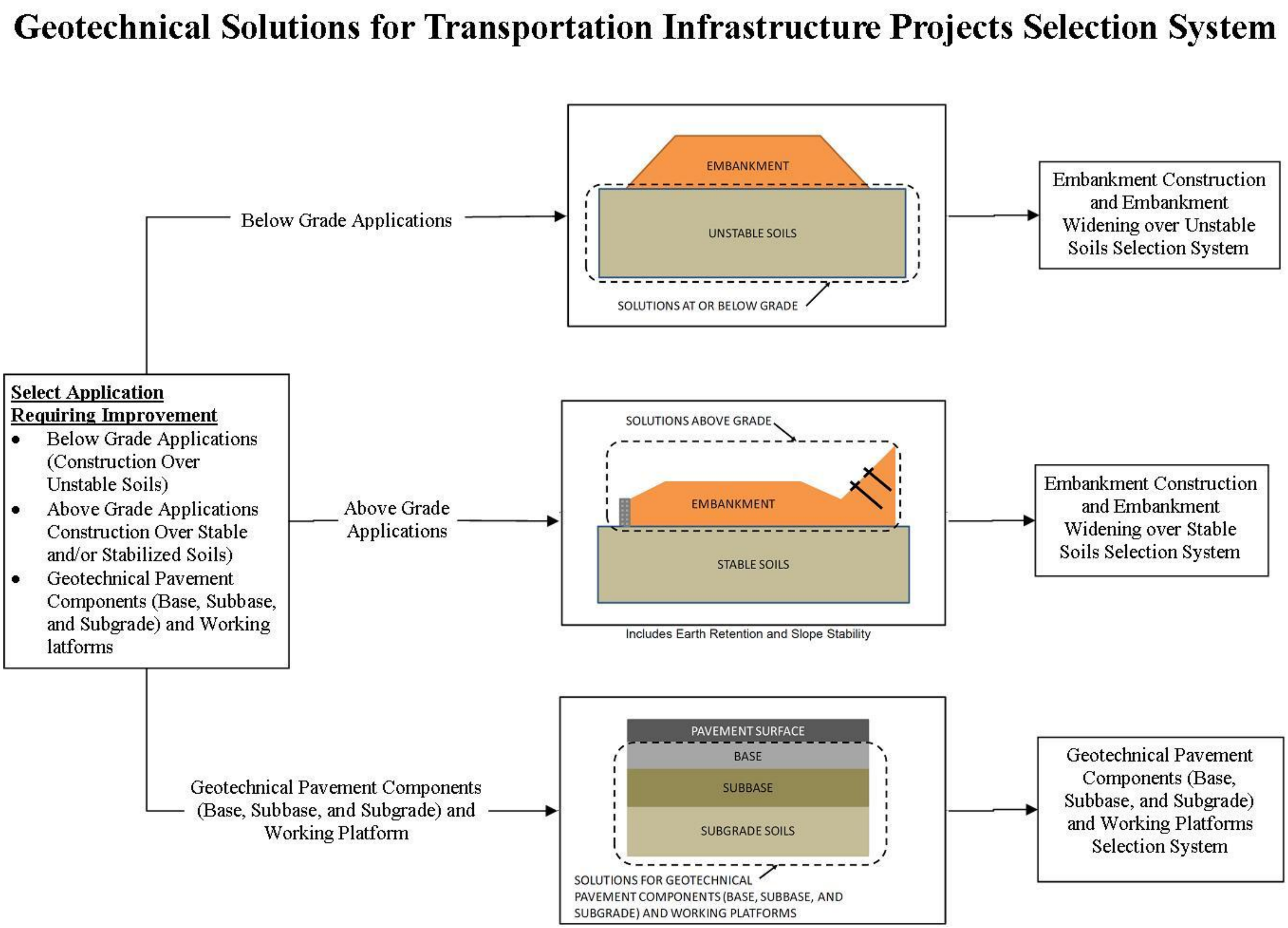
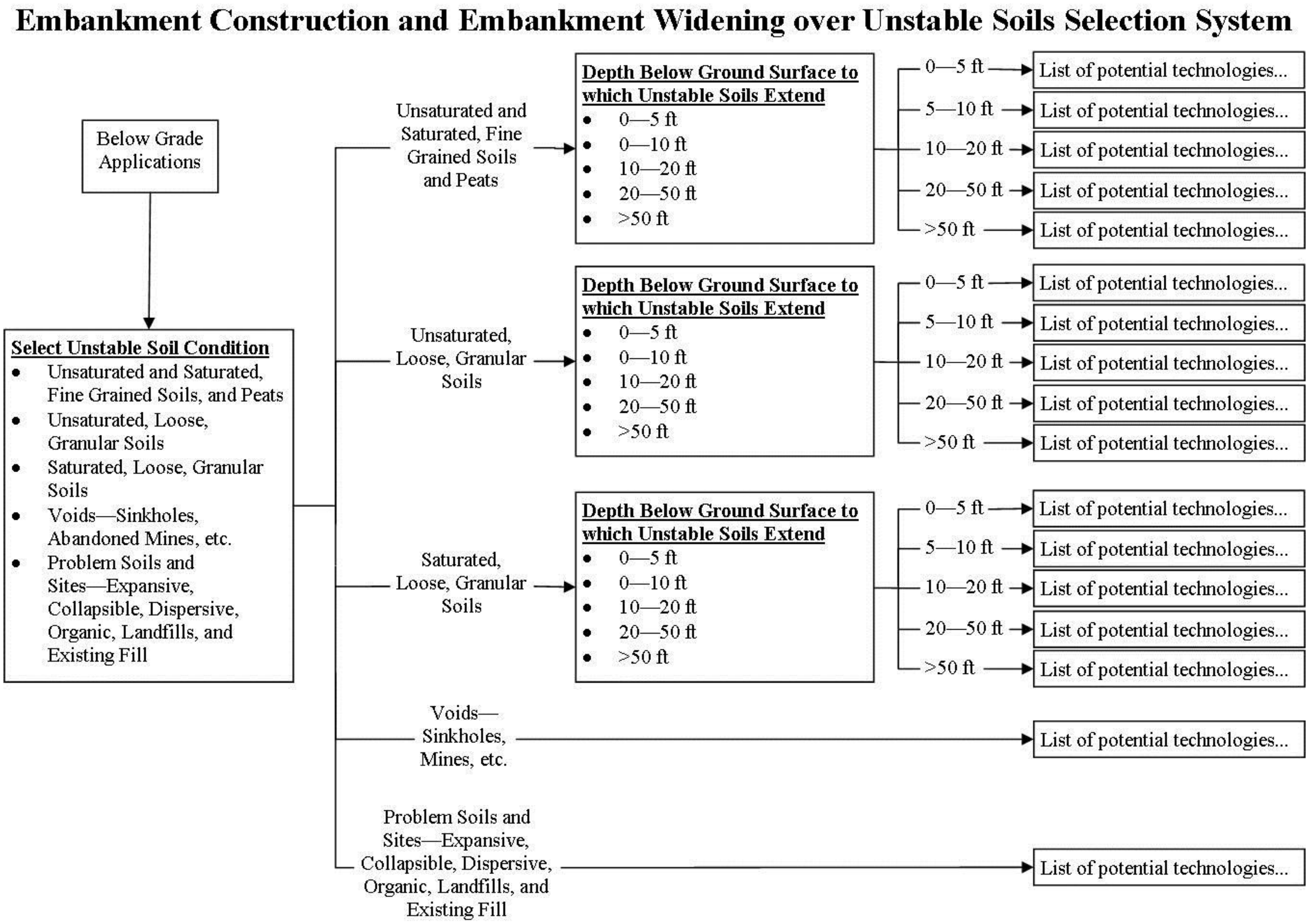


Figure 75. Selection guidance system application section



Embankment Construction and Embankment Widening over Unstable Soils Selection System

Figure 76. Selection guidance system input parameters for below grade applications

RIC Comprehensive Technology Summary

The CTS document for RIC is provided in the Appendix G. The basic function, advantages and disadvantages, geologic applicability, etc. for RIC are all summarized within the document. Information used to populate the CTS was obtained from published research papers, case histories, and reports from an experienced RIC contractor.

RIC is applicable to the following SHRP2 R02 elements:

1. construction of new embankments and roadways over areas of unstable soils;
2. widening and expansion of existing roadways and embankments, and
3. improvement and stabilization of the support beneath the pavement structure.

RIC is used to compact loose foundation soils, therefore the technology can be used to stabilize weak embankment foundations via densification. RIC can be used to construct embankments by compacting in thick lifts. Geotechnical pavement layers can be better compacted with RIC.

RIC Task 10 Assessment of Design Methods and QC/QA Procedures

The Task 10 document for RIC is provided in Appendix H. Potential RIC applications for transportation infrastructure projects include compaction (i.e. embankment construction), support of embankments or structures, liquefaction mitigation, and settlement reduction. The corresponding design inputs and outputs for the potential applications are summarized within the document.

There is currently one design/analysis procedure for RIC. The procedure is entitled *Direct measurement of improvement depth following construction*. This design/analysis procedure is applicable to the previously identified transportation project applications. However, this design/analysis procedure in its current state is only being used for commercial/private projects.

QC objectives for RIC include process control and measurements related to equipment performance. Although multiple QC methods exist, both process control and measurements from equipment performance for RIC are usually monitored by the data acquisition system within the cab of the RIC unit. This method encompasses the standard of practice; however its effectiveness (e.g., accuracy and precision) has yet to be evaluated. Therefore the applicability of the data acquisition system to transportation infrastructure projects involving RIC is inconclusive.

QA objectives for RIC include bearing capacity, predicted settlement, and liquefaction susceptibility. In situ penetration tests (i.e., SPT, CPT, etc.) are typically used to evaluate the QA objectives. Although other QA methods exist, in situ penetration tests are used due to the large compaction depths produced from RIC. These test methods are relatively common, follow test standards, and are routinely used to empirically determine design parameters. In situ penetration tests are therefore highly applicable to RIC related transportation projects.

Currently, the QA/QC procedure for RIC is somewhat flawed. Although in situ penetration tests provide a good interpretation of magnitude and depth of improvement, spatial non-uniformity across a site may not be adequately captured with a limited number of test boring locations. Additional research into QA/QC is advised to allow for a better evaluation of non-uniform site conditions for the RIC procedure. The potential of various other QA/QC tests should be investigated including advanced machine integrated systems.

RIC Task 12 Assessment of Existing Specifications

The Task 12 document for RIC is provided in Appendix I. There is currently one preferred specification for RIC. This specification is used by an RIC contractor for all of its commercial projects but has not been implemented on a transportation infrastructure project.

The specification is a performance approach. The current RIC specification is regarded as a performance-related specification because performance-related properties (i.e., SPT-N_{60}) are measured at the end of construction. A desired post-compaction level based on SPT or CPT is specified for the RIC contractor to achieve.

A detailed evaluation of the specification in terms of clarity, risk allocation, ability to be fairly bid, constructability, and QC/QA verification is provided in the task 12 assessment. The RIC specification has suitable components for transportation infrastructure applications but it is targeted towards commercial projects in its current state. The specification requires improvement before it can be applied on a transportation infrastructure project.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The utilization of RIC in transportation infrastructure projects has been prevented by multiple obstacles. This study has mitigated some of these obstacles and has therefore increased the likelihood of a transportation infrastructure project employing RIC.

In the pursuit of different research objectives, RIC obstacles have been mitigated and/or mitigation strategies have been proposed (Table XX).

Table 18. RIC obstacle mitigation measures

Obstacle	Mitigation Measure from this Research	Proposed Future Mitigation Measures
Lack of Simple, comprehensive, and nonproprietary design procedure	Design procedures for RIC within the commercial sector have been reported	Develop design charts for degree of compaction; develop model for estimating compaction depth
Lack of established engineering parameters and/or performance criteria	QC/QA procedures for RIC within the commercial sector have been reported	Develop QC/QA guidelines from correlations to QC data, design charts, etc.
Lack of easy-to-use tools for selecting technology	Establishment of selection guidance system	
Lack of long-term performance data	Performance data, although short-term, from commercial RIC projects have been reported	Construct controlled test sections for long-term monitoring
Environmental impacts (i.e., vibrations)	Vibration data from different RIC projects has been presented	
Performance uncertainty	Performance data from commercial projects have been reported	Construct controlled test sections for long-term monitoring
Lack of accessible case histories	Multiple commercial sector RIC case histories have been provided	Implement field demonstration studies on transportation projects

The objectives were to develop an expanded RIC knowledge base from published material and information gathered from RIC contractors; to present a detailed case history of an RIC project; and to assess the applicability of RIC's design procedures, quality control procedures, quality assurance procedures, and specification procedures to transportation infrastructure projects. Information was obtained from GeoStructures, Inc. and data was gathered in the laboratory in addition to a field study in Springfield, MA.

Conclusions

The main conclusions developed from the three objectives are summarized as follows:

1. *Development of an expanded RIC knowledge base*
    - There is a standard, albeit highly qualitative, design procedure.
    - Quality control practices based on rules of thumb have been developed.
    - Multiple RIC case histories within the United States exist.
    - Results from vibration studies at different RIC projects can be used to predict the expected peak particle velocities.
    - RIC has approximately a \$37,000 mobilization cost with a \$9.7/m^2 (\$0.9/SF) unit cost.
2. *Presentation of a detailed RIC case history*
    - RIC effectively compacted the loose soil underlying the presented site.
    - Effective correlations between dynamic penetration index and relative can be developed base on soil type.
    - Spatial analysis of final set values for sequence 1 impact points after one compaction pass can show spatial variability of a site and act as a diagnostic tool.
    - Spatial analyses of final set values after additional sequences and passes demonstrate the high uniformity of compaction achieved within the shallow subsurface.
    - From spatial analyses of relative density, the post-RIC subsurface profile comprises an extremely dense region (i.e., the *soil plug*) and a dense region beneath the *soil plug* extending laterally.
3. *Assessment for transportation applications*
    - RIC is applicable to transportation infrastructure applications including:
        - stabilization of loose soils (i.e., deep compaction) underlying proposed embankments and roadways;
        - embankment compaction; and

    - improving the support beneath the pavement structure.
- The current RIC design procedure has only been implemented on commercial projects, therefore requires transitioning before it can be used effectively on transportation infrastructure projects.
- Proper evaluations of the current RIC QC/QA procedures need to be made before they can gain acceptance on transportation infrastructure projects.
- There is currently a performance-related specification for RIC; however, because the specification has only been implemented on commercial projects, the specification requires improvement before it can be applied on a transportation infrastructure project.

Recommendations

The recommendations for future research include:

- Perform multiple case histories featuring RIC with different applications pertaining to transportation infrastructure projects which will include:
    - field demonstration studies;
    - long-term monitoring; and
    - establishment of QC/QA guidelines.
- Develop a guide specification for applying RIC to different transportation infrastructure construction projects.
- Correlate RIC QC data to both performance-based (e.g., elastic modulus) and performance-related (e.g., SPT-N_{60}) properties for different soil types.
- Develop a model for determining RIC depth of compaction.
- Develop design charts for estimating degree of compaction based on applied energy and soil properties (e.g., percent fines).

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APPENDIX A: SAMPLE SPREADSHEET FOR AVERAGE SPT-N

Table 19. Pre-RIC SPT-N_{60} values for Tampa, FL

Depth (m)	SPT-N60 Value			
			Average	
	SB-01	TF-02	SPT-N60	Std. Dev
0.6	11	15	13	3
1.2	19	22	21	2
1.8	18	17	18	1
2.4	5	11	8	4
3.0	5	11	8	4
4.0	0		0	
4.6		0	0	
5.2	4		4	
6.1	8	2	5	4
7.6	11	8	10	2
9.1	5	11	8	4

SPT-N60 weighted average within compaction depth (4.0 m) = 11

Table 20. Post-RIC SPT-N_{60} values for Tampa, FL

Depth (m)	SPT-N60 Value						
						Average	
	AR-1	AR-2	AR-3	AR-4	AR-5	SPT-N60	Std. Dev
0.6	20	6	23	29	16	19	9
1.2	18	13	23	16	15	17	4
1.8	19	17	13	14	14	15	3
2.4	39	20	11	45	13	26	15
3.0	53	32	24	33	20	32	13
3.7	7	4	7	9	5	6	2
4.3	14	13	16	32	11	17	8
4.9	9	6	7	16	7	9	4
5.5	5	7	3	4	3	4	2
6.1	10	6	6	6	9	7	2
6.7	6	18	12	16	14	13	5
7.3	20	16	16	15	19	17	2
7.9	16	22	20	22	26	21	4
8.5	16	20	19	12	32	20	7
9.1	16	23	26	18	27	22	5

SPT-N_{60} weighted average within compaction depth (4.0 m) = 18

APPENDIX B: RESULTS OF SEM X-RAY ANALYSIS

Table 21. X-ray analysis for Hard Pack medium sized particles at 25x magnification (Figure 48)

Element	Spect.	Element	Atomic
O K	ED	39.62	55.43
Na K	ED	2.60	2.53
Mg K	ED	1.46	1.35
Al K	ED	8.70	7.21
Si K	ED	32.83	26.17
P K	ED	-0.02*	-0.01*
S K	ED	0.55	0.38
K K	ED	2.29	1.31
Ca K	ED	5.11	2.86
Ti K	ED	0.42	0.20
Mn K	ED	0.04*	0.02*
Fe K	ED	6.40	2.56
Total		100.00	100.00

Table 22. X-ray analysis for Hard Pack fine particles at 30x magnification (Figure 49a)

Element	Spect.	Element	Atomic
O K	ED	38.02	54.74
Na K	ED	2.34	2.34
Mg K	ED	2.00	1.90
Al K	ED	9.90	8.45
Si K	ED	26.98	22.13
P K	ED	-0.05*	-0.04*
S K	ED	0.49	0.35
K K	ED	3.21	1.89
Ca K	ED	6.92	3.97
Ti K	ED	0.78	0.38
Mn K	ED	0.35	0.15
Fe K	ED	9.05	3.73
Total		100.00	100.00

Table 23. X-ray analysis for Hard Pack fine particles at 100x magnification (Figure 49b)

Element	Spect.	Element	Atomic
O K	ED	39.62	55.43
Na K	ED	2.60	2.53
Mg K	ED	1.74	1.35
Al K	ED	9.06	7.21
Si K	ED	27.91	26.17
P K	ED	0.03*	-0.01*
S K	ED	0.49	0.38
K K	ED	2.43	1.31
Ca K	ED	6.45	2.86
Ti K	ED	1.36	0.20
Mn K	ED	0.26*	0.02*
Fe K	ED	9.53	2.56
Total		100.00	100.00

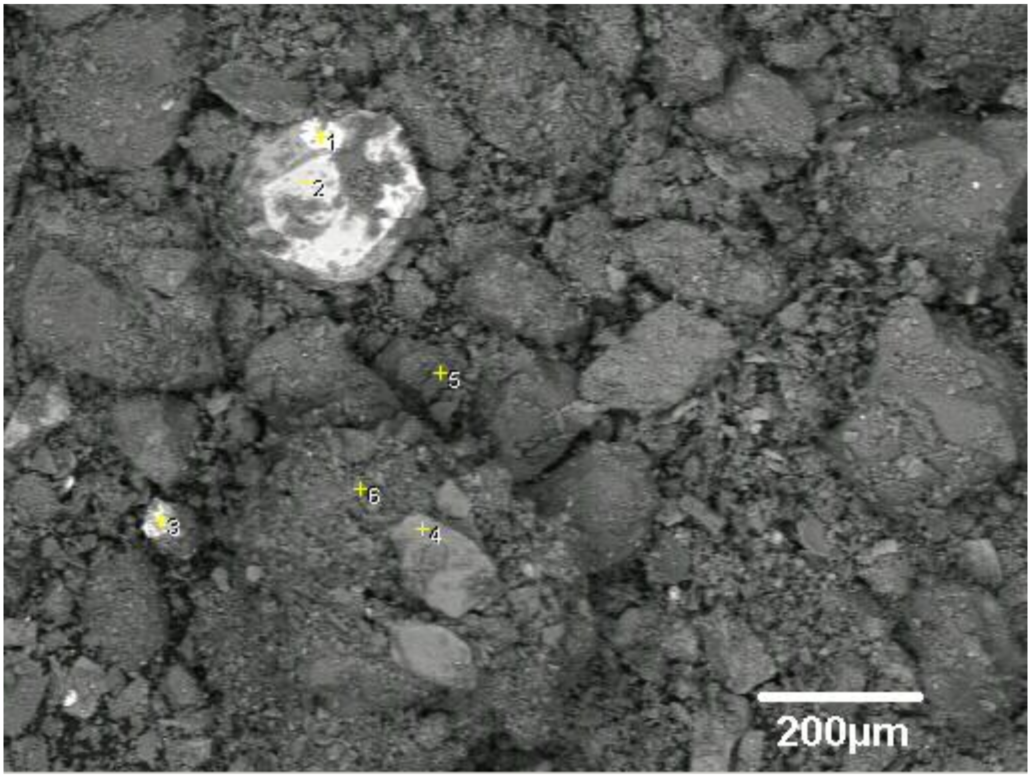


Figure 77. Point locations of x-ray analyses on 100x magnification Hard Pack fine particles

Table 24. Point x-ray analyses on 100x magnification Hard Pack fine particles (Figure 77)

Point	Element		Spect.	Element	Atomic
1	O	K	ED	35.55	65.50
	Na	K	ED	-0.38*	-0.48*
	Mg	K	ED	0.65	0.79
	Al	K	ED	2.79	3.05
	Si	K	ED	5.53	5.81
	P	K	ED	16.12	15.35
	S	K	ED	0.14*	0.13
	K	K	ED	0.16	0.12
	Ca	K	ED	1.91	1.40
	Ti	K	ED	0.38	0.24
	Mn	K	ED	-1.55*	-0.83*
	Fe	K	ED	2.43	1.28
	La	K	ED	10.35	2.20
	Ce	K	ED	25.91	5.45
	Total			100.00	100.00
2	O	K	ED	21.34	45.70
	Na	K	ED	0.42	0.63
	Mg	K	ED	0.35	0.49
	Al	K	ED	1.01	1.28
	Si	K	ED	1.41	1.72
	P	K	ED	0.06*	0.07*
	S	K	ED	-0.01*	-0.01*
	K	K	ED	0.18	0.16
	Ca	K	ED	0.36	0.31
	Ti	K	ED	36.01	25.76
	Mn	K	ED	3.96	2.47
	Fe	K	ED	34.91	21.42
	Total			100.00	100.00

Table 20. Point x-ray analyses on 100x magnification Hard Pack fine particles (Figure 77) (continued)

3	O K	ED	27.14	50.85
	Na K	ED	7.71	10.05
	Mg K	ED	1.69	2.08
	Al K	ED	3.85	4.28
	Si K	ED	7.81	8.34
	P K	ED	0.10*	0.09*
	S K	ED	1.94	1.81
	K K	ED	0.40	0.30
	Ca K	ED	3.19	2.39
	Ti K	ED	0.63	0.39
	Mn K	ED	0.42	0.23
	Fe K	ED	3.05	1.64
	Zn K	ED	36.51	16.74
	Pb K	ED	5.57	0.81
	Total		100.00	100.00
4	O K	ED	17.84	34.73
	Na K	ED	0.81	1.10
	Mg K	ED	2.87	3.67
	Al K	ED	9.42	10.87
	Si K	ED	15.16	16.81
	P K	ED	0.04*	0.04*
	S K	ED	0.31	0.30
	K K	ED	7.29	5.80
	Ca K	ED	2.59	2.01
	Ti K	ED	3.26	2.12
	Mn K	ED	0.36*	0.20*
	Fe K	ED	40.07	22.35
	Total		100.00	100.00

Table 20. Point x-ray analyses on 100x magnification Hard Pack fine particles (Figure 77) (continued)

5	O K	ED	40.61	56.91
	Na K	ED	1.46	1.42
	Mg K	ED	1.63	1.50
	Al K	ED	14.19	11.79
	Si K	ED	22.19	17.72
	P K	ED	0.06*	0.05*
	S K	ED	1.01	0.71
	K K	ED	5.95	3.41
	Ca K	ED	8.15	4.56
	Ti K	ED	0.50	0.24
	Mn K	ED	0.14	0.06*
	Fe K	ED	4.10	1.65
	Total		100.00	100.00
6	O K	ED	39.28	56.09
	Na K	ED	1.34	1.33
	Mg K	ED	5.45	5.12
	Al K	ED	12.31	10.43
	Si K	ED	21.86	17.78
	P K	ED	0.20	0.15
	S K	ED	0.67	0.48
	K K	ED	1.71	1.00
	Ca K	ED	3.59	2.05
	Ti K	ED	0.30	0.14
	Mn K	ED	0.16*	0.07*
	Fe K	ED	13.13	5.37
	Total		100.00	100.00

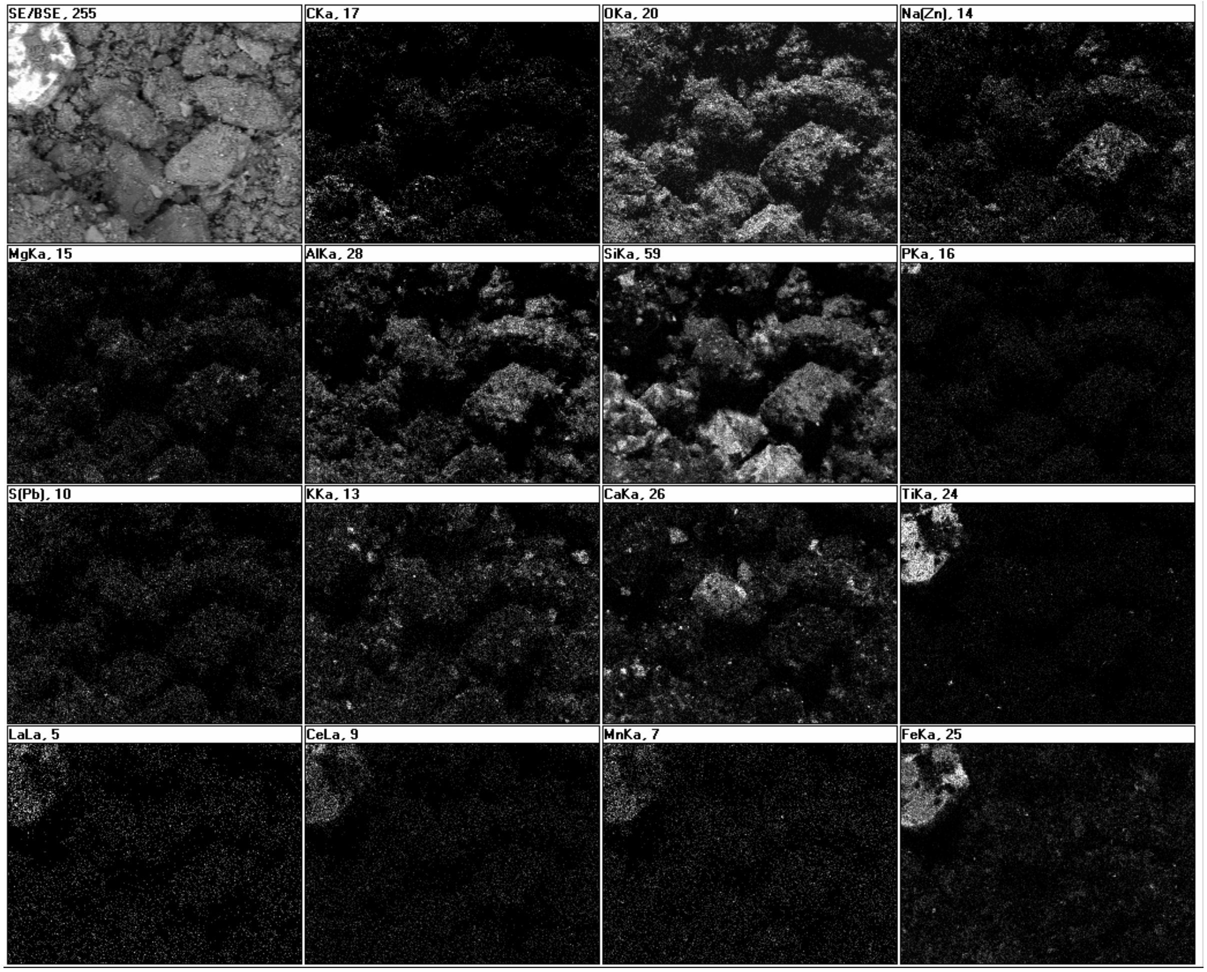


Figure 78. Elemental map for Hard Pack fine particles at 200x magnification

APPENDIX C: RESULTS OF SPT TESTING

Table 25. Results of SPT testing before compaction

FW-501		FW-503		FW-504		FW-505		FW-511	
Depth (m)	**SPT-N_{60}**	**Depth (m)**	**SPT-N_{60}**	**Depth (m)**	**SPT-N_{60}**	**Depth (m)**	**SPT-N_{60}**	**Depth (m)**	**SPT-N_{60}**
0.3	50	0.3	10	0.3	15	0.3	15	0.3	15
1.8	5	1.8	18	1.8	2	1.8	8	1.8	18
3.4	2	3.4	11	3.4	6	3.4	5	3.4	8
4.9	7	4.9	10	4.9	19	4.9	24	4.9	25
6.4	2	6.4	2	6.4	6	6.4	9	6.4	7
7.9	2	7.9	2	7.9	6	7.9	5	7.9	11
		9.4	6					9.4	11
		11.0	5					11.0	39
		12.5	8					12.5	24
		14.0	24					14.0	71
		15.5	35						
		17.1	110						

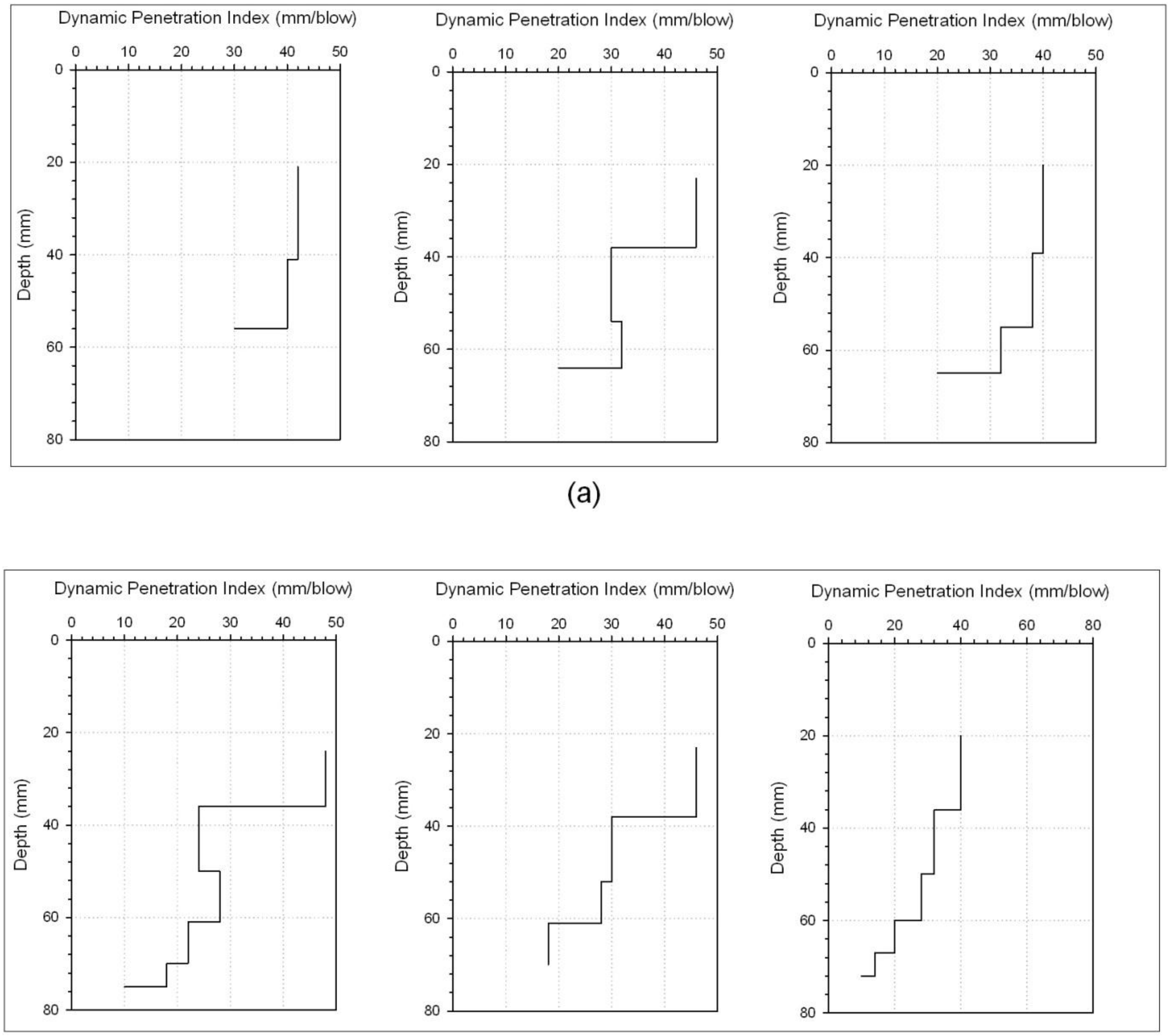
Table 25. Results of SPT testing before compaction (continued)

FW-512		FW-513		Average		
Depth (m)	SPT-N_{60}	Depth (m)	SPT-N_{60}	Depth (m)	SPT-N_{60}	Std. Dev.
0.3	42	0.3	52	0.3	28	19
1.8	5	1.8	13	1.8	10	7
3.4	2	3.4	11	3.4	6	4
4.0	2					
4.9	14			4.9	17	7
6.4	6			6.4	5	3
7.9	6			7.9	5	3
9.4	11			9.4	9	3
11.0	9			11.0	18	19
12.5	33			12.5	22	13
14.0	21			14.0	39	28
15.5	29			15.5	32	4

Table 26. Results of SPT testing after compaction

Depth (m)	SPT-N60 Value									
									Average	
	RIC-1	RIC-2	RIC-3	RIC-8	RIC-7	RIC-4	RIC-5	RIC-6	SPT-N60	Std. Dev
0.0										
0.3	22	67						24	38	25
0.6			64		56	96	84		75	18
0.9	40	33						36	36	4
1.2			30	64	66	73	36		54	19
1.5	45	14						49	36	19
1.8				49	20	22	37		32	14
2.1	61	17						50	43	23
2.4				54	17	18	39		32	18
2.7	36	13						41	30	15
3.0				31	19	20	56		32	17
3.4	17	16						35	23	11
3.7				27	22	36	51		34	13
4.0	45	24						25	31	12
4.3				31	19	23	50		31	14
4.6	17	15						21	18	3
4.9				32	10	10	11		16	11
5.2	42	27						44	38	9
5.5					24	23	24		24	1
5.8	15	11						13	13	2
6.1					14	7	8		10	4

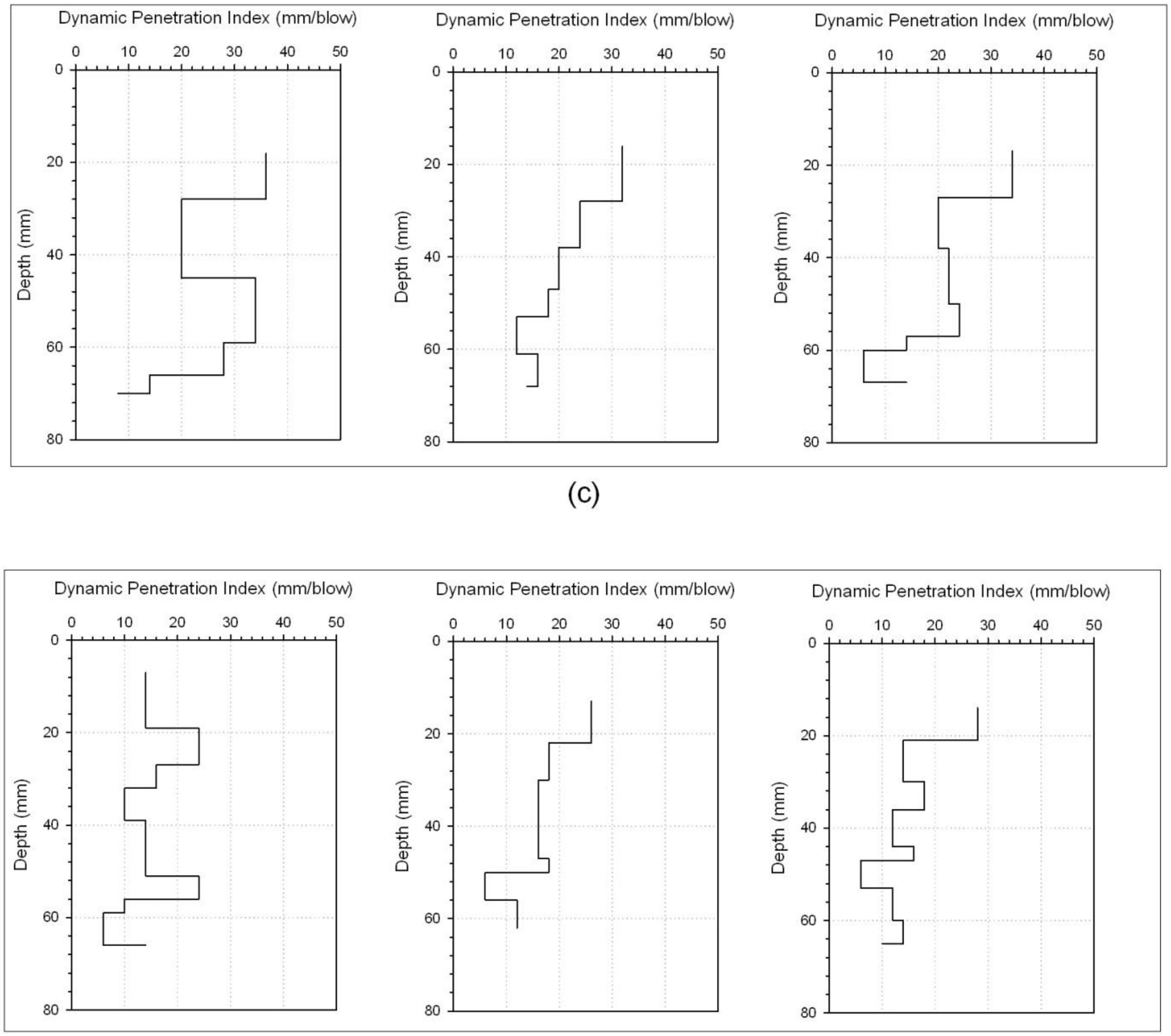
APPENDIX D. RESULTS OF LABORATORY DCP TESTS



(a)

(b)

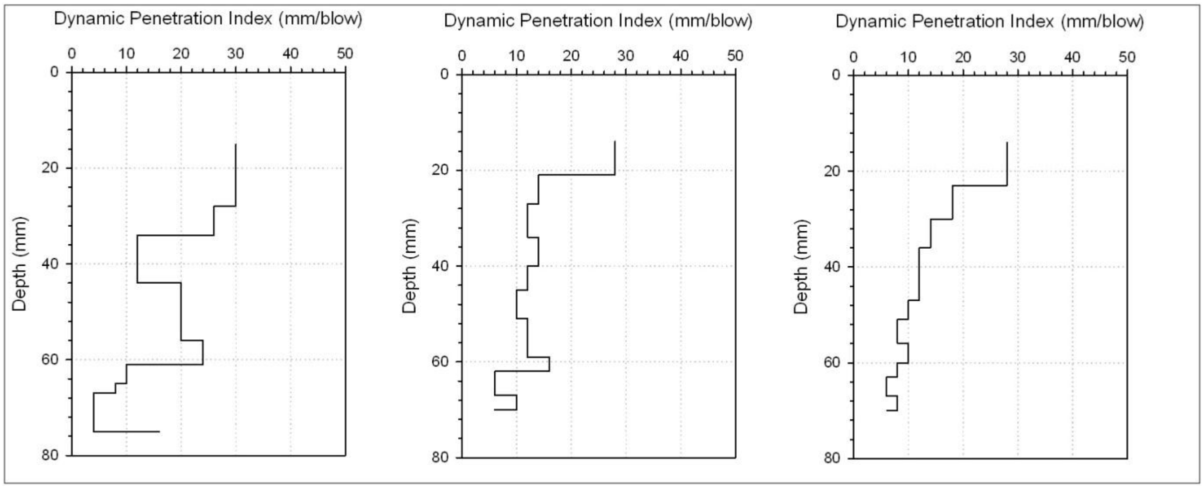
Figure 79. Laboratory DPI profiles for Springfield Fill after (a) 5 sec, (b) 15 sec, (c) 30 sec, (d) 60 sec, and (e) 120 sec



(c)

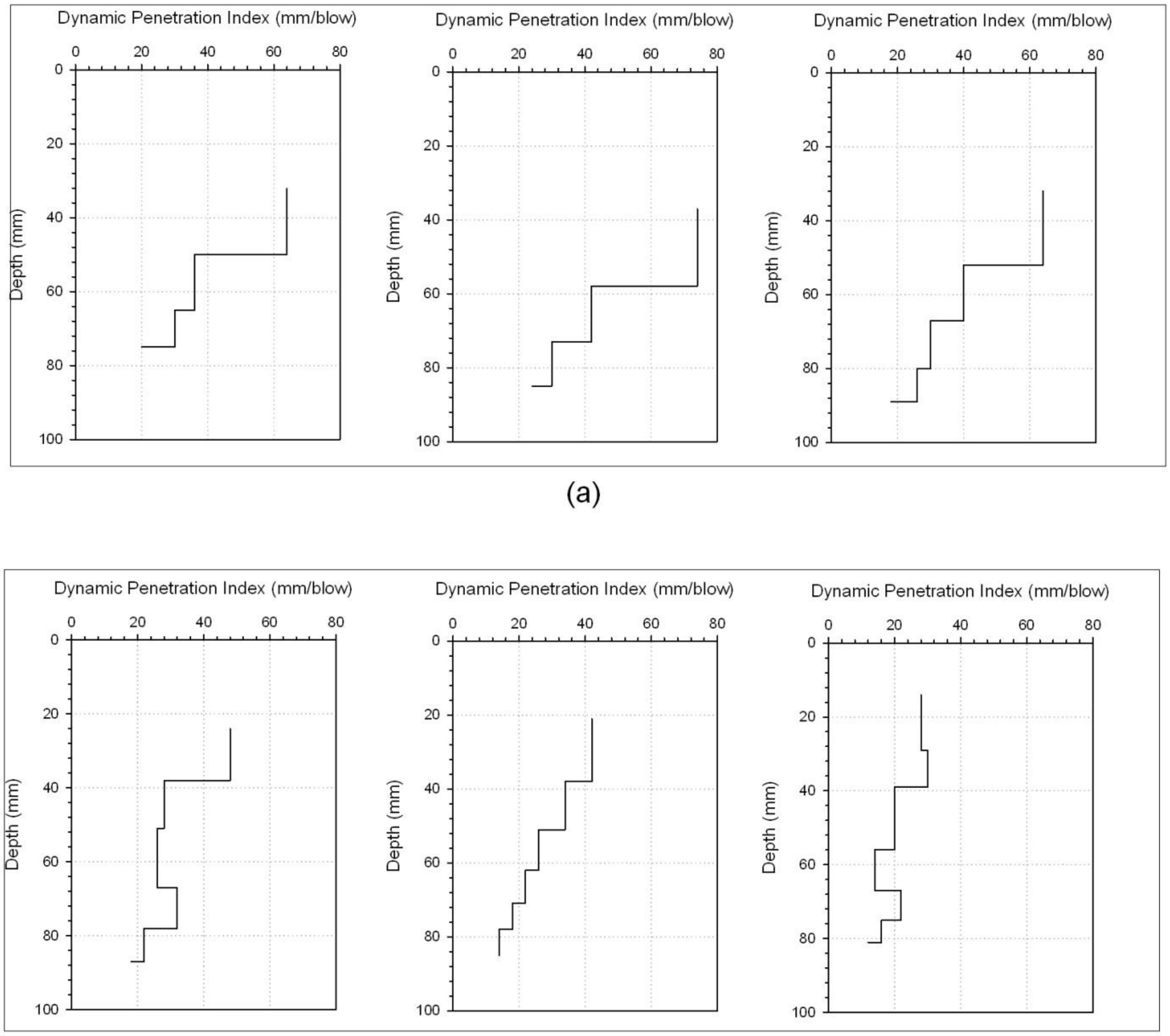
(d)

Figure 88. Laboratory DPI profiles for Springfield Fill after (a) 5 sec, (b) 15 sec, (c) 30 sec, (d) 60 sec, and (e) 120 sec (continued)



(e)

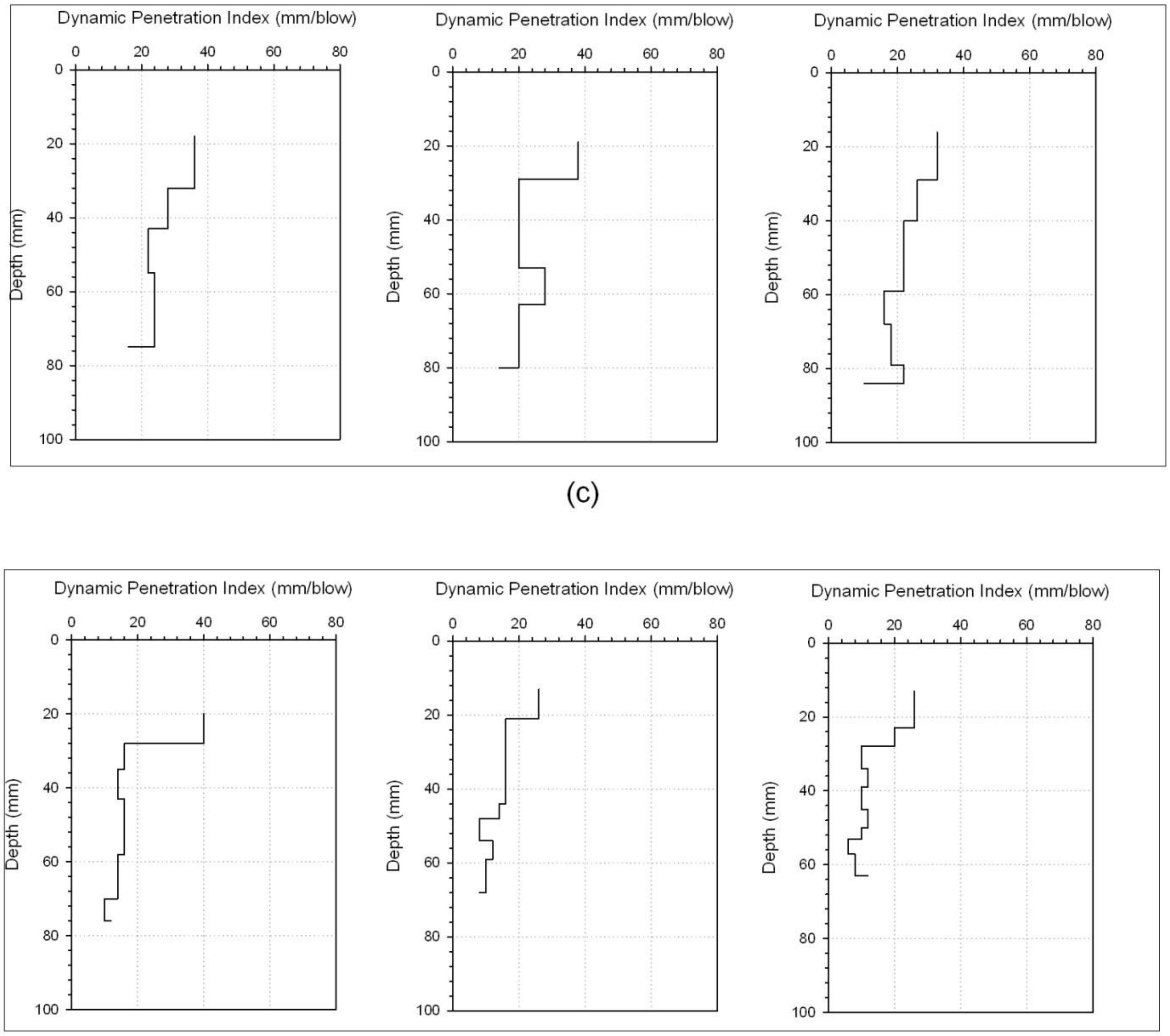
Figure 88. Laboratory DPI profiles for Springfield Fill after (a) 5 sec, (b) 15 sec, (c) 30 sec, (d) 60 sec, and (e) 120 sec (continued)



(a)

(b)

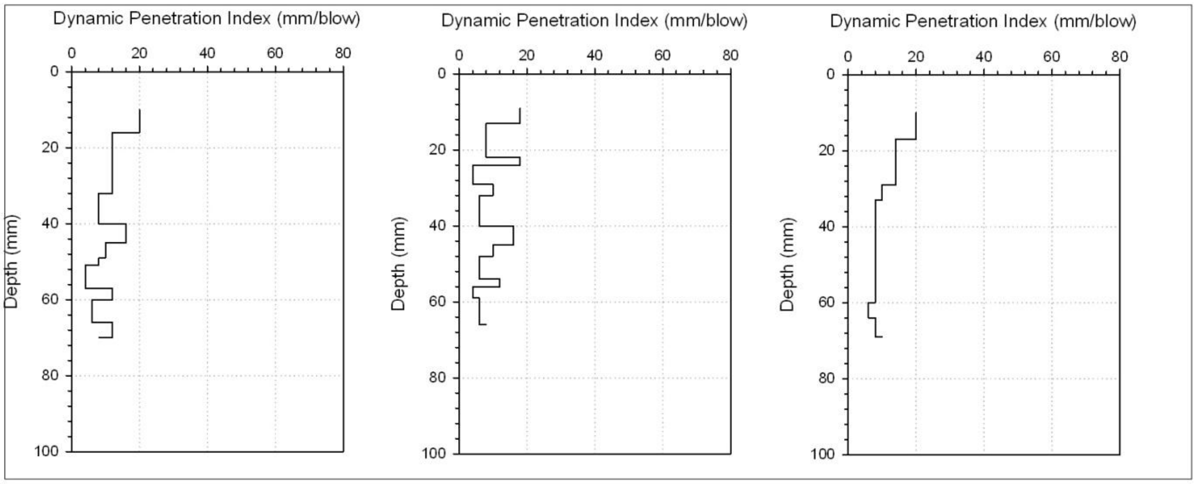
Figure 80. Laboratory DPI profiles for Hard Pack after (a) 1 sec, (b) 2 sec, (c) 3.5 sec, (d) 5 sec, (e) 15 sec, and (f) 30 sec



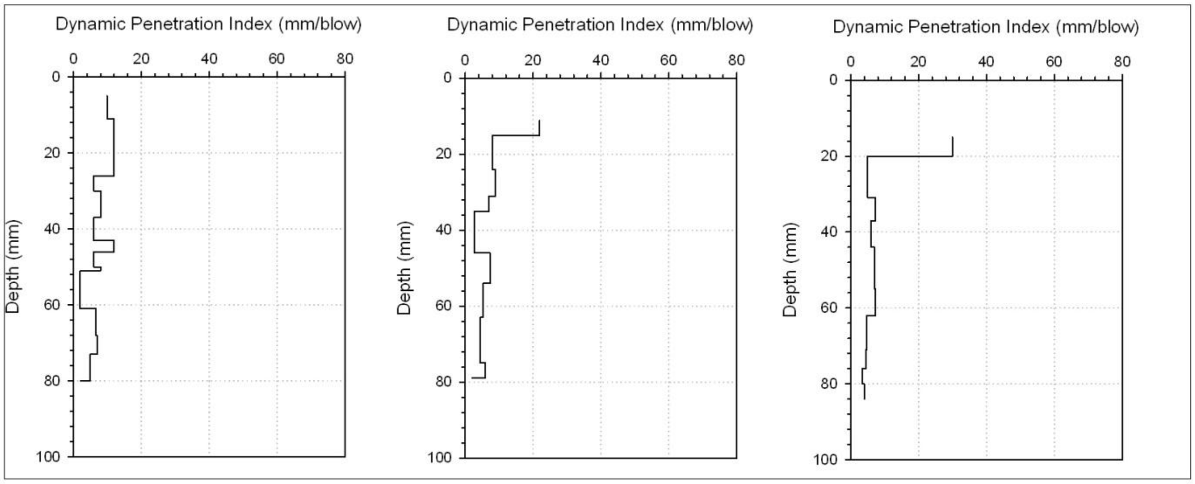
(c)

(d)

Figure 89. Laboratory DPI profiles for Hard Pack after (a) 1 sec, (b) 2 sec, (c) 3.5 sec, (d) 5 sec, (e) 15 sec, and (f) 30 sec (continued)



(e)



(f)

Figure 89. Laboratory DPI profiles for Hard Pack after (a) 1 sec, (b) 2 sec, (c) 3.5 sec, (d) 5 sec, (e) 15 sec, and (f) 30 sec (continued)

APPENDIX E. QC SPATIAL ANALYSIS FIGURES

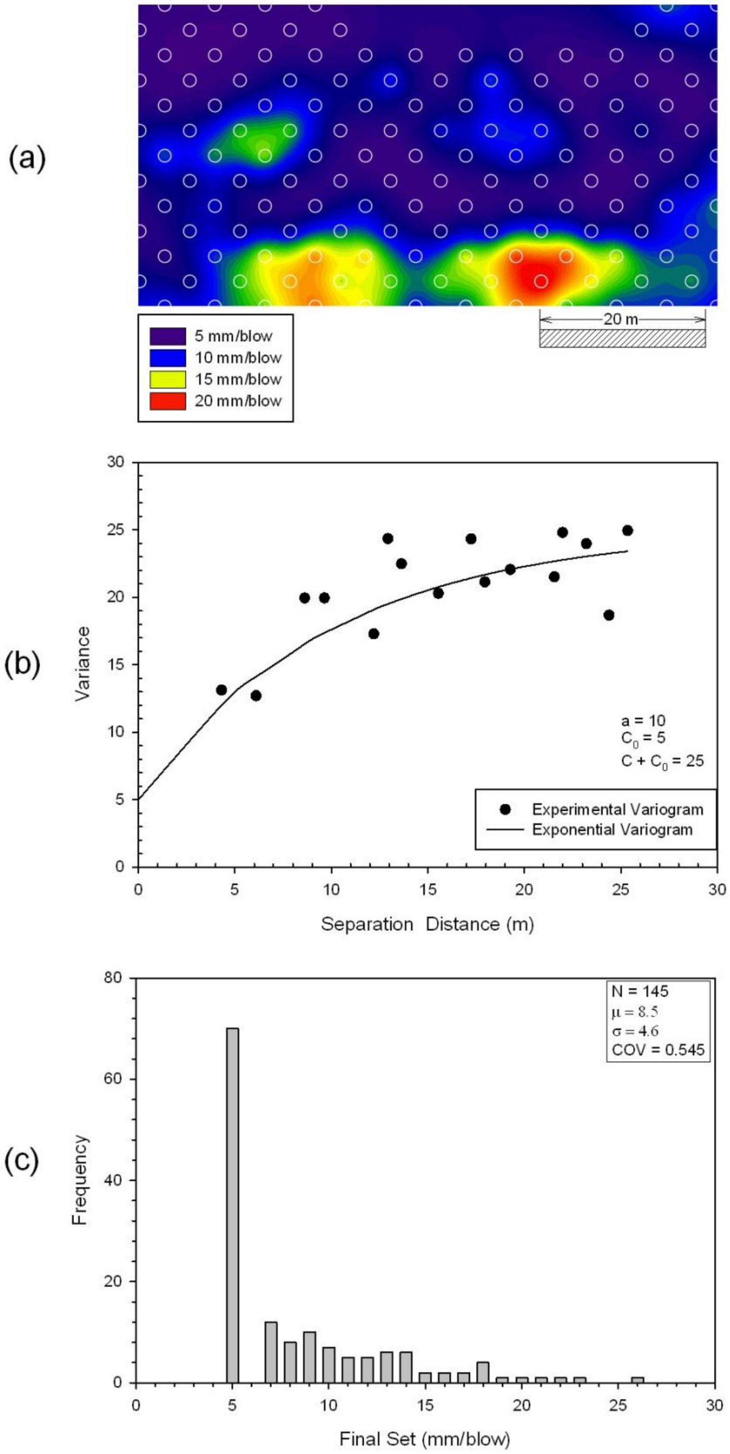


Figure 81. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 1, pass 1

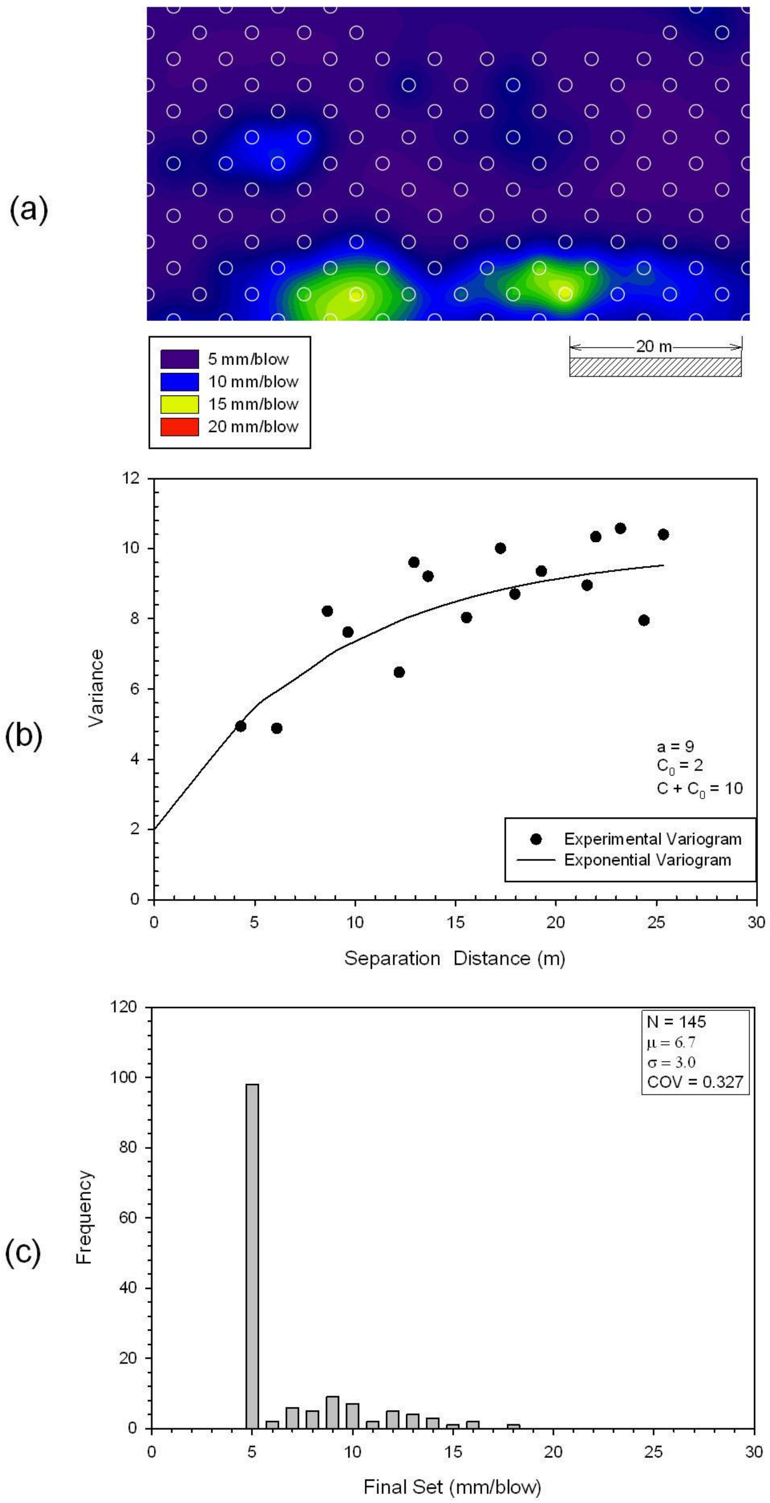


Figure 82 (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 1, pass 2

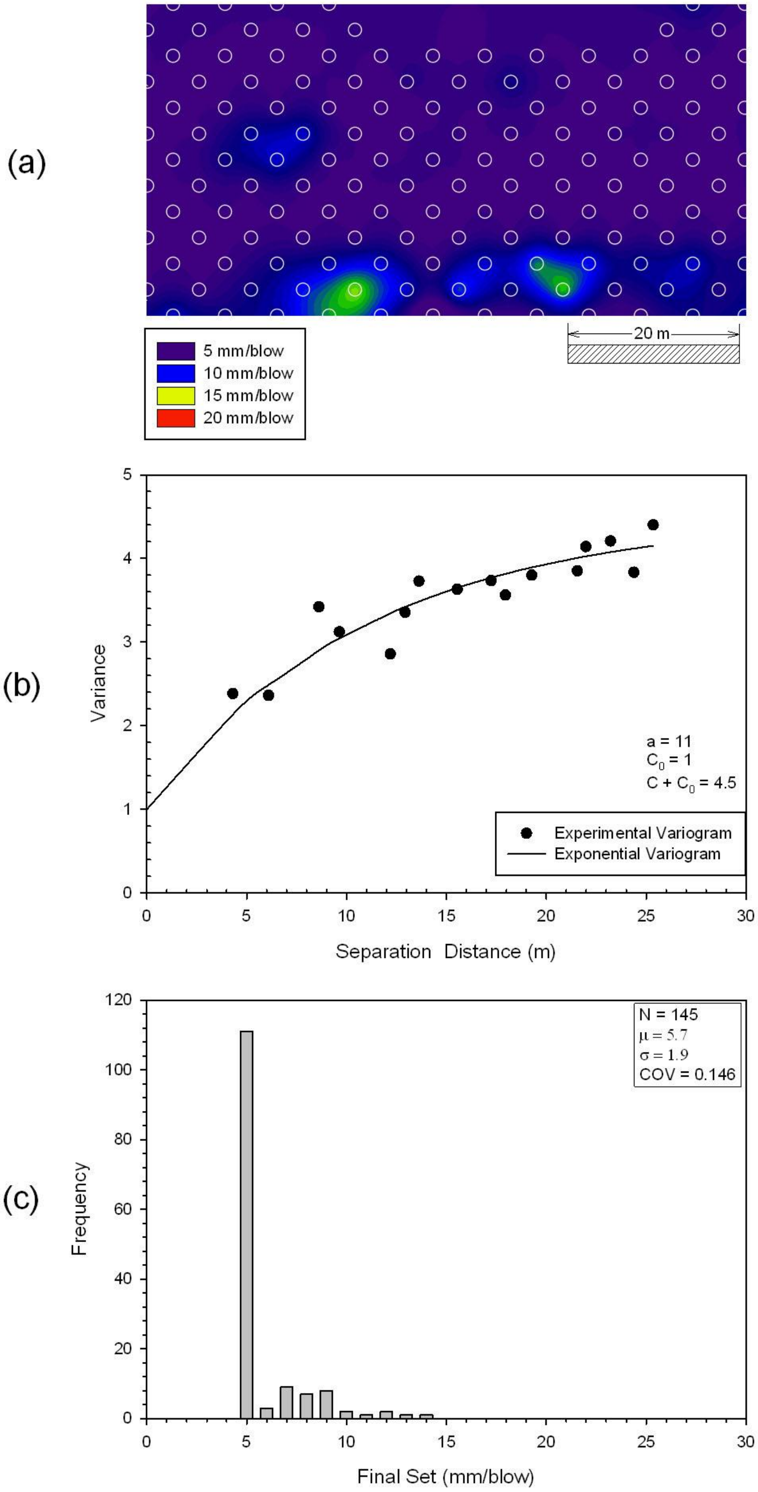


Figure 83. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 1, pass 3

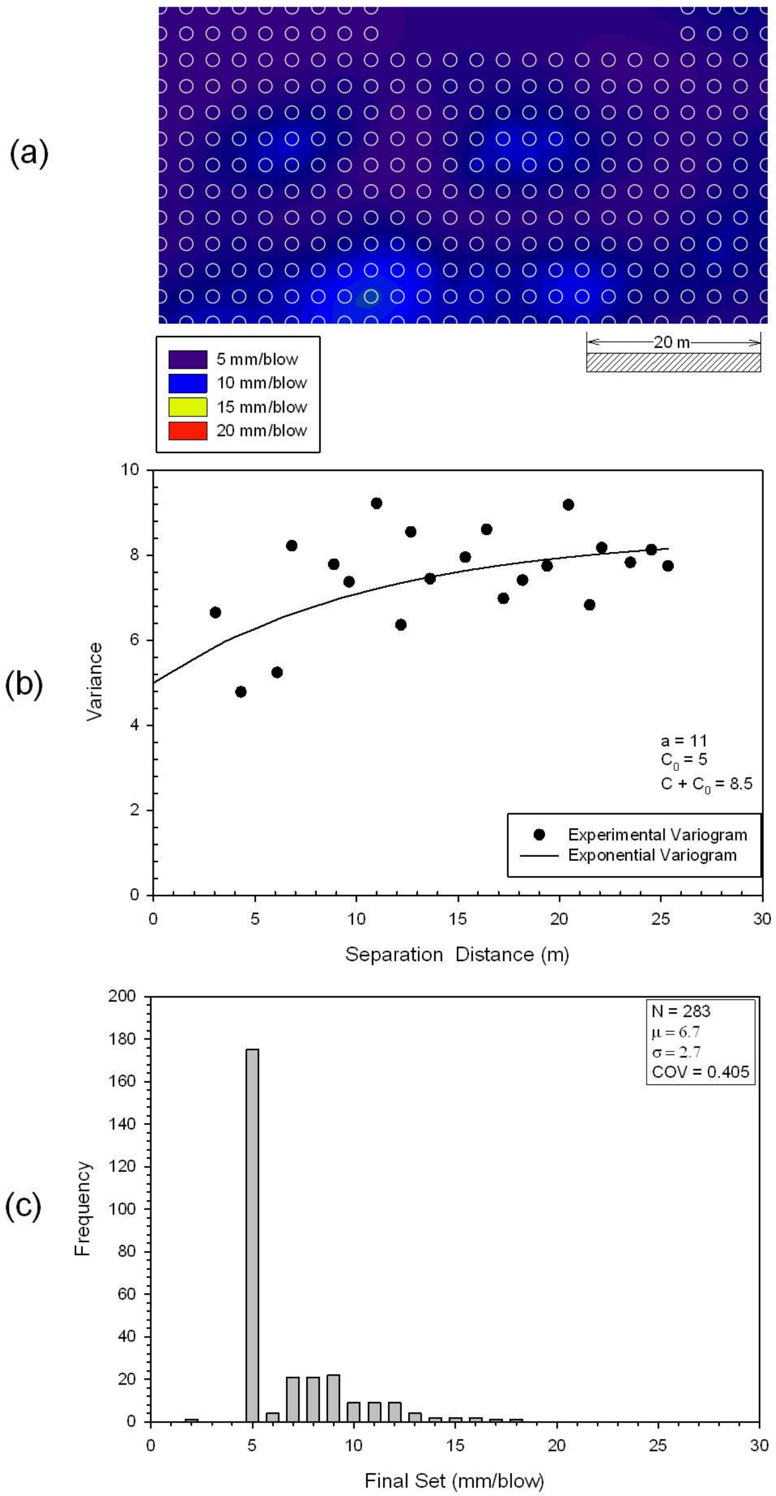


Figure 84. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 2, pass 1

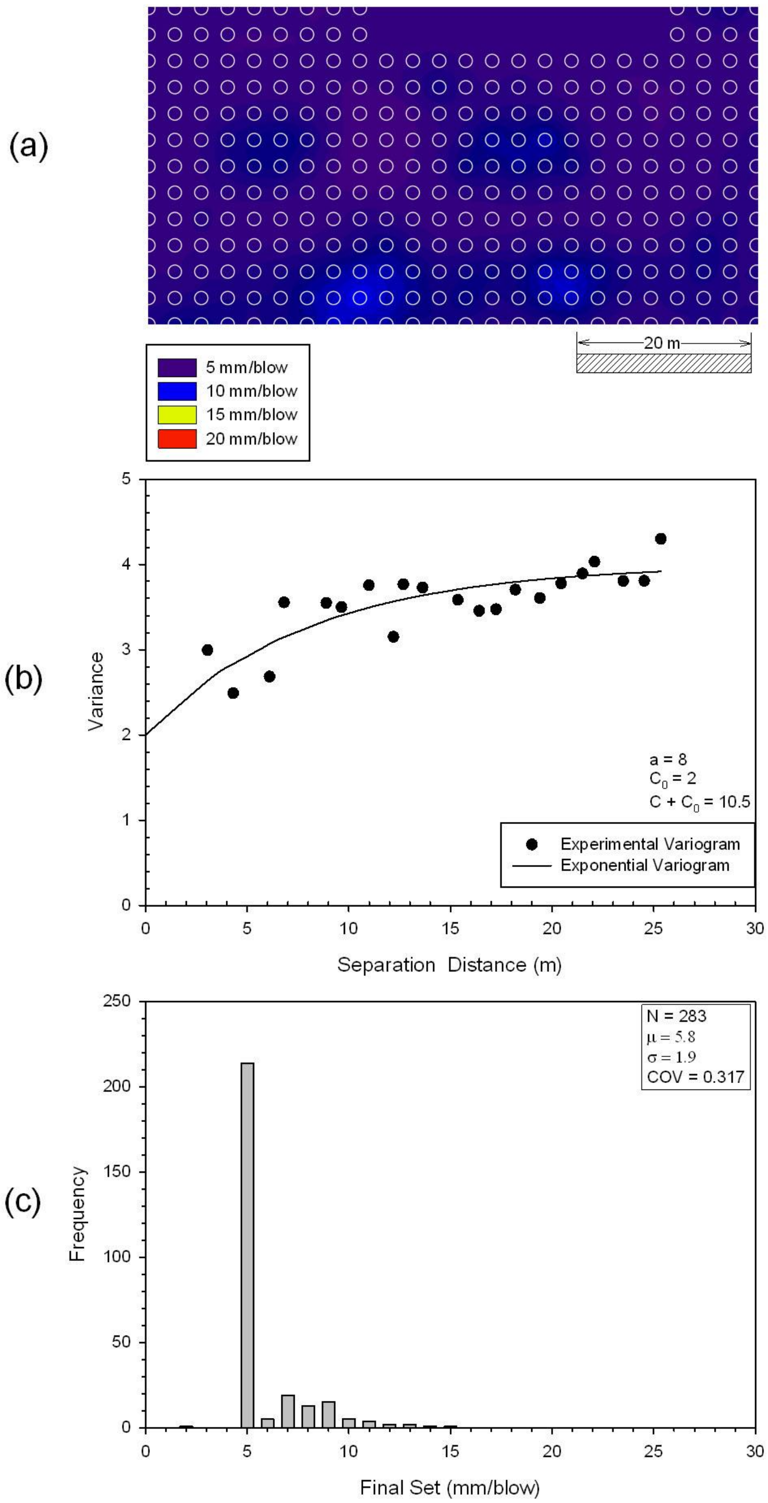


Figure 85. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 2, pass 2

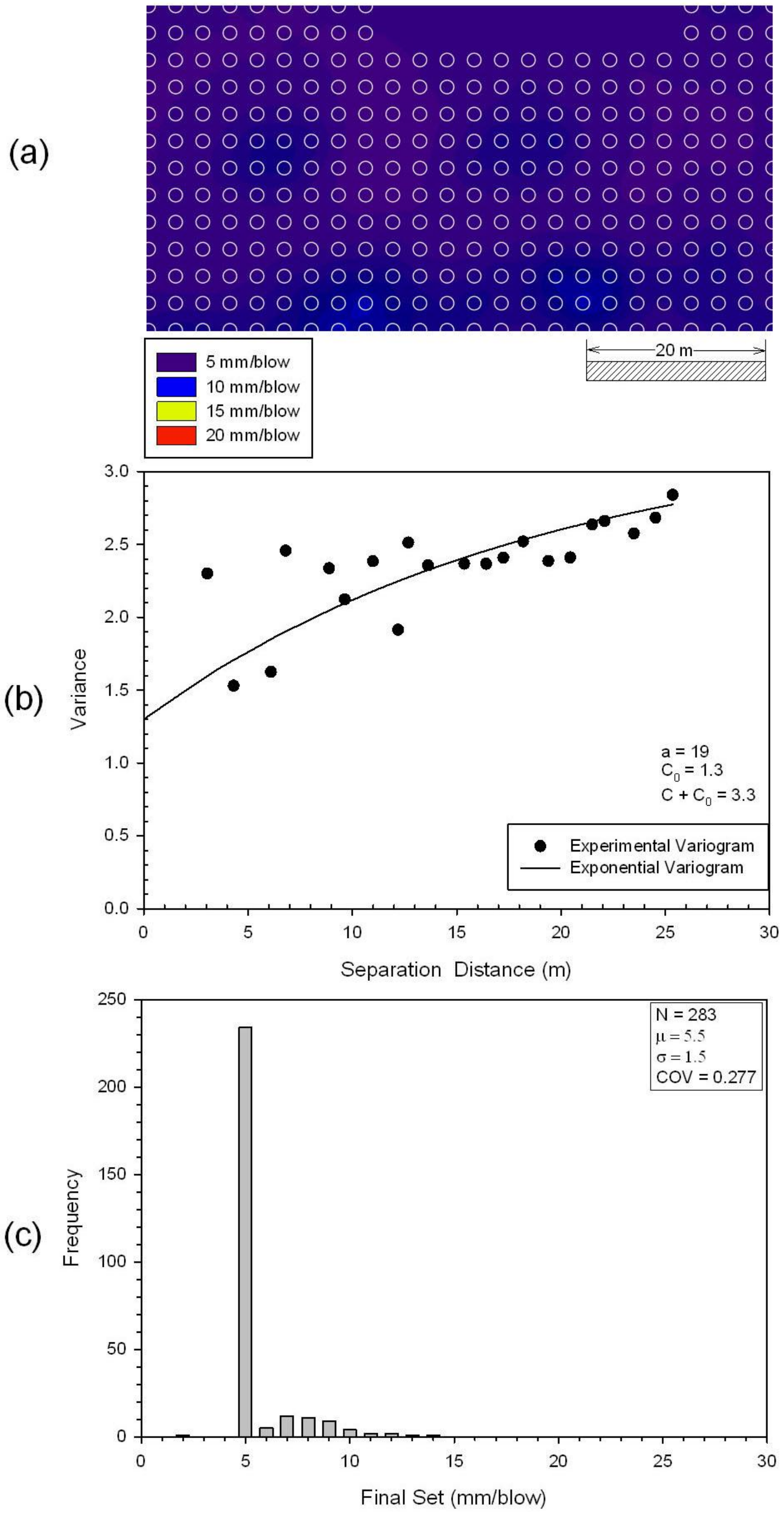


Figure 86. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 2, pass 3

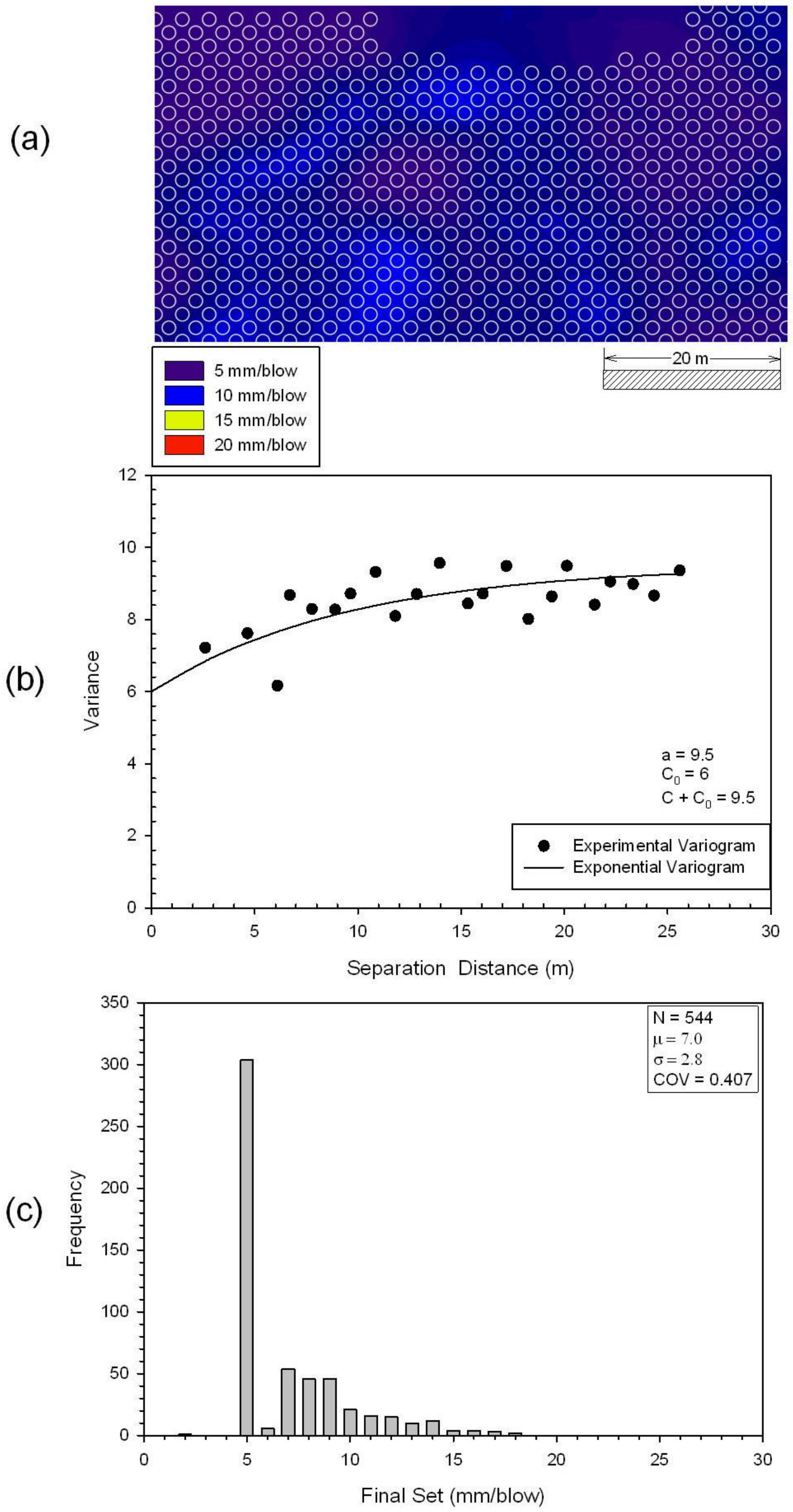


Figure 87. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 3, pass 1

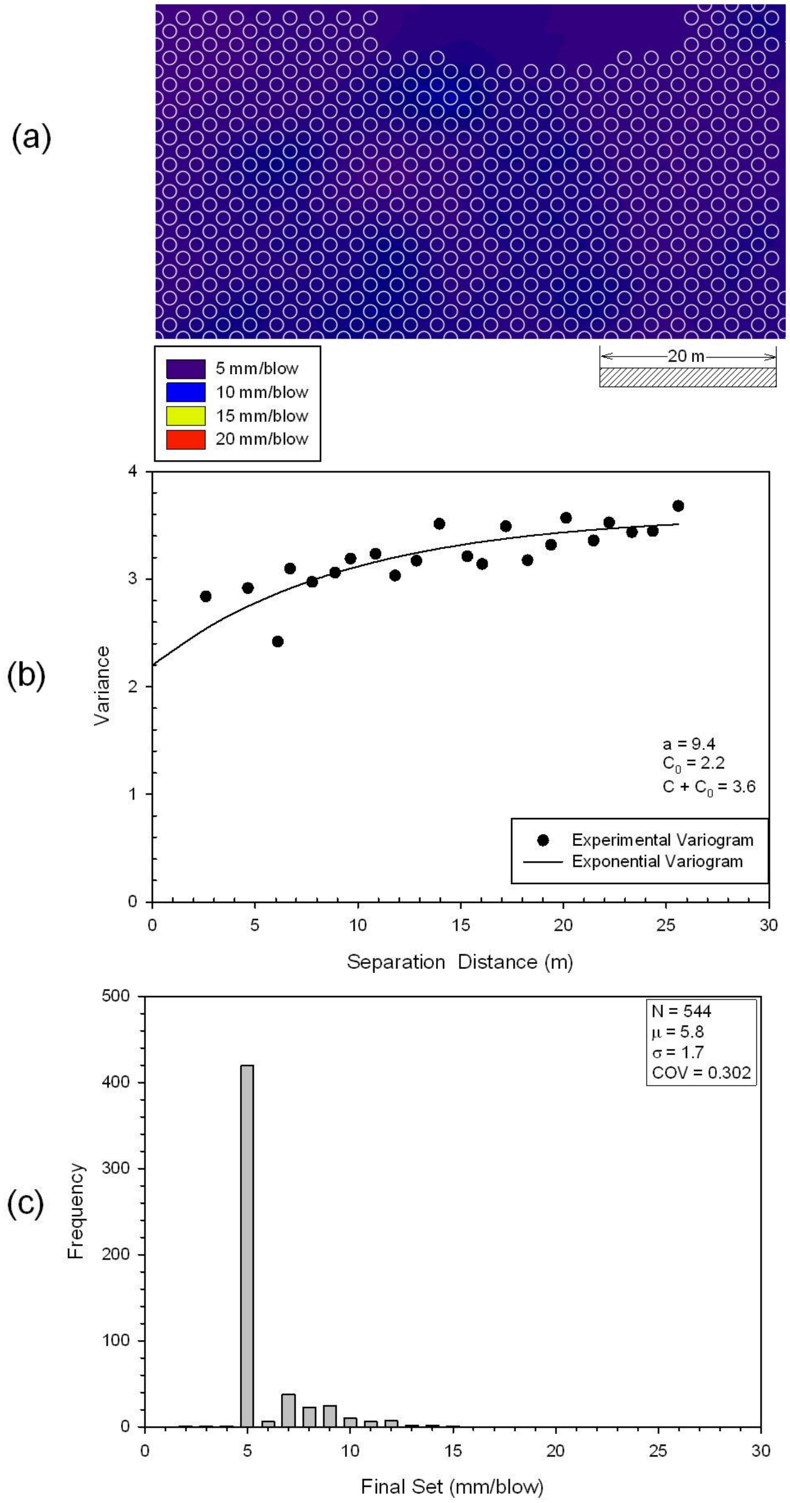


Figure 88. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 3, pass 2

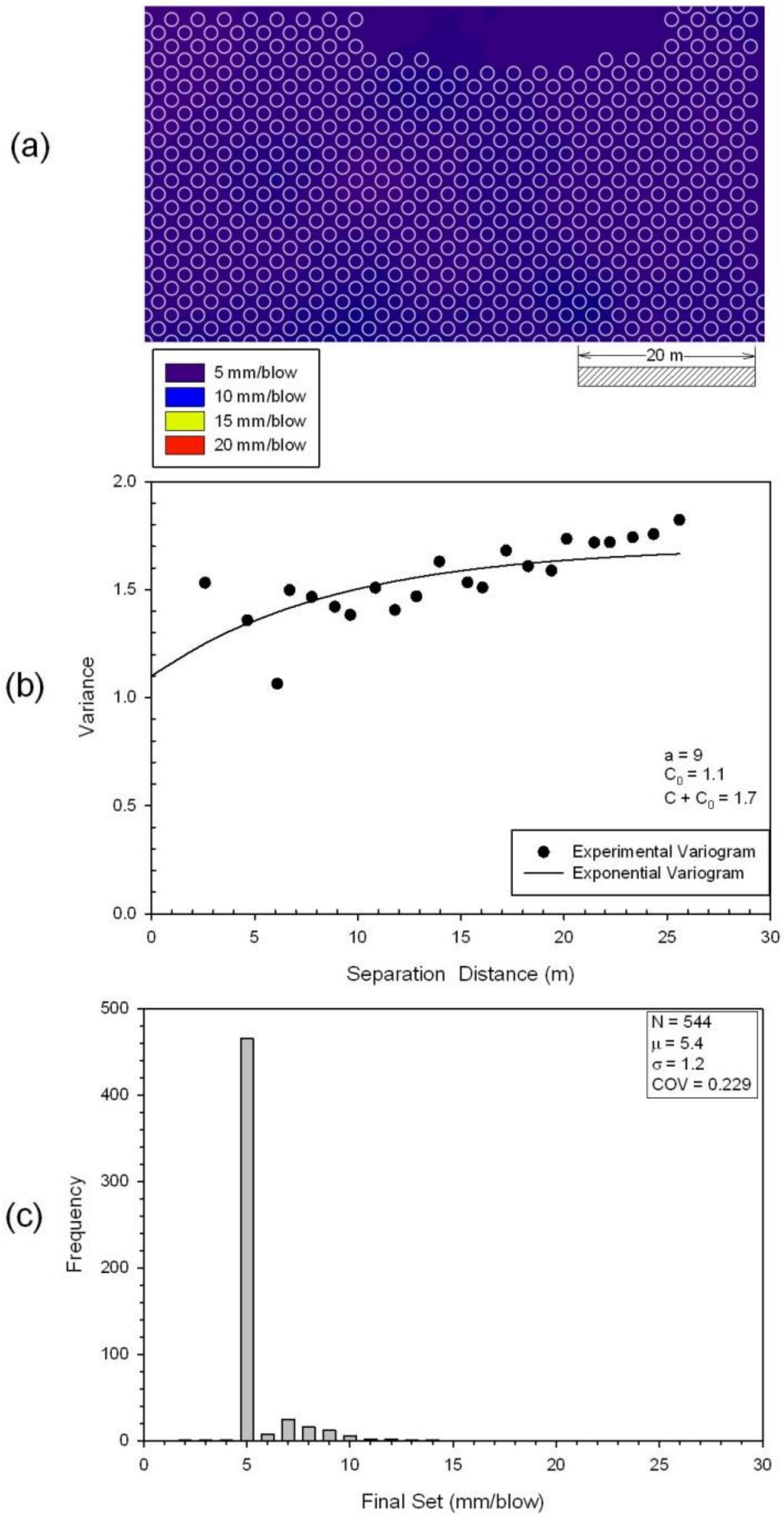


Figure 89. (a) Kriged contour map, (b) variogram, and (c) histogram for final set after sequence 3, pass 3

APPENDIX F. SAMPLE SPREADSHEET FOR DPI TO D_R CALCULATIONS

Table 27. Sample spreadsheet for DPI to D_R

Scenario:
Pre-RIC; Liao and Whitman (1986) Correction Factor Method

Depth, D (mm)	Depth,D (m)	DPI (mm/blow)	Material	*w* (%)	γ_d (pcf) - Guess	γ_t (pcf)	σ'_{V0} (psf)	C_{DPI}	$DPI_{7.2kPa}$ (mm/blow)	D_R (%)	γ_d (pcf) - Actual
58	0.058	19.33	Hard Pack	11.3	124.79	138.89	26.43	2.38	8.12	102.37	124.79
113	0.113	11.00	Hard Pack	11.3	128.30	142.80	52.20	1.70	6.49	113.96	128.30
162	0.162	9.80	Hard Pack	11.3	127.26	141.64	74.97	1.41	6.93	110.56	127.26
260	0.26	9.80	Hard Pack	11.3	123.68	137.66	119.23	1.12	8.74	98.55	123.68
323	0.323	12.60	Hard Pack	11.3	118.58	131.98	146.51	1.01	12.45	80.19	118.58
394	0.394	14.20	Hard Pack	11.3	115.72	128.80	176.51	0.92	15.40	69.17	115.72
484	0.484	18.00	Hard Pack	11.3	111.53	124.13	213.16	0.84	21.46	52.00	111.53
563	0.563	15.80	Hard Pack	11.3	112.26	124.95	245.55	0.78	20.22	55.09	112.26
607	0.607	14.67	Hard Pack	11.3	112.74	125.48	263.66	0.75	19.44	57.10	112.74
676	0.676	17.25	Hard Pack	11.3	110.16	122.61	291.41	0.72	24.04	46.11	110.16
763	0.763	17.40	Hard Pack	11.3	109.39	121.75	326.17	0.68	25.66	42.74	109.39
842	0.842	15.80	Hard Pack	11.3	109.98	122.41	357.89	0.65	24.41	45.33	109.98
941	0.941	19.80	Hard Pack	11.3	106.79	118.86	396.50	0.62	32.19	30.99	106.79
1006	1.006	13.00	Hard Pack	11.3	111.32	123.90	422.92	0.60	21.83	51.12	111.32
1106	1.106	10.00	Hard Pack	11.3	114.00	126.88	464.55	0.57	17.60	62.27	114.00
1216	1.216	11.00	Springfield Fill	12	111.14	124.48	509.47	0.54	20.27	85.09	111.14
1244	1.244	14.00	Springfield Fill	12	109.07	122.16	520.69	0.54	26.08	80.65	109.07
1288	1.288	14.67	Springfield Fill	12	108.56	121.59	538.24	0.53	27.78	79.54	108.56
1349	1.349	15.25	Springfield Fill	12	108.08	121.05	562.47	0.52	29.53	78.47	108.08
1401	1.401	17.33	Springfield Fill	12	106.94	119.77	582.90	0.51	34.17	75.90	106.94
1456	1.456	18.33	Springfield Fill	12	106.37	119.13	604.40	0.50	36.80	74.59	106.37

Table 27. Sample spreadsheet for DPI to D_R (continued)

1511	1.511	18.33	Springfield Fill	12	106.23	118.98	625.87	0.49	37.45	74.29	106.23
1571	1.571	20.00	Springfield Fill	12	105.43	118.08	649.11	0.48	41.60	72.44	105.43
1643	1.643	24.00	Springfield Fill	12	103.93	116.40	676.61	0.47	50.97	68.86	103.93
1776	1.776	26.60	Springfield Fill	12	102.92	115.27	726.91	0.45	58.56	66.42	102.92
1804	1.804	28.00	Springfield Fill	12	102.51	114.81	737.46	0.45	62.08	65.39	102.51
1854	1.854	25.00	Springfield Fill	12	103.23	115.62	756.42	0.45	56.14	67.16	103.23
1914	1.914	30.00	Springfield Fill	12	101.83	114.05	778.87	0.44	68.36	63.70	101.83
1986	1.986	36.00	Springfield Fill	12	100.45	112.50	805.45	0.43	83.42	60.19	100.45
2056	2.056	35.00	Springfield Fill	12	100.53	112.59	831.31	0.42	82.40	60.41	100.53
2084	2.084	28.00	Springfield Fill	12	102.04	114.28	841.81	0.42	66.33	64.23	102.04

APPENDIX G. COMPREHENSIVE TECHNOLOGY SUMMARY (CTS)

8. RAPID IMPACT COMPACTION
LEAD AUTHOR(S): Peter Becker
MENTOR(S) / PRIMARY REVIEWER(S): David White
REVIEWER(S): Mike Cowell, Ed O'Malley, and David Horhota
DATE OF THIS VERSION: December 15, 2010
FILE NAME FOR THIS VERSION: 08 Rapid Impact Compaction [Stand-Alone].docx

A research project titled "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform" is sponsored by the Strategic Highway Research Program (SHRP2). The project includes three elements: (1) new embankment and roadway construction over unstable soils, (2) roadway embankment widening, and (3) stabilization of pavement working platforms. Project details are described in the Phase 1 project report. As part of Phase 2, Comprehensive Technology Summary (CTS) documents are being prepared for over 40 ground improvement technologies. The CTS documents are working documents that contain source material for completing the Phase 2 tasks, and they will be updated as the project progresses. Each CTS consists of the sections listed in the following table of contents. Some of the sections are labeled with task numbers that correspond to components of Phase 2. A complete reference matrix and bibliography for this technology is contained in a separate document.

Technology Definition/Description

Rapid Impact Compaction (RIC) is a process that provides controlled impact compaction of the earth using excavator mounted equipment with a 5 to 9 ton (4.5 to 8 tonne) weight (7.5 ton/7tonne common) which is dropped approximately 4 ft (1.2 m) on to a 5 ft (1.5 m) diameter tamper capable of imparting 40 to 60 blows per minute. The resulting force can densify soils to depths on the order of 10 to 20+ ft (3 to 6 m). The depth of compaction is dependent on the soil properties, groundwater conditions, and compaction energy. Evidence suggests that the higher the energy input, the greater the depth of compaction for some soils. The initial blows in RIC create a dense plug of soil immediately beneath the tamper. Further blows advance the compaction zone. RIC can be considered an alternative to deep dynamic compaction. Approximately 9,000 to 30,000 SF (800 to 2500 m2) can be covered in an average single-shift day (SAICE 2006). Typically, the RIC method is used for the treatment of granular fills in order to improve their geotechnical properties (stiffness and bearing capacity) and to reduce settlement. Some rules of thumb for RIC ground improvement are as follows (personal communication, Cowell 2008):

Table 28. RIC ground improvement rules of thumb

Soil Type	Resulting N Values	Depth of Influence
Sands	N= 20 to 30+ typical	15 to 20+ ft
Silty Sands	N = 15 to 20+ typical	15+ feet
Sandy Silts	N = 10 to 15+ typical	12 to 15+ ft
Misc. Fills	N > 10	10 to 15+ ft

RIC has also been used in collapsible loess soils, ash fill, waste fill, and building waste. The technique is generally not effective in low permeability saturated soils. RIC allows identification of weak zones or “suspect” zones where hard debris fill exists to identify suspect areas which need more treatment (more tamps and/or localized over excavation followed by RIC).

RIC delivers compaction energy to the ground in a relatively controlled manner (e.g., multiple blows with less energy per blow) which allows it to be used closer to existing structures. Peak particle velocities of 2.0 in/s (50 mm/s) at a distance of 30 ft (9.1 m) have been reported (personal communication, O’Malley 2010). Peak noise levels are on the order of 88 dBA (SAICE 2006). In the urban environment, the RIC technique has a number of specific advantages compared to the conventional drop weight dynamic compaction technique including: (1) equipment is relatively small, (2) treatment can be carried out in closer proximity to existing structures and services vulnerable to vibration damage, (3) generally no danger from flying debris, (4) discrete, relatively small foundation areas can be treated, and (5) energy is more efficiently transferred through the compaction foot which remains in contact with the ground.

Quality control is performed by monitoring the compaction energy and deflection of the soil on each blow. An integrated monitoring system can show when optimal compaction is achieved (when additional blows will yield minimal improvement). Preliminary trials are an important aspect at each site to identify optimum compaction operations. Quality assurance can be accomplished by recording the before and after results to see that the average SPT N-value or CPT cone resistance is achieved for the zone needing improvement. Plate bearing tests for different field trials are also used to evaluate bearing characteristics and some in-situ geophysical tests have been suggested to overcome potential shortcomings of other in-situ tests. For fine-grained soils, piezometers can be used to monitor magnitude and dissipation of excess pore water pressure.

Tasks 9 and 10C: Technology Applicability Screening Parameters

The screening parameters outlined in this section will provide much of the raw material for Task 9, which is to develop a catalog of materials and systems for rapid renewal projects, and for the component of Task 10 to develop technology selection guidance. As described in the Phase 2 proposal, these screening parameters will be integrated into a comprehensive technology catalog and guidance system. This section allows for review and documentation of the different reported conditions for which this technology is most applicable. The parameters investigated include depth limits, soil types, groundwater conditions, project specific constraints, environmental considerations, equipment needs, approximate costs, potential advantages, potential disadvantages, and alternate solutions. References are listed alphabetically by author in each table below, as well as in subsequent sections of this comprehensive technology summary. If a page number is included in the “Reference” column, then it refers to the page number where the listed information was found in the reference. If information about a topic was not found in the literature, then the table entry for that topic is left blank.

Table 29. Technology overview documents

Reported Data	Reference
This document describes the RIC method and how it compares with conventional dynamic compaction. Descriptions and results of a test program of RIC are enclosed.	Braithwaite and du Preez (1997)
This document provides a design methodology, a quality assurance and control procedure, specifications and an overall description of RIC.	Building Research Establishment (2003)
This document provides results of pre-treatment and post-RIC-treatment geotechnical investigations of a project in Vancouver, Canada. In addition, the document provides descriptions of the RIC construction process.	Kristiansen and Davies (2003)
This document describes a particular case in which RIC successfully improved the subsurface conditions and mitigated liquefaction potential of the specific project site.	Kristiansen and Davies (2004)
This document describes a case in which RIC was deemed to be insufficient in improving the subsurface conditions and mitigating liquefaction potential of the specific project site.	Kristiansen and Kostaschuk (2006)
This document describes the design and operation of a model compactor simulating the RIC process.	Merrifield et al. (1998)
This document describes research into the understanding of the low-energy dynamic compaction (RIC) process, and the development of a novel technique of real time monitoring that can demonstrate soil improvement in quantitative engineering units during the process. Research was conducted in the field and the laboratory using a geotechnical centrifuge.	Merrifield and Davies (2000)
This document describes work undertaken to evaluate a prototype high speed dynamic compactor (RIC). The work reported was intended to implement a monitoring system for the machine to provide an indication when optimum compaction had been achieved.	Neilson et al. (1998)
This document describes the soil response due to RIC modeled in a geotechnical centrifuge.	Parvizi (2009)
This document describes the design and operation of a unique model compactor simulating the process of low energy dynamic compaction (RIC) in a geotechnical centrifuge. Using the WAK test method, an estimate was obtained of the change in stiffness, damping coefficient, mass of vibrated soil and effective depth of influence with increasing number of blows.	Parvizi and Merrifield (2000)
This document provides a detailed overview of RIC in regards to machine specifications, applications, parameters affecting compaction, environmental effects, etc.	SAICE (2006)

Table 29. Technology overview documents (continued)

This document provides an overview of RIC, design procedures and quality assurance and quality control procedures. Additionally, several case studies featuring the use of RIC are provided.	Serridge and Synac (2006)
This document describes a particular case in which RIC successfully improved the subsurface conditions and mitigated liquefaction potential of the specific project site.	Simpson et al. (2008)
This document provides a description of work conducted to monitor and assess the vibrations generated by the RIC and the densification effects of RIC compaction. Results and discussions of the work are enclosed.	Tara and Wilson (2004)
This document provides a general overview of RIC along with multiple case studies using RIC.	Watts and Charles (1993)
This document provides information on a wide assortment of geotechnical processes including RIC. A general overview of RIC is provided.	Woodward (2005)

Table 30. Applications

Reported Data	Reference
Rapid Impact compaction provides a technically sound and economical alternative for the improvement of weak soils in the depth range 3 to 13 ft (1 to 4 m). It is specifically aimed at the rapid treatment of extensive areas where a limited depth of treatment is required. The primary areas of application are likely to include projects such as housing, schools, clinics, taxi ranks etc. Remedial work on roads, railways and paved areas are also highly suitable.	Braithwaite and du Preez (1997)
Regular compaction of the loosely deposited waste materials at landfill sites using RIC can be used to reduce the volume of the deposited waste thus significantly extending the operational life of the landfill.	Braithwaite and du Preez (1997)
The RIC method appears to offer an effective alternative to other more commonly used ground improvement methods. This appears to particularly be the case where the required depth of in-situ ground improvement is less than about 20 ft (6.0 m) and even up to depths of almost 30 ft (9 m) at sites with similar subsurface conditions as those described in Kristiansen and Davies (2004).	Kristiansen and Davies (2004)
RIC is applicable when it is not necessary to achieve ground improvement to great depths: for example, when the ground to be modified consists of a layer of loose material with a depth of only a few meters, or when only a small increase in bearing capacity is required without concern for settlement.	Merrifield and Davies (2000)
The RIC equipment can also serve as a diagnostic tool, identifying zones that do not respond well to dynamic compaction. Such zones may include high-plasticity soils and any uncompressible debris.	SAICE (2006)

Table 30. Applications (continued)

Current and potential applications include: Compaction of loose granular soils to improve bearing capacity and reduce settlement Mitigation of soil liquefaction potential Densification of bulk fills (i.e. lifts of approximately 20 ft (6 m)), eliminating the need for small lifts and making possible the use of compaction equipment within confined excavations Compaction of foreshore fills, where granular material has been placed both above and below the water table Foundation compaction below footings and bearing walls Densification of bridge end-fills and highway subgrades Backfilling excavations at remediation sites, particularly where excavations extend below the water table and groundwater pumping is not desirable because of pre-disposal treatment requirements Compaction of loose native granular soils to limit the potential for liquefaction during seismic events Use in association with deep compaction technologies such as vibro-flotation or stone columns to meet the compaction requirements in the upper 7 to 16 ft (2 to 5 m) Use in association with conventional dynamic compaction or blast densification to improve the compaction achieved in the upper zone In conjunction with wick drains to expedite surge charging of materials	SAICE (2006)
RIC can be used to reduce the collapse potential in loess soils and other collapsible soils[1].	Serridge and Synac (2006)
The RIC technique is given consideration for further improvement of soil stiffness, particularly beneath high specification ground bearing floor slab areas where, for example, stone columns have already been installed. This method has been loosely described as “energizing” the stone columns thereby further improving competent stiffness. Additionally, consideration has been given to the application of the RIC technique to landfill sites, for example to improve landfill space in older landfills, and to improve the integrity of the final cover systems. However, this warrants further research accompanied by appropriate risk assessment.	Serridge and Synac (2006)

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[1] The features that are typical to most collapsible soils are: (1) an open structure, (2) a high void ratio, (3) a low dry density, (4) a high porosity, (5) geologically young or recently altered deposit, (6) high sensitivity and (7) low interparticle bond strength (Rogers 1994).

Table 30. Applications (continued)

Typically, the RIC method is used for the treatment of granular fills in order to improve their geotechnical properties (stiffness and bearing capacity) and to reduce settlement.	SHRP2 R02 Phase 1 Technology Assessment
In the urban environment, the RIC technique has a number of specific advantages compared to the conventional drop weight dynamic compaction technique including: (1) equipment is relatively small, (2) treatment can be carried out in closer proximity to existing structures and services vulnerable to vibration damage, (3) generally no danger from flying debris, (4) discrete, relatively small foundation areas can be treated, and (5) energy is more efficiently transferred through the compaction foot which remains in contact with the ground.	SHRP2 R02 Phase 1 Technology Assessment
RIC allows identification of weak zones or “suspect” zones where hard debris fill exists to identify suspect areas which need more treatment (more tamps and/or localized over excavation followed by RIC)	SHRP2 R02 Phase 1 Technology Assessment
RIC can be used to mitigate liquefaction potential and increase lateral resistance of soils.	Simpson et al. (2008)
Adequate for a large number of reclamation projects where ground improvement is currently carried out by vibrated stone columns and dynamic compaction	Watts and Charles (1993)

Table 31. Soil types

Reported Data	Reference
Rapid Impact Dynamic compaction is suitable for the improvement of a wide variety of loose soils and fills, but it is not recommended for weak, low permeability soils with a high moisture content.	Braithwaite and du Preez (1997)
Clayey soils and fills do not respond as well to RIC as to falling-weight dynamic compaction, but dynamic replacement using this technique may be an option.	Building Research Establishment (2003)
Cohesionless soils are more easily densified than cohesive soils.	SAICE (2006)
The RIC technique is effective in natural sandy and gravelly soils.	Serridge and Synac (2006)
A desirable objective would be to establish a centralized data base for gathering of experience and case histories on RIC experiences, to increase understanding of the range of soil types and profiles which the technique can be applied to and assist in further development of the RIC system as a whole.	Serridge and Synac (2006)
The loess soil response to RIC is dependent on soil properties, principally degree of saturation; moisture content and plasticity. The greater the magnitude of these soil properties, the less effective RIC is at ground densification. These aspects warrant further investigation and research in respect of any time dependent improvements in high plasticity, more saturated loess soils.	Serridge and Synac (2006)
RIC is typically used for the treatment of granular fills. RIC has also been used in collapsible loess soils, ash fill, wastefill and building waste. This technique is generally not effective in low permeability saturated soils.	SHRP2 R02 Phase 1 Technology Assessment
Layers with higher fines content are not ideal for improvement by RIC.	Simpson et al. (2008)
The rapid impact compactor has the ability to effectively improve the engineering properties of a range of fills (generally of a granular nature) and natural sandy soils.	Watts and Charles (1993)
Suitable for granular soils and fill, but not for natural silts and clays.	Woodward (2005)

Table 32. Groundwater conditions

Reported Data	Reference
In clay soils and mixed fills, excess pore pressures may be established with RIC and may require a few days, or in some situations even longer, to dissipate.	Building Research Establishment (2003)
Excess pore water pressures may inhibit densification if not allowed to dissipate sufficiently between drops.	SAICE (2006)
Groundwater level is an important factor for consideration of suitability of the RIC method as shallow groundwater level can act as a hydraulic barrier reducing effective energy transfer to the fill materials.	Serridge and Synac (2006)
Generally, recommendations include retreating areas no sooner than 24 hours after the initial treatment to allow pore water pressures to dissipate.	Simpson et al. (2008)
The groundwater table should be at least 3 ft (1 m) below ground level. At sites where this requirement is not satisfied, a sump pump can be used to lower the groundwater table and proceed with compaction.	Tara and Wilson (2004)

Table 33. Depth limits

Reported Data	Reference
RIC is specifically designed to compact generally granular soil types to depths of less than 4 m. The depth of influence typically ranges from 7 ft (2 m) (at 10 to 25 blows) to 10 ft (3 m) (at 20 to 40 blows). The depth of influence may be increased by increasing the unit energy applied (more blows).	Braithwaite and du Preez (1997)
The number of blows at a compaction point or the energy applied overall to the ground surface has the greatest effect on depth of improvement. Typical examples of the range of ground type and depths of compaction are as follows: (1) Loose building waste: total energy applied is 50 ton-ft/ft^2 (150 tonne-m/m^2), depth of compaction is 13 ft (4 m); (2) Ash fill: total energy applied is 50 ton-ft/ft^2 (150 tonne-m/m^2), depth of compaction is 11½ ft (3.5 m); (3) Select granular fill: total energy applied is 50 ton-ft/ft^2 (150 tonne-m/m^2), depth of compaction is 13 ft (4 m) and (5) Sandy silt and silty sand: total energy applied is 27 ton-ft/ft^2 (80 tonne-m/m^2) and 64 ton-ft/ft^2 (190 tonne-m/m^2), depth of compaction is 7 ft (2 m) and 10 ft (3 m).	Building Research Establishment (2003)
The influence depth of RIC is typically around 16 to 20 ft (5 to 6 m) although this is depending on several issues such as soil type, degree of saturation, soil stiffness and other factors. Locally, the depth of impact is often on the order of minimum 20 ft (6 m), but depth of impact up to almost 33 ft (10 m) has been observed on projects in Asia.	Kristiansen and Davies (2004)
The depth of densification is often a minimum of 20 ft (6 m).	Kristiansen and Kostaschuk (2006)
The degree of soil improvement and the extent to which the improvement penetrates the soil bed depend on a number of factors: (1) the nature of the soil, including soil classification, degree of saturation, initial relative density, permeability and drainage path length; (2) mass of the drop weight or pounder, distance of fall and energy imparted to the soil per impact and (3) number of impacts per location and spacing of the impact locations over the area being treated.	Merrifield et al. (1998)
Experience has shown that the depth of improvement using this method is restricted to less than 16 ft (5 m).	Parvizi (2009)

Table 33. Depth limits (continued)

Data derived from a model compactor simulating low energy dynamic compaction in a geotechnical centrifuge, such as the transient pressures and soil mass accelerations, during impact may be used to compute the increased stiffness and depth of the compaction process.	Parvizi and Merrifield (2000)
The RIC treatment is typically effective up to depths of 20 ft (6 m), although improvements have been seen up to 30 ft (9 m) in some conditions.	SAICE (2006)
Depth of influence of RIC treatment is a function of soil grading characteristics and groundwater regime.	Serridge and Synac (2006)
Can densify soils to depths on the order of 10 to 20 ft (3.0 to 6.1 m).	SHRP2 R02 Phase 1 Technology Assessment
Depth affected is limited to about 13 ft (4 m).	Watts and Charles (1993)
Depth of improvement is between 7 and 10 ft (2 and 3 m).	Woodward (2005)

Table 34. Material properties of improved soils

Reported Data	Reference
Based on interpretation of plate load testing, improvements in soil stiffness on the order of 2 to 10 times can be achieved. Within the zone of influence, the dynamic probing super heavy (DPSH) blow count is commonly improved by about 30 blows per 1 ft (305 mm).	Braithwaite and du Preez (1997)
There is a significant international precedent, particularly in wet or fine grained soils, suggesting strength with time.	Braithwaite and du Preez (1997)
Irrespective of soil type, plots of the cumulative penetration vs. blow count suggest that after about 70 blows the soil has reached maximum compaction. This can be explained by assuming that at the level a cone of compacted soil has been created whose inertia is equal to the impact energy.	Braithwaite and du Preez (1997)
The magnitude of the peak particle velocities and the peak pressures are inversely proportional to the relative density of the soil. This is confirmed by the increase in magnitude of the peak signals with each succeeding impact as the relative density is increased with each successive blow on the target. The attenuation of the peak pressures away from the source is assumed to approximate the inverse radius squared (r^{-2}). The densifying effect is most dominant during the first seven to eight blows. Thereafter the effect diminishes steadily.	Parvizi (2009)
The post-improvement N value for sands is typically between 20 and greater than 30. The post-improvement N value for silty sands is typically between 15 and greater than 20. The post-improvement N value for sandy silts is typically between 10 and greater than 15. The post-improvement N value for miscellaneous fills is typically greater than 10.	SHRP2 R02 Phase 1 Technology Assessment

Table 35. Material properties of additives and/or inclusions

Reported Data	Reference
Where the ground surface prior to treatment is soft and easily sheared, a gravel sized pioneer aggregate layer may be placed on the surface to more efficiently transmit the compactive effort into the underlying ground.	Braithwaite and du Preez (1997)
The material imported to infill the depressions formed by the tamper or compaction foot during treatment should be hard, inert, granular material, similar to, or the same as, that used to form the working blanket. The Institution of Civil Engineers (ICE) Specification for Ground Treatment stipulates that imported fill used to make up ground levels to the working surface or for filling the depressions formed by compaction should be no greater than 8 in (200 mm) in diameter and contain no more than 10% passing the BS 75 μm (USA Standard No. 200) sieve. This material only forms part of the working platform, but is likely to be displaced into the underlying ground during subsequent treatment passes. It should not form weak pockets within the treated ground or have any detrimental effect on foundations or building components.	Building Research Establishment (2003)

Table 36. Project specific constraints

Reported Data	Reference
Any natural barrier, such as a very dense layer or a layer of soft soil, can absorb compactive energy that is intended for deeper soil layers, inhibiting compaction of these deeper layers.	SAICE (2006)
The compaction point grid spacing is dictated by the depth and thickness of the compressible soil layer.	SAICE (2006)
Craters are formed at each compaction point. Crater depths typically range from about 6 to 24 in (150 to 610 mm). Craters deeper than about 18 in (460 mm) indicate the near surface soil may be so loose that the energy cannot propagate sufficiently deep to improve the soil below the water table. In these areas, retreatment is performed. If deep craters are created during the second round of treatment, shallow soft soil may be present.	Simpson et al. (2008)
Interbedded clay layers may attenuate compactive energies, making it difficult to improve deeper layers.	Simpson et al. (2008)

Table 37. Environmental considerations

Reported Data	Reference
Vibrations increase as the level of compaction increases. Vibrations attenuate very rapidly with distance. Noise does not attenuate very rapidly with distance. Reducing the drop height (i.e. impact energy) does not affect the level of vibration significantly, but a trench more than halves the transmitted vibrations. On potentially sensitive projects, site monitoring of sound and vibrations levels is recommended in order to establish safe limiting distances.	Braithwaite and du Preez (1997)
The following potential hazards should be assessed prior to the design of RIC treatment: (1) the exact location, alignment, depth, height and construction of any buried services; (2) the location of any oversite services, (3) vibration and (4) noise.	Building Research Establishment (2003)
RIC can often be completed as close as about 5 m to adjacent structures without vibration from the compaction works inducing structural damage.	Kristiansen and Davies (2004)
The peak particle velocity of the soil adjacent to the compaction site increases with increasing compaction.	Neilson et al. (1998)
The attenuation of the peak particle velocities away from the source is assumed to approximate the inverse radius squared (r^{-2}).	Parvizi (2009)
Measured noise levels are on the order of 88 dBA at 8 meters.	SAICE (2006)

Table 37. Environmental considerations (continued)

At 100 ft (30 m) the peak particle velocities have been measured to vary from 0.06 to 0.20 in/s (1.5 to 5 mm/s)[2]. Vibrations will vary with material type and will increase as the degree of compaction increases. Results to date indicate that without site specific testing; a safe working distance to structures can be in the order of 16 ft (5 m). To further mitigate any vibration transgressing towards surrounding structures, a cut-off trench is excavated before compaction activities commence.	SAICE (2006)
The potential effect of the vibrations from RIC on nearby improvements should be considered.	Simpson et al. (2008)
Subject to consideration of building vibration and noise, the rig may be operated relatively close to buildings as less flying debris is produced.	Woodward (2005)

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[2] Criteria for Vibration Damage Potential Threshold for existing structures and conditions under continuous/frequent intermittent sources include the following: (1) Extremely fragile historic buildings/ruins/ancient monuments: Maximum Peak Particle Velocity (PPV_{max}) is 0.08 in/s (2.0 mm/s); (2) Fragile buildings: PPV_{max} is 0.1 in/s (2.5 mm/s); (3) Historic and some old buildings: PPV_{max} is 0.25 in/s (6.4 mm/s); (4) Older residential structures: PPV_{max} is 0.3 in/s (7.6 mm/s); (5) New residential structures: PPV_{max} is 0.5 in/s (12.7 mm/s) and (6) Modern industrial/commercial buildings: PPV_{max} is 0.5 in/s (12.7 mm/s).

Criteria for human responses of annoyance due to vibration from continuous/frequent intermittent sources include the following: (1) Barely perceptible: PPV_{max} is 0.01 in/s (0.3 mm/s); (2) Distinctly perceptible: PPV_{max} is 0.04 in/s (1.0 mm/s); (3) Strongly perceptible: PPV_{max} is 0.10 in/s (2.5 mm/s) and (4) Severe: PPV_{max} is 0.4 in/s (10.2 mm/s) (Jones & Stokes 2004).

Table 38. Equipment needs

Reported Data	Reference
In excess of 25 blows, the near surface material between print positions starts becoming disturbed resulting in a secondary “ironing” phase becoming necessary.	Braithwaite and du Preez (1997)
To compact ground close to the surface layer, the 5 ft (1.5 m) diameter foot can be replaced with a 6 ft (1.8 m) square plate and a pass of closely passed compactions can take place.	Building Research Establishment (2003)
The hammer drop height, number of blows, penetration per blow and total penetration are recorded by the RIC data acquisition system, which can also control the final set to a predetermined penetration per blow.	Kristiansen and Davies (2004)
The RIC is carried out at close spacing with many compaction locations within an area of 20 ft by 20 ft (6 m by 6 m).	Kristiansen and Davies (2004)
The compactor comprises five main parts: a crawler, the guide frame, a hydraulic lifting mechanism, the drop weight and the foot. A variety of different sized feet may be fitted to suit particular applications. The weight falls down on the guide frame and strikes the foot which is sitting on the soil to be compacted.	Neilson et al. (1998)
Approximately 9,000 to 30,000 SF (800 to 2500 m^2) can be covered in an average single-sift day (depending on the blow-per-position setting).	SAICE (2006)
During a possible ironing phase, the area is leveled using a plate with dimensions of 8 ft by 8ft (2.5 m by 2.5 m) which can be attached to the bottom of the compaction foot	SAICE (2006)
Mounted typically as an attachment to a hydraulic excavator, the machine comes in 5.5 ton (5 tonne), 7.5 ton (7 tonne) and 10 ton (9 tonne) modes (with 7.5 ton (7 tonne) modes typically used in the UK).	Serridge and Synac (2006)
RIC treatment typically consists of performing 13 compaction points per 20 ft by 20 ft (6 m by 6 m) area.	Simpson et al. (2008)
Provides controlled impact compaction of the earth using excavator mounted equipment with a 5 to 9 ton (4.5 to 8 tonne) weight (7.5 ton/7tonne common) which is dropped approximately 4 ft (1.2 m) on to a 5 ft (.5 m) diameter tamper capable of imparting 40 to 60 blows per minute.	SHRP2 R02 Phase 1 Technology Assessment
Construction uses a specialist heavy crawler rig with a hydraulically operated hammer, capable of around 50 blows per minute from a height of 3 ft (1 m). Total energy at each initial imprint is up to 80 ton-ft/ft^2 (250 tonne-m/m^2) on a 5 ft (1.5 m) diameter plate.	Woodward (2005)

Table 39. Advantages

Reported Data	Reference
The energy per blow is small compared to each weight drop for dynamic compaction but the rate and number of blows is considerably higher and can result in a much greater total energy input per unit area of the site.	Braithwaite and du Preez (1997)
As the foot remains in contact with the ground, the energy should be much more efficiently used in compacting the fill than in dynamic compaction where the weight may fall on an irregular fill surface in such a way that much of the energy is dissipated in deforming the irregularities of the fill.	Building Research Establishment (2003)
Since the RIC tamping foot is always in contact with the ground, there is no risk of flying debris or danger from a falling weight as with conventional dynamic compaction. Other activities in the immediate neighborhood can therefore proceed during the compaction operation.	Braithwaite and du Preez (1997)
The quality of compaction achieved has been found to be excellent both in terms of the degree of compaction as well as the uniformity achieved.	Braithwaite and du Preez (1997)
Having the RIC mounted on a tracked machine gives it the versatility to move about in narrow and limited spaces.	SAICE (2006)
Since the energy per blow is less than in conventional dynamic compaction, the consequential risk of damage to the existing infrastructure is potentially reduced.	Serridge and Synac (2006)
The major advantage of RIC over penetrative ground improvement techniques, such as vibro stone columns, is that greater control can be exercised to avoid exposure of hazardous material existing in miscellaneous fill (e.g. chemicals, asbestos etc.) to the atmosphere whilst facilitating compaction of the soil at depth.	Serridge and Synac (2006)
In the urban environment, the RIC technique has a number of specific advantages compared to the conventional drop weight dynamic compaction technique including: (1) equipment is relatively small, (2) treatment can be carried out in close proximity to existing structures and services vulnerable to vibration damage, (3) generally no damage from flying debris, (4) discrete, relatively small foundation areas can be treated and (5) energy is more efficiently transferred through the compaction foot which remains in contact with the ground.	SHRP2 R02 Phase 1 Technology Assessment

Table 39. Advantages (continued)

RIC is considerably more efficient than deep dynamic compaction since RIC is better at optimizing the transfer of energy during the compaction process. This is due to the fact that the RIC foot maintains contact with the ground. Compared with deep dynamic compaction, RIC will result in higher peak particle velocity values which are indicative of more efficient or superior coupling between the mechanism of energy transfer and the soil being treated.	Tara and Wilson (2004).

Table 40. Disadvantages

Reported Data	Reference
With ground improvement techniques involving surface impacts such as RIC there cannot be direct control of treatment depth, as would be the case with vibro stone columns.	Serridge and Synac (2006)

Table 41. Alternate solutions

Reported Data	Reference
RIC is in principle analogous to conventional dynamic compaction and that it is likely that existing empirical data from the global dynamic compaction database may be extrapolated to RIC.	Braithwaite and du Preez (1997)
Liquefaction potential mitigation alternatives include vibroflotation with stone columns and deep dynamic compaction.	Kristiansen and Davies (2004)
In the case of liquefaction susceptible hydraulic fill that could trigger possible flow slides under seismic conditions, vibroflotation is an alternative solution to RIC.	Kristiansen and Kostaschuk (2006)
Regarding liquefaction potential mitigation, alternate solutions to RIC include compaction grouting, excavation and replacement, vibroflotation and deep dynamic compaction.	Miller (2006)
The selection of the compaction method (DC or RIC) and plant type for a particular project will depend on ground and groundwater conditions, and requirements for design and execution. Each system has merits and limitations. It is important that these are understood and considered in the design and application of DC/RIC on a particular site and in the context of the prevailing ground conditions. Indeed, it may be necessary for more than one technique to be employed at a particular site to gain maximum benefit.	Serridge and Synac (2006)
An alternate solution can be deep dynamic compaction.	SHRP2 R02 Phase 1 Technology Assessment
In order to mitigate liquefaction potential; alternatives to RIC include compaction grouting, stone columns and vibroflotation.	Simpson et al. (2008)

Tasks 9 and 10C: Case History Database

The case studies presented in this section will be an important part of Task 9, which is to develop a catalog of materials and systems for rapid renewal projects. Each case study appears in a standard format to allow for an efficient gathering of pertinent information. The information reported for each case study is as follows: the technologies used, a general project description, the date and duration of the project, the approximate size of the project, subsurface conditions, design details, construction details, QA/QC method used, short and long-term performance, problems encountered, project costs, other information about the project, and contact information of participants. This section compliments the literature database and will provide the end-user with a valuable resource for evaluating potential technologies for a project.

Table 42. Case history 1

Naval Square Biddle Hall Annex and Townhomes: Philadelphia, PA	
Technologies used:	Geopier Intermediate Foundation Support, Rapid Impact Compaction
General Project Description:	Condominium units on a site strewn with fills that required extensive undercutting and replacement.
Date/Duration:	April/May 2005
Project Size:	N/A
Subsurface Conditions:	Scattered spots of "historical" debris fill covered the site which required extensive undercutting and replacement.
Design Details:	Geopier Immediate Foundation Supports were utilized for 7 ksf (330 kPa) loaded spread footings and Rapid Impact Compaction was utilized for 4 ksf (190 kPa) continuous wall footings.
Construction Details:	N/A
QA/QC Methods:	Borings were made after rapid impact compaction treatment.
Short and Long Term Performance:	Post-treatment borings revealed that the allowable bearing capacity was indeed the specified 4 ksf (190 kPa).
Problems Encountered:	N/A
Cost:	Rapid Impact Compaction saved approximately $75,000.
Other:	N/A
Source:	GeoStructures, Inc. (2009). Naval Square. Retrieved May 19, 2009, from http://www.geostructures.com/default.asp?ContentID=14.
Contact Information Provided By Authors:	GeoStructures, Inc. Corporate Office 413 Browning Court Purcellville, VA 20132 1-877-846-3165 eomalley@geostructures.com

Table 43. Case history 2

Pasco Middle School Building EE: Land O'Lakes, FL	
Technologies used:	RIC
General Project Description:	A two story school to be built on a site with loose sands 10 to 20 feet deep.
Date/Duration:	N/A
Project Size:	120,000 SF (11,000 m^2)
Subsurface Conditions:	Loose sands (SP and SM) extended to depths of 10 to 20 ft (3 to 6 m). The upper 15 ft (4.6 m) had SPT values of 1 to 6 blows per ft (305 mm). The groundwater table was located at 3 to 5 ft (1 to 1.5 m) below ground surface.
Design Details:	Footings with bearing pressures of 2,500 psf (120 kPa) and column loads up to 720 kips (3200 kN) with typical column loads less than 200 kips (900 kN).
Construction Details:	N/A
QA/QC Methods:	The RIC was able to monitor the set of the tamper to see when full densification was achieved. CPTs were used to show that the equivalent SPT values were improved as needed for the footings.
Short and Long Term Performance:	RIC improved the in-situ sands to an SPT value greater than 20 blows per foot (305 mm) to a depth of 25 ft (7.6 m).
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	GeoStructures, Inc. (2009). Pasco Middle School Building EE. Retrieved May 19, 2009, from http://www.geostructures.com/default.asp?ContentID=14.
Contact Information Provided By Authors:	GeoStructures, Inc. Corporate Office 413 Browning Court Purcellville, VA 20132 1-877-846-3165 eomalley@geostructures.com

Table 44. Case history 3

Tampa Terminal Tank 6: Tampa, FL	
Technologies used:	Rapid Impact Compaction
General Project Description:	The relocation of a 43,000 BBL (Barrel) tank onto a site that was susceptible to total and differential settlements.
Date/Duration:	August 2006
Project Size:	N/A
Subsurface Conditions:	The site was underlain by groundwater at a depth of 3 ft (1 m) below ground surface and loose sands that could have caused excessive total and differential settlements.
Design Details:	Rapid impact compaction was chosen to improve the soils to a depth of approximately 20 ft (6 m) below ground surface in order to reduce the effects of settlement.
Construction Details:	
QA/QC Methods:	Post-treatment soil borings and CPTs
Short and Long Term Performance:	The soil's SPT N-values were increased to depths up to 30 ft (9 m) below the ground surface.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	GeoStructures, Inc. (2009). Tampa Terminal Tank 6. Retrieved May 19, 2009, from http://www.geostructures.com/default.asp?ContentID=14.
Contact Information Provided By Authors:	GeoStructures, Inc. Corporate Office 413 Browning Court Purcellville, VA 20132 1-877-846-3165 eomalley@geostructures.com

Table 45. Case history 4

Wyvern Hotel: Punta Gorda, FL	
Technologies used:	Rapid Impact Compaction
General Project Description:	A 63 room hotel at a site susceptible to settlement.
Date/Duration:	N/A
Project Size:	12,000SF (1,100 m^2)
Subsurface Conditions:	Soil was susceptible to extensive settlements.
Design Details:	Ground improvement was required to extend to a depth of 13 ft (4 m) below ground surface in order to provide support for the structure on a reinforced mat foundation.
Construction Details:	N/A
QA/QC Methods:	An on-board monitoring system was used to determine the optimum number of rapid impact compaction passes. SPTs were used to verify that the soils were improved as needed.
Short and Long Term Performance:	Rapid impact compaction improved the in-situ sands from N=5 to 10 blows per foot to greater than 15 blows per foot (305 mm). N-values were increased to greater than 15 blows per foot (305 mm) to depths of 13 ft (4 m) with some areas reaching 50 blows per foot (305 mm).
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	GeoStructures, Inc. (2009). Wyvern Hotel. Retrieved May 19, 2009, from http://www.geostructures.com/default.asp?ContentID=14.
Contact Information Provided By Authors:	GeoStructures, Inc. Corporate Office 413 Browning Court Purcellville, VA 20132 1-877-846-3165 eomalley@geostructures.com

Table 46. Case history 5

Ground Improvement Using Rapid Impact Compaction	
Technologies used:	Rapid Impact Compaction
General Project Description:	A combined fire station and office building complex designated as a post-disaster structure required to withstand a 1 in 475 year earthquake. The complex was constructed on a site containing liquefaction susceptible soils.
Date/Duration:	Site investigation was conducted on October 3, 2002. The one-day pilot study was completed in December of 2002 with an investigation of the study area to evaluate the density increase. After the compaction works were completed over the entire site, a final investigation of the site was conducted on February 25, 2003.
Project Size:	130 ft x 260 ft (40 m x 80 m)
Subsurface Conditions:	The soil conditions generally consisted of granular fill over interbedded sand and silt layers underlain by granular deposits. The fill thickness was typically about 1 ft (0.3 m), but soft silt fill extended to 5 ft (1.5 m) depth at one location. The sand content in the underlying interbedded deposit appeared greater than the silt content and the sand content was even significant in the silt zones, which resulted in a generally cohesionless deposit. However, cohesive silt zones up to about 1 ft (0.3 m) thick were occasionally encountered immediately below the fill at a few test hole locations. The cohesive and cohesionless zones were typically firm and loose to compact, respectively. The underlying native granular deposit was typically encountered at about 10 ft (3 m) depth and consisted of sand with variable gravel content and minor silt content and occasional cobbles. The upper zone of this granular soil deposit was compact to very dense with typically equivalent SPT-N_{60} values of the order of 17 blows per ft (305 mm) or more to an approximately 21 ft (6.5 m) depth. However, loose to compact zones up to about 8 ft (2.5 m) thick existed between a 21 ft (6.5 m) and 33 ft (10 m) depth. Interpretation of BPT data indicated dense to very dense granular soil from about a 33 to 49 ft (10 to 15 m) depth over compact to dense granular soil to about a 66 ft (20 m) depth, which in turn was underlain by very dense granular soil.

Table 46. Case history 5 (continued)

Design Details:	The complex was required to withstand a 1 in 475 year earthquake with at worst only limited structural damage. However, liquefaction susceptible soils were detected at varying depths in the soil, thus warranting the use of ground improvement. The improvement alternatives included vibroflotation with stone columns, dynamic compaction and rapid impact compaction. The chosen alternative was rapid impact compaction. A pilot program revealed that improvement depths would extend to a depth of 30 ft (9 m) below ground surface and the risk of seismic liquefaction induced by a 1 in 475 year earthquake would be below the acceptable risk threshold. As a result, the geotechnical recommendation was to use shallow depth spread footings in conjunction with ground improvement using rapid impact compaction. Compaction points were carried out at close spacing with many compaction locations within a 20 ft x 20 ft (6 m x 6 m) area.
Construction Details:	Due to wet weather conditions prior to and during the rapid impact compaction construction program, the top 1½ to 3 ft (0.5 to 1 m) of the soil was sub-excavated and backfilled with sand with minor gravel then compacted using a smooth drum ride-on vibratory compactor. After sub-excavation and replacement, rapid impact compaction works were carried out on the entire building footprint. The rapid impact compaction consisted of hydraulically dropping a 7.5 ton (7 tonne) weight from a controlled height onto a 5 ft (1.5 m) diameter tamper at a rate of 40 to 60 blows per minute. Each area was compacted with a minimum of two passes with each pass having a minimum of 13 compaction points. Each point was compacted by sufficient blows to achieve a final set (deformation) during the second pass of maximum 3/8 in (10 mm). Shallow trenches were excavated between vibration sensitive structures to dampen the impact of the rapid impact compaction.
QA/QC Methods:	A data acquisition system was used to monitor the rapid impact compaction construction. Pre-treatment analysis included solid stem augers, Dynamic Cone Penetration Tests (DCPTs), CPTs and Becker Penetration Tests (BPTs). Post-treatment analysis using BPTs occurred approximately one month after treatment.

Table 46. Case history 5 (continued)

Short and Long Term Performance:	The rapid impact compaction works appreciably densified all liquefaction susceptible soils at the project site. The method densified the in-situ soils appreciably to a depth of approximately 20 ft (6 m) below ground surface. It was judged that granular zones on the subject site with equivalent SPT-N_{60} values of approximately 15 blows per foot (305 mm) or less between depths of 20 ft (6 m) and almost 30 ft (9 m) were densified to equivalent SPT-N_{60} values of about 20 blows per foot (305 mm) or more.
Problems Encountered:	N/A
Cost:	N/A
Other:	Rapid impact compaction can often be completed as close as 16 ft (5 m) to adjacent structures without vibration from the compaction works inducing structural damage.
Source:	Kristiansen, H. and Davies, M. (2003), “Results of Becker Penetration Testing, Chilliwack Fire Hall”, AMEC Earth & Environmental, Inc., Burnaby, B.C., Canada, 10p. Kristiansen, H. and Davies, M. (2004), “Ground Improvement Using Rapid Impact Compaction”, Proceedings from the 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, Paper No. 496.
Contact Information Provided By Authors:	Henrik Kristiansen Senior Geotechnical Engineer AMEC Earth & Environmental 2227 Douglas Road Burnaby, BC V5C 5A9 Canada henrik.kristiansen@amec.com Michael Davies Senior Geotechnical Engineer AMEC Earth & Environmental 2227 Douglas Road Burnaby, BC V5C 5A9 Canada michael.davies@amec.com

Table 47. Case history 6

Assessment of Ground Improvement Required for Structure on Hydraulic Fill Along Foreshore	
Technologies used:	RIC, Vibroflotation
General Project Description:	The construction of a Chiller/Freezer building a top of hydraulic fill located immediately adjacent to the foreshore. The fill was determined to be susceptible to liquefaction.
Date/Duration:	N/A
Project Size:	The proposed building had dimensions of 50 ft x 80 ft (15 m by 25 m).
Subsurface Conditions:	A preliminary site investigation revealed the potential presence of liquefaction susceptible soils that could result in global instability of the foreshore due to 1 in 475 year earthquake loads inducing a peak horizontal bedrock acceleration of 0.22 g. Using CPTs and solid stem boreholes, a secondary site investigation revealed that the soil profile consisted of granular fill over native sand, which was underlain by very dense (till-like) sand over bedrock. The thickness of the granular fill ranged from 20 to 23 ft (6 to 7 m). The surface of the very dense sand deposit was assessed to be at depths varying from 34 to 37 ft (10.3 to 14.4 m). All CPTs encountered refusal at the surface of the very dense layer of sand. The underlying bedrock surface was estimated to be at depths between 39 and 49 ft (12 and 15 m). The groundwater table was located at a depth of 7 ft (2 m) below ground surface. The potential liquefaction zones were determined to be located in the granular fill between the depths of 13 and 20 ft (4 and 6 m) and in the natural sand deposit between a depth of 26 ft (8 m) below ground surface and the top of the very dense sand layer.
Design Details:	The governing provincial building code required that the proposed Chiller/Freezer building be designed to limit the impact of a 1 in 475 year earthquake to structural damage without building collapse. Using the computer software FLAC, the seismic response of the site was modeled and predicted. A FLAC analysis was conducted for the site using RIC treatment and an assumed depth of improvement of 33 ft (10 m). The analysis revealed that the site would result in complete flow-slide failure with unpredictably large displacements. RIC was therefore determined to be an inadequate solution to the potential liquefaction of the underlying soil since the depth of improvement would still not have been deep enough to mitigate all potential liquefaction susceptible layers. Vibroflotation was chosen instead.

Table 47. Case history 6 (continued)

Construction Details:	N/A
QA/QC Methods:	N/A
Short and Long Term Performance:	N/A
Problems Encountered:	The depth of improvement for RIC was not deep enough to improve all liquefaction susceptible soils of the soil profile.
Cost:	N/A
Other:	N/A
Source:	Kristiansen, H. and Kostaschuk, R. (2006). "Assessment of Ground Improvement Required for Structure on Hydraulic Fill Along Foreshore." Proceedings of the 8th National Conference on Earthquake Engineering, San Francisco, California, Paper No. 1509.
Contact Information Provided By Authors:	N/A

Table 48. Case history 7

Low-Energy Dynamic Compaction Field Trial	
Technologies used:	RIC
General Project Description:	A field trial of the RIC in order to determine the effectiveness of the compactor in the improvement of fill properties and to assess the on-board monitoring instrumentation of the compactor.
Date/Duration:	N/A
Project Size:	33 ft x 33 ft (10 m x 10 m)
Subsurface Conditions:	The site consisted of high-plasticity sandy clay which was excavated to a depth of 10 ft (3 m) then backfilled with a graded fill material including sand and small fragments of rock and concrete.
Design Details:	N/A
Construction Details:	The compaction procedure included 50 impacts per location, at the rate of about one per second, on a square grid at 5 ft (1.5 m) spacing in a single pass.
QA/QC Methods:	In-situ tests consisting of SPTs, dynamic probes and zone loading tests were conducted after the fill was backfilled. In-situ tests were repeated following compaction.
Short and Long Term Performance:	The dynamic probe revealed that the depth of improvement extended to a depth of 10 ft (3 m) below ground surface. The SPT revealed that the depth of improvement extended to a depth of between 7 and 8 ft (2 and 2.5 m). The zone loading test revealed a fourfold increase in stiffness.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Merrifield, C.M and Davies, M.C.R. (2000). “A study of low-energy dynamic compaction: field trials and centrifuge modeling,” Géotechnique, 50(6), p. 675-681.
Contact Information Provided By Authors:	N/A

Table 49. Case history 8

Vibration assessment of high speed dynamic compaction	
Technologies used:	RIC
General Project Description:	A field trial to evaluate a prototype RIC compactor. The trial was intended to implement a monitoring system for the machine to provide an indication when optimum compaction had been achieved.
Date/Duration:	March 1997
Project Size:	N/A
Subsurface Conditions:	The site was reported to be mixed fill.
Design Details:	N/A
Construction Details:	For the points P1, P2 and P6; the compactor was run in a single shot mode and the acceleration of the foot for each blow was recorded on tape for subsequent analysis. At site P15 the ground compaction was carried out in continuous running mode in two phases: phase 1 – 22 blows, phase 2 – 13 blows. The total number of blows for points P1, P2, P6 and P15 was 20, 4, 50 and 35; respectively.
QA/QC Methods:	The site was subjected to pre-treatment and post-treatment dynamic penetration testing.
Short and Long Term Performance:	At P6, where 50 blows were used to compact the ground, an increase in ground resistance to a depth of around 10 to 13 ft (3 to 4 m) can be seen. At P4, which did not receive any compaction blows but was positioned 6 ft (1.8 m) from P6, an increase in ground resistance between 7 and 13 ft (2 and 4 m) below ground surface can be seen. This means that sites adjacent to a treatment point will receive some benefit prior to actually being treated themselves however a definition of the radius of influence of compaction has yet to be determined.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Neilson, R.D., Rodger, A.A., Oliver, K.D., Wright, R.H. and Elliott, R.M. (1998). “Vibration assessment of high speed dynamic compaction.” In B.O. Skipp (Eds.), Ground Dynamics and Man-Made Processes (p. 143-154). London: Thomas Telford.
Contact Information Provided By Authors:	N/A

Table 50. Case history 9

Hydrojet Facility	
Technologies used:	RIC
General Project Description:	A structure to be used as an office and warehouse with a footprint of approximately 34,346 SF (3,191 m^2) was to be built upon miscellaneous fill that was deemed to be unsuitable to be used for structural support unless field investigations indicated otherwise. RIC was specified to increase the support conditions of the ground.
Date/Duration:	Compaction began on August 13, 2008 and was completed on August 28, 2008 (15 days)
Project Size:	Treatment area was 44,175 SF (4,104 m^2)
Subsurface Conditions:	The subsurface investigation of the site consisted of 11 test borings and 2 auger probes. The borings were advanced to a maximum depth of 22.5 ft (6.9 m) below existing grade or auger refusal. The auger probes were advanced to a maximum depth of 15 ft (4.6 m). Site investigations revealed that the site was underlain by miscellaneous fill material ranging from 6 to 22.5 ft (1.8 to 6.9 m). The fill consisted of metal, slag, wood, concrete, foundry sand, brick, etc. in a soil mixture and was considered unsuitable to support the proposed structure. SPT values in this layer ranged from 2 to more than 100 bpf. The unusually high SPT values were associated with the SPT encountering rock and concrete fragments. Below the fill was a layer of natural soils composed of fine sand and silty clay with occasional or many limestone fragments. The soil was derived from glacial till or frost-churned material weathered from limestone and was classified as ML (sandy silt with gravel). The natural moisture content varied from 22.5% to 36.5%. The thickness of this layer ranged from 7 to 16 ft (2.1 to 4.9 m). SPT values in this layer ranged from 8 to 37 bpf. Groundwater was not encountered at any test boring or auger probe location at the time of drilling.

Table 50. Case history 9 (continued)

Design Details:	RIC was determined to possibly be effective to compact the miscellaneous fill that was present on the site. An RIC test area (20-foot-by-20-foot) was specified to determine the depth and magnitude of improvement of RIC at the site. Pre-compaction and post-compaction SPTs were conducted to measure the improvement. Following the RIC test, the RIC procedures were deemed acceptable in improving the bearing characteristics of the ground. A total of 884 impact points were designed to be conducted over the footprint of the structure. The points were to be conducted over three sequences of compaction. The compaction of the site was carried out in 20-foot-by-20-foot sections.
Construction Details:	Compaction was delivered at each point until one of the following criteria was satisfied: (1) 98 blows at a single point, (2) a final crater depth of approximately 800 mm, (3) manual override of the compactor or (4) the deflections due to each blow were consistently 4 mm.
QA/QC Methods:	For each compaction point, the on-board computer portion of the compactor recorded the date of compaction, the time of compaction, the total number of blows, the final deflection, the final crater depth, the total energy input, the average drop height and the reason for termination of compaction. Seven post-compaction SPTs were conducted over the RIC treatment area.
Short and Long Term Performance:	According to the post-compaction SPTs, RIC affected the site to depths ranging from 15 to 20 ft (4.6 to 6.1 m) below grade. Over a depth of 30 ft (9.1 m) , the average post-compaction SPT values over the 7 SPT borings ranged from 24 to 50 bpf with an average of 40 bpf for the entire set of SPTs.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Personal communication. Ed O'Malley. 2010.
Contact Information Provided By Authors:	GeoStructures, Inc. Corporate Office 413 Browning Court Purcellville, VA 20132 1-877-846-3165 eomalley@geostructures.com

Table 51. Case history 10

St Oswald's Park: Gloucester (UK)	
Technologies used:	RIC
General Project Description:	A shopping and leisure development was to be built upon a former cattle market site.
Date/Duration:	8 week total duration from November 2004 to March 2005
Project Size:	430,000 SF (40,000 m^2)
Subsurface Conditions:	Before the site was used as a cattle market, the site had served as a domestic landfill up until the 1960s.
Design Details:	Piles were specified for the foundations of the structures. RIC was utilized to compact the top 10 to 13 ft (3 to 4 m) of fill for land devoted to access and service roads, parking lots and delivery areas to minimize settlements from any organic gradation.
Construction Details:	A total of 2 treatment passes were utilized with each compaction point receiving 20 to 30 blows.
QA/QC Methods:	Pre-treatment and pos-treatment CPTs, plate load tests and zone tests were used for quality assurance.
Short and Long Term Performance:	N/A
Problems Encountered:	N/A
Cost:	$303,000[3] (£160,000)
Other:	N/A
Source:	Pennine. St. Oswald's Park, Gloucester. Retrieved May 19, 2009, from http://www.pennine.co.uk/pennine/technical-library/?entryid7=2073&q=0%C2%ACoswald%27s%C2%AC.
Contact Information Provided By Authors:	Pennine Head Office & Northern Office New Line Bacup Lancashire OL13 9RW T 01706 877555 F 01706 879754 E info@pennine.co.uk

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[3] Using an exchange rate of 1.8934 UK pounds to US dollars (average exchange rate from November 2004 to March 2005)

Source: Federal Reserve. (2009, June 22). Foreign Exchange Rates. Retrieved June 26, 2009 from http://www.federalreserve.gov/releases/h10/Hist/

Table 52. Case history 11

Potentially Combustible ground and proximity working to existing structure: West Midlands, West Bromwich (UK)	
Technologies used:	RIC, Vibro stone columns
General Project Description:	Construction of a new warehouse and offices adjacent to an existing warehouse on top of a fill material consisting of miscellaneous rubble and incomplete combustions products.
Date/Duration:	N/A
Project Size:	N/A
Subsurface Conditions:	The site consisted of made ground deposits comprised of gravely (sometimes silty) sand of ash, clinker, slag, coal, mudstone and sandstone. Brick and concrete rubble also existed to a depth of about 10 ft (3 m) below ground level. The made ground was typically black in color indicative of the potential presence of incomplete combustion products. Lime was also present which may have suggested that it was injected into the ground to extinguish underground fires. The ground was fairly uniform and was predominately granular in nature with a loose relative density. The grading of the made fill was 5-13% clay/silt, 33-40% sand, 50-54% gravel and 0-4% cobbles. The made ground extended to depths of up to between 26 and 33 ft (8 and 10 m) below ground surface and was underlain by competent glacial deposits in turn resting on bedrock.
Design Details:	Vibro stone columns were rejected since they were likely to exacerbate the potential for any underground combustion by allowing ready access for oxygen along and introducing friction between the vibro equipment and the surrounding soil during stone column installation. Dynamic compaction was also rejected due to the close proximity of the adjacent warehouse. RIC was selected as the main ground improvement for the site. The new warehouse and office would then be constructed on a shallow pad and strip foundations with a ground bearing floor slab. To minimize any increase in stress below the level of effective ground improvement, foundation depths were kept as shallow as possible. Stone columns were used within 33 m (10 m) of the existing warehouse due to possible vibration damage to the structure as a result of the RIC also since the soil near the existing warehouse was later determined to be more cohesive and less combustible.

Table 52. Case history 11 (continued)

Construction Details:	Up to three treatment passes were undertaken with a total energy input of around 70 ton-ft/ft^2 (200 tonne-m/m^2) applied to provide sufficient bearing capacity beneath the main foundations and with 30 ton-ft/ft^2 (90 tonne-m/m^2) beneath ground bearing floor slab areas. Imprint depths under the earlier treatment passes were of the order of 18 to 20 in (450 to 500 mm) (for a total of 40 blows at each imprint position), reducing to around 4 to 8 in (100 to 200 mm) (for a total of 30 blows at each imprint position) on the later treatment passes.
QA/QC Methods:	N/A
Short and Long Term Performance:	The bearing pressure beneath the main foundations after treatment was 3,100 psf (150 kPa). The bearing pressure beneath the floor slab after treatment was 730 psf (35 kPa).
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Serridge, C.J. and Synac, O. (2006). “Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils.” Proceedings of IAEG2006, London, Paper No. 294.
Contact Information Provided By Authors:	N/A

Table 53. Case history 12

Coastal Reclamation Project: Assalouyeh (Iran)	
Technologies used:	RIC, dynamic compaction
General Project Description:	Construction of a 12½ mi (20 km) coastal petrochemical refinery on reclaimed land approximately ½ mi (0.8 km) in width protected by a rock armor defense wall.
Date/Duration:	N/A
Project Size:	N/A
Subsurface Conditions:	Fill used in the land reclamation for the refinery comprised crushed rock and ranged from in depth from 10 ft (3 m) (landward end) to 46 ft (14 m) (seaward end).
Design Details:	
Construction Details:	RIC was carried out using two main treatment passes using RIC compactors with drop weights weighing 10 tons (9 tonnes). Conventional dynamic compaction was utilized for areas that necessitated greater depths of improvement.
QA/QC Methods:	Pre-treatment and post-treatment SPTs.
Short and Long Term Performance:	The depth of improvement of RIC was on the order of 20 ft (6 m) below ground surface.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Serridge, C.J. and Synac, O. (2006). “Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils.” Proceedings of IAEG2006, London, Paper No. 294.
Contact Information Provided By Authors:	N/A

Table 54. Case history 13

Improvement in CBR: Dagenham, Essex (UK)	
Technologies used:	RIC
General Project Description:	Construction of a parking lot for semis within a zone of waste ground.
Date/Duration:	N/A
Project Size:	400,000 SF (37,000 m^2)
Subsurface Conditions:	The waste fill consisted of essentially granular materials comprising sand, gravel, ash, founding waste and demolition rubble placed in an uncontrolled manner.
Design Details:	Achievement of a CBR of 20% following RIC treatment and proof rolling, prior to constructing the surfacing/hardstanding.
Construction Details:	Construction employed two main treatment passes (on offset grids) with between 20 and 30 blows at each compaction point.
QA/QC Methods:	Compaction trials/checks and plate load tests were used to verify the efficiency of the treatment technique during and after its execution respectively.
Short and Long Term Performance:	N/A
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Serridge, C.J. and Synac, O. (2006). “Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils.” Proceedings of IAEG2006, London, Paper No. 294.
Contact Information Provided By Authors:	N/A

Table 55. Case history 14

Liquefaction Mitigation: Hokkaido (Japan)	
Technologies used:	RIC
General Project Description:	An oil tank foundation that was to be constructed on liquefaction susceptible soil.
Date/Duration:	N/A
Project Size:	8,100 SF (750 m^2)
Subsurface Conditions:	The soil profile consisted of loose to medium dense natural sand and gravel deposits. The groundwater level was very shallow, typically at around 3 ft (1 m) depth.
Design Details:	A total of 5 passes with 50 blows per footprint were specified (an energy input of (220 ton-ft/ft^2) 650 tonne-m/m^2).
Construction Details:	The shallow groundwater depth made it necessary to excavate and dewater the site so that groundwater level was about 11½ ft (3.5 m) below the proposed treatment level (20 ft (6 m) below ground surface). Passes 1, 3 and 5 were undertaken on the same 6 ft (1.8 m) grid, with passes 2 and 4 undertaken on a 6 ft (1.8 m) offset grid from passes 1, 3 and 5. Following each treatment pass imprints were dozed in using surrounding granular material from entirely within the treatment area and a level survey undertaken.
QA/QC Methods:	Pre-treatment and post-treatment SPTs.
Short and Long Term Performance:	SPTs showed a significant improvement in the upper 16 ft (5 m) (improvement in SPT value of between 20 and 30). Some improvement in relative density was reported to of up to around 33 ft (10 m) below the initial treatment start level. The recorded enforced settlement was on the order of 16 in (400 mm).
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Serridge, C.J. and Synac, O. (2006). "Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils." Proceedings of IAEG2006, London, Paper No. 294.
Contact Information Provided By Authors:	N/A

Table 56. Case history 15

Loess Soil: Karachaganak, Kazakhstan	
Technologies used:	RIC
General Project Description:	Petrochemical processing plant at a site composed of collapsible loess. Stable foundations were required for two different processing plants at two separate sites (KPC and U2) which were approximately 2 mi (3 km) apart from one another.
Date/Duration:	N/A
Project Size:	Both sites = 7,000 acres (3,000 Hectares) Site KPC = 650,000 SF (60,000 m^2)
Subsurface Conditions:	The site was atop by loess extending to about 56 ft (17 m) below ground surface. The top 7 ft (2 m) of the loess was characterized as being a desiccated "crust" in which the highest in-situ strengths of the soil profile was located. The groundwater table at the KPC site was found to be located at a depth of 98 ft (30 m) below ground surface. The groundwater table at the U2 site was found to be located at a depth of around 7 to 14 ft (3.0 to 4.2 m) below ground surface. The soils at both sites were generally the same except the soil at the KPC site; the degree of saturation was lower, the natural moisture content was lower, the clay content was lower and the sand content was higher. Testing revealed that the upper 10½ ft to 13 ft (3.2 to 4 m) of the loess soil profile for both sites had collapse potential. The soil was classified as (Type 1) settling /collapsing soil, in accordance with Russian standards.
Design Details:	Provide a required bearing capacity of 3,100 (150 kPa) with a long-term settlement requirement less than 1 in (25 mm) for foundations not exceeding 33 ft (10 m) in width. Based upon the results of site specific trials and time constraints on program, full RIC ground improvement was conducted at the KPC site only.
Construction Details:	The sequence of works involved the following: [Stage 1] excavation to foundation level, leveling and rolling; [Stage 2] pre-treatment in-situ testing; [Stage 3] first pass by RIC rig (70 blows), leveling and rolling; [Stage 4] level survey and in-situ testing; [Stage 5] second pass by RIC rig (50 blows), leveling and rolling; [Stage 6] level survey and post-treatment in-situ testing and [Stage 7] restoration of levels to underside of foundation level using selected granular material placed and compacted in layers.

Table 56. Case history 15 (continued)

QA/QC Methods:	In-situ testing occurred before RIC treatment, in between RIC treatment passes and after RIC treatment. At each testing phase, dynamic probe tests (DPTs) were conducted to monitor the effectiveness of the treatment. After RIC treatment, plate bearing tests (PBTs) were conducted in addition to DPTs to more accurately appraise the bearing characteristics of the RIC treated soil.
Short and Long Term Performance:	Both the compaction trials and the main works verification testing showed that the RIC technique was successful in reducing collapse potential in loess soil at the KPC site. The recorded / observed depth of improvement was typically of the order of 10 ft (3 m) from the treatment commencement level, (i.e. from the base of the “crust”, with level of improvement diminishing with depth).
Problems Encountered:	N/A
Cost:	N/A
Other:	Prior to commencement of the main works, preliminary trials were undertaken at the KPC and U2 sites, to assess the suitability and effectiveness of the RIC method, including the most appropriate treatment regime and depth and degree of improvement. The trials were executed after excavation of the top desiccated “crust” to coincide with the foundation depth that was specified to lie beneath the “crust” layer. The trial at site KPC proved that the technique in achieving improvement to depths of around 10 ft (3.0 m) below the “crust” and therefore successful in reducing collapse potential of the loess soil. The trial at site U2 showed that RIC did not result in any immediate improvement and the soil exhibited a weaker plastic type of behavior associated with excessive pore pressure elevation. Due to time and program constraints on the project, it was not possible to investigate any improvement attributed to any potential time/ageing effects following pore pressure dissipation. Compared with UK applications and practice the number of blows per pass and therefore total energy input was significantly larger. This was attributed to the fact that the trials did not exhibit a limiting energy for which a significant heave takes place and beyond which soil is displaced rather than compacted.

Table 56. Case history 15 (continued)

Source:	Serridge, C.J. and Synac, O. (2006). "Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils." Proceedings of IAEG2006, London, Paper No. 294.
Contact Information Provided By Authors:	Pennine Vibropiling Head Office & Northern Office New Line Bacup Lancashire OL 13 9RW T 01706 877555 F 01706 879754 E info@pennine.co.uk

Table 57. Case history 16

Loose Building Waste Landfill: Waterbeach, UK	
Technologies used:	RIC
General Project Description:	A field trial of the RIC compactor for its original application of rapid repair of airfield runways for the British military.
Date/Duration:	1990
Project Size:	23 ft x 23 ft (7 m x 7 m)
Subsurface Conditions:	Loose fill consisting of brick, concrete, wood, glass and some soil (principally sand sized particles) spread in 3 ft (1 m) lifts without systematic compaction extending to a depth of 21 ft (6.5 m). Overlaying the layer of loose fill was a natural clay deposit. The ground water level was about 15 ft (4.5 m) below the upper surface of the fill.
Design Details:	N/A
Construction Details:	The 23 ft x 23 ft (7 m x 7 m) area of the site was treated with RIC using a 7.5 ton (7 tonne) hammer falling through 3 ft (1.0 m) onto a 5 ft (1.5 m) diameter compacting foot. Abutting treatment points were used spaced at 5 ft (1.5 m) centers, and each treatment point received 50 blows. The average energy input was 50 ton-ft/ft^2 (150 tonne-m/m^2).
QA/QC Methods:	Dynamic probing (DPH) was conducted before and after treatment to assess the effectiveness of the RIC treatment however the dynamic probe was unable to penetrate the treated fill at the majority of attempts. The measurement of Rayleigh wave velocity was one of the methods used to assess the properties of the made ground before and after RIC treatment. Dynamic shear modulus was calculated from these results and which demonstrated significant improvement.
Short and Long Term Performance:	Significant compression was measured to a depth of 13 ft (4 m) below ground surface. Values for the dynamic shear modulus of the soil profile showed that there had been a substantial improvement to a depth of about 10 ft (3 m) below ground surface.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A

Table 57. Case history 16 (continued)

Source:	Serridge, C.J. and Synac, O. (2006). “Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils.” Proceedings of IAEG2006, London, Paper No. 294. Watts, K.S. and Charles, J.A. (1993). “Initial assessment of a new rapid impact ground compactor.” Proceedings of the Conference on Engineered Fills, London, Paper No. 32.
Contact Information Provided By Authors:	N/A

Table 58. Case history 17

Old Ash Fill: Sheffield, UK	
Technologies used:	RIC, dynamic compaction, vibro compacton
General Project Description:	Non-engineered, loose fill adjacent to existing railway lines sensitive to vibrations.
Date/Duration:	N/A
Project Size:	130 ft x 110 ft (40 m x 35 m)
Subsurface Conditions:	Non-engineered, loose fill consisting mainly of ash, clinker and slag historically deposited to a depth of 11½ ft (3.5 m) over natural alluvial valley deposits.
Design Details:	N/A
Construction Details:	A 1½ ft (0.5 m) thick granular working blanket of demolition waste was placed over the fill to safely support the weight of the RIC rig and act as a source of granular material to doze into imprints formed during the RIC treatment. A treatment pattern of almost abutting compaction points was adopted, with each compaction point receiving 50 blows of a 7.5 ton (7 tonne) hammer dropped through a height of 4 ft (1.2 m) giving a total applied energy input of around 50 ton-ft/ft^2 (150 tonne-m/m^2).
QA/QC Methods:	Settlement with depth was measured by a specially installed magnet extensometer.
Short and Long Term Performance:	The loose essentially granular fill underwent significant compression and densification during treatment as demonstrated by the magnet extensometer readings and post treatment dynamic probe results.
Problems Encountered:	N/A
Cost:	N/A
Other:	In common with dynamic compaction (DC), the lack of compaction close to the ground surface demonstrated the need for proof rolling of the treated surface following RIC completion.
Source:	Serridge, C.J. and Synac, O. (2006). “Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils.” Proceedings of IAEG2006, London, Paper No. 294. Watts, K.S. and Charles, J.A. (1993). “Initial assessment of a new rapid impact ground compactor.” Proceedings of the Conference on Engineered Fills, London, Paper No. 32.
Contact Information Provided By Authors:	N/A

Table 59. Case history 18

Liquefaction Potential Mitigation using Rapid Impact Compaction (Site A)	
Technologies used:	Rapid Impact Compaction
General Project Description:	Five-story affordable housing building on a site composed of liquefiable fill and compressible marine clay. The soil was evaluated before and after treatment using in-situ testing.
Date/Duration:	N/A
Project Size:	170 ft x 250 ft (52 m x 76 m)
Subsurface Conditions:	The top layer of soil consisted of a 14 to 24 ft (4.3 to 7.3 m) thick layer of heterogeneous fill composed of gravel, sand, clay and miscellaneous building rubble. Underneath the layer of fill was a layer of Bay Clay, a marine clay native to the area. The groundwater table was determined to be at a depth between 5 to 10 ft (1.5 to 3m) below the ground surface. A potentially liquefiable layer 1½ to 14 ft (0.5 to 4.3 m) thick consisting of loose to medium dense sand and gravel with some silt and clay was present just above or below the groundwater table.
Design Details:	Cone Penetration Tests (CPTs) and/or rotary wash borings were performed to evaluate the liquefaction potential at each site. In-situ testing revealed the presence of liquefiable fill and excessive consolidation settlement from the underlying marine clay layer. Due to the stated hazards, steel H-piles driven to rock would need to be required. As a result of the liquefiable fill, lateral resistance in the fill layer was low, thus requiring a significant number of piles to resist base shear. Ground improvement was specified in order to decrease foundation costs. Rapid Impact Compaction was selected because of its relative speed and economy. Treatment consisted of performing 13 compaction points per 20 ft x 20 ft (6 m x 6 m) area. Additional ground improvement methods that were considered included compaction grouting, stone columns and vibroflotation.
Construction Details:	Tamping was conducted by dropping a 7.5tons (7 tonne) weight from a height of 3 ft (1 m) onto a 5 ft (1.5 m) diameter steel plate at a rate of 40 to 60 blows per minute. Each compaction point received a total of 50 blows.
QA/QC Methods:	If the penetration depth after 50 blows was greater than 18 in (460 mm) deep, the area was to be retreated 24 hours after the initial treatment to allow for pore water pressures to dissipate. Vibrations due to the compaction were measured at varying distances using seismographs. CPTs were used to confirm the level of improvement.

Table 59. Case history 19 (continued)

Contact Information Provided By Authors:	Post-treatment CPTs revealed an increase in the tip resistance at the same depth of the liquefiable fill of up to 200%. Some liquefaction potential remained after improvement however remaining deposits were thin, intermittent and non-continuous. It was determined that the fill was sufficiently improved to increase the lateral pile capacity.
Problems Encountered:	During the RIC program, the contractor could not get the data acquisition system functioning. Drop height, number of blows and penetration per blow could not be monitored or controlled by the on-board data acquisition system. A criterion of 50 blows per compaction point was adapted by the contractor.
Cost:	N/A
Other:	N/A
Source:	Simpson, L.A., S.T. Jang, C.E. Ronan and L.M. Splitter (2008) "Liquefaction Potential Mitigation using Rapid Impact Compaction." Proceedings of the Conference of Geotechnical Earthquake Engineering and Soil Dynamics IV, Sacramento, CA, Paper No. 181.

Table 59. Case history 19 (continued)

Contact Information Provided By Authors:	Lori A. Simpson, M. ASCE, G.E. Principal Engineer Treadwell & Rollo, Inc. 501 14th St 3rd Fl Oakland, CA 94612 lasimpson@treadwellrollo.com Serena T. Jang, M. ASCE, G.E. Senior Engineer Treadwell & Roll, Inc. 555 Montgomery St. #1300 San Francisco, CA 94111 stjang@treadwellrollo.com Cary E. Ronan, M. ASCE, G.E. Senior Engineer Treadwell & Roll, Inc. 555 Montgomery St. #1300 San Francisco, CA 94111 ceronan@treadwellrollo.com Lisa M. Splitter, M. ASCE, P.E. Project Engineer Treadwell & Rollo, Inc. 501 14th St 3rd Fl Oakland, CA 94612 lmsplitter@treadwellrollo.com

Table 60. Case history 20

Liquefaction Potential Mitigation using Rapid Impact Compaction (Site B)	
Technologies used:	Rapid Impact Compaction
General Project Description:	Five-story affordable housing building on a site composed of liquefiable fill and compressible marine clay. The soil was evaluated before and after treatment using in-situ testing.
Date/Duration:	N/A
Project Size:	275 ft x 650 ft (84 m x 198 m)
Subsurface Conditions:	The top layer of soil consisted of a 6 to 49 ft (1.8 to 15 m) thick layer of heterogeneous fill composed of gravel, sand, clay and miscellaneous building rubble. Underneath the layer of fill was a layer of Bay Clay, a marine clay native to the area. The groundwater table was determined to be at a depth between 4½ to 7½ ft (1.4 to 2.3 m) below the ground surface. A potentially liquefiable layer 7 to 20 ft (2.1 to 6.1 m) thick consisting of loose to medium dense sand with some silt and clay was present just below the groundwater table.
Design Details:	CPTs and/or rotary wash borings were performed to evaluate the liquefaction potential at each site. In-situ testing revealed the presence of liquefiable fill and excessive consolidation settlement from the underlying marine clay layer. Due to the stated hazards, steel H-piles driven to rock would need to be required. As a result of the liquefiable fill, lateral resistance in the fill layer was low, thus requiring a significant number of piles to resist base shear. Ground improvement was specified in order to decrease foundation costs. Rapid Impact Compaction was selected because of its relative speed and economy. Treatment consisted of performing 13 compaction points per 20 ft x 20 ft (6 m x 6 m) area. Additional ground improvement methods that were considered included compaction grouting, stone columns and vibroflotation.
Construction Details:	Tamping was conducted by dropping a 7.5ton (7 tonne) weight from a height of 3 ft (1 m) onto a 5 ft (1.5 m) diameter steel plate at a rate of 40 to 60 blows per minute. Compaction points were placed on a 10 ft (3 m) on-center grid pattern in the first pass; the second pass consisted of points at 10 ft (3 m) on-center midway between points of the first pass.

Table 60. Case history 20 (continued)

QA/QC Methods:	Drop height, number of blows and penetration per blow were monitored and/or controlled by an on-board data acquisition system. The dropping of the weight at each point is ceased when one the following criteria is met: (1) the deflection for the final blow is 0.2 in (5 mm), or (2) 40 total blows, whichever occurs first. Craters deeper than 18 in (460 mm) required retreatment which occurred 24 hours after the initial treatment to allow for pore water pressures to dissipate. Vibrations due to the compaction were measured at varying distances using seismographs. CPTs were used to confirm the level of improvement.
Short and Long Term Performance:	Some liquefaction potential remained, although the remaining liquefiable layers were significantly thinner and the post-treatment tip resistances are significantly higher than the pre-treatment values. Therefore, the overall results indicate fill at the site was sufficiently improved such that the liquefaction potential was reduced. Lateral pile capacity was increased by about 30 to 35%.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Simpson, L.A., S.T. Jang, C.E. Ronan and L.M. Splitter (2008) “Liquefaction Potential Mitigation using Rapid Impact Compaction.” Proceedings of the Conference of Geotechnical Earthquake Engineering and Soil Dynamics IV, Sacramento, CA, Paper No. 181.

Table 60. Case history 20 (continued)

Contact Information of Participants:	Lori A. Simpson, M. ASCE, G.E. Principal Engineer Treadwell & Rollo, Inc. 501 14th St 3rd Fl Oakland, CA 94612 lasimpson@treadwellrollo.com Serena T. Jang, M. ASCE, G.E. Senior Engineer Treadwell & Roll, Inc. 555 Montgomery St. #1300 San Francisco, CA 94111 stjang@treadwellrollo.com Cary E. Ronan, M. ASCE, G.E. Senior Engineer Treadwell & Roll, Inc. 555 Montgomery St. #1300 San Francisco, CA 94111 ceronan@treadwellrollo.com Lisa M. Splitter, M. ASCE, P.E. Project Engineer Treadwell & Rollo, Inc. 501 14th St 3rd Fl Oakland, CA 94612 lmsplitter@treadwellrollo.com

Table 61. Case history 21

RIC Ground Improvement Vibration Monitoring and Densification Assessment: Squamish, British Columbia (Canada)	
Technologies used:	RIC
General Project Description:	A testing program with the intention of monitoring and assessing the vibrations generated by RIC and the densification effects of RIC compaction.
Date/Duration:	N/A
Project Size:	N/A
Subsurface Conditions:	The soil profile comprised about 7 ft (2 m) of variable, native silt and silty sand over loose to compact, clean sand. The groundwater table was determined to be located at 1½ ft (0.5 m) below ground surface.
Design Details:	N/A
Construction Details:	Site preparation prior to compaction comprised removal of the majority of the surficial silt layer and replacement with end-dumped granular fill (either crushed basalt or pit run sand and gravel). Due to the relatively high groundwater table, a sump pump was required to maintain the groundwater level at least 3 ft (1 m) below the surface of the working platform granular fill. Treatment with the RIC followed. Ground vibrations were monitored on the fill pad surface and on the adjacent native ground surface at various distances from the compactor.
QA/QC Methods:	Pre-treatment and post-treatment Dynamic Cone Penetration Tests (DCPTs) were used for quality assurance.
Short and Long Term Performance:	The DCPTs revealed that treatment with the RIC resulted in significant improvement to at least a 16 ft (5 m) depth. The depth of improvement for compaction points at the edge of the treatment area extended to a depth of 20 ft (6 m). DCPTs conducted at 10 and 15 ft (3 and 4.5 m) from the perimeter compaction points of the treatment area show some nominal improvement extending laterally beyond the zone of improvement.
Problems Encountered:	The high groundwater table warranted the use of pumping in order to lower its depth.
Cost:	N/A
Other:	Measured dominant vibration frequencies generally ranged from about 5 to 40 Hz with an average value of approximately 10 Hz beyond about 33 (10 m) from the compaction point.
Source:	Tara, D.J and P.J. Wilson (2004). “Rapid Impact Compactor Ground Improvement Vibration Monitoring and Densification Assessment, Downtown site, Squamish, British Columbia”, Thurber Engineering, Ltd., 9p.

Table 61. Case history 21 (continued)

Contact Information Provided By Authors:	Thurber Engineering Ltd. David J. Tara, P.Eng. Project Principal Paul J. Wilson, EIT Project Engineer

Table 62. Case history 22

Natural Sand Deposits: West Freugh (UK)	
Technologies used:	RIC
General Project Description:	An assessment of the RIC at a coastal site where an area of sand fill lay over natural sand deposits of sandy peat and windblown sand.
Date/Duration:	N/A
Project Size:	N/A
Subsurface Conditions:	The soil profile comprised a 10 ft (3 m) thick layer of sand fill over natural sand deposits of sandy peat and windblown sand. The sand fill was a naturally poorly graded windblown sand, placed by heavy plant above the original ground surface.
Design Details:	N/A
Construction Details:	Half of the area was compacted with 60 blows with an average energy input of 80 ton-ft/ft^2 (225 ton-m/m^2). The other half of the area was treated with abutting compaction points on a triangular grid, with a second pass compacting the intermediate points and giving an average energy input of 140 ton-ft/ft^2 (420 tonne-m/m^2).
QA/QC Methods:	CPTs, dynamic probing and geophyisics were used to measure pre-treatment and post-treatment ground conditions.
Short and Long Term Performance:	The sand fill near the surface was loosed by the RIC process, although less so where a second pass was carried out. It was determined that this layer was at or near its maximum relative density so RIC would have caused overall loosening of the material. The peat layer had been compressed substantially. Significant densification of the deeper natural sand layers below the fill extended to 20 ft (6 m) below ground surface.
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Watts, K.S. and Charles, J.A. (1993). “Initial assessment of a new rapid impact ground compactor.” Proceedings of the Conference on Engineered Fills, London, Paper No. 32.
Contact Information Provided By Authors:	N/A

Table 63. Case history 23

Select Granular Fill: Sheffield (UK)	
Technologies used:	RIC
General Project Description:	Light industrial development to be constructed on granular fill comprising crushed concrete and masonry.
Date/Duration:	N/A
Project Size:	130 ft x 100 ft (40 m x 30 m)
Subsurface Conditions:	Select fill consisting of crushed concrete and masonry was placed over the existing soil in approximately 1 ft (305 mm) thick lifts but received no systematic compaction. The average thickness of the fill was 11½ ft (3.5 m) with isolated refilled deep excavations up to 26 ft (8 m) thick. Underlying the fill was an alluvial material. Bedrock was located at a depth of 23 ft (7 m) below ground level.
Design Details:	The compaction pattern featured strips ranging from widths of 3 to 5 compactions points in an arc shape.
Construction Details:	Each compaction point received 50 blows giving an average total energy input of 57 ton-ft/ft^2 (170 tonne-m/m^2).
QA/QC Methods:	The total penetration and rate of penetration for each point was recorded.
Short and Long Term Performance:	The treatment induced some settlement through the full depth of the fill, but compression was principally in the upper 10 to 13 ft (3 to 4 m).
Problems Encountered:	N/A
Cost:	N/A
Other:	N/A
Source:	Watts, K.S. and Charles, J.A. (1993). “Initial assessment of a new rapid impact ground compactor.” Proceedings of the Conference on Engineered Fills, London, Paper No. 32.
Contact Information Provided By Authors:	N/A

Task 10A: Summary of Design Procedures

This section provides short summaries of design procedures found in various sources for this technology. These summaries are not intended to be comprehensive, but rather to serve as a starting point for assessment of the currently available procedures. The following references should be reviewed in more detail as part of Task 10, which includes development of design procedures for the technologies.

Braithwaite and du Preez (1997)

A detailed description of the ground must be obtained from the profiling of test pits and should be complemented by foundation indicator and moisture content tests on representative soil samples. Soil structure (cementing, relic jointing etc.) must be carefully and comprehensively described and should be supported by laboratory tests (such as collapse potential tests) as appropriate. The initial strength and density of the soil (quantified by density and penetrometer testing) as well as depth to water table will have considerable bearing on the correct planning of the job and should be clearly described.

In addition the type of structure to be developed must be considered (footing layouts and loadings etc.) along with acceptable levels of settlements and angular distortions.

All of this information must be carefully assessed and should culminate in a clear and appropriate statement of the depth of treatment required as well as the level of improvement required. A typical specification will include target bearing capacity and stiffness (Young's Modulus) values.

A final consideration is the proximity of adjacent structures and buried services and the possible effects of transmitted vibrations and noise on these structures or their occupants.

The layout of tamping points is usually based on an arc whose center is described by the fulcrum of the crane. Prints are spaced at approximately 7 ft (2 m) centers for primary tamping and, if necessary, secondary tamping at immediate locations overlapping the primary points may be used.

Building Research Establishment (2003)

The ground responds to RIC in a "top-down" process instead of the "bottom-up" response associated with conventional dynamic compaction. The first few blows in RIC create a dense plug immediately beneath the compaction foot, which remains in contact with the ground surface. Further blows push this plug deeper, which compacts soil in a deeper layer. This process progresses until little further penetration of the compaction foot can be achieved with increasing blows. The effect of the compaction process is confined largely to the ground vertically below the compaction point and treatment is therefore carried out on a closely spaced square or triangular pattern or sequenced on an arc about the center of rotation of the compactor carrier. Additional passes are often offset from the primary pass.

With the RIC, fixed energy per blow is not the major influence on the depth of compaction due to the progressive top down improvement of the treated ground. Of much greater significance to the effective depth of compaction is the number of blows at a compaction point or the energy applied overall to the ground surface. For typical energy impact spacing, 35 blows will impart about 57 ton-ft/ft2 (170 tonne-m/m2) of treatment. This level of energy input has produced significant compaction to depths between 10 and 13 ft (3 and 4 m) in generally granular fill and up to 10 ft (3 m) in natural sandy and silty soils.

Kristiansen and Davies (2004)

The potential effectiveness of the RIC method is evaluated in a pilot program that provides requisite information for preparation of specification for the RIC work. Pre and post treatment in-situ analyses are conducted to evaluate the density increase and thus the specified design criteria.

Parvizi (2009)

Soil response values including peak particle velocities and peak soil pressures due to the rapid impact compaction process can be predicted using centrifuge modeling. The relationship between the normalized peak value of both particle velocity and normal earth pressure induced by the impact on the target are best described by a power function. Models can be developed that relate both soil responses to number of blows, radius distance from the target center and initial relative density. The values can then be expressed in terms of field values by up scaling the relationships using conventional centrifuge scaling laws. These normalized relationships may be used to predict the attenuation of the dynamic pressure wave in congested areas surrounded by sensitive structures and assist in the choice of an appropriate number of blows required providing a modest but efficient and cost effective improvement to the foundation soils.

SAICE (2006)

The grid pass sequence and spacing are determined prior to the commencement of RIC. This is dependent on the type of material, depth of material to be compaction and the water table. If the spacing is too wide, there may be windows of undensified soils, and if the spacing is too narrow at the beginning of the program, the upper soils may densify too soon, inhibiting compaction of the lower soils.

There are 13 positions (impact points), referred to as the 13-spot, in each 20 to 30 ft (6 to 9 m) grid, depending on the above criteria. The 13 spots are performed in three passes. This is to ensure that when the second and third passes are done, the pore water pressure has sufficient time to dissipate. Typical strips of 23 ft by 164 ft (7 m by 50 m) are completed per pass. In addition, a fourth pass (ironing pass) can be introduced.

Serridge and Synac (2006)

RIC design in the UK firstly involves geotechnical characterization of the soils to be treated, with emphasis placed on quantifying in-situ relative density and grading characteristics.

The number of blows at a compaction point or the energy applied overall to the ground surface has the greatest significance to the effective depth of compaction.

However, it is the “compaction trial,” which provides the designer with the necessary information to permit refinement of the design. The “compaction trial,” in particular is important for the evaluation of ground response. During the trials, the degree of compaction can be monitored by comparison of pre and post treatment in-situ testing.

Woodward (2005)

Design is based on measuring the improvements in the ground during and after construction – to a specified settlement per blow. Depth of improvement is between 7 and 10 ft (2 and 3 m). The layout of imprints is typically on a square grid at 7 ft (2 m) centers with secondary tamping between the initial imprints.

Task 10B: Summary of QA/QC Procedures

This section provides short summaries of QA/QC procedures found in various sources for this technology. These summaries are not intended to be comprehensive, but rather to serve as a starting point for assessment of the currently available procedures. The following references should be reviewed in more detail as part of Task 10, which includes development of QA/QC procedures for the technologies.

Braithwaite and du Preez (1997)

Real time monitoring of the treatment process can be effective for quality control and assurance purposes. Before beginning compaction, a site specific minimum energy input is determined by observing the blow count above which continued blows produce negligible further penetration of the foot. This so-called “penetration test” is carried out at several locations on the site and is compared with the empirically predicted value. During the subsequent compaction process, the operator monitors the number of blows on every print position and ensures that the minimum energy level indicated by the penetration testing is supplied. Level surveys of the penetrations associated with each print position are also recorded and are used to calculate the volumetric change (i.e. densification) of the ground within the treatment depth.

Due to the speed of testing, continuous dynamic probes are ideal for use before, during and after compaction in order to demonstrate the effectiveness and depth of treatment. In current practice a dynamic probe testing rate of approximately 1 per 4,300 SF (400 m2) is recommended.

Plate load tests are probably the most direct measure of whether the specified settlement/strength criteria have been met. Frequency of testing should be related to the uniformity of ground conditions but should typically not be less than about one test per 22,000 SF (2000 m2) treated.

Building Research Establishment (2003)

It is normal procedure to test treated ground during the progress of the compaction works for the control purposes to assess the effectiveness of the treatment. This provides the Dynamic Compaction Designer with assurance that the specified level of compaction will achieve the degree of improvement required. Quality control testing during treatment often involves in-situ penetration tests which may form part of the final assurance regime. The frequency of testing will be affected by factors particular to each project, for example, the variability of the ground before treatment, the nature of the structure to be supported and its sensitivity to post-treatment movements.

The operator monitors and can record the number of impacts, the total energy input, the foot penetration per blow and the cumulative penetration. When any operating parameter reaches a specified parameter, for example, total foot penetration or set per blow, an alarm is triggered and the equipment is moved to the next tamping location.

Using the data from the compaction record (total settlement/final depth for each compaction point) and the coordinates for each compaction point, the site can be mapped to identify possible weak zones, thus serving as a diagnostic tool for the site.

Performance testing is carried out to verify the degree to which ground improvement has been achieved and confirm that this meets the specified objectives.

Probing or penetration testing such as the standard penetration test (SPT) in pre-drilled boreholes, static cone penetration tests (CPT) and dynamic probing[4] (DP) may be used to categorize a treatment area. Penetration testing before and after the treatment will measure the change in penetration resistance in soils. Results should be correlated with borehole data.

DP is lightweight, easy and economical to operate and relatively robust for use in miscellaneous fills. DP provides rapid assessment of variability but for more detailed information other testing is required. Where cohesive soils are present the use of a piezocone (CPTU), in which pore water pressures can be measured, may be appropriate.

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[4] The dynamic probing test (DP) covers the determination of the resistance of soils and soft rocks in-situ to the dynamic penetration of a cone. A hammer of a given mass and a given falling height is used to drive the cone. The penetration resistance is defined as the number of blows required driving the penetrometer over a defined distance. A continuous record is provided with respect to depth but no samples are recovered. Four test procedures using DP testing are commonly used: (1) Dynamic Probing Light (DPL): test representing the lower end of the mass range of dynamic equipment, (2) Dynamic Probing Medium (DPM): test representing the medium to very heavy mass range of dynamic equipment, (3) Dynamic Probing Heavy (DPH): test representing the medium to very heavy mass range of dynamic equipment and (4) Dynamic Probing Super-Heavy (DPSH): test representing the upper end of the mass range of dynamic equipment. The test results from the DP test can be used to qualitatively determine a soil profile together with direct explorations (e.g. drilling) or as a relative comparison of other in-situ tests. Test results can also be used for the determination of the strength and deformation properties of soils, generally of the cohesionless type but also possibly in fine-grained soils, through appropriate correlations. The results can also be used to determine the depth to very dense ground layers indicating the length of end bearing piles. The dynamic probing test procedure is outlined in the International Organization for Standardization Standard, ISO 22476-2 (Eitner et al. 2002).

The dynamic probing test (DP) covers the determination of the resistance of soils and soft rocks in-situ to the dynamic penetration of a cone. A hammer of a given mass and a given falling height is used to drive the cone. The penetration resistance is defined as the number of blows required driving the penetrometer over a defined distance. A continuous record is provided with respect to depth but no samples

Other forms of in-situ tests may be used to assess properties of the ground prior to and following dynamic compaction ground treatment. Pressuremeter tests (PMT) investigate in-situ stress, stiffness and strength of the ground. The Marchetti dilatometer test (DMT) gives an indication of soil type and properties such as density, shear strength and stiffness.

Geophysical techniques can be used to assess ground properties and have some major advantages: (1) fieldwork is relatively rapid and, with modern data-logging facilities and processing software, the results can be presented very quickly; (2) non-intrusive surveys can be carried out from the ground surface and (3) representative values of soil parameters can be measured or inferred. In general, the techniques should be used in conjunction with conventional procedures, and not as an alternative. The results require careful correlation with borehole data. Seismic methods are the most commonly used geophysical techniques, but other methods such as ground-probing radar and electrical resistivity may also be used.

Merrifield and Davies (2000)

In common with other ground improvement processes, the effectiveness of ground modification using RIC may be assessed by conducting pre and post treatment site investigations. Whilst these investigations are essential, constraints of cost and time will limit the range of these investigations, and will not provide any information about the effectiveness of the process until treatment is complete. In-process monitoring is therefore most attractive, because it allows a continuous record of the effectiveness of the treatment at each location, which, combined, provide a complete record of the area treated. Additionally, the effectiveness of the technique may be monitored during operation, permitting treatment to be stopped, with associated financial savings, once predetermined values have been reached or continued treatment at one location is no longer effective.

Neilson et al. (1998)

Estimation of the degree of compaction achieved should be possible using and accelerometer attached to the foot of the compactor or by using surface peak particle velocity measurement (although the former route is probably preferable).

SAICE (2006)

The RIC employs an on-board computer to control impact set termination criteria and to record critical data. The data are exported to a personal computer for further analysis.

Depending on the soil condition and the amount of consolidation achieved the termination is set. These parameters include the number of blows required at each impact point and the final settlement, or set (the as it is more commonly referred to as, (in millimeters) specified, for example 60 blows per impact point and final set point of 5 mm (0.20 in).

Two proximity sensors situated inside the frame and along the 10 ton (9 tonne) drop weight measures the impact velocity. The on-board computer then calculates the energy transferred and the stroke height for each blow then records the data for each impact point.

The acquired data at each impact point include: (1) time of impact point, (2) total blow count, (3) final set (mm), (4) final depth achieved (mm) and (5) total energy input (kN·m). By controlling the impact loading the deflection of the soils is monitored on a per blow basis to determine when compaction of the soil is complete (i.e., when additional blow counts will not be effective).

During compaction activities, ongoing tests are performed and together with the data recorded from the on-board computer the consolidation of the material can be monitored.

In some instances it is advisable to install piezometers to monitor the water table during compaction activities. The ground response can also be monitored by installing settlement plates at different depths. Sufficient time, at least five to seven days should be allowed to pass before the post compaction tests are performed to ensure that pore water pressures have dissipated.

Post compaction tests such as SPTs and/or Dynamic Probes Super Heavy (DPSH) tests are performed and compared to the pre-compaction test results. These pre and post compaction results illustrate the increased bearing capacity of the material and are expressed in N-values.

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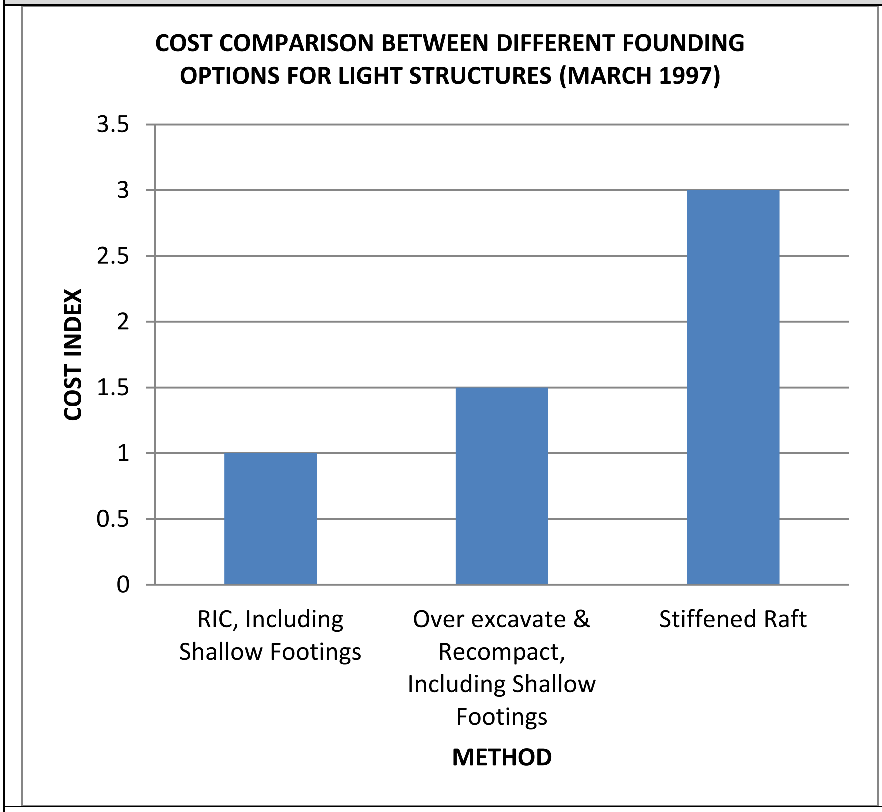
Quality control is performed by monitoring the compaction energy and deflection of the soil on each blow. An integrated monitoring system can show when optimal compaction is achieved (when additional blows will yield minimal improvement). Preliminary trials are an important aspect at each site to identify optimum compaction operations. Quality assurance can be accomplished by recording the before and after results to see that the average SPT N-value or CPT cone resistance is achieved for the zone needing improvement. Plate bearing tests for different field trials are also used to evaluate bearing characteristics and some in-situ geophysical tests have been suggested to overcome potential shortcomings of other in-situ tests.

Task 11: Cost Information

This section provides cost data for this technology from the sources that were reviewed in the literature database. The listed costs are those stated in the source; they are not adjusted for inflation. When available from the source document, separate entries are listed here for unit costs, mobilization and demobilization costs, and other cost components. If the costs are identified in the source as being from a single case history or from a collection of sources, that information is indicated here.

Table 64. Cost information

Reported Data	Reference
	Braithwaite and du Preez (1997)
RIC ground improvement costs can be approximated using the relationship $C = 0.91A + 36{,}375$; where C = cost ($), A = treatment area (SF)	O'Malley (2010)
Owing to fast ground coverage and compaction efficiency, this method of compaction generates a significant cost saving over conventional dynamic compaction methods.	SAICE (2006)
In comparison to vibroflotation with stone columns, the rapid impact compaction method can be as much as about 3 to 4 times less expensive.	Kristiansen (2004)

Task 12: Available Specifications

This section provides information about specifications found in various sources for this technology. These summaries are not intended to be comprehensive, but rather to serve as a starting point for assessment of the currently available specifications. The following references should be reviewed in more detail as part of Task 12, which is to develop sample guide specifications for these geotechnical materials and systems.

Building Research Establishment (2003)

The Building Research Establishment (BRE) provides a detailed specification for both conventional dynamic compaction and RIC in report BR458, “Specifying Dynamic Compaction.”

Responsibility for various actions in the Specification will depend on particular contractual arrangements and, for clarity, only two essential functions are defined. The Dynamic Compaction Designer is responsible for carrying out the treatment and the Specialist Contractor is responsible for carrying out the treatment. However, many dynamic compaction treatments are both designed and implemented by a Specialist Contractor. In these circumstances clauses in the Specification would have to be modified so that information such as site investigation is made available to the Specialist Contractor before the design stage. The parties responsible for all other actions should be agreed and defined in contract documents. Apportioning and acceptance of contractual risk should be clearly stated in contract documents.

The topics covered in BRE’s specification and how they relate to the roles of the Dynamic Compaction Designer and the Specialist Contractor include: (1) general overview of the treatment, (2) site investigation, (3) ground conditions, (4) treatment methods, (5) design, (6) execution of treatment and (7) testing. The specification

The construction Industry Board’s Code of Practice for the selection of Subcontractors contains a glossary of the key players likely to be involved in the procurement, design, application and supervision of the dynamic compaction works. They are the following: (1) consultant, (2) designer, (3) lead contractor, (4) main contractor and (5) specialist contractor.

In the 1987 ICE Specification for Ground Treatment: Notes for Guidance four common types of contractual arrangement, under which ground treatment including dynamic compaction may be undertaken, are presented. Essentially, these are the following: (1) a contract for civil engineering works with an Engineer responsible to an Employer for design and supervision, (2) a contract for building works with an Architect responsible to an Employer for design and supervision and advised by an Engineer, (3) a contract for building or civil engineering works with a contractor responsible to an Employer for design and construction, but who may appoint an independent Engineer to undertake the engineering duties appertaining to the dynamic compaction treatment and (4) a contract for building works with an Architect responsible to an Employer for design and supervision but having no engineering advisor.

O'Malley (2010)

For the case history, "Hydro Jet Facility," GeoStructures, Inc. used the following specification:

PART 1: GENERAL REQUIREMENTS

Description

Ground Improvement shall consist of rapid impact compaction (RIC) using a modified pile driving hammer and a compaction foot that delivers multiple applications of a 7.5-ton ram falling from a height of 3.3 feet onto a 5-foot diameter foot in rapid succession. The compaction equipment shall monitor both the number of blows and the ground deflection as the result of each blow at each compaction point.

Approved Installers

RIC contractors shall have demonstrated experience with projects of similar size and type. The RIC Contractor shall be pre-approved by the Owner's Geotechnical Engineer of Record (GER) at least two weeks prior to the bid opening. RIC Contractors currently approved for this project are:

GeoConstructures, Inc.
413 Browning Court
Purcellville, VA 20132
703-771-9846 (phone)

Reference Data

A. Geotechnical Data – Prior to the bid all pertinent site, geotechnical, and structural information including: soil reports, soil borings, laboratory test data, monitoring well data, foundation loading, site grading, and utility information shall be provided to the RIC Contractor.

B. Hazard Assessment – The Owner shall have performed a hazard assessment at the site which will include location and nature of all known above- and below-ground utilities, the nature, proximity and condition of adjacent structures and the nature of any waste or hazardous materials which could generate gases during compaction. This information shall be provided to the RIC Contractor prior to the bid and confirmed in the field prior to the start of RIC.

C. Vibration Monitoring – If required, the GC or Owner shall be responsible for monitoring vibration of the RIC and how it may affect adjacent structures. Should vibrations become excessive the Owner's representative shall notify the RIC Contractor immediately.

Certifications and Submittals

A. RIC Submittal – Prior to mobilization, the RIC Contractor shall provide a proposed layout for compaction points in the area to be compacted. A typical layout including spacing between compaction points shall also be provided.

B. RIC Quality Control (QC) Data – The RIC Contractor shall provide the Owner with the QC records for the project. The QC records shall include the number of RIC passes for each point and final deflection achieved as each RIC point.

PART 2: MATERIALS

2.01 Granular Fill Materials

Granular fill with less than 15 percent passing the No. 200 sieve shall be used for filling of RIC point craters and in areas where excavation of obstructions or soft soils is required.

In areas where the groundwater table is encountered, a granular fill with less than 5 percent passing the No. 200 sieve shall be used. Fill materials shall be provided by others.

PART 3: EXECUTION

3.01 Site Grading and Stabilization

Prior to RIC equipment mobilization, the General Contractor shall clear, grub, and grade the area to be compacted such that it is capable of supporting a Caterpillar 345 trackhoe. The site shall be graded such that water will not pond. Any boulders, large debris, or rubble that is uncovered during grading operations or is encountered during RIC operations that may interfere with RIC effectiveness shall be removed and replaced with granular fill.

3.02 Pre-RIC Test Area

Prior to commencement of compaction, a 20-foot-by-20-foot test area shall be tested. The test area shall be selected by the GER. Test borings with continuous SPT testing, shall be performed by the GER to a minimum depth of 20 feet to characterize the pre-compaction subsurface conditions. The test area shall be treated by RIC per the procedure proposed by the RIC contractor. Post-compaction test borings with continuous SPT testing, shall be conducted to a minimum depth of 20 feet by the GER to determine if the compactive energy delivered to the test area will yield the desired improvement. If the results are below the requirement for the project, then either additional compaction shall be performed or the design shall be modified to utilize the compaction which is achievable as determined by the GER. RIC termination criteria, in terms of final deflection per blow and expressed in millimeters, determined during RIC testing shall be used in production RIC. Additional test areas identified and tested by the GER shall be paid per the contract schedule of values.

3.03 RIC Impact Point Layout

The General Contractor shall provide layout of the area to be compacted prior to mobilization of the RIC equipment. Stakes shall be placed at approximately 50-foot centers based on the layout provided to the RIC Contractor. Ground elevations shall be provided to the RIC Contractor in sufficient detail to estimate the ground surface elevation across the site. The RIC contractor shall provide layout of individual RIC points.

3.04 Production RIC

Production RIC shall proceed based on the layout and compaction procedure submitted by the RIC Contractor and confirmed in the test area, if required. RIC point craters that are 24 inches deep or deeper, and do not meet deflection termination criteria, following initial compaction, shall be filled with approved granular fill and recompacted with RIC. Any point that has been filled and recompacted and exhibits compaction crater of 24 inches or greater and does not meet the deflection termination criteria following a total of 3 passes of RIC treatment shall be identified by the GER as an area requiring additional improvement.

Areas that are found to be excessively loose or soft following RIC recompaction of craters 24 inches deep or deeper, or obstructions (boulders, concrete slabs or blocks, tree trunks, etc.) shall either be overexcavated, filled with approved granular fill, and recompacted with RIC or mitigated by means and methods other than RIC as directed by the GER. The horizontal and vertical extents of the excavation shall be documented to ensure that these areas have been adequately treated and for payment purposes. Overexcavation and replacement activities shall be performed by others in a timely manner to prevent interruption of the RIC operation.

3.05 RIC Quality Control

The RIC Contractor shall provide a layout plan showing each impact point and its serial number and a summary table for each impact point for use by the GER’s onsite representative.

The GER's onsite representative shall observe and document RIC operations including initial compaction and, where needed, additional compaction. Where and when encountered, the GER's onsite representative shall observe and document horizontal and vertical extents and obstructions or excessively soft or loose soils.

3.06 Acceptance

Upon completion of the RIC treatment, the GER shall prepare a completion letter that confirms that RIC has been performed satisfactorily and that foundation and slab performance will be acceptable.

3.07 Measurement and Payment

Measurement of the compacted area will be on a square foot of area basis

Payment shall include layout drawing preparation, mobilization, test area compaction, and compaction of area to be improved. Recompaction due to unsuitable materials, obstructions or soft soils; delays; any other additional compaction; remobilization as documented and approved by the Owner or Owner's Engineer, shall be paid for under separate pay items.

APPENDIX H: TASK 10 ASSESSMENT OF DESIGN METHODS AND QC/QA PROCEDURES

#8 Rapid Impact Compaction
ASSESSOR(S): PETER BECKER
ASSESSMENT REVIEWER(S): DAVID WHITE
ADDITIONAL REVIEWER(S): MIKE COWELL
DATE OF THIS ASSESSMENT: MARCH 30, 2010
FILE NAME FOR THIS VERSION: #8_RAPID_IMPACT_COMPACTION_TASK 10
ASSESSMENT DOCUMENT [V36_E3_V[7]].DOC

Introduction

Background Information

Design procedures of one form or another already exist for many of the technologies that are being evaluated in the Strategic Highway Research Program's (SHRP2) research project R02, "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of Pavement Working Platform." Some technologies already have well-established design procedures, some have a variety of published design procedures, some have proprietary design procedures, and others have developing design procedures.

Some technologies have worthwhile analysis procedures that are not integrated into comprehensive design procedures. To avoid excluding such material, the design assessment sections of this document refer to both design and analysis procedures.

There are also many technologies for which establishing suitable QC/QA procedures is arguably the critical limiting factor preventing more widespread application of the technologies. Providing clear, precise, and effective guidelines for QC/QA procedures will remove an important source of uncertainty that currently makes some designers hesitant to apply these technologies.

Document Purpose

This document provides instructions and a template for assessing and characterizing design/analysis procedures and QC/QA methods for technologies that are applicable to Element 3 of the SHRP2 R02 project. Element 3 addresses stabilization of the working platform. The assessments and characterizations in this document will be used to complete other work items associated with Task 10, as described in the Phase 2 work plan in the Phase 1 report.

Description of Document Contents

The next two sections of this document provide instructions and a matrix for relating important inputs and outputs of design/analysis procedures to potential applications for the technology. These are organized in categories of performance criteria/indicators, subsurface conditions, loading conditions, material characteristics, construction techniques, and geometry. By identifying applicable input and output items first, assessors will be in a good position to evaluate design/analysis procedures.

The sections about design/analysis inputs and outputs are followed by two sections that provide instructions and a matrix for assessing published design/analysis procedures for this technology. These sections are followed by a section for detailed comments about each procedure, and then there are sections for characterizing the technology according to the status of its design/analysis procedures.

Sections for assessing the QC/QA methods follow a pattern similar to the design/analysis portion. The first section identifies objectives of QC/QA activities and relates them to potential applications of the technology. By first identifying QC/QA objectives, assessors will be in a good position to evaluate QC/QA methods. The QC/QA objectives should be closely related to the construction requirements produced as outputs of design procedures.

The section identifying QC/QA objectives is followed by two sections that provide instructions and a matrix for assessing published QC/QA procedures. These sections are followed by a section for detailed comments about each design procedure. Finally, there is a section for concluding remarks about QC/QA procedures in which the assessors can provide descriptions of the ways that individual QC/QA procedures can be integrated to form a comprehensive QC/QA program for a technology.

Inputs and outputs for design and analysis procedures, instructions

A matrix has been developed for listing inputs and outputs for analysis and design procedures. This section provides a description of the matrix and guidance for completing the matrix.

In the matrix, specific input and output items appropriate for a particular technology are arranged in the following categories: Performance Criteria/Indicators, Subsurface Conditions, Loading Conditions, Material Characteristics, Geometry, and Construction Techniques. Examples of specific items in each category are listed in the following table.

Table 65. Example design inputs and outpus

Categories of Input and Output Items for Analysis and Design Procedures	Some Example Items
Performance Criteria/Indicators	Minimum factor of safety values, load and resistance factor values, allowable settlements, allowable lateral deformations, reliability, drainage, time
Subsurface Conditions	Stratigraphy, ground water level, particle size distribution, plasticity, unit weight, relative density, water content, strength, compressibility, chemistry, organic content, variability
Loading Conditions	Traffic load, embankment pressure, structure loads, earthquake acceleration and duration, water pressures
Material Characteristics	Unit weight, water content, particle size distribution, internal friction angle, shear strength, inclusion dimensions, compressive strength, tensile strength, compressibility, modulus, stiffness, interface friction angle, permeability, equivalent opening size
Construction Techniques	Vibration densification, impact densification, shoot in nails, screw in nails, paddle mixing, combined cutter and jet mixing
Geometry	Diameter, spacing, depth, thickness, length, slope

The objective here is for assessors to develop a list of specific items that are appropriate inputs and outputs for analysis and design procedures for each application of this technology. The application categories relevant to Element 1 and 2 technologies are support of embankments, support of structures, earth retention, and slope stabilization. The assessors' list of input and output items should be inserted in the matrix, organized according to the categories provided.

The matrix is arranged without distinguishing whether a particular item is an input or an output because the same item might serve as an input to an analysis procedure and as an output of a design procedure. For example, the diameter and spacing of columns used to support an embankment are inputs to analysis procedures, but they can be considered outputs of design procedures. Similarly, the calculated factor of safety against slope instability is an output of an analysis procedure, and the required minimum factor of safety may be an input to a design procedure.

The Construction Techniques category is provided to accommodate technologies for which multiple techniques exist, such as gravel columns that can be compacted with vibrators or with impact rammers. For many technologies, only one construction technique is used or variations in construction technique do not impact design. In such cases, it is not necessary to have any entries in the Construction Techniques category.

After inserting the specific input and output items that are relevant for a particular technology, the assessor should indicate which items are relevant to which application.

The design/analysis performance criteria/indicators and specific items for static and dynamic analyses may not all be the same. Some items are used for both static and dynamic analyses, while others are used only for dynamic analyses. After developing lists of items and performance criteria/indicators, an “S” can be inserted in the matrices for items that are relevant only for static analyses for the potential application of the technology; "S/D" can be inserted for items that are relevant for both static and dynamic analyses; and “D” can be inserted for items that are relevant only for dynamic analyses. In many cases, only "S/D" and "D" will be used because the items that are relevant for static analyses are also generally relevant for dynamic analyses.

Table 66. Inputs and outputs for design and analysis procedures, matrix (part 1)

		Potential Applications											
	Specific Items for This Technology	PAVEMENT FOUNDATION STAB.	CONSTRUCTION WORKING PLATFORMS	COMPACTION	VOID FILLING	RECYCLING/REUSE	DRAINAGE	MOISTURE BARRIER/ SEPARATION LAYER	SUPPORT OF EMBANK[5] OR STRUCTURES[6]	LIQUEFACTION MITIGATION	SETTLEMENT REDUCTION	THICKNESS RED. OF PAV. SECTION	PROLONGING PAV. SERVICE LIFE
PERFORMANCE CRITERIA/INDICATORS	SPT blow count (to specified depth)			S					S	D	S		
	CPT tip resistance (to specified depth)			S					S	D	S		
SUBSURFACE CONDITIONS	Groundwater level			S					S	D	S		
	Soil classification			S					S	D	S		
	Particle size distribution			S					S	D	S		
	Plasticity			S					S	D	S		
	Relative density			S					S	D	S		
	Water content			S					S	D	S		
	Compressibility			S					S	D	S		
	Permeability			S					S	D	S		
	Statigraphy								S	D	S		
LOADING CONDITIONS	Structure Load								S	D	S		
	Earthquake Acceleration and Duration									D			

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[5] Embankments are defined as soil or rock fill that may or may not be reinforced

[6] Structures are defined as constructed objects that are relatively rigid. Examples include footings, retaining walls, MSE wall facings, culverts, etc.

Table 67. Inputs and outputs for design and analysis procedures, matrix (part 2)

		Potential Applications											
	Specific Items for This Technology	PAVEMENT FOUNDATION STAB.	CONSTRUCTION WORKING PLATFORMS	COMPACTION	VOID FILLING	RECYCLING/REUSE	DRAINAGE	MOISTURE BARRIER/ SEPARATION LAYER	SUPPORT OF EMBANK[7] OR STRUCTURES[8]	LIQUEFACTION MITIGATION	SETTLEMENT REDUCTION	THICKNESS RED. OF PAV. SECTION	PROLONGING PAV. SERVICE LIFE
MATERIAL CHARACTERISTICS	Particle sized distribution (crater backfill material)			S					S	D	S		
	Bearing Capacity			S					S	D			
	Stiffness			S					S		S		
	Relative Density			S					S	D	S		
CONSTRUCTION TECHNIQUES	Number of blows per compaction point (energy applied overall to the ground surface)			S					S	D	S		
	Energy per drop (Hammer weight, drop height)			S					S	D	S		
	Time between compaction passes			S					S	D	S		
	Tamper diameter			S					S	D	S		
	Number of passes			S					S	D	S		
GEOMETRY	Spacing and layout of compaction points			S					S	D	S		
	Improvement Depth			S					S	D	D		

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[7] Embankments are defined as soil or rock fill that may or may not be reinforced

[8] Structures are defined as constructed objects that are relatively rigid. Examples include footings, retaining walls, MSE wall facings, culverts, etc.

Design/analysis procedure assessment, instructions

A matrix has been developed to assess existing design/analysis procedures. The matrix contains four sections: Design/Analysis Procedures, References, Applications, and Assessment of Design/Analysis Procedure. Each of these sections is described below.

Design/Analysis Procedures

Some design/analysis procedures have recognized names, such as the Coherent Gravity Method for MSE walls. For such cases, list the names of these procedures in this section of the matrix. If the procedure does not have a recognized name, provide a phrase that can be used to identify the procedure.

References

Each reference addressing a design/analysis procedure should be listed in author (date) format in this portion of the matrix. If a given reference addresses a design/analysis procedure, insert a check in the appropriate box. Some references will address multiple design/analysis procedures and some design/analysis procedures will be addressed by multiple references. Complete citations for the references can be found in the technology's bibliography document.

Applications

In some cases, the design/analysis of a particular technology may differ significantly from one application to another. This portion of the matrix is for recording the correspondence between design/analysis procedures and applications. If a given design/analysis procedure addresses a particular application, insert a check in the appropriate box.

Assessment of Design/Analysis Procedures

This section of the matrix is for assessing the existing design/analysis procedures using the categories described below. In general, H stands for high, M for medium, L for low, U for insufficient information to permit a rating, and N/A for not applicable. The U category should be used only if necessary. The N/A will seldom apply, but is included for completeness. Further discussion of these ratings is provided below.

Performance Criteria/Indicators *(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)*

H: The design procedure appropriately uses performance criteria, and/or the analysis procedure generates appropriate performance indicators.

M: The design procedure uses appropriate performance criteria to a limited extent, and/or the analysis procedure generates appropriate performance indicators to a limited extent.

L: The design procedure does not appropriately use performance criteria, and/or the analysis procedure does not generate appropriate performance indicators.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Performance criteria/indicators are not applicable to the design/analysis procedure.

Subsurface Conditions *(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)*

H: The design/analysis procedure appropriately uses relevant information about subsurface conditions.

M: The design/analysis procedure uses relevant information about subsurface conditions to a limited extent.

L: The design/analysis procedure does not adequately use relevant information about subsurface conditions.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Subsurface conditions are not applicable to the design/analysis procedure.

Loading Conditions *(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)*

H: The design/analysis procedure appropriately uses relevant information about loading conditions.

M: The design/analysis procedure uses relevant information about loading conditions to a limited extent.

L: The design/analysis procedure does not adequately use relevant information about loading conditions.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Loading conditions are not applicable to the design/analysis procedure.

Material Characteristics ***(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)***

H: The design/analysis procedure appropriately uses relevant construction material characteristics.

M: The design/analysis procedure uses relevant construction material characteristics to a limited extent.

L: The design/analysis procedure does not adequately use relevant construction material characteristics.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Material characteristics are not applicable to the design/analysis procedure.

Construction Techniques ***(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)***

H: The design/analysis procedure appropriately incorporates relevant considerations of construction technique.

M: The design/analysis procedure incorporates relevant considerations of construction technique to a limited extent.

L: The design/analysis procedure does not incorporate relevant considerations of construction technique.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Differences in construction techniques are not applicable to the design/analysis procedure.

Geometry *(see list of specific items in the Matrix of Input and Output Items for Design/Analysis Procedures)*

H: The design/analysis procedure produces the geometric information that should be included in the plans and specifications for construction.

M: The design/analysis procedure produces most of the geometric information that should be included in the plans and specifications for construction.

L: The design/analysis procedure does not produce sufficient geometric information for developing plans and specifications for construction.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

N: Geometric outputs are not applicable to the design/analysis procedure.

Validation of Procedure

H: The design/analysis procedure has been validated to a great extent. Methods of validation may include instrumented case histories; the absence of known failures due to inadequacy of the design/analysis procedure; long-term performance data; extensive numerical; and/or physical modeling.

M: The design/analysis procedure has been validated with limited case histories and limited numerical and/or physical modeling.

L: The design/analysis procedure has not been validated, or there are failures due to inadequacy of the design/analysis procedure.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Rational-Empirical Basis

R: The design/analysis procedure is based primarily on rational principles of soil mechanics, mechanics of materials, and methods of analysis.

S: The design/analysis procedure is semi-mechanical and semi-empirical.

E: The design/analysis procedure is primarily empirical.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Ease of Use

H: The design/analysis procedure can be implemented by practicing engineers with tools readily available to them in an amount of time consistent with the degree of complexity and importance of the application (if intricate analyses are required, user-friendly software is available to perform these analyses). Procedure is highly standardized and can easily be applied to a variety of different site and loading conditions.

M: The design/analysis procedure can be implemented by practicing engineers, but implementation requires an excessive amount of time, it involves analysis methods not typically used in geotechnical practice, and/or the procedure cannot be easily applied to a variety of site and loading conditions.

L: The design/analysis procedure is complex and cannot be implemented by most practicing geotechnical engineers.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

LRFD Status

Y: The design/analysis procedure is an LRFD procedure.

N: The design/analysis procedure is not an LRFD procedure.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Mechanistic-Empirical Pavement Design Status (Element 3)

Y: The design/analysis procedure is a mechanistic-empirical pavement design procedure.

N: The design/analysis procedure is not a mechanistic-empirical pavement design procedure.

U: References for this design/analysis procedure do not provide sufficient information to enable a rating.

Table 68. Design/analysis procedure assessment matrix (part 1)

		Design/Analysis Procedure								
		Direct measurement of improvement depth following construction								
REFERENCES[9]	Kristiansen and Davies (2003)	✓								
	Kristiansen and Davies (2004)	✓								
	SAICE (2006)	✓								
	Serridge and Synac (2006)	✓								
	Simpson et al. (2008)	✓								
	Woodward (2004)	✓								

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[9] Complete citations for the references shown above can be found in the bibliography document for this technology.

Table 69. Design/analysis procedure assessment matrix (part 2)

		Design/Analysis Procedure								
		Direct measurement of improvement depth following construction								
APPLICATIONS	PAVEMENT FOUNDATION STABILIZATION	N/A								
	CONSTRUCTION WORKING PLATFORMS	L								
	COMPACTION	H								
	VOID FILLING	N/A								
	RECYCLING/REUSE	N/A								
	DRAINAGE	N/A								
	MOISTURE BARRIER/SEPARATION LAYER	N/A								
	SUPPORT OF EMBANKMENTS OR STRUCTURES	H								
	LIQUEFACTION MITIGATION	H								
	SETTLEMENT REDUCTION	H								
	THICKNESS REDUCTION OF PAVEMENT SECTION	L								
	PROLONGING PAVEMENT SERVICE LIFE	L								
ASSESSMENT	PERFORMANCE CRITERIA/INDICATORS	M								
	SUBSURFACE CONDITIONS	M								
	LOADING CONDITIONS	M								
	MATERIAL CHARACTERISTICS	M								
	CONSTRUCTION TECHNIQUES	M								
	GEOMETRY	L								
	VALIDATION OF PROCEDURE	M								
	RATIONAL-EMPIRICAL BASIS	E								
	EASE OF USE	L								
	LRFD STATUS	N								
	MECH. – EMP. PVMT. DESIGN STATUS	U								

Design/analysis procedure assessment comments

The following section can be used to provide a descriptive summary of the procedure and to comment on the ratings given in the Design Procedure Assessment Matrix. The ratings in this section should correspond to those given in the Matrix.

Design/analysis procedure: Direct measurement of improvement depth following construction (Kristiansen and Davies 2003; Kristiansen and Davies 2004; Serridge and Synac 2006; Simpson et al. 2008; Woodward 2004)

Summary of procedure

An independent party, typically the Geotechnical Engineer of Record (GER), performs in-situ testing such as SPTs or CPTs in order to analyze the expected effectiveness of RIC compaction on the ground. The subsurface analysis allows the RIC contractor to develop an optimum compaction plan to best achieve the specified depth and degree of improvement. The RIC contractor then carries out a "compaction trial" over a section of the area to be improved to determine whether RIC will indeed achieve the specified depth and degree of improvement. Following the "compaction trial," in-situ tests are performed once again and then compared to the pre-compaction tests. If the post-compaction tests prove to have attained the desired specifications, RIC is deemed suitable for the entire area to be improved.

Performance Criteria/Indicators

Comments: The performance criteria for each usage of RIC is governed by its application; whether that is improved foundation support, reduced settlement or liquefaction potential mitigation. All of these applications have in essence their own performance criteria, therefore the performance criteria for RIC is evaluated in a case by case process. The best way to evaluate RIC performance is by performing in-situ tests such as the SPT or CPT.

Rating: M

Subsurface Conditions

Comments: The inclusion of subsurface conditions into the design process is strictly qualitatively and based upon experience. For example, it is known that the groundwater level will cause the compaction energy to attenuate therefore diminishing the degree of improvement; however the amount of energy attenuated based on the height of the *groundwater table is a value that cannot be calculated. Another example is soil classification. It is well established that RIC works well for noncohesive soils*

Rating: M

Loading Conditions

Comments: Loading conditions for RIC are limited to the weight of the structures that the improved ground will need to support and any earthquake loads that the improved ground will need to endure if RIC is specified to mitigate liquefaction potential. Case histories that have either used or considered RIC as an option have specified that the ground must withstand a 1 in 475 year earthquake with at worst only structural damage to the overlying structure.

Rating: M

Material Characteristics

Comments: RIC has only one material input which is used for backfilling compaction points after craters have developed. Material characteristic outputs are based upon "rules of thumb" for a given soil type.

Rating: L

Construction Techniques

Comments: Since RIC is essentially a construction technique, the construction input items for RIC consist of more specific items pertaining to the technology. Input items may be hammer weight, tamper diameter, hammer drop height, number of blows per compaction point and time between compaction (pore water pressure dissipation).

Rating: M

Geometry

Comments: Compaction point layout and spacing is governed by design inputs relating to the site stratigraphy and geology. The improvement depth output is empirical at best with improvement depth being based upon "rules of thumb" for a given soil type.

Rating: L

Validation of Procedure

Comments: Validated on a limited number of case histories.

Rating: M

Rational-Empirical Basis

Comments: The design process is empirical at best with output parameters based upon "rules of thumb."

Rating: E

Ease of Use

Comments: Most practicing engineers do not have the experience dealing with RIC so design is usually left up to the RIC contractor.

Rating: L

LRFD Status

Comments: N/A

Rating: N

Mechanistic-Empirical Pavement Design Status

Comments: Insufficient information on the use of RIC for Mechanistic-Empirical Pavement Design.

Rating: U

After completing the Design/Analysis Procedure Assessment, each of the technology's applications should be characterized based on the assessments of the relevant design procedures for that application. Several design/analysis procedures may exist for an application, but the intent here is to characterize the overall status of that application of the technology based on the previous assessments of all the relevant design/analysis procedures for that application. If desired, the next section can be used to comment on the characterizations.

Table 70. Design/analysis procedure characterization matrix

Design/Analysis Procedure Characterization Categories	Applications											
	PAVEMENT FOUNDATION STAB.	CONSTRUCTION WORKING PLATFORMS	COMPACTION	VOID FILLING	RECYCLING/REUSE	DRAINAGE	MOISTURE BARRIER/ SEPARATION LAYER	SUPPORT OF EMBANK[10] OR STRUCTURES[11]	LIQUEFACTION MITIGATION	SETTLEMENT REDUCTION	THICKNESS RED. OF PAV. SECTION	PROLONGING PAV. SERVICE LIFE
One preferred procedure exists: One of the existing design/analysis procedures is satisfactory and clearly preferred. No further development is needed.												
Selection guidance: More than one design/analysis procedure and/or computer program exists for this application of the technology. Guidance is needed to select which procedure and/or computer program should be used. Selection of the most appropriate procedures may depend on project-specific parameters.												
Combine: More than one suitable design/analysis procedure exists. Procedures may need to be combined into a single consistent recommended procedure using the best elements of two or more procedures.												
Verification: An existing design/analysis procedure appears to be suitable; however, the accuracy and reliability of the procedure needs to be verified.												
Improve: An existing design/analysis procedure has suitable components, but improvement is needed in some areas.			✓					✓	✓	✓		
Transition: An existing design/analysis procedure needs to be transitioned into LRFD or mechanistic-empirical design format.												
Develop: No suitable design/analysis procedure exists, and a new design procedure must be developed		✓	✓					✓	✓	✓	✓	✓

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[10] Embankments are defined as soil or rock fill that may or may not be reinforced

[11] Structures are defined as constructed objects that are relatively rigid. Examples include footings, retaining walls, MSE wall facings, culverts, etc.

Design/analysis procedure characterization comments

The following section can be used to comment on the characterizations given in the Design/Analysis Procedure Characterization Matrix. The characterizations in this section should correspond to those given in the Design/Analysis Procedure Characterization Matrix.

Pavement Foundation Stabilization

Comments: No designs for this application have been conceived

Characterization: Develop

Construction Working Platforms

Comments: No designs for this application have been conceived

Characterization: Develop

Compaction

Comments: The current design procedure is at its developing stages.

Characterization: Improve, develop

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments: The current design procedure is at its developing stages.

Characterization: Improve, develop

Liquefaction Mitigation

Comments: The current design procedure is at its developing stages.

Characterization: Improve, develop

Settlement Reduction

Comments: The current design procedure is at its developing stages.

Characterization: Improve, develop

Thickness Reduction of Pavement Section

Comments: No designs for this application have been conceived

Characterization: Develop

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Objectives

Construction quality is achieved by meeting established requirements, as detailed in project plans and specifications, including applicable codes and standards. Quality Control (QC) and Quality Assurance (QA) are terms applied to the procedures, measurements, and observations used to ensure that construction projects satisfy the requirements in the project plans and specifications. QC and QA are often misunderstood and used interchangeably. Herein, Quality Control refers to procedures, measurements, and observations used by the contractor to monitor and control the construction quality such that all applicable requirements are satisfied. Quality Assurance refers to measurements and observations by the owner or the owner's engineer to provide assurance to the owner that the facility has been constructed in accordance with the plans and specifications.

In order to assess the QC/QA methods for a technology, the assessor(s) should first develop a list of objectives for QC/QA activities. It is recommended that assessor(s) review the list of input and output items from the first matrix in this document as part of developing the list of QC/QA objectives. The general principal is that all the desired outputs from design procedures (many of which may also be inputs for analysis procedures) should be subject to QC/QA activities and should be reflected in the QC/QA objectives.

Table 71. QC/QA objectives

QC/QA Objectives
Bearing Capacity - QA
Settlement Reduction (Collapsible soils) – QA
Soil liquefaction – QA
Process Control – QC
Equipment Performance – QC

QC/QA Method Assessment, Instructions

A matrix has been developed to assess existing QC/QA methods. Six sections are contained in the matrix: QC/QA Methods, References, QC/QA Objectives, Applicability to QC and QA, Assessment of QC/QA Methods, and Usefulness of QC/QA Method for Application. Each of these sections is described below.

QC/QA Methods

In this portion of the matrix, list each QC/QA method that applies to the technology.

References

This section of the matrix should contain references in author (date) format that discuss QC/QA methods for the technology. For a given reference, insert a check in the appropriate box for each QC/QA method it addresses. Some references will address multiple QC/QA methods and some QC/QA methods will be addressed by multiple references.

QC/QA Objectives

This section of the matrix should contain the objectives listed in the QC/QA Objectives section of this document. If a QC/QA method helps achieve a particular objective, insert a check in the appropriate box.

Applicability to QC and QA

Some methods apply only to QC, some apply only to QA, and others apply to both QC and QA. In this portion of the matrix, insert a check in the appropriate box(es) if the method applies to QC, QA, or both QC and QA.

Assessment of QC/QA Method

This section of the matrix is used to assess the existing design methods using the categories described below. In general, H stands for high, M for medium, and L for low. Further discussion of these ratings is provided below to help the assessment.

Accuracy and Precision

H: The QC/QA method accurately and precisely assesses construction quality for this technology.

M: The QC/QA method provides an approximate assessment of construction quality for this technology.

L: The QC/QA method does not provide a reliable assessment of construction quality for this technology.

Adequacy of Coverage

H: The QC/QA method can be implemented to provide an adequate assessment of the inclusions and/or the entire quantity of improved soil, using a reasonable number of tests.

M: The QC/QA method can be implemented to provide an adequate assessment of the inclusions and/or the entire quantity of improved soil, but the number of tests required is significantly more than desirable.

L: The published QC/QA methods cannot be implemented to provide an adequate assessment of the inclusions and/or the entire quantity of improved soil without an excessive number of tests.

Implementation Requirements

H: Implementation requirements (cost, personnel, training, equipment, and time) for the QC/QA method are not excessive.

M: Implementation requirements (cost, personnel, training, equipment, and time) for the QC/QA method are somewhat greater than desired.

L: Implementation requirements (cost, personnel, training, equipment, and time) for the QC/QA method are prohibitive.

Applicability to Method Approach Specifications

H: The QC/QA method is applicable to method approach[12] specifications; example specifications incorporating the QC/QA method exist in the literature.

M: The QC/QA method is somewhat applicable to method approach specifications.

L: The QC/QA method is not applicable to method approach specifications.

---

[12] Method approach specifications require the contractor to produce and place a product using specified materials in definite proportions and with specific types of equipment and methods. The agency is responsible for performance provided that the contractor has followed the specified methods. (After http://www.fhwa.dot.gov/construction/specs.cfm and TRB Circular E-C074)

Applicability to Performance Approach Specifications

H: The QC/QA method is applicable to performance approach [13] specifications; example specifications incorporating the QC/QA method exist in the literature.

M: The QC/QA method is somewhat applicable to performance approach specifications.

L: The QC/QA method is not applicable to performance approach specifications.

Usefulness of QC/QA Method For Application

This portion of the matrix is for the assessor(s) to provide an overall rating of the usefulness of each QC/QA method for various applications. Each QC/QA method should be given an H, M, or L rating unless the method is not relevant to the application, in which case, an N should be inserted. The four ratings are described below.

H: The QC/QA method is highly useful for the application.

M: The QC/QA method somewhat useful for the application.

L: The QC/QA method is of little use for the application.

N: The QC/QA method is not relevant to the application.

---

[13] Performance approach specifications encompass: End-Result specs; Quality Assurance specs; Performance-Related specs; Performance-Based specs; Warranty Provisions; and Incentive Provisions for Time and Quality (SHRP2 R07 Performance Specifications for Rapid Renewal project, 2009 TRB presentation). End-result specifications require the contractor to take the entire responsibility for producing and placing materials to achieve a specified final product. The agency's responsibility is to either accept or reject the final product or to apply a price adjustment commensurate with the degree of compliance with the specifications. (After http://www.fhwa.dot.gov/construction/specs.cfm and TRB Circular E-C074). End-result specifications are the typical type of performance approach specification used for Element 1 and 2 technologies.

Table 72. QC/QA Method Assessment Matrix (Part 1)

		QC/QA Method[14]									
		In-situ penetration tests	On-board computer	Geophysical Techniques	Piezometers	Plate Load Tests	Level Surveys				
References[15]	Braithwaite and du Preez (1997)	✓				✓	✓				
	Building Research Establishment (2003)	✓	✓	✓							
	Kristiansen and Davies (2003)	✓									
	Kristiansen and Davies (2004)	✓	✓								
	SAICE (2006)	✓	✓		✓						
	Serridge and Synac (2006)	✓		✓		✓					
	Simpson et al. (2008)	✓	✓				✓				
QC/QA Objectives[16]	Bearing Capacity	✓				✓					
	Settlement Reduction (Collapsible soils)	✓				✓					
	Soil Liquefaction	✓									
	Process Control		✓	✓	✓		✓				
	Equipment Performance		✓				✓				

---

[14] These QC/QA Methods should match those shown in Part 2 of this matrix.

[15] Complete citations for the references shown above can be found in the bibliography document for this technology.

[16] These objectives should match those listed in the QC/QA Objectives section.

Table 73. QC/QA method assessment matrix (part 2)

		QC/QA Method[17]									
		In-situ penetration tests	In cab computer	Geophysical Techniques	Piezometers	Plate Load Tests	Level Surveys				
Applicability to QC and QA	APPLICABLE TO QC	✓	✓	✓	✓	✓	✓				
	APPLICABLE TO QA	✓		✓		✓					
Assessment of QC/QA Method	ACCURACY AND PRECISION	M to H	N/A	N/A	N/A	N/A	N/A				
	ADEQUACY OF COVERAGE	M	H	N/A	M to H	L	H				
	IMPLEMENTATION REQUIREMENTS	M	L	N/A	M	L	H				
	APPLICABILITY TO METHOD APPROACH SPECS.	M	L	N/A	L	L	M				
	APPLICABILITY TO PERFORMANCE APPROACH SPECS.	H	H	N/A	H	L	H				
Usefulness of QC/QA Method for Application	PAVEMENT FOUNDATION STABILIZATION	N	N	N	N	N	N				
	CONSTRUCTION WORKING PLATFORMS	L	H	L	L	H	M				
	COMPACTION	M	H	L	L	L	M				
	VOID FILLING	N	N	N	N	N	N				
	RECYCLING/REUSE	N	N	N	N	N	N				
	DRAINAGE	N	N	N	N	N	N				
	SUPPORT OF EMBANKMENTS OR STRUCTURES	H	H	M	L	L	M				
	LIQUEFACTION MITIGATION	H	H	M	L	L	M				
	SETTLEMENT REDUCTION	H	H	M	L	L	M				
	THICKNESS REDUCTION OF PAVEMENT SECTION	L	H	L	L	H	M				
	PROLONGING PAVEMENT SERVICE LIFE	N	N	N	N	N	N				

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[17] These QC/QA Methods should match those shown in Part 1 of this matrix.

QC/QA Method Assessment Comments

This section can be used to provide a descriptive summary of the method and to comment on the assessment and usefulness ratings given in the QC/QA Method Assessment Matrix. The General Comments paragraph under the heading below for Usefulness of QC/QA Method for Application is for comments that are relevant to all applications of the technology. Information about a QC/QA method that is unique to a particular application can be provided in the location indicated for that application. The ratings in this section should correspond to those given in the QC/QA Method Assessment Matrix. If available, numerical values (e.g., costs, coverage volume per tests) can be provided in the comments.

QC/QA Method: In-situ penetration tests (Braithwaite and du Preez 1997; BRE 2003; Kristiansen and Davies 2003; Kristiansen and Davies 2004; SAICE 2006; Serridge and Synac 2006; Simpson et al. 2008)

Method Summary

This method tests the improvement resulting from RIC by using some kind of in-situ penetration test including SPT, CPT, BPT (Becker Penetration Test) or DP (Dynamic Probe). In In-situ penetration tests can serve as either quality control or quality assurance. Quality control testing during treatment often involves in-situ penetration tests which may form part of the final assurance testing regime.

Post compaction tests such as SPTs and/or DP tests are performed and compared to the pre-compaction test results. These pre and post compaction results illustrate the increased bearing capacity of the material and are expressed in N-values (SAICE, 2006). In-situ penetration tests may be used where changes in properties of soil due to dynamic compaction can be measured and directly related to criteria set out in the contract documents or compared with pre-treatment test data (Building Research Establishment, 2003). Due to the speed of testing, continuous DP tests are ideal for use before, during and after compaction in order to demonstrate the effectiveness and depth of treatment (Braithwaite and du Preez, 1997).In Canada, BPTs have been used for coarser soils (Serridge and Synac, 2006).

Assessment of QC/QA Method

Accuracy and Precision

Comments: For the most part, the accuracy and precision is high for comparing before and after blow count or penetrative resistance values at specified depths. Typically, it is beneficial to carry out in-situ penetration tests to confirm ground improvement after a period of about minimum two weeks after completion of the ground improvement works due to an observed increase in density as a result of aging effects (Kristiansen and Davies, 2003). Due to the heterogeneous nature of some fills, it is somewhat very difficult to evaluate the improvement with accuracy (Serridge and Synac, 2006).

Rating: M to H

Adequacy of Coverage

Comments: Sufficient evaluation coverage requires many penetration tests. Frequency of testing is affected by factors particular to each project, for example, the variability of the ground before treatment, the nature of the structure to be supported and its sensitivity to post-treatment movements (Building Research Establishment, 2003).

Rating: M

Implementation Requirements

Comments: Experience and equipment to perform are commonly available.

Rating: M

Applicability to Method Approach Specifications

Comments: In-situ penetration tests, when used for quality control, can be used for method specifications.

Rating: M

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: In-situ penetration tests, when used for quality assurance, can be used for end-result specifications. End-result specifications are more common in current practice. Can be used with Performance-Based Specifications

Rating: H

Usefulness of QC/QA Method for Application

General Comments

Correlations can be used to relate blow count or penetrative resistance to values to pertaining to liquefaction susceptibility or bearing strength.

Pavement Foundation Stabilization

Comments:

Characterization:

Construction Working Platforms

Comments: In-situ penetration depths such as SPTs or CPTs are too deep for practical construction working platform purposes

Characterization: L

Compaction

Comments: Blow count or penetrative values can be used to verify bearing capacity requirements deep compactive fills

Characterization: M

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments: Blow count or penetrative values can be used to verify bearing capacity requirements.

Characterization: H

Liquefaction Mitigation

Comments: Blow count or penetrative values can be used to verify bearing capacity requirements when dealing with collapsible soils.

Characterization: H

Settlement Reduction

Comments: Blow count or penetrative values can be used to verify bearing capacity requirements when dealing with collapsible soils.

Characterization: H

Thickness Reduction of Pavement Section

Comments: In-situ penetration depths such as SPTs or CPTs are too deep for practical thickness reduction of pavement section purposes

Characterization: L

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Method: On-Board Computer (BRE 2003; Kristiansen and Davies 2004; SAICE 2006; Simpson et al. 2008)

Method Summary

The RIC employs an on-board computer to control impact set termination criteria and to record critical data. The data are exported to a personal computer for further analysis (SAICE, 2006).

The acquired data at each impact point include: (1) time of impact point, (2) total blow count, (3) final set (mm), (4) final depth achieved (mm) and (5) total energy input (kN·m). By controlling the impact loading the deflection of the soils is monitored on a per blow basis to determine when compaction of the soil is complete (i.e., when additional blow counts will not be effective) (SAICE, 2006).

Depending on the soil condition and the amount of compaction achieved the termination is set. These parameters include the number of blows required at each impact point and the final deflection, or set (as it is more commonly referred, (in millimeters)), for example 60 blows per impact point and final set point of 5 mm (0.20 in) (SAICE, 2006).

When any operating parameter reaches a specified parameter, for example, total foot penetration or set per blow, an alarm is triggered (Building Research Establishment, 2003).

Assessment of QC/QA Method

Accuracy and Precision

Comments: Level of accuracy and precision of this procedure has not been documented.

Rating: N/A

Adequacy of Coverage

Comments: The operator monitors the number of blows on every print position and ensures that the minimum energy level indicated by the penetration testing is supplied.

Rating: H

Implementation Requirements

Comments: Very specialized equipment is required exclusive to an RIC licensee is required

Rating:L

Applicability to Method Approach Specifications

Comments: This procedure is generally not used for method specifications.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: This procedure is more commonly associated with end-result specifications.

Rating: H

Usefulness of QC/QA Method for Application

General Comments

This technique is applicable to process control and equipment performance.

Pavement Foundation Stabilization

Comments:

Characterization:

Construction Working Platforms

Comments:

Characterization: H

Compaction

Comments:

Characterization: H

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments:

Characterization: H

Liquefaction Mitigation

Comments:

Characterization: H

Settlement Reduction

Comments:

Characterization: H

Thickness Reduction of Pavement Section

Comments:

Characterization: H

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Method: Geophysical Techniques (BRE 2003, Serridge and Synac 2006)

Method Summary

Geophysical techniques are emerging QC/QA techniques for RIC. Aside from a few references mentioning the capabilities of geophysical techniques, there is no information on how to implement them.

Geophysical techniques are used increasingly to assess ground properties; seismic methods are the most common geophysical techniques employed (Building Research Establishment, 2003).

Use of some form of in-situ geophysical testing also has an important application and can potentially overcome some of the limitations of in-situ penetration tests (Serridge and Synac, 2006).

Assessment of QC/QA Method

Accuracy and Precision

Comments:

Rating: M

Adequacy of Coverage

Comments:

Rating: M

Implementation Requirements

Comments: Some experience and special equipment is necessary

Rating: M

Applicability to Method Approach Specifications

Comments: This procedure is generally not used for method specifications.

Rating: L

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: This procedure is more commonly associated with end-result specifications. Can be used with Performance-Based Specifications.

Rating: H

Usefulness of QC/QA Method for Application

General Comments

Geophysical techniques can be used to adequately evaluate ground improvement. Therefore, they are useful for most conventional applications of RIC.

Pavement Foundation Stabilization

Comments:

Characterization:

Construction Working Platforms

Comments:

Characterization: L

Compaction

Comments:

Characterization: L

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments:

Characterization: H

Liquefaction Mitigation

Comments:

Characterization: H

Settlement Reduction

Comments:

Characterization: H

Thickness Reduction of Pavement Section

Comments:

Characterization: L

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Method: Piezometers (SAICE 2006)

Method Summary

Piezometers are used to measure the hydraulic head in the ground. In some instances it is advisable to install piezometers to monitor the water table during compaction activities (SAICE, 2006). Sufficient time, at least five to seven days should be allowed to pass before the post compaction tests are performed to ensure that pore water pressures have dissipated (SAICE, 2006).

Assessment of QC/QA Method

Accuracy and Precision

Comments: Accurate and precise procedure.

Rating: M to H

Adequacy of Coverage

Comments:

Rating: M

Implementation Requirements

Comments: Some experience and special equipment is necessary

Rating: M

Applicability to Method Approach Specifications

Comments: This procedure is generally not used for method specifications.

Rating: M

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: This procedure is more commonly associated with end-result specifications. Can be used with Performance-Based Specifications.

Rating: H

Usefulness of QC/QA Method for Application

General Comments

Piezometers are exclusively used for process control.

Pavement Foundation Stabilization

Comments:

Characterization:

Construction Working Platforms

Comments:

Characterization: L

Compaction

Comments:

Characterization: M

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments:

Characterization: H

Liquefaction Mitigation

Comments:

Characterization: H

Settlement Reduction

Comments:

Characterization: H

Thickness Reduction of Pavement Section

Comments:

Characterization: L

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Method: Plate Load Tests (Braithwaite and du Preez 1997; Serridge and Synac 2006)

Method Summary

The plate load test uses a steel bearing plate and a hydraulic jack to apply a known load then measure the resulting surface deflection. Using this value the modulus of subgrade reaction can be determined. Large scale plate load tests are probably the most direct measure of whether the specified settlement/strength criteria have been met (Braithwaite and du Preez, 1997). Plate bearing tests carried out at different levels during the trials and after treatment may enable more accurate appraisal of the bearing characteristics of treated fills (Serridge and Synac, 2006).

Assessment of QC/QA Method

Accuracy and Precision

Comments: Accurate and precise procedure.

Rating: M to H

Adequacy of Coverage

Comments: Frequency of testing should be related to the uniformity of ground conditions but should typically not be less than about one test per 22,000 SF (2000 m^2) treated.

Rating: M

Implementation Requirements

Comments: Some experience and special equipment is necessary

Rating: M

Applicability to Method Approach Specifications

Comments: This procedure is generally not used for method specifications.

Rating: M

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: This procedure is more commonly associated with end-result specifications. Can be used with Performance-Based Specifications.

Rating: H

Usefulness of QC/QA Method for Application

General Comments

Plate Load Tests with RIC are applicable to improved bearing characteristics and pavement foundations Pavement Foundation Stabilization

Comments:

Characterization:

Construction Working Platforms

Comments:

Characterization: H

Compaction

Comments:

Characterization: H

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments:

Characterization: M

Liquefaction Mitigation

Comments:

Characterization: M

Settlement Reduction

Comments:

Characterization: M

Thickness Reduction of Pavement Section

Comments:

Characterization: H

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Method: Level Surveys (Braithwaite and du Preez 1997; Simpson et al. 2008)

Method Summary

Level surveys are used to simply measure the penetration depth associated with each compaction point. Level surveys of the penetrations associated with each point are recorded and are used to calculate the volumetric change (densification) of the ground within the treatment depth (Braithwaite and du Preez, 1997).

Compaction point penetration depths that are deeper than about 18 in (460 mm) indicate the near surface soil may be so loose that the energy cannot propagate sufficiently deep to improve the soil below the water table. In these areas, retreatment is performed. If deep craters are created during the second round, shallow soft soil may be present (Simpson et al., 2008).

Assessment of QC/QA Method

Accuracy and Precision

Comments: Accurate and precise procedure.

Rating: M to H

Adequacy of Coverage

Comments: *Is applied to every compaction point location.*

Rating: H

Implementation Requirements

Comments: Level surveys are considered to be rather time consuming (personal communication, O'Malley, 2010).

Rating: L

Applicability to Method Approach Specifications

Comments: This procedure is generally not used for method specifications.

Rating: M

Applicability to Performance Approach Specifications (These encompass end-result specs; quality assurance specs; performance-related specs; performance-based specs; warranty provisions; and incentive provisions for time and quality.)

Comments: This procedure is more commonly associated with end-result specifications.

Can be used with Performance-Based Specifications.

Rating: H

Usefulness of QC/QA Method for Application

General Comments

Level surveys are exclusively used for process control.

Comments:

Characterization:

Construction Working Platforms

Comments:

Characterization: M

Compaction

Comments:

Characterization: M

Void Filling

Comments:

Characterization:

Recycling/Reuse

Comments:

Characterization:

Drainage

Comments:

Characterization:

Moisture Barrier/Separation Layer

Comments:

Characterization:

Support of Embankments or Structures

Comments:

Characterization: M

Liquefaction Mitigation

Comments:

Characterization: M

Settlement Reduction

Comments:

Characterization: M

Thickness Reduction of Pavement Section

Comments:

Characterization: M

Prolonging Pavement Service Life

Comments:

Characterization:

QC/QA Method Assessment, Concluding Remarks

The QC/QA assessments up to this point have focused on individual QC/QA methods, rather than overall QC/QA programs for this technology. This section provides an opportunity to describe how individual QC/QA methods are applied within a comprehensive QC/QA program for the technology. References should be cited where available. If adequate QC/QA methods and/or a comprehensive QC/QA program for this technology are lacking, that can be discussed in this section also

.

In the majority of the RIC case histories, in-situ penetration tests are used for quality assurance and use of the on-board computer is used for quality control. In most cases, in-situ penetration tests are simply conducted before and after treatment to determine the effectiveness of the treatment. During compaction, the on-board computer provides real time data regarding the treatment to which is then applied to quality control of the process and the equipment performance. Many RIC references include other QA/QC tests for RIC; however there is no record of their use in any cases of RIC use.

Currently, the QA/QC procedure for RIC is somewhat flawed. Although In-situ penetration tests provide a good interpretation of magnitude and depth of improvement, adequate testing coverage of the improved area is difficult to attain unless an extremely large amount of tests are conducted. Additional research into QA/QC is advised in order to allow for a better evaluation for the RIC procedure. The potential of various other QA/QC tests should be investigated.

APPENDIX I: TASK 12 ASSESSMENT OF EXISTING SPECIFICATIONS

#8 Rapid Impact Compaction
Assessor(s): Peter Becker
Assessment Reviewer(s): David White
Additional Reviewer(s): Ed O'Malley
Date of this Assessment: 2/21/2011
File Name for this Version: 08 RIC Task 12 Assessment Document [V19].doc

Introduction

Background Information

Existing specifications from a variety of sources (FHWA documents, individual project documents in the public record, industry guide specifications, etc.) will be collected and evaluated in the Strategic Highway Research Program's (SHRP2) research project R02, "Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of Pavement Working Platform." Some technologies already have well-written example specifications, some have a variety of different types of specifications, and others only have specifications that have been written for specific projects. The objective of this task is to provide/develop high-quality sample guide specifications to facilitate widespread use of soil improvement technologies.

Document Purpose

This document provides instructions and a template for assessing and characterizing published specifications for technologies that are applicable to Elements 1, 2, and 3 of the SHRP2 R02 project. Element 1 addresses new embankments and roadways constructed over unstable soils, Element 2 addresses widening of existing roadways and embankments, and Element 3 addresses stabilization of pavement working platforms. The assessments and characterizations in this document will be used to complete other work items associated with Task 12, as described in the Phase 2 work plan in the Phase 1 report.

Description of Document Contents

The first section provides instructions and matrices for characterizing the available specifications as either method, performance, or performance/method approach specifications and by performance level. Descriptions of these three categories of specifications and performance levels are given in the instructions.

The characterization section is followed by a section that provides instructions and a matrix for assessing the completeness of the specifications.

The completeness section is followed by two sections that assess the specification for factors such as clarity, risk allocation, ability to be fairly bid, constructability, QC/QA verification, and completeness. The first section includes instructions and a matrix for assessing the specification based on these factors. The second section provides any comments about the assessment.

The assessment sections are followed by a section where concluding remarks about the available specifications can be made.

After an assessment is completed there may be a decision to develop a guide specification. If so, previously developed guide specifications should serve as examples of the typical layout and commentary to be followed. Good guide specification examples include the “Standard Performance Approach Specification for Vibro-Concrete Columns” and the “SMSE Performance Spec.” It should be noted that specification sections and subsections are technology dependent. Their organization and content should be determined on a case-by-case basis and need not be consistent with the example guide specifications.

Specification Type, Instructions

The following matrix is used to list the available specifications, the references from which they were obtained, and to indicate the specification type. Each portion of the matrix is described below as well as the descriptions for each specification type.

References

Each reference containing a specification should be listed in author (date) format in this portion of the matrix. Some references may include multiple specifications. Complete citations for the references can be found in the technology's bibliography document. However, many of the specifications will not be from a referenced source but rather provided by a State DOT, engineer or contractor. The source of each specification will be identified.

Specification Type

In this portion of the matrix a designation should be provided to indicate the specification type. Specification type refers to both the specification category (i.e., method approach, performance approach, or performance/method approach) and, for specifications with performance elements, the performance level provided for in the specification. To indicate specification category, a check should be inserted in the corresponding row for each specification. For performance approach specifications and performance/method approach specifications, it is also necessary to indicate the performance level based on the designations below.

Descriptions and Designations

Method Approach Specifications

Method approach specifications require the contractor to produce and place a product using specified materials in definite proportions and with specific types of equipment and methods. The agency is responsible for performance provided that the contractor has followed the specified methods[18].

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[18] http://www.fhwa.dot.gov/construction/specs.cfm, TRB Circular E-C074, and FHWA NHI-05-037 Section 8.2

Performance Approach Specifications

Definitions for types of performance approach specifications are not always consistent[19]. For the purposes of this project, the performance levels defined below have been adopted to differentiate between the various types of performance approach specifications. In addition, it should be noted that any performance approach specification may also include provisions for statistical sampling or incentives based on time and quality of construction.

Performance level refers to the manner in which a specification requires performance characteristics to be measured in order to determine project acceptance. Performance levels have been separated based on the following designations:

1. Actual performance measured after construction (e.g., settlement at a specific time) and warranty provisions might be included
2. Performance-related properties measured at end of construction (e.g., CPT, vane shear, etc.)
3. Design properties measured during construction (e.g., modulus measured for each lift)
4. Design-related properties measured during construction (e.g., density and water content measured for each lift)

Single or combined designations should be used as applicable based on the descriptions. An example of a combined designation for a specification that measures performance characteristics based on both design (3) and design-related properties (4) would be 3/4.

Performance/Method Approach Specifications

Performance/method approach specifications contain a combination of method and performance or design related requirements. These specifications often include minimum geometric requirements and also require that minimum performance characteristics are satisfied.

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19 http://www.fhwa.dot.gov/construction/specs.cfm, TRB Circular E-C074, and FHWA NHI-05-037 Section 8.2

Table 74. Specification type, Matrix

		Specification Name/Number					
		Building Research Establishment Technical Specification For Ground Treatment Using Dynamic Compaction	GeoStructures Example RIC Specification				
Specification Type	METHOD APPROACH	✓					
	PERFORMANCE APPROACH	✓	✓				
	COMBINED PERFORMANCE/ METHOD APPROACH						
	└PERFORMANCE LEVEL	2	2				
REFERENCES/SOURCE[20]	Building Research Establishment (2003)	✓					
	O'Malley (2010)		✓				

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[20] Complete citations for the references shown above can be found in the bibliography document for this technology.

Specification completeness, instructions and definitions

The following matrix should be filled out to determine the completeness of the specification. A check mark should be placed in the box to show that a section is present in the specification. If there are additional important sections, these can be added to the matrix. This could include adding subsections that are important and should be included in all the specifications for a specific technology. The section titles listed below may not match exactly to a section in the specification, but if the information is included anywhere in the specification a check should be placed in the corresponding box. In addition, some of the sections listed below may not be applicable to the technology. If this is the case, N/A should be placed the corresponding box.

The following definitions apply to the standard sections listed in the matrix below.

Project Objectives: This section describes the project and the reasons for employing the soil improvement/geoconstruction technology.

Site Conditions: This section describes the construction site including the subsurface conditions, extents of the proposed soil improvement/geoconstruction and any special conditions or requirements.

References: This section lists the standards including ASTM and/or AASHTO standards that are referenced in the specification.

Definitions: This section defines any terms not commonly used or defined elsewhere in the contract.

Minimum Contractor Qualifications: This section lists the required qualifications that the contractor must possess.

Submittals: This section provides a list of the required submittals as well as due dates. The following sub-sections are used to specify the type of submittals required.

Material: This may include a material sample, manufacturer or mill certificate, fabricator certificate, and/or lab test results that can be used to verify the appropriateness of the material for the project and/or that certifies the material meets all project requirements.

Design: This may include calculations and shop drawings that demonstrate the proposal meets the design and/or geometric requirements. It may also include certificates from the manufacturer stating that the product meets project requirements.

Construction: This may include certificates from the contractor or design engineer stating that the project has been constructed as proposed and/or that all project requirements have been met upon completion. It may also include QC test reports and summaries submitted during construction.

Accepted Systems: This section describes the systems that have been approved for use during construction. For example, with mechanically stabilized earth walls the owner may have a list of approved MSE wall systems.

Pre-Construction Meeting: This section gives the details of any required pre-construction meetings including location, time in relation to other contract requirements and participants.

Design Requirements: This section is only applicable to performance and performance/method approach specifications, and it describes the requirements that must be satisfied by contractor design of the soil improvement/geoconstruction technology, such as bearing capacity, factor of safety, settlement, etc. The following sub-sections may also be included when the specifications require design by the contractor:

Design Methodology: This sub-section identifies the procedure(s) that should be followed during the design of the soil improvement/geoconstruction technology.

Field Geotechnical Conditions: This sub-section lists the values of geotechnical parameters that should be used in the design. If values are not provided by the owner, this could affect the ability of the project to be fairly bid and should be commented on in the Specification Assessment.

Material Requirements: This section lists the requirements for the materials used during construction.

Geometric Requirements: This section describes the required geometry that must be satisfied during construction.

Equipment: This section lists any equipment required for construction.

Construction Requirements: This section describes any required construction methods and procedures that must be followed.

QC/QA Requirements: This section explains any required QC/QA tests as well as the frequency and location of the tests. If a test should be performed with an unusual method, it will also be discussed in this section.

Acceptance Criteria: This section lists the criteria and methods of measurement for acceptance. For method approach specifications, this includes acceptance based on conformance to construction/design requirements such as equipment or dimensional requirements. It may also include acceptance based on conformance to quality control requirements, for example, as determined by review of quality control records. For performance approach specifications (by performance level), this could include acceptance based on: **(1)** conformance to performance requirements such as capacity or settlement from load tests after construction, **(2)** conformance to performance-related requirements such as CPT or vane shear values measured at end of construction, **(3)** conformance to design properties such as modulus values measured during construction for each lift, or **(4)** conformance to design-related properties such as values of density and water content measured during construction for each lift. Method/performance approach specifications and specifications with multiple performance levels should contain a combination of the above listed acceptance criteria as appropriate.

Maintenance: This section lists any required maintenance that must occur after construction is complete.

Measurement: This section describes how the construction work will be measured for payment.

Payment: This section describes how the contractor will be paid for the work.

Table 75. Specification completeness, matrix

		Specification Name/Number			
		Building Research Establishment Technical Specification For Ground Treatment Using Dynamic Compaction	GeoStructures Example RIC Specification		
Sections Included	PROJECT OBJECTIVES	✓	✓		
	SITE CONDITIONS				
	REFERENCES				
	DEFINITIONS				
	MINIMUM CONTRACTOR QUALIFICATIONS		✓		
	SUBMITTALS	✓	✓		
	└MATERIAL				
	└DESIGN		✓		
	└CONSTRUCTION		✓		
	ACCEPTED SYSTEMS				
	PRE-CONSTRUCTION MEETING				
	DESIGN REQUIREMENTS	✓			
	└DESIGN METHODOLOGY				
	└FIELD GEOTECHNICAL CONDITIONS				
	MATERIAL REQUIREMENTS	✓	✓		
	GEOMETRIC REQUIREMENTS				
	EQUIPMENT		✓		
	CONSTRUCTION REQUIREMENTS	✓	✓		
	QC/QA REQUIREMENTS	✓	✓		
	ACCEPTANCE CRITERIA		✓		
	MAINTENANCE				
	MEASUREMENT		✓		
	PAYMENT		✓		

Specification Assessment, Instructions

A matrix has been developed to assess existing specifications for clarity, risk allocation, ability to be fairly bid, constructability, QC/QA verification, and completeness. In general, H stands for high, M for medium, and L for low. Further discussion of these ratings is described below.

Clarity

H: The specification is easy to read, logically ordered, and provides clear instructions for completing the work. There are no conflicting statements in the specification.

M: The specification has one or two conflicting statements and portions have ambiguous language.

L: There are numerous conflicting statements or the specification is incomplete or the language could be considered ambiguous.

Risk Allocation[21]

O: Risk is inappropriately allocated to the owner.

S: Risk is appropriately shared between the owner and the contractor.

C: Risk is inappropriately allocated to the contractor.

Ability to be Fairly Bid

H: Contractors can bid on the work without needing additional information and the specification allows substitution for proprietary products.

M: The specification requirements favor certain contractors or products. Contractors may find it difficult to create realistic bids because some information is lacking.

L: The specification does not provide enough information and/or multiple contractors cannot bid the project.

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[21] "Appropriately shared" means that the risk has been appropriately allocated to either the contractor, the owner, or some combination of the two parties. The appropriate allocation will vary based on the type of specification. For example, the owner should bear the risk when using a method specification. In a combined method/performance specification, each party will bear part of the risk. "Inappropriately allocated to the contractor" means that the risk has been allocated to the contractor in a situation where it should be allocated to the owner. For example, in a method specification, the owner should bear the risk and not require the contractor to meet performance criteria. "Inappropriately allocated to the owner" means that substantial risk has been allocated to the owner when it should be allocated the contractor, such as in a Level I performance specification.

Constructability

H: The specification does not require overly elaborate or expensive construction methods.

M: All construction requirements are buildable, but the specified methods are unnecessarily difficult.

L: The construction requirements are very difficult or expensive to achieve.

QC/QA Verification

H: The specification contains all the detailed requirements necessary for QC/QA, as appropriate to the technology and specification type.

M: The specification includes some detailed requirements for QC/QA, as appropriate to the technology and specification type, but it only provides general guidance for other aspects of QC/QA.

L: The specification includes no guidance or only general guidance for QC/QA.

Completeness

H: The specification contains all pertinent sections, as appropriate for the technology and specification type, and it is considered complete.

M: The specification contains most of the necessary sections but is lacking some important items.

L: The specification is missing many important items.

Table 76. Specification assessment, matrix

		Specification Name/Number					
		Building Research Establishment Technical Specification For Ground Treatment Using Dynamic Compaction	GeoStructures Example RIC Specification				
Specification Rating	CLARITY	L	M				
	RISK ALLOCATION	M	M				
	ABILITY TO BE FAIRLY BID	L	M				
	CONSTRUCTABILITY	M	M				
	QC/QA VERIFICATION	L	M				
	COMPLETENESS	L	M				

Specification Assessment, comments

The following section can be used to comment on the ratings made in the Specification Assessment Matrix, if necessary. The ratings in this section should correspond to those given in the Matrix.

Specification: Building research establishment technical specification for ground treatment using dynamic compaction (BRE 2003)

General Comments

Clarity

Comments: This specification was intended as a general specification outline for both Deep Dynamic Compaction (DDC) and RIC. The language refers to both technologies as “dynamic compaction” thereby creating confusion as to which aspects of the specification actually apply to RIC.

Rating: L

Risk Allocation

Comments: If problems or any unforeseen circumstances arise during RIC, the RIC contractor must inform the RIC designer who will in turn decide on what adjustments are to be made to the RIC process. Since RIC is performed by a specialty contractor, the RIC contractor and RIC designer are the representatives of the same entity therefore placing the majority of the risk on the contractor.

Rating: M

Ability To Be Fairly Bid

Comments: The specification is far too general to allow bidding. The specification does not provide any minimum contractor qualifications.

Rating: L

Constructability

Comments: Site requirements, construction requirements and QA/QC requirements are straightforward and are not at all complicated.

Rating: M

QC/QA Verification

Comments: There is no guidance provided in terms of QC/QA

Rating: L

Completeness

Comments:

Rating:L

Specification: GeoStructures Example RIC Specification

General Comments

Clarity

Comments: The specification is sufficiently clear for all parties involved with RIC. The parties involved with construction of RIC include the RIC contractor, the owner, the owner's geotechnical engineer of record and the general contractor. The role of each party is clearly stated in the specification.

Rating: M

Risk Allocation

Comments: The RIC contractor is not responsible if the ground does not respond well to the ground improvement. The general contractor of the project must take care of excavating and replacing excessively soft or loose ground or obstructions.

Rating: M

Ability To Be Fairly Bid

Comments: Since the specification is written by the RIC specialty contractor, the specification favors the stated RIC contractor only. The information provided by the specification is directed more towards the owner, the owner's geotechnical engineer of record and the general contractor rather than the RIC contractor.

Rating: M

Constructability

Comments: RIC, the main construction method of the specification, can only be carried out by a specialty contractor thereby making the construction of RIC quite difficult to complete. Other construction methods mentioned in the specification such as excavating and replacing are less difficult to execute however.

Rating:M

QC/QA Verification

Comments: Some guidance is provided in terms of QC/QA

Rating: M

Completeness

Comments:

Rating: M

Specification Characterization, Instructions and Matrix

After completing the Specification Assessment, specifications should be characterized based on the current state of the available specifications. Several specifications of each category may exist for a technology, but the intent here is to characterize the overall status of the specifications based on the previous assessments. If a specification category is not applicable to this technology, put N/A for all characterization categories. In some cases, it may be appropriate to select multiple characterization categories for a given specification category column. This might occur if multiple characterization categories are applicable for all the specifications in a given specification category. Or, for performance or performance/method approach specifications, specifications having different performance levels may also require different characterizations. If desired, the next section can be used to comment on the characterizations.

Table 77. Specification characterization, matrix

Specification Characterization Categories	METHOD APPROACH SPECIFICATION	PERFORMANCE APPROACH SPECIFICATION	COMBINED PERFORMANCE/ METHOD APPROACH SPECIFICATION
One preferred specification exists: One of the existing specifications is satisfactory and clearly preferred. No further development is needed.	N/A		N/A
Selection guidance: More than one specification exists for this technology. Guidance is needed to select which specification is to be used. Selection of the most appropriate specification may depend on project-specific parameters.	N/A		N/A
Combine: More than one specification exists. Specification sections may need to be combined into a single consistent recommended specification using the best elements of two or more specifications.	N/A		N/A
Improve: An existing specification has suitable components, but improvement is needed in some areas.	N/A	✓	N/A
Develop: No suitable specification exists, and a new specification would have to be developed.	N/A		N/A

Specification Characterization, Comments

The following section can be used to comment on the characterizations given in the Specification Characterization Matrix. The characterizations in this section should correspond to those given in the Specification Characterization Matrix. If a specification type is not applicable to this technology, this should be discussed in these comments. In addition, if one specification type is more applicable than the other, this should be mentioned.

Method Approach Specification

Comments: RIC requires the contracting of a specialty contractor therefore a method approach specification for RIC is not applicable.

Characterization: N/A

Performance Approach Specification

Comments: Current RIC specifications either utilize an approach similar to Deep Dynamic Compaction or utilize an approach directed by the RIC specialty contractor. Specifications that are suited for a state DOT are nonexistent and need to be developed.

Characterization:Improve

Combined Performance/Method Approach Specification

Comments: RIC requires the contracting of a specialty contractor therefore a performance/method approach specification for RIC is not applicable.

Characterization: N/A

Additional Comments and Concluding Remarks

This section provides an opportunity to make any additional comments and conclusions about the specifications that were reviewed. These comments and conclusions may include a discussion of the quality of the specifications, the suitability of the specifications for use in developing guide specification examples for certain specification types, and any additional information that may be needed to create the guide specification examples. The reviewer should also comment as to whether all the necessary QC/QA procedures listed in the guidelines developed during the Task 10 Assessment are included in the reviewed specifications. These comments should include listing any QC/QA procedures that are not included in the specifications and whether the frequency or other portion of the procedure described in the specifications should be changed to match the guidelines from the Task 10 Assessment document.

Specification Type Comments

Since RIC is currently a proprietary technology that requires the use of a specialty contractor, only performance specifications can apply to RIC at this stage in the technology's usage. Much of the RIC design procedure consists of qualitative analysis performed by the specialty contractor. Method specifications will not be able to apply to RIC until a proper design procedure is introduced. If this scenario were attained, then a method specification would resemble a method specification for deep dynamic compaction.

Specification Completeness Comments

Available specifications are lacking completeness. As evidence by the specification matrix, many important sections that should be covered by the available specifications are nonexistent. The content of the sections that are covered are vague and do not contain sufficient detail to allow for proper contracting procedures.

Concluding Remarks

The use of RIC on construction projects in the United States has been limited to private, non-transportation related projects. For this reason, there are no transportation related specifications currently in existence. This lack of a more complete specification more suitable for a state DOT has hindered the use of RIC for transportation related projects. In order to overcome this obstacle, a new specification must be composed that will comprise all aspects pertinent to an acceptable specification for a state DOT. The new specification should then be implemented and evaluated on a transportation project case history.

APPENDIX J: SELECTION GUIDANCE SYSTEM DOCUMENTS

RAPID IMPACT COMPACTION

Hammer and anvil portion of Rapid Impact Compactor

Rapid Impact Compactor following first pass of compaction points

Rapid Impact Compactor in the process of compaction

January 14, 2010

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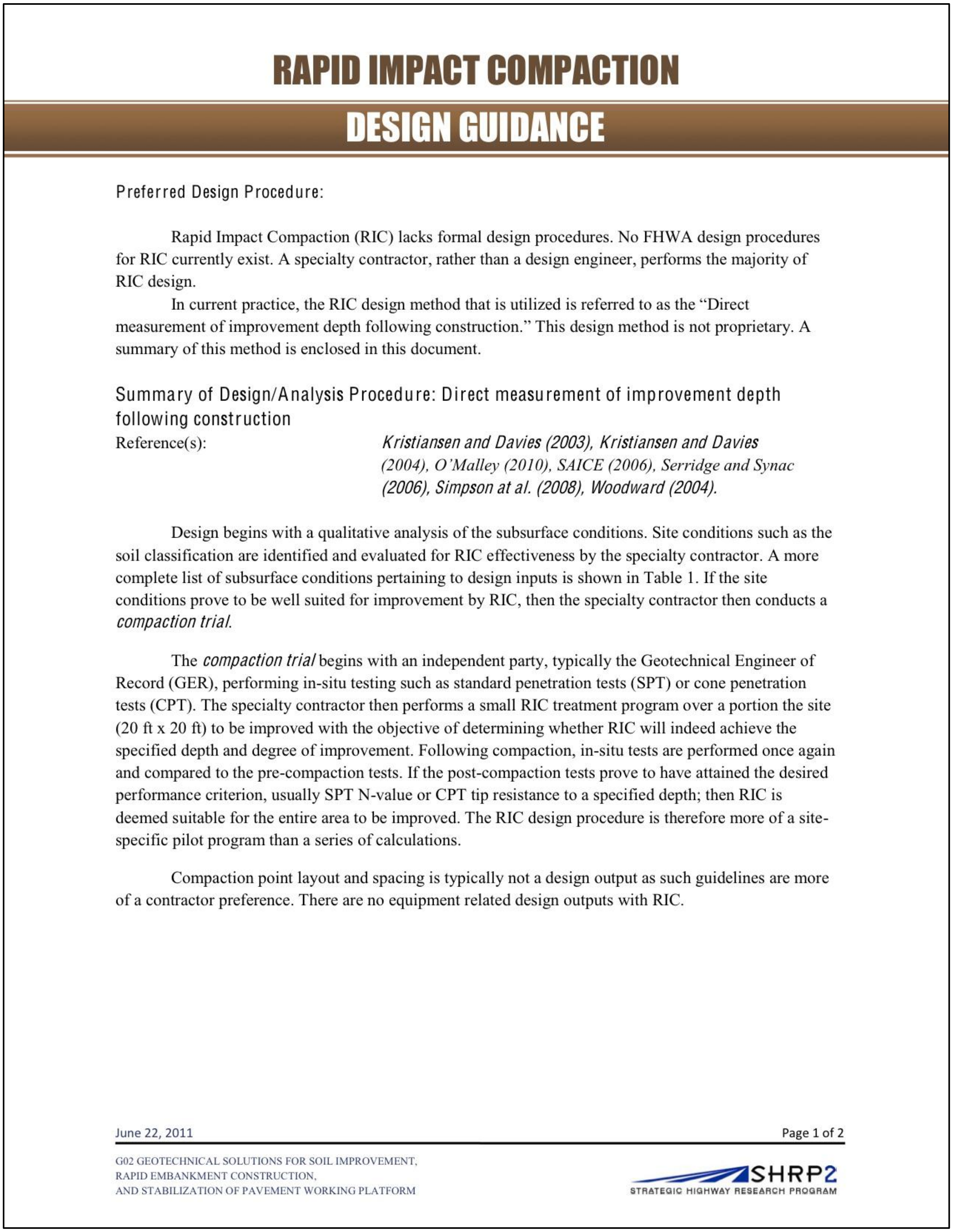
PHOTOGRAPHS

Figure 90. Photographs document



RAPID IMPACT COMPACTION

DESIGN GUIDANCE

Preferred Design Procedure:

Rapid Impact Compaction (RIC) lacks formal design procedures. No FHWA design procedures for RIC currently exist. A specialty contractor, rather than a design engineer, performs the majority of RIC design.

In current practice, the RIC design method that is utilized is referred to as the "Direct measurement of improvement depth following construction." This design method is not proprietary. A summary of this method is enclosed in this document.

Summary of Design/Analysis Procedure: Direct measurement of improvement depth following construction

Reference(s): *Kristiansen and Davies (2003), Kristiansen and Davies (2004), O'Malley (2010), SAICE (2006), Serridge and Synac (2006), Simpson at al. (2008), Woodward (2004).*

Design begins with a qualitative analysis of the subsurface conditions. Site conditions such as the soil classification are identified and evaluated for RIC effectiveness by the specialty contractor. A more complete list of subsurface conditions pertaining to design inputs is shown in Table 1. If the site conditions prove to be well suited for improvement by RIC, then the specialty contractor then conducts a *compaction trial*.

The *compaction trial* begins with an independent party, typically the Geotechnical Engineer of Record (GER), performing in-situ testing such as standard penetration tests (SPT) or cone penetration tests (CPT). The specialty contractor then performs a small RIC treatment program over a portion the site (20 ft x 20 ft) to be improved with the objective of determining whether RIC will indeed achieve the specified depth and degree of improvement. Following compaction, in-situ tests are performed once again and compared to the pre-compaction tests. If the post-compaction tests prove to have attained the desired performance criterion, usually SPT N-value or CPT tip resistance to a specified depth; then RIC is deemed suitable for the entire area to be improved. The RIC design procedure is therefore more of a site-specific pilot program than a series of calculations.

Compaction point layout and spacing is typically not a design output as such guidelines are more of a contractor preference. There are no equipment related design outputs with RIC.

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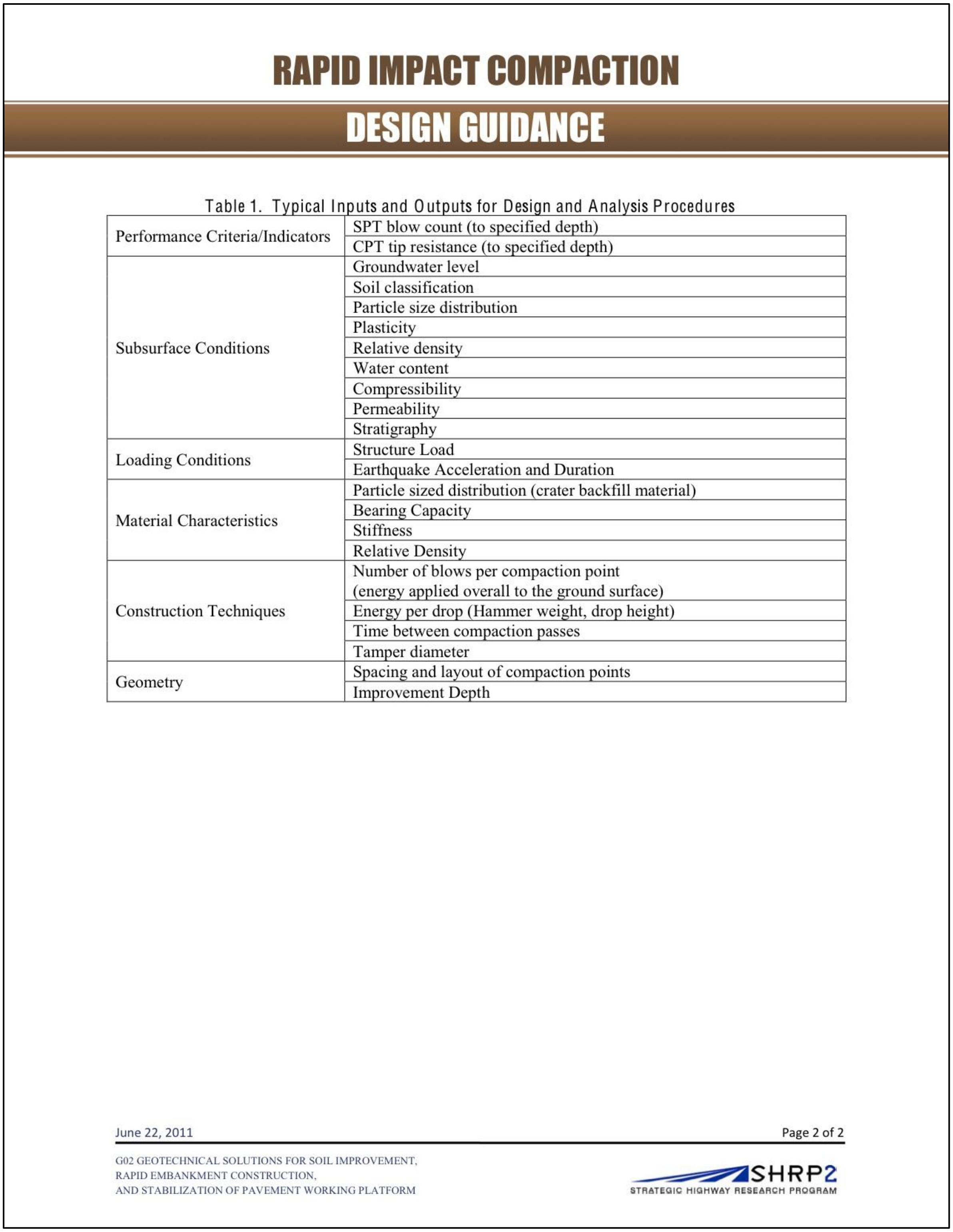
Figure 91.Design document



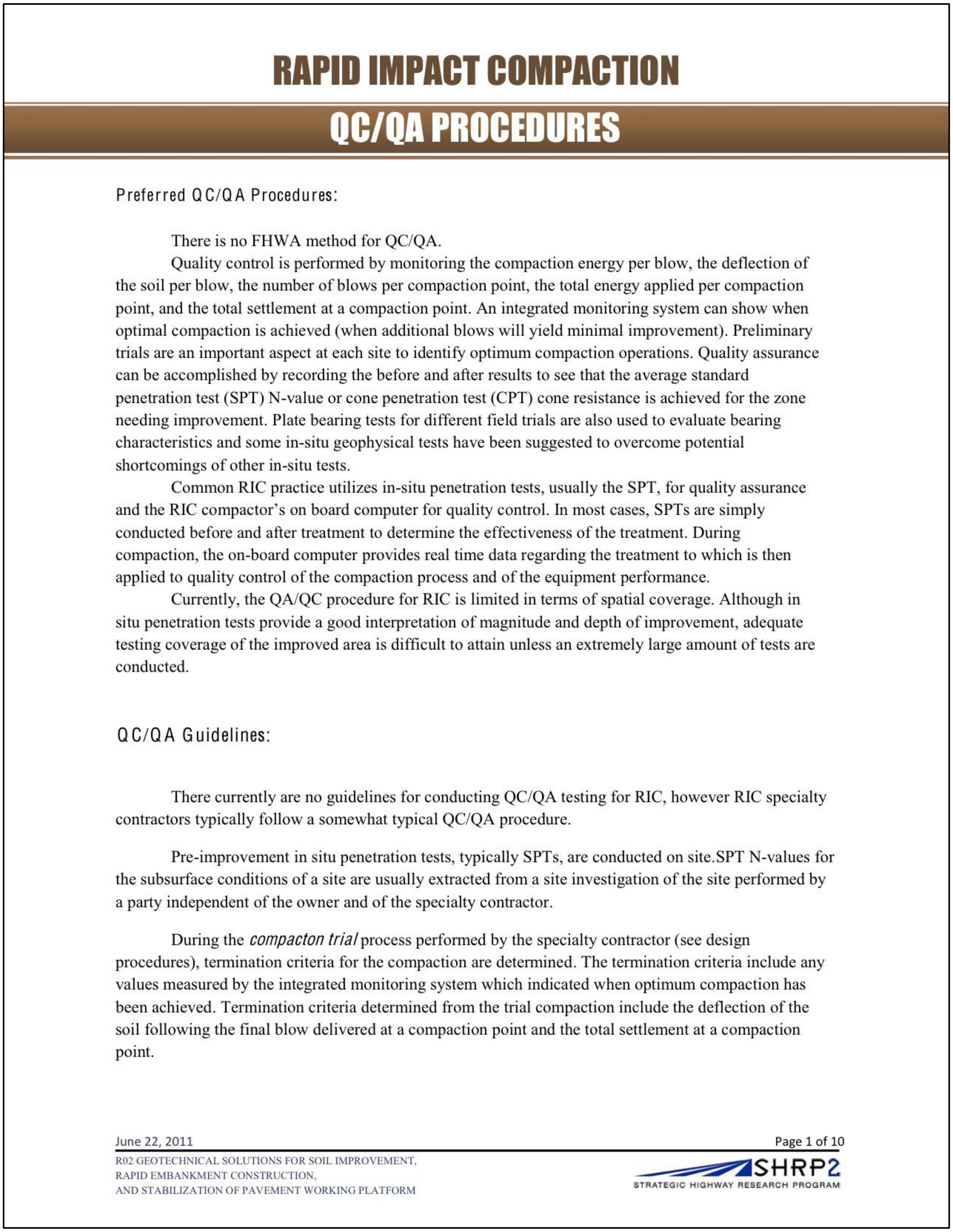
RAPID IMPACT COMPACTION

DESIGN GUIDANCE

Table 1. Typical Inputs and Outputs for Design and Analysis Procedures

Performance Criteria/Indicators	SPT blow count (to specified depth)
	CPT tip resistance (to specified depth)
Subsurface Conditions	Groundwater level
	Soil classification
	Particle size distribution
	Plasticity
	Relative density
	Water content
	Compressibility
	Permeability
	Stratigraphy
Loading Conditions	Structure Load
	Earthquake Acceleration and Duration
Material Characteristics	Particle sized distribution (crater backfill material)
	Bearing Capacity
	Stiffness
	Relative Density
Construction Techniques	Number of blows per compaction point (energy applied overall to the ground surface)
	Energy per drop (Hammer weight, drop height)
	Time between compaction passes
	Tamper diameter
Geometry	Spacing and layout of compaction points
	Improvement Depth

Figure 91. Design document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

Preferred QC/QA Procedures:

There is no FHWA method for QC/QA.

Quality control is performed by monitoring the compaction energy per blow, the deflection of the soil per blow, the number of blows per compaction point, the total energy applied per compaction point, and the total settlement at a compaction point. An integrated monitoring system can show when optimal compaction is achieved (when additional blows will yield minimal improvement). Preliminary trials are an important aspect at each site to identify optimum compaction operations. Quality assurance can be accomplished by recording the before and after results to see that the average standard penetration test (SPT) N-value or cone penetration test (CPT) cone resistance is achieved for the zone needing improvement. Plate bearing tests for different field trials are also used to evaluate bearing characteristics and some in-situ geophysical tests have been suggested to overcome potential shortcomings of other in-situ tests.

Common RIC practice utilizes in-situ penetration tests, usually the SPT, for quality assurance and the RIC compactor's on board computer for quality control. In most cases, SPTs are simply conducted before and after treatment to determine the effectiveness of the treatment. During compaction, the on-board computer provides real time data regarding the treatment to which is then applied to quality control of the compaction process and of the equipment performance.

Currently, the QA/QC procedure for RIC is limited in terms of spatial coverage. Although in situ penetration tests provide a good interpretation of magnitude and depth of improvement, adequate testing coverage of the improved area is difficult to attain unless an extremely large amount of tests are conducted.

QC/QA Guidelines:

There currently are no guidelines for conducting QC/QA testing for RIC, however RIC specialty contractors typically follow a somewhat typical QC/QA procedure.

Pre-improvement in situ penetration tests, typically SPTs, are conducted on site.SPT N-values for the subsurface conditions of a site are usually extracted from a site investigation of the site performed by a party independent of the owner and of the specialty contractor.

During the *compacton trial* process performed by the specialty contractor (see design procedures), termination criteria for the compaction are determined. The termination criteria include any values measured by the integrated monitoring system which indicated when optimum compaction has been achieved. Termination criteria determined from the trial compaction include the deflection of the soil following the final blow delivered at a compaction point and the total settlement at a compaction point.

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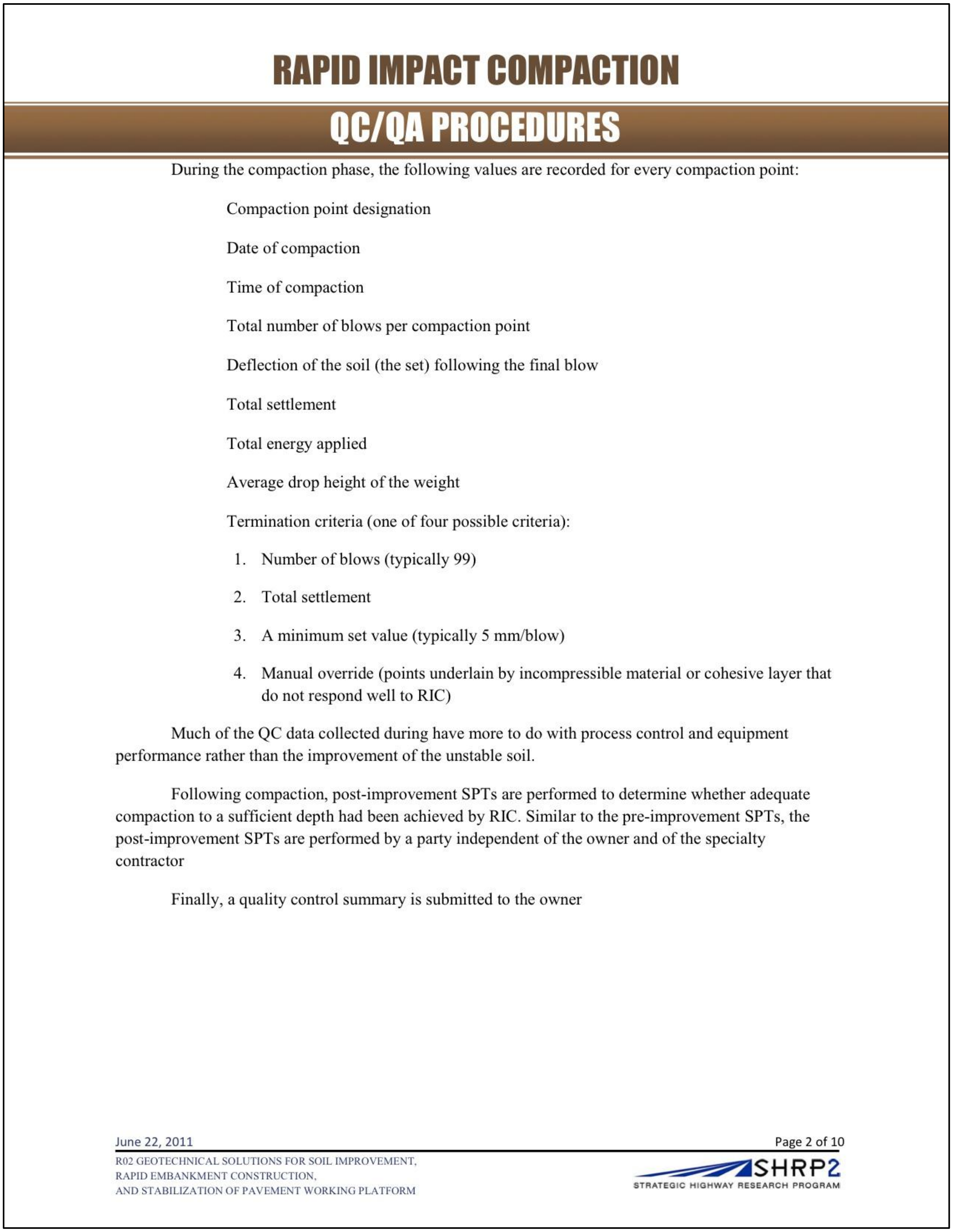
Figure 92. QC/QA document



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

During the compaction phase, the following values are recorded for every compaction point:

Compaction point designation

Date of compaction

Time of compaction

Total number of blows per compaction point

Deflection of the soil (the set) following the final blow

Total settlement

Total energy applied

Average drop height of the weight

Termination criteria (one of four possible criteria):

1. Number of blows (typically 99)
2. Total settlement
3. A minimum set value (typically 5 mm/blow)
4. Manual override (points underlain by incompressible material or cohesive layer that do not respond well to RIC)

Much of the QC data collected during have more to do with process control and equipment performance rather than the improvement of the unstable soil.

Following compaction, post-improvement SPTs are performed to determine whether adequate compaction to a sufficient depth had been achieved by RIC. Similar to the pre-improvement SPTs, the post-improvement SPTs are performed by a party independent of the owner and of the specialty contractor

Finally, a quality control summary is submitted to the owner

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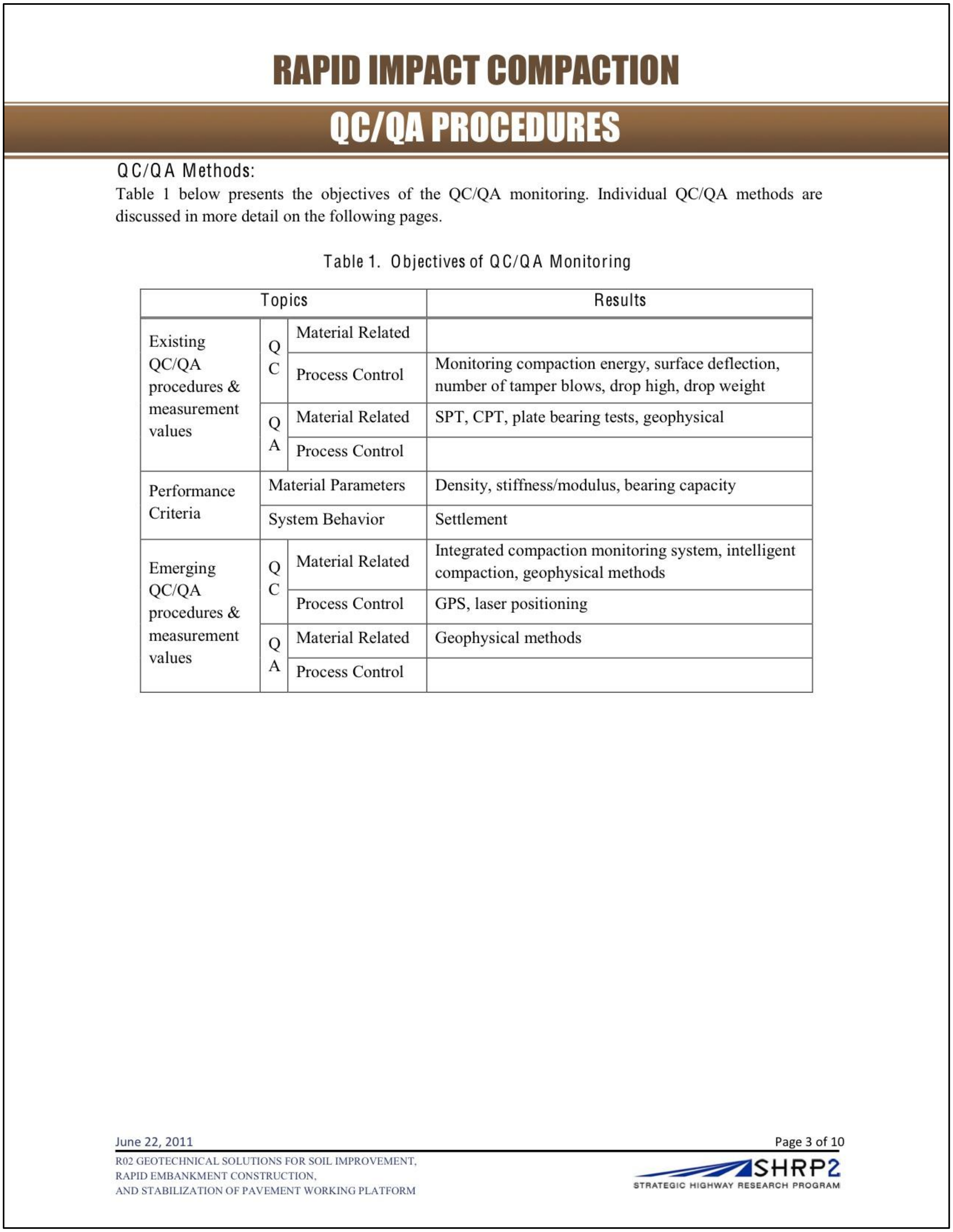
Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

QC/QA Methods:

Table 1 below presents the objectives of the QC/QA monitoring. Individual QC/QA methods are discussed in more detail on the following pages.

Table 1. Objectives of QC/QA Monitoring

Topics			Results
Existing QC/QA procedures & measurement values	QC	Material Related	
		Process Control	Monitoring compaction energy, surface deflection, number of tamper blows, drop high, drop weight
	QA	Material Related	SPT, CPT, plate bearing tests, geophysical
		Process Control	
Performance Criteria	Material Parameters		Density, stiffness/modulus, bearing capacity
	System Behavior		Settlement
Emerging QC/QA procedures & measurement values	QC	Material Related	Integrated compaction monitoring system, intelligent compaction, geophysical methods
		Process Control	GPS, laser positioning
	QA	Material Related	Geophysical methods
		Process Control	

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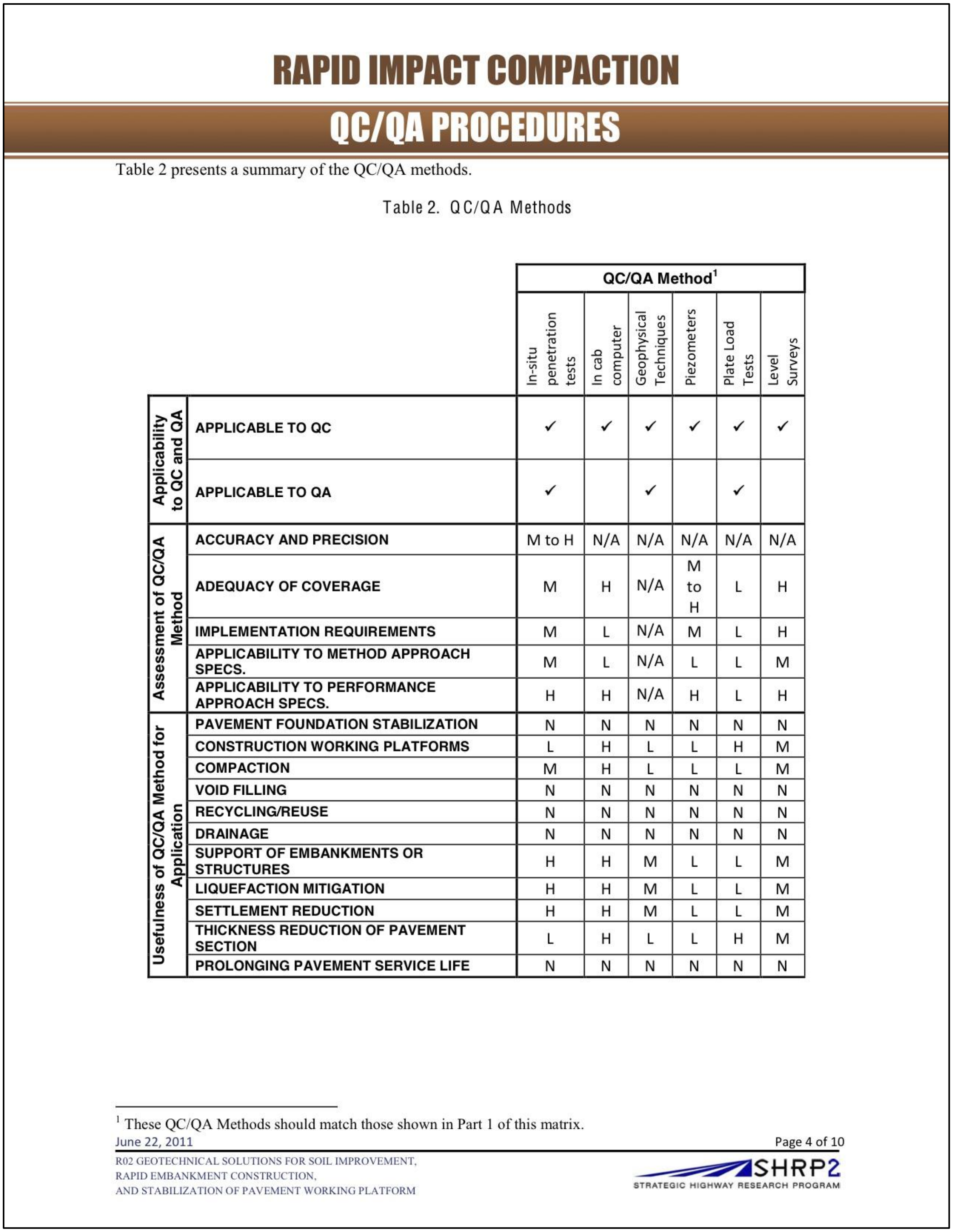
Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

Table 2 presents a summary of the QC/QA methods.

Table 2. QC/QA Methods

		QC/QA Method[1]					
		In-situ penetration tests	In cab computer	Geophysical Techniques	Piezometers	Plate Load Tests	Level Surveys
Applicability to QC and QA	APPLICABLE TO QC	✓	✓	✓	✓	✓	✓
	APPLICABLE TO QA	✓		✓		✓	
Assessment of QC/QA Method	ACCURACY AND PRECISION	M to H	N/A	N/A	N/A	N/A	N/A
	ADEQUACY OF COVERAGE	M	H	N/A	M to H	L	H
	IMPLEMENTATION REQUIREMENTS	M	L	N/A	M	L	H
	APPLICABILITY TO METHOD APPROACH SPECS.	M	L	N/A	L	L	M
	APPLICABILITY TO PERFORMANCE APPROACH SPECS.	H	H	N/A	H	L	H
Usefulness of QC/QA Method for Application	PAVEMENT FOUNDATION STABILIZATION	N	N	N	N	N	N
	CONSTRUCTION WORKING PLATFORMS	L	H	L	L	H	M
	COMPACTION	M	H	L	L	L	M
	VOID FILLING	N	N	N	N	N	N
	RECYCLING/REUSE	N	N	N	N	N	N
	DRAINAGE	N	N	N	N	N	N
	SUPPORT OF EMBANKMENTS OR STRUCTURES	H	H	M	L	L	M
	LIQUEFACTION MITIGATION	H	H	M	L	L	M
	SETTLEMENT REDUCTION	H	H	M	L	L	M
	THICKNESS REDUCTION OF PAVEMENT SECTION	L	H	L	L	H	M
	PROLONGING PAVEMENT SERVICE LIFE	N	N	N	N	N	N

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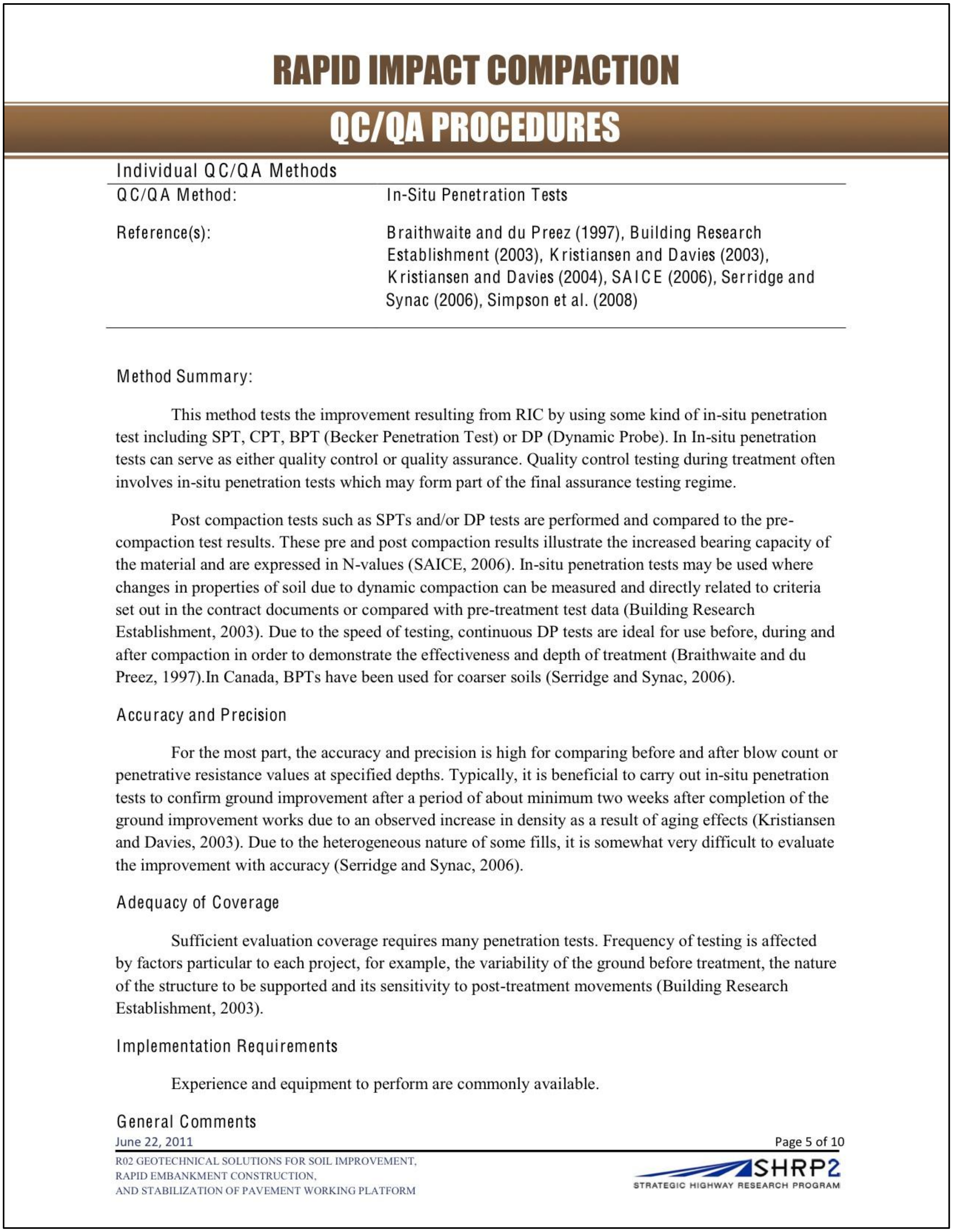
[1] These QC/QA Methods should match those shown in Part 1 of this matrix.

Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

Individual QC/QA Methods

QC/QA Method:	In-Situ Penetration Tests
Reference(s):	Braithwaite and du Preez (1997), Building Research Establishment (2003), Kristiansen and Davies (2003), Kristiansen and Davies (2004), SAICE (2006), Serridge and Synac (2006), Simpson et al. (2008)

Method Summary:

This method tests the improvement resulting from RIC by using some kind of in-situ penetration test including SPT, CPT, BPT (Becker Penetration Test) or DP (Dynamic Probe). In In-situ penetration tests can serve as either quality control or quality assurance. Quality control testing during treatment often involves in-situ penetration tests which may form part of the final assurance testing regime.

Post compaction tests such as SPTs and/or DP tests are performed and compared to the pre-compaction test results. These pre and post compaction results illustrate the increased bearing capacity of the material and are expressed in N-values (SAICE, 2006). In-situ penetration tests may be used where changes in properties of soil due to dynamic compaction can be measured and directly related to criteria set out in the contract documents or compared with pre-treatment test data (Building Research Establishment, 2003). Due to the speed of testing, continuous DP tests are ideal for use before, during and after compaction in order to demonstrate the effectiveness and depth of treatment (Braithwaite and du Preez, 1997).In Canada, BPTs have been used for coarser soils (Serridge and Synac, 2006).

Accuracy and Precision

For the most part, the accuracy and precision is high for comparing before and after blow count or penetrative resistance values at specified depths. Typically, it is beneficial to carry out in-situ penetration tests to confirm ground improvement after a period of about minimum two weeks after completion of the ground improvement works due to an observed increase in density as a result of aging effects (Kristiansen and Davies, 2003). Due to the heterogeneous nature of some fills, it is somewhat very difficult to evaluate the improvement with accuracy (Serridge and Synac, 2006).

Adequacy of Coverage

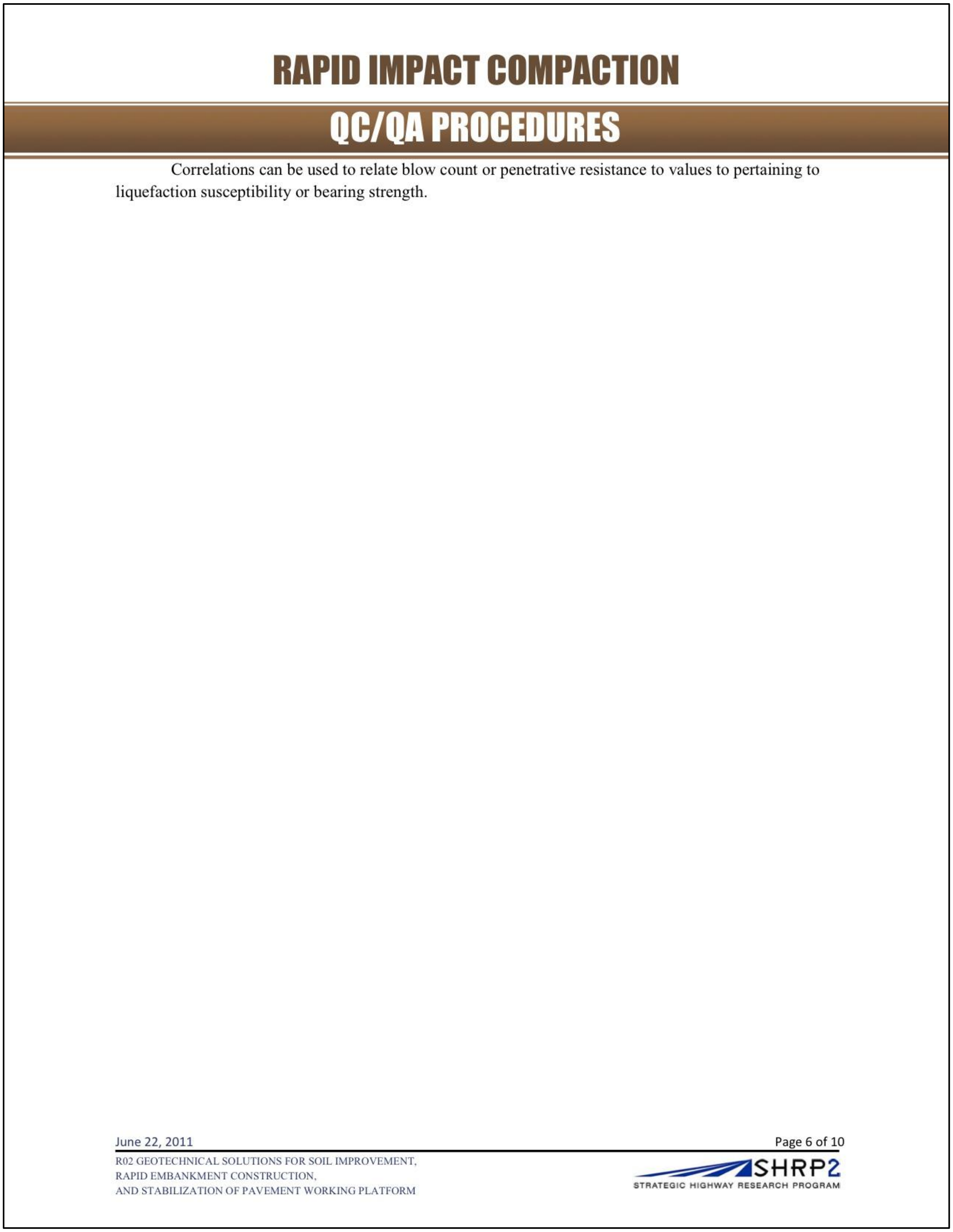
Sufficient evaluation coverage requires many penetration tests. Frequency of testing is affected by factors particular to each project, for example, the variability of the ground before treatment, the nature of the structure to be supported and its sensitivity to post-treatment movements (Building Research Establishment, 2003).

Implementation Requirements

Experience and equipment to perform are commonly available.

General Comments

Figure 92. QC/QA document (continued)

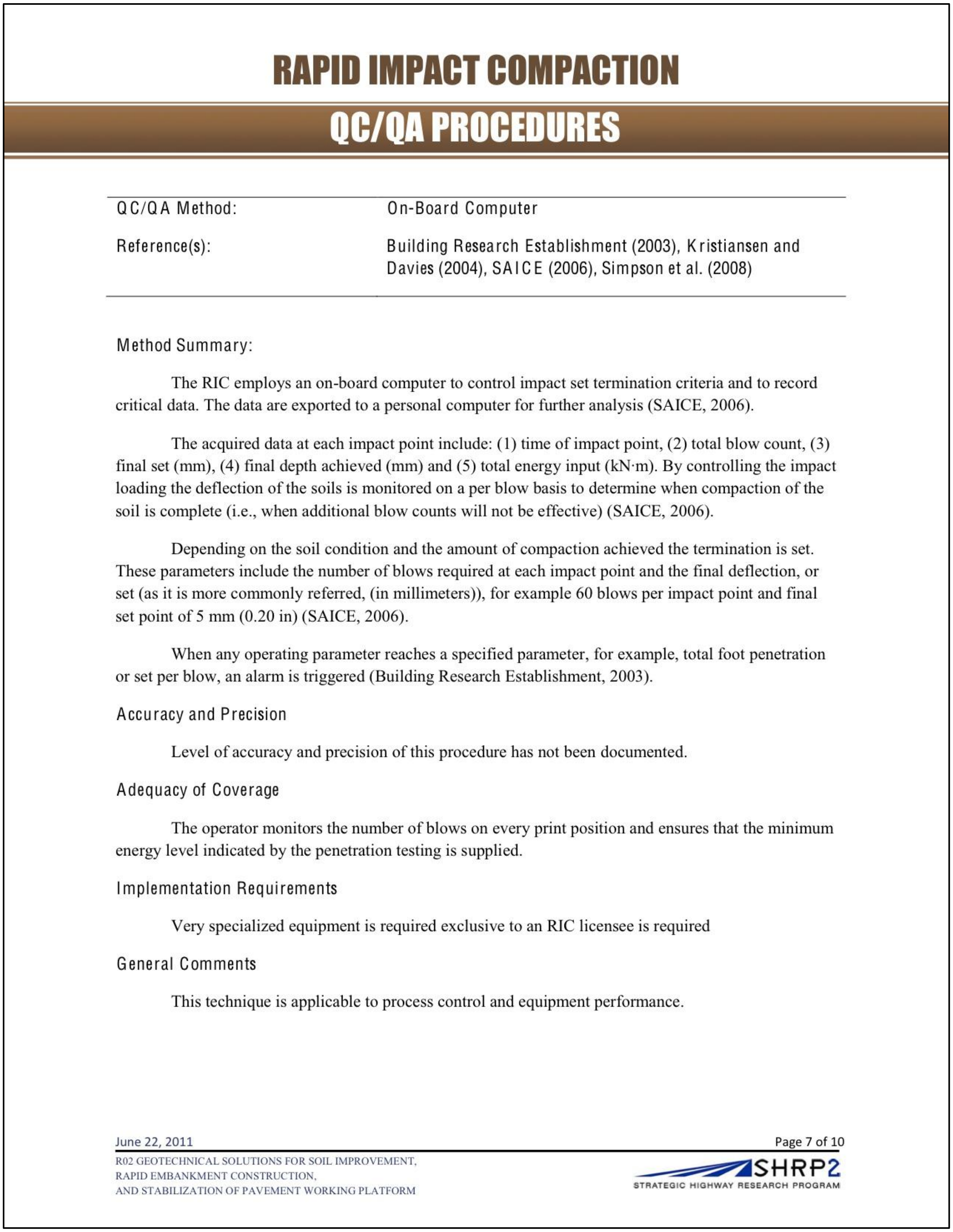


RAPID IMPACT COMPACTION

QC/QA PROCEDURES

Correlations can be used to relate blow count or penetrative resistance to values to pertaining to liquefaction susceptibility or bearing strength.

Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

QC/QA Method:	On-Board Computer
Reference(s):	Building Research Establishment (2003), Kristiansen and Davies (2004), SAICE (2006), Simpson et al. (2008)

Method Summary:

The RIC employs an on-board computer to control impact set termination criteria and to record critical data. The data are exported to a personal computer for further analysis (SAICE, 2006).

The acquired data at each impact point include: (1) time of impact point, (2) total blow count, (3) final set (mm), (4) final depth achieved (mm) and (5) total energy input (kN·m). By controlling the impact loading the deflection of the soils is monitored on a per blow basis to determine when compaction of the soil is complete (i.e., when additional blow counts will not be effective) (SAICE, 2006).

Depending on the soil condition and the amount of compaction achieved the termination is set. These parameters include the number of blows required at each impact point and the final deflection, or set (as it is more commonly referred, (in millimeters)), for example 60 blows per impact point and final set point of 5 mm (0.20 in) (SAICE, 2006).

When any operating parameter reaches a specified parameter, for example, total foot penetration or set per blow, an alarm is triggered (Building Research Establishment, 2003).

Accuracy and Precision

Level of accuracy and precision of this procedure has not been documented.

Adequacy of Coverage

The operator monitors the number of blows on every print position and ensures that the minimum energy level indicated by the penetration testing is supplied.

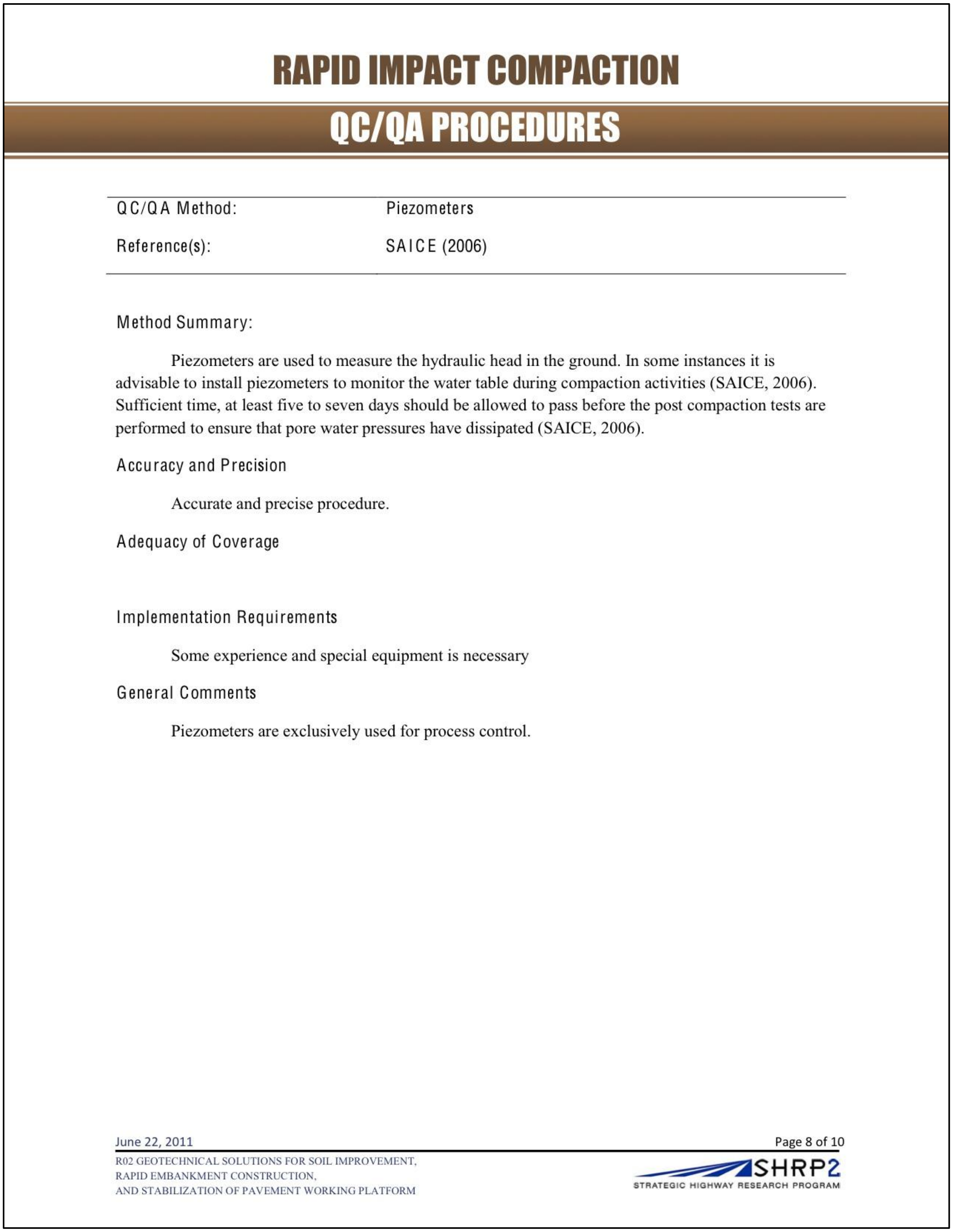
Implementation Requirements

Very specialized equipment is required exclusive to an RIC licensee is required

General Comments

This technique is applicable to process control and equipment performance.

Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

QC/QA Method:	Piezometers
Reference(s):	SAICE (2006)

Method Summary:

Piezometers are used to measure the hydraulic head in the ground. In some instances it is advisable to install piezometers to monitor the water table during compaction activities (SAICE, 2006). Sufficient time, at least five to seven days should be allowed to pass before the post compaction tests are performed to ensure that pore water pressures have dissipated (SAICE, 2006).

Accuracy and Precision

Accurate and precise procedure.

Adequacy of Coverage

Implementation Requirements

Some experience and special equipment is necessary

General Comments

Piezometers are exclusively used for process control.

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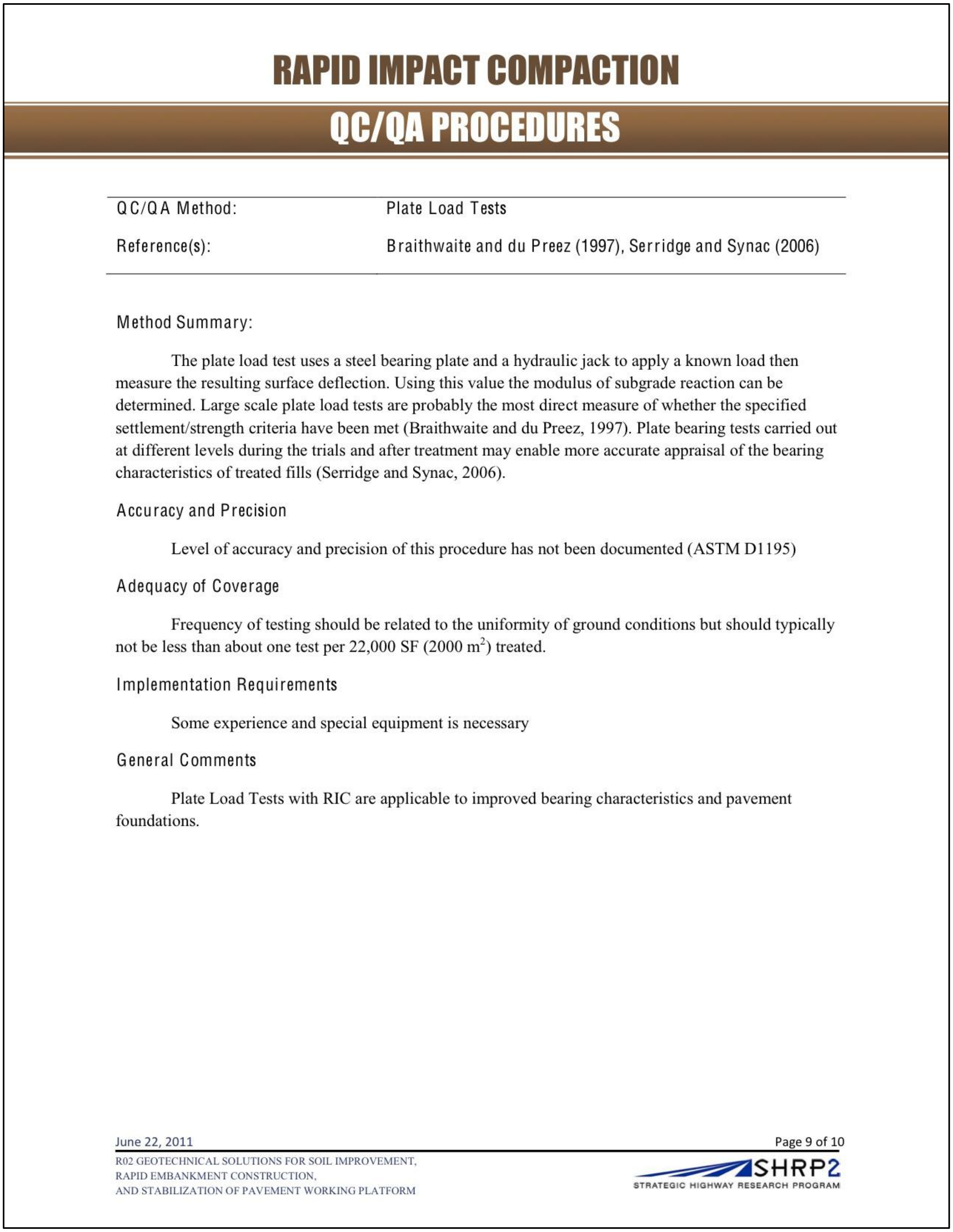
Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

QC/QA Method:	Plate Load Tests
Reference(s):	Braithwaite and du Preez (1997), Serridge and Synac (2006)

Method Summary:

The plate load test uses a steel bearing plate and a hydraulic jack to apply a known load then measure the resulting surface deflection. Using this value the modulus of subgrade reaction can be determined. Large scale plate load tests are probably the most direct measure of whether the specified settlement/strength criteria have been met (Braithwaite and du Preez, 1997). Plate bearing tests carried out at different levels during the trials and after treatment may enable more accurate appraisal of the bearing characteristics of treated fills (Serridge and Synac, 2006).

Accuracy and Precision

Level of accuracy and precision of this procedure has not been documented (ASTM D1195)

Adequacy of Coverage

Frequency of testing should be related to the uniformity of ground conditions but should typically not be less than about one test per 22,000 SF (2000 m^2) treated.

Implementation Requirements

Some experience and special equipment is necessary

General Comments

Plate Load Tests with RIC are applicable to improved bearing characteristics and pavement foundations.

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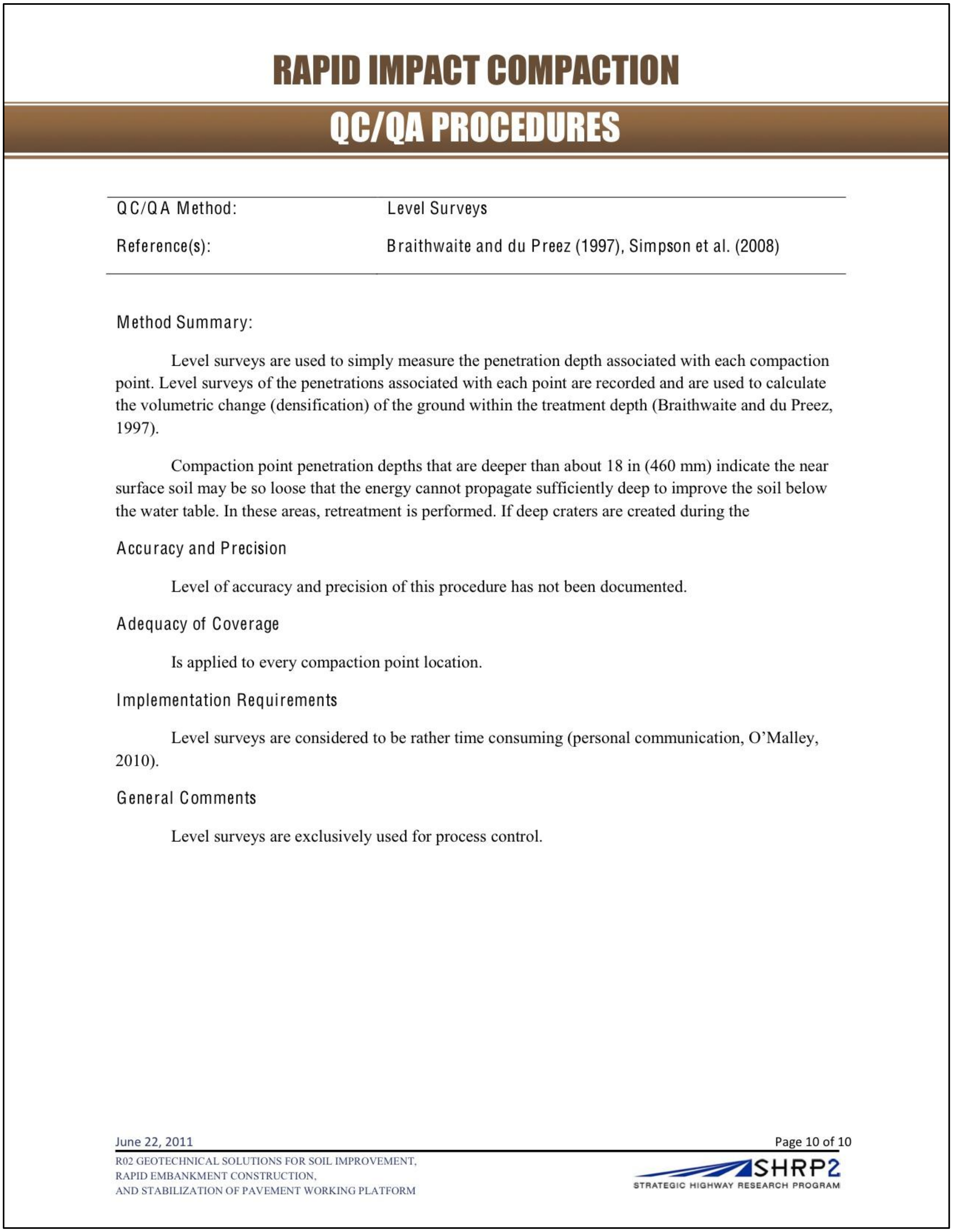
Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

QC/QA PROCEDURES

QC/QA Method:	Level Surveys
Reference(s):	Braithwaite and du Preez (1997), Simpson et al. (2008)

Method Summary:

Level surveys are used to simply measure the penetration depth associated with each compaction point. Level surveys of the penetrations associated with each point are recorded and are used to calculate the volumetric change (densification) of the ground within the treatment depth (Braithwaite and du Preez, 1997).

Compaction point penetration depths that are deeper than about 18 in (460 mm) indicate the near surface soil may be so loose that the energy cannot propagate sufficiently deep to improve the soil below the water table. In these areas, retreatment is performed. If deep craters are created during the

Accuracy and Precision

Level of accuracy and precision of this procedure has not been documented.

Adequacy of Coverage

Is applied to every compaction point location.

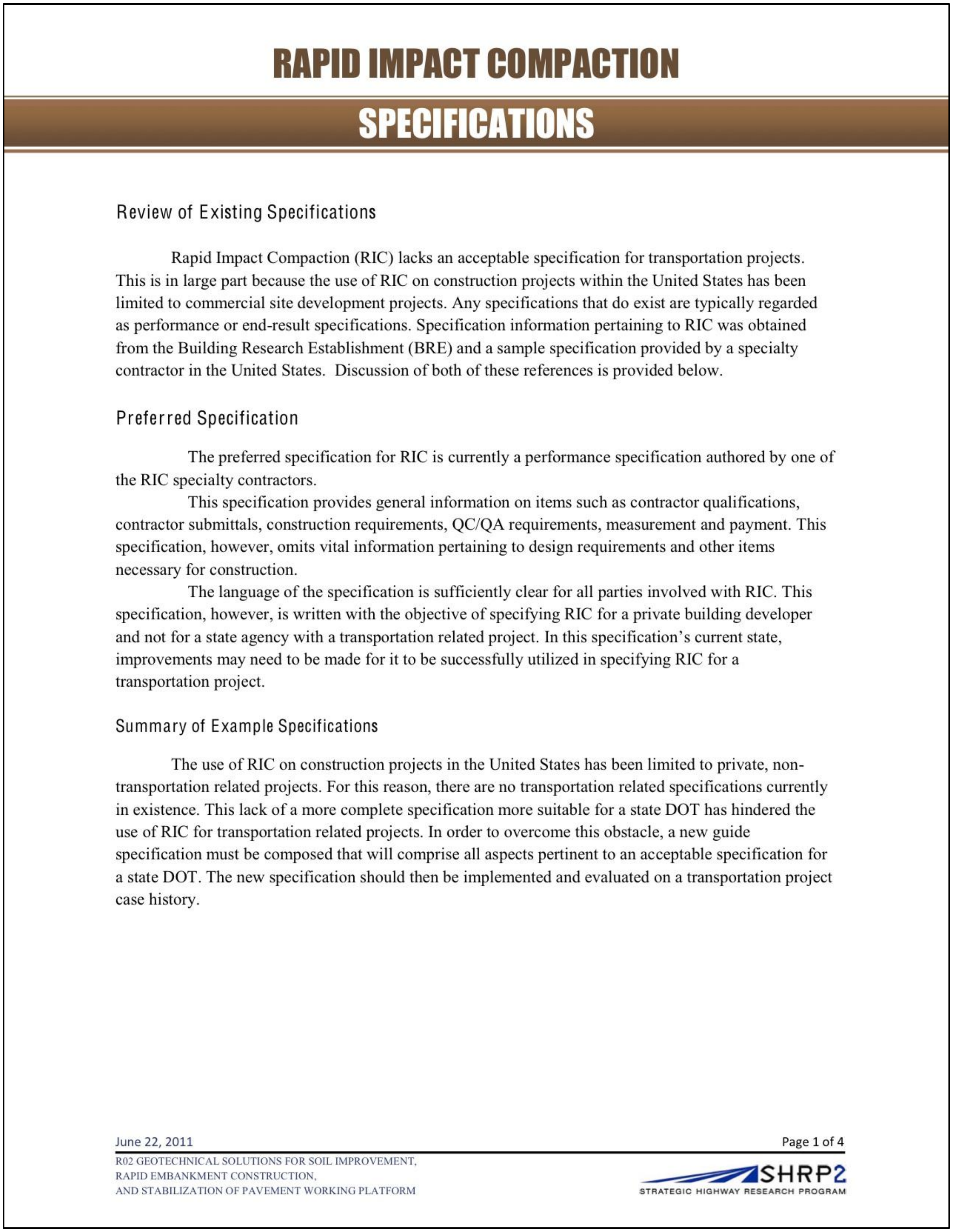
Implementation Requirements

Level surveys are considered to be rather time consuming (personal communication, O'Malley, 2010).

General Comments

Level surveys are exclusively used for process control.

Figure 92. QC/QA document (continued)



RAPID IMPACT COMPACTION

SPECIFICATIONS

Review of Existing Specifications

Rapid Impact Compaction (RIC) lacks an acceptable specification for transportation projects. This is in large part because the use of RIC on construction projects within the United States has been limited to commercial site development projects. Any specifications that do exist are typically regarded as performance or end-result specifications. Specification information pertaining to RIC was obtained from the Building Research Establishment (BRE) and a sample specification provided by a specialty contractor in the United States. Discussion of both of these references is provided below.

Preferred Specification

The preferred specification for RIC is currently a performance specification authored by one of the RIC specialty contractors.

This specification provides general information on items such as contractor qualifications, contractor submittals, construction requirements, QC/QA requirements, measurement and payment. This specification, however, omits vital information pertaining to design requirements and other items necessary for construction.

The language of the specification is sufficiently clear for all parties involved with RIC. This specification, however, is written with the objective of specifying RIC for a private building developer and not for a state agency with a transportation related project. In this specification's current state, improvements may need to be made for it to be successfully utilized in specifying RIC for a transportation project.

Summary of Example Specifications

The use of RIC on construction projects in the United States has been limited to private, non-transportation related projects. For this reason, there are no transportation related specifications currently in existence. This lack of a more complete specification more suitable for a state DOT has hindered the use of RIC for transportation related projects. In order to overcome this obstacle, a new guide specification must be composed that will comprise all aspects pertinent to an acceptable specification for a state DOT. The new specification should then be implemented and evaluated on a transportation project case history.

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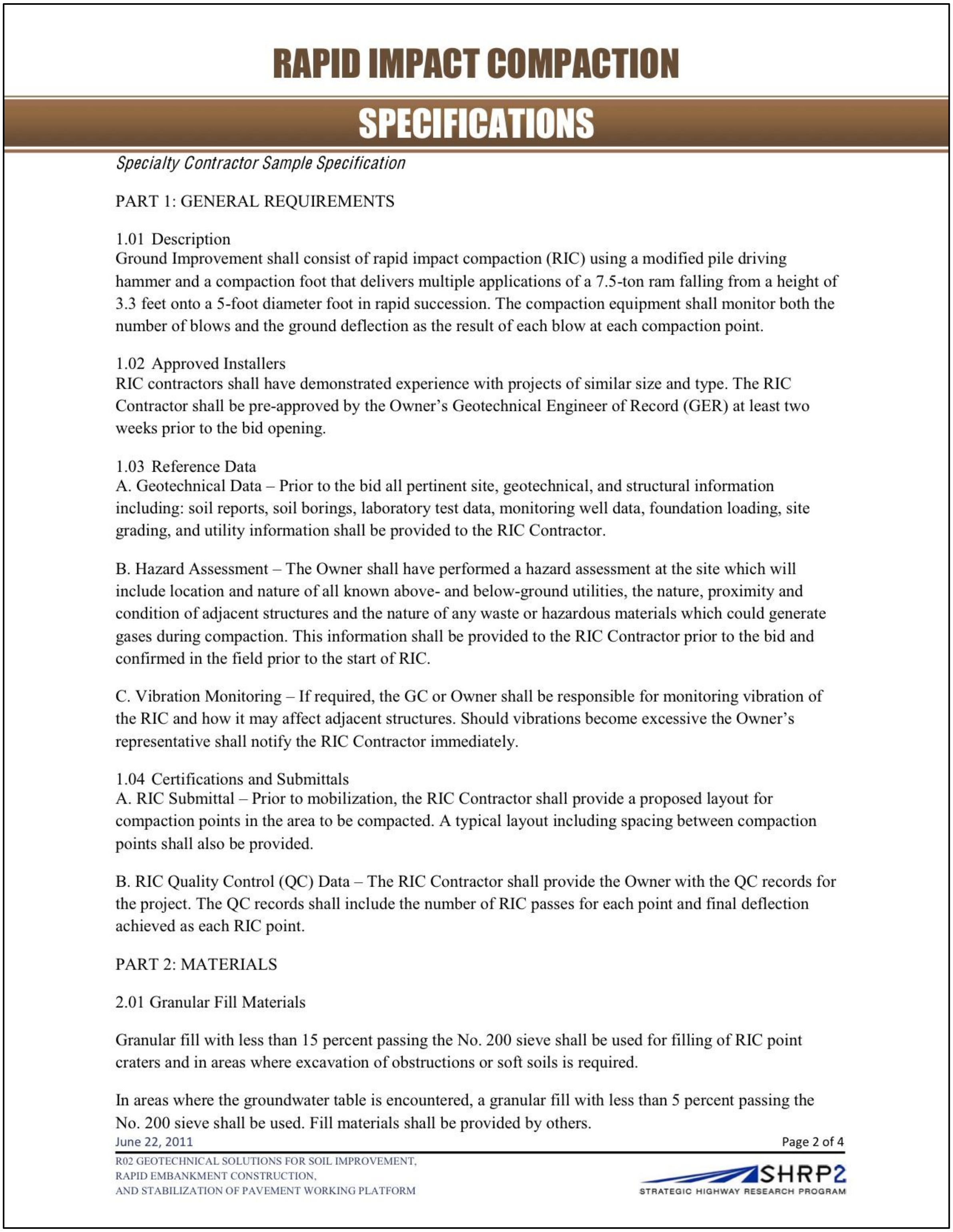
Figure 93. Specifications document



RAPID IMPACT COMPACTION

SPECIFICATIONS

Specialty Contractor Sample Specification

PART 1: GENERAL REQUIREMENTS

1.01 Description
Ground Improvement shall consist of rapid impact compaction (RIC) using a modified pile driving hammer and a compaction foot that delivers multiple applications of a 7.5-ton ram falling from a height of 3.3 feet onto a 5-foot diameter foot in rapid succession. The compaction equipment shall monitor both the number of blows and the ground deflection as the result of each blow at each compaction point.

1.02 Approved Installers
RIC contractors shall have demonstrated experience with projects of similar size and type. The RIC Contractor shall be pre-approved by the Owner's Geotechnical Engineer of Record (GER) at least two weeks prior to the bid opening.

1.03 Reference Data
A. Geotechnical Data – Prior to the bid all pertinent site, geotechnical, and structural information including: soil reports, soil borings, laboratory test data, monitoring well data, foundation loading, site grading, and utility information shall be provided to the RIC Contractor.

B. Hazard Assessment – The Owner shall have performed a hazard assessment at the site which will include location and nature of all known above- and below-ground utilities, the nature, proximity and condition of adjacent structures and the nature of any waste or hazardous materials which could generate gases during compaction. This information shall be provided to the RIC Contractor prior to the bid and confirmed in the field prior to the start of RIC.

C. Vibration Monitoring – If required, the GC or Owner shall be responsible for monitoring vibration of the RIC and how it may affect adjacent structures. Should vibrations become excessive the Owner's representative shall notify the RIC Contractor immediately.

1.04 Certifications and Submittals
A. RIC Submittal – Prior to mobilization, the RIC Contractor shall provide a proposed layout for compaction points in the area to be compacted. A typical layout including spacing between compaction points shall also be provided.

B. RIC Quality Control (QC) Data – The RIC Contractor shall provide the Owner with the QC records for the project. The QC records shall include the number of RIC passes for each point and final deflection achieved as each RIC point.

PART 2: MATERIALS

2.01 Granular Fill Materials

Granular fill with less than 15 percent passing the No. 200 sieve shall be used for filling of RIC point craters and in areas where excavation of obstructions or soft soils is required.

In areas where the groundwater table is encountered, a granular fill with less than 5 percent passing the No. 200 sieve shall be used. Fill materials shall be provided by others.

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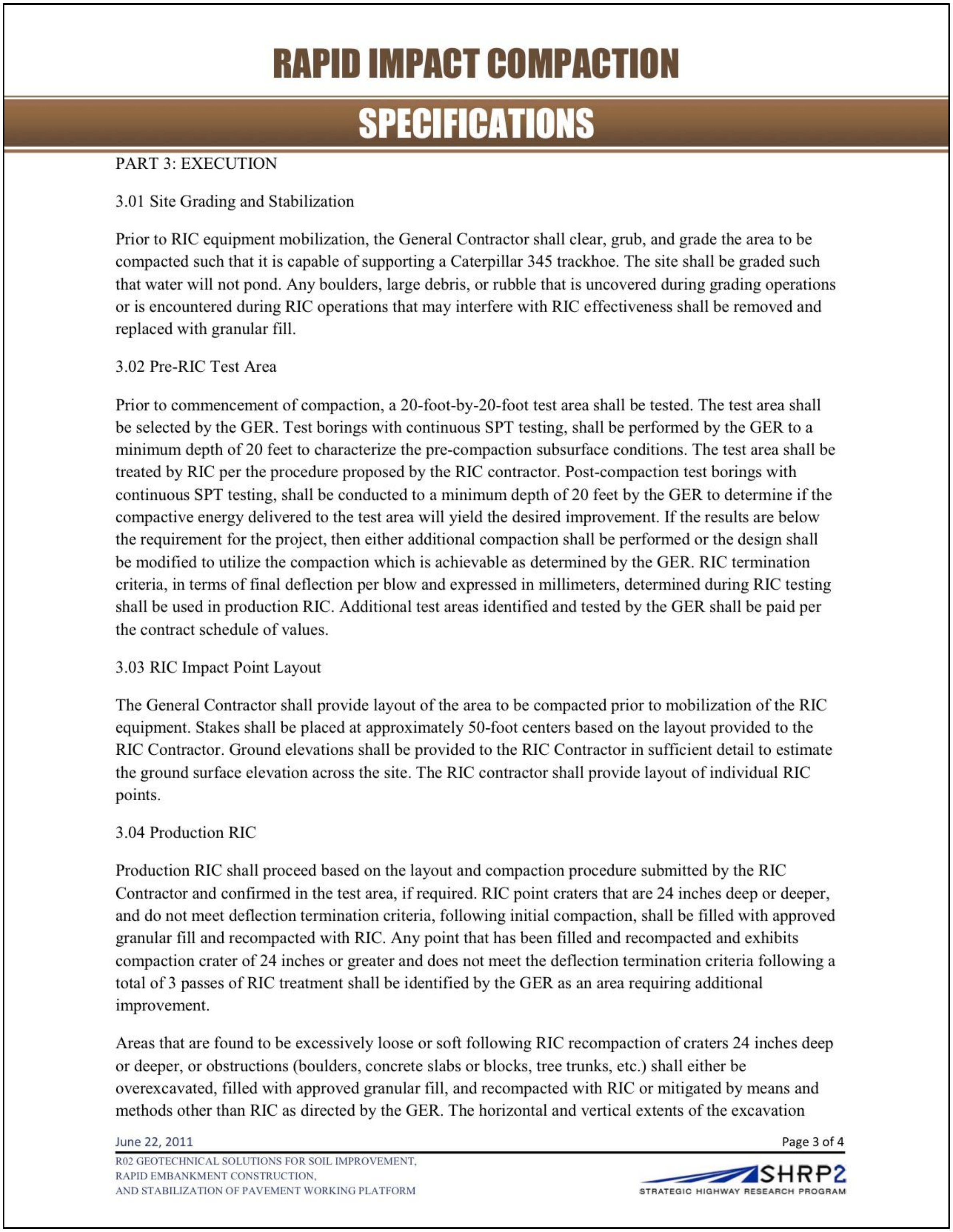
Figure 93. Specifications document (continued)



RAPID IMPACT COMPACTION

SPECIFICATIONS

PART 3: EXECUTION

3.01 Site Grading and Stabilization

Prior to RIC equipment mobilization, the General Contractor shall clear, grub, and grade the area to be compacted such that it is capable of supporting a Caterpillar 345 trackhoe. The site shall be graded such that water will not pond. Any boulders, large debris, or rubble that is uncovered during grading operations or is encountered during RIC operations that may interfere with RIC effectiveness shall be removed and replaced with granular fill.

3.02 Pre-RIC Test Area

Prior to commencement of compaction, a 20-foot-by-20-foot test area shall be tested. The test area shall be selected by the GER. Test borings with continuous SPT testing, shall be performed by the GER to a minimum depth of 20 feet to characterize the pre-compaction subsurface conditions. The test area shall be treated by RIC per the procedure proposed by the RIC contractor. Post-compaction test borings with continuous SPT testing, shall be conducted to a minimum depth of 20 feet by the GER to determine if the compactive energy delivered to the test area will yield the desired improvement. If the results are below the requirement for the project, then either additional compaction shall be performed or the design shall be modified to utilize the compaction which is achievable as determined by the GER. RIC termination criteria, in terms of final deflection per blow and expressed in millimeters, determined during RIC testing shall be used in production RIC. Additional test areas identified and tested by the GER shall be paid per the contract schedule of values.

3.03 RIC Impact Point Layout

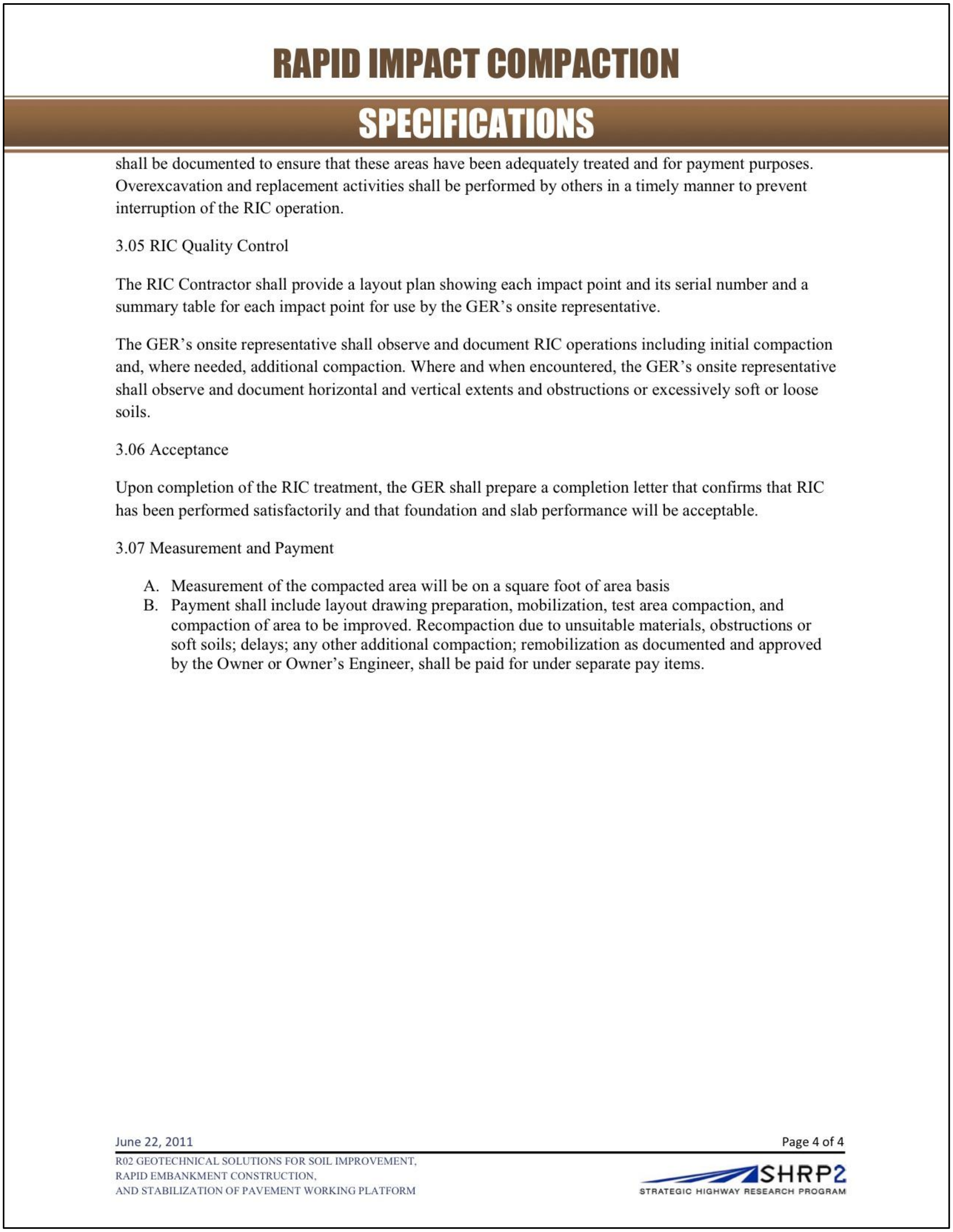
The General Contractor shall provide layout of the area to be compacted prior to mobilization of the RIC equipment. Stakes shall be placed at approximately 50-foot centers based on the layout provided to the RIC Contractor. Ground elevations shall be provided to the RIC Contractor in sufficient detail to estimate the ground surface elevation across the site. The RIC contractor shall provide layout of individual RIC points.

3.04 Production RIC

Production RIC shall proceed based on the layout and compaction procedure submitted by the RIC Contractor and confirmed in the test area, if required. RIC point craters that are 24 inches deep or deeper, and do not meet deflection termination criteria, following initial compaction, shall be filled with approved granular fill and recompacted with RIC. Any point that has been filled and recompacted and exhibits compaction crater of 24 inches or greater and does not meet the deflection termination criteria following a total of 3 passes of RIC treatment shall be identified by the GER as an area requiring additional improvement.

Areas that are found to be excessively loose or soft following RIC recompaction of craters 24 inches deep or deeper, or obstructions (boulders, concrete slabs or blocks, tree trunks, etc.) shall either be overexcavated, filled with approved granular fill, and recompacted with RIC or mitigated by means and methods other than RIC as directed by the GER. The horizontal and vertical extents of the excavation

Figure 93. Specifications document (continued)



RAPID IMPACT COMPACTION

SPECIFICATIONS

shall be documented to ensure that these areas have been adequately treated and for payment purposes. Overexcavation and replacement activities shall be performed by others in a timely manner to prevent interruption of the RIC operation.

3.05 RIC Quality Control

The RIC Contractor shall provide a layout plan showing each impact point and its serial number and a summary table for each impact point for use by the GER's onsite representative.

The GER's onsite representative shall observe and document RIC operations including initial compaction and, where needed, additional compaction. Where and when encountered, the GER's onsite representative shall observe and document horizontal and vertical extents and obstructions or excessively soft or loose soils.

3.06 Acceptance

Upon completion of the RIC treatment, the GER shall prepare a completion letter that confirms that RIC has been performed satisfactorily and that foundation and slab performance will be acceptable.

3.07 Measurement and Payment

A. Measurement of the compacted area will be on a square foot of area basis
B. Payment shall include layout drawing preparation, mobilization, test area compaction, and compaction of area to be improved. Recompaction due to unsuitable materials, obstructions or soft soils; delays; any other additional compaction; remobilization as documented and approved by the Owner or Owner's Engineer, shall be paid for under separate pay items.

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Figure 93. Specifications document (continued)

ACKNOWLEDGEMENTS

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Last but certainly not least, I am eternally grateful to my family for their immeasurable support and unconditional love. Even during what has seemed like an endless academic career, the encouragement from my family has failed to relent and has in fact strengthened.

It is safe to say that without my wife and confidant, Rita, this thesis would have never been written. She; as well as my newborn son, Montgomery; were the driving force propelling me to the title of Master of Science.