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Evaluation of the slope stability of streambanks at saturated riparian buffer sites

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Evaluation of the slope stability of streambanks at saturated riparian buffer sites

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DEDICATION

For my mom, Nancy Burgus.

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NOMENCLATURE

BEHI	Bank Hazard Erosion Index
CEM	Channel Evolution Model
FS	Factor of Safety
GLM	General linear model
SRB	Saturated riparian buffer
USDA-NRCS	United States Department of Agriculture - National Resources Conservation Service
US	United States

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ABSTRACT

Saturated riparian buffers (SRBs) reduce nitrate export from agricultural tile drainage by infusing drainage water into carbon-rich riparian soils where denitrification and plant uptake can occur. The water quality benefits from SRBs are well documented but concerns about their effect on streambank stability have led to restrictive design standards that prevent widespread implementation. The relationship between SRB design conditions and streambank stability was examined through numerical slope stability modeling. The effect of the SRB installation was assessed by comparing no-flow and SRB flow conditions at study sites under a range of simulated conditions. In most cases, the addition of SRB flow did not cause instability, which indicates SRBs have little effect on the overall stability of the streambank. A study of how the streambank height affects stability showed no significant relationship between the two when all other factors were considered. Regression analysis of dimensionless parameters derived from SRB site conditions resulted in a function to predict the factor of safety against failure at potential SRB sites.

CHAPTER 1: GENERAL INTRODUCTION

Subsurface drainage of agricultural land, through the use of underdrain pipes, often referred to as "tile drainage," is commonly used to drain hydric soils throughout the Corn Belt region of the United States (Zucker and Brown, 1998). Corn and soybeans require a well aerated root zone for optimal growth; however, many soils in the heavily cropped Upper Midwest are hydric soils with naturally high groundwater which saturate the root zone. Tile drainage alleviates saturation by routing water to an outlet at an adjacent stream or drainage ditch. Recent studies estimate 33% of cropland in the state of Iowa, equivalent to 8.8 million acres (3.6 million hectares), has subsurface tile drainage (Sugg, 2007).

Although drainage increases crop yield, the short-circuiting of the groundwater cycle degrades water quality (Skaggs et al., 1994). Nitrate, which is abundant in shallow groundwater beneath agricultural land, is particularly susceptible to export via tile drainage (Skaggs et al., 1994). Concentrations of up to 61 mg/L per liter, more than six times the Environmental Protection Agency Class C surface water quality limit, have been observed in samples of agricultural tile drainage water (Baker and Johnson, 1981). Export from corn and soy growing regions is the largest contributor to elevated nitrate levels in surface waters (David et al., 1997). Excessive nitrate concentrations in drinking water can be harmful to human health (Schilling and Wolter, 2009). Further downstream, nitrate-rich water carried by the Mississippi River flows into the Gulf of Mexico creating conditions that induce eutrophication. Consequently, hypoxic regions develop in the water column causing fish kills and degradation of aquatic life. This phenomenon is commonly referred to as the "Dead Zone." Rabalais et al. (2001) and Dale et al. (2010) have shown nitrate export from upstream to be the primary cause of the Dead Zone.

Due to concerns about adverse effects of nutrient export, conservation practices emerged to reduce nutrient concentrations in water leaving agricultural land. At first, many practices emphasized reducing the source or treating surface runoff. Restoration or establishment of a riparian buffer zones between cropland and adjacent streams is a conservation practice used to increase infiltration of surface runoff. Riparian buffers are effective at reducing sediment and nutrient export via plant uptake, immobilization and denitrification (Lee et al., 2000; Groh, 2019). Due to this finding, riparian buffer zones were promoted by Natural Resource Conservation Service (NRCS) conservation programs and subsequently widely adopted by farmers throughout the Midwest. When research began to show most of the nitrate exits the field through drainage tile, interest in treating subsurface drainage water increased. Although effective at treating surface flow, riparian buffers were shown to have little impact at sites with tile drainage as the buffers were hydrologically disconnected from the tile water (Jaynes and Isenhart, 2014).

Findings from previous work led researchers Jaynes and Isenhart to consider use of soils within existing riparian buffer zones to retain drainage water and, thereby, facilitate nitrate reduction through plant uptake and denitrification. The new practice, designated saturated buffers (SRB), restores the hydrologic connection between the riparian zone and drainage water by intercepting the tile main and distributing water laterally along the stream through the soil. Nitrate removal rates are maximized when soils containing organic carbon reach saturated conditions (Hill, 1996). In SRBs, these conditions are created by raising the groundwater table to reach carbon-rich areas near the soil surface.

SRBs hydrologically connect tile drainage to the riparian zone by intercepting and retaining drainage water in the soil profile. An inline multi-chambered control structure is installed by excavating the tile main, which allows tile water to flow out laterally through perforated distribution pipes to the buffer. During large flow events water unable to enter the buffer bypasses to discharge at the stream ensuring proper function of the field drainage system. Flow may be measured by use of V-notch weirs and pressure transducers in the water control structure. The water level in the buffer is controlled by adjustable flashboards within the structure. The distribution pipe is trenched into the buffer parallel to the stream at a typical depth of 2.5 ft. (0.76 m) below the soil surface (Christianson et al., 2016).

SRBs can remove up to 100% of nitrate in water diverted to the buffer (Jaynes and Isenhart, 2014). If water cannot flow to the buffer, no treatment will occur; therefore, the total nitrate removal rate depends on the ratio of total tile flow and the flow diverted to the buffer. Total water diverted to the SRB depends on site conditions including field and drainage system size, precipitation, topography, soil characteristics, dimensions of the buffer, site geology, and stream conditions (Jaynes and Isenhart, 2019).

NRCS Code 604 standardizes SRB design and appropriate site conditions. Code 604 stipulates buffers shall not be installed at sites with incised channel depths greater than 8 feet (2.4 m) without a slope stability analysis showing an acceptable degree of safety against slope failure. Slope stability analysis requires a geotechnical investigation and report, which add significant cost to the project. Since typical drainage ditches are greater than 8 ft. (2.4 m) deep, placement of SRBs is considerably restricted preventing further adoption of the practice. Additionally, Code 604 states a minimum width of 30 ft. (9.1 m) between distribution pipe and streambank must be achieved.

Conditions under which SRBs impact slope stability are not clear. SRBs elevate the water levels in the soil, which reduces the effective shear strength and increases the weight of the soil.

Though the groundwater level is elevated close to the SRB distribution pipe, water levels may decline to nearly pre-buffer conditions close to the stream. Although extensive research into slope stability has been conducted for roadway and building design, no investigations of stability at SRB sites are available. Concerns regarding bank failure motivate conservative guidelines until further research can be conducted.

The objectives of this work are to (1) gain insight into SRB function and their effect on streambank stability, (2) investigate existing SRB sites to inform a conceptual model, (3) study how SRB width affects streambank stability, (4) examine the relationship between the streambank height and slope stability, and (5) improve design guidance for the implementation of SRBs. Improving the understanding of streambank stability at SRB sites will allow more sites to be eligible for the practice, thus increasing the implementation of SRBs and improving water quality locally and regionally. In the following chapters, a thorough geotechnical slope stability analysis of SRB conditions is presented. Chapter 2 outlines the general theory of streambank stability and explains the interaction between mechanical slope stability and fluvial in-stream processes. In Chapter 3, an assessment of the effect of SRB flow on stability is presented for one study site. The fourth chapter is an overview of the effect of the SRB width on the overall stability of the streambank. Chapter 5 outlines the impact of simulated SRB design conditions on streambank stability, examines the relationship between bank height and stability, and presents a regression equation to predict stability at future SRB sites. Conclusions of this work and their implications for the design and implementation of SRBs are summarized in Chapter 6.

CHAPTER 2: STREAMBANK STABILITY THEORY

Streambank instability and subsequent failures impair waterways, damage property, risk human lives, and degrade ecosystems throughout the world. Bank failures can contribute substantial sediment loading to surface waters. For example, Belmont et al. (2011) found the dominant source of sediment to the upper Mississippi originated from streambank material, which contributed more than upland erosion. Expenditures on stream stabilization and restoration projects have skyrocketed, with costs exceeding $1 billion annually in the US (Bernhardt et al., 2005). Public safety risks arise when streambanks fail, especially if the failure occurs in densely populated or popular recreation areas. Aquatic and riparian ecosystems are jeopardized by bank instability, and evidence shows excessive sedimentation diminishes biodiversity of sediment biota (Palmer et al., 2000). Due to the numerous detriments caused by bank instability, the necessity to find solutions and improve understanding of the problem has gained urgency.

Two corresponding mechanisms, erosion and mass failure contribute to bank instability (Osman and Thorne, 1988). Bank and bed erosion caused by fluvial processes leads to high and steep banks, which then fail due to mechanical instability. Shear stress induced by hydraulic forces erode the toe and base of the slope, creating steepened banks (Simon et al., 2000). Hydrologic forces are usually assumed to act laterally to the slope and are time dependent. Mass failure is a type of mechanical failure where a mass of soil detaches from the slope and slides downward (Thorne and Tovey, 1981). Mechanical failure of this type is precipitated by a reduction in soil strength and is typically analyzed by consideration of a 2-dimensional cross section of the slope at a single point in time corresponding to the time of failure. Erosion and fluvial processes are intrinsic to geomorphology, but soil mechanics falls under the realm of geotechnical engineering, creating a disconnect which can inhibit understanding of bank instability. To gain a deeper understanding of bank instability, one must study both fluvial geomorphology and geotechnical soil mechanics.

Bank Erosion

Bank instability is often a direct product of erosion caused by in-channel processes. Firstly, erosion causes banks to recede as soil materials are carried away with the flow. This process is best visualized by consideration of cut-banks that can rapidly recede during moderate to high flow events (Osman and Thorne, 1988). Secondly, erosion of bank materials directly shapes the streambank form, thereby altering the slope angle and height of the bank. When banks become high and steep, mechanical failure ensues leading to a destructive feedback loop (Osman and Thorne, 1988; Turner et al., 2010; Simon et al., 1999). The linkage between the two processes highlights the necessity of a holistic approach to the problem of bank instability.

Erosion of bank materials occurs when hydraulic shear stresses along the base and sides of the channel exceed a critical stress threshold (Papanicolaou et al., 2007). Shear stress is a function of channel geometry, slope, roughness, and flowrate which creates a fluid drag force initiating particle entrainment (Chiu and Lin, 1983). The critical strength of non-cohesive bed materials is a function of particle, shape, diameter, and arrangement that create a gravitational force resisting motion (Shields, 1936). Erosion rates for cohesionless materials in a particular channel can be predicted by calculating the effective stress acting on the channel interface if the coefficient of erodibility is known (Hanson, 1990).

Estimating erosion rates of cohesive bank materials is more difficult. Erodibility of cohesive materials depends on soil properties including clay mineralogy, density, particle arrangement, moisture conditions, organic fraction, and complex chemical, physical and biological interactions in gas and water occupying the soil void spaces (Hanson and Simon, 2001). Cohesive particles can experience attraction or repulsion due to electrostatic forces, van der Waal forces, matric suction, and biochemical forces (Simon and Collison, 2001). At a streambank with mostly homogenous soils where strength and erodibility parameters are constant with depth, the erosion rate can be calculated by determining the excess shear stress acting along the bank.

Mechanical Slope Failure

The mechanical, or geotechnical slope stability depends on the geometry of the slope, the shear strength and unit weight of the constitutive soil, water conditions near the slope, and external loading or reinforcement. The geometry of the slope in this application equates to the height and the angle of inclination of the streambank. Shear strength, τ' is determined by the effective normal stress σ_n' applied to the shear plane, and soil parameters of effective cohesion c', and effective friction angle ϕ'. Shear strength is expressed by the Mohr-Coulomb equation (Coulomb, 1776) for shear strength:

$$\tau' = \sigma_n' \tan\phi' + c' \qquad [2.1]$$

where the normal stress acting in the vertical plane on a point at depth z in a soil with unit weight γ is given by:

$$\sigma_n = \gamma z \qquad [2.2]$$

The presence of groundwater decreases the shear strength of the soil. Loading is conveyed to the water present in the void spaces of the soil which generates pore water pressure. Pore water pressure u decreases the soil strength by reducing the total normal stress:

$$\sigma_n' = \sigma_n - u \qquad [2.3]$$

which reduces the frictional component of the shear strength (Terzaghi, 1943). Water in the channel exerts confining pressure on the slope and influences the groundwater level in the streambank. External loading or reinforcement applied to the slope include buildings, roadways, vegetation, machinery, or other structural elements.

Methods to Assess Streambank Stability

Channel Evolution Model (CEM)

The CEM is a simple process depiction which describes stages of channel morphology following channelization (straightening) of a formerly meandering stream (Booth and Fischenich, 2015). In Stage II, channelization reduces the stream length thus increasing the slope of the reach and inducing greater shear stress along the channel interface. Stage II shows the effect of increased shear stress where bank erosion leads to bed degradation and incision. Both degradation and widening occur in Stage III as mechanical mass failures occur due to high and steep banks generated in the previous stage. In Stage V, the increase in cross sectional area of the channel slows flow and promotes particle settling, or aggradation, along the channel bed. In Stage VI, an equilibrium state is reached. Although the CEM is not a quantitative model, it is useful to gain a conceptual understanding of fluvial geomorphology and predict future changes to a reach if the current stage can be determined. For instance, if a channel is undergoing degradation it could be assumed to be in Stage III of the CEM, indicating channel widening is likely to occur next.

Bank Hazard Erosion Index (BEHI)

The BEHI was developed by Rosgen (1998) to rank the severity of streambank erosion and predict future bank instability. BEHI does not directly evaluate mechanical slope stability, although bank height and slope angle are incorporated into the metrics of the index. Rather, BEHI is an observational assessment of streambank properties such as soil material, stratigraphy, root depth, bankfull height, geometry, and surface cover (Newton and Drenten, 2015). Risk ratings range from 1 to 10, with 10 being the worst condition. BEHI may have useful applications in small-scale projects where simple measures can be employed to reduce bank instability.

Geotechnical Slope Stability Analysis

Slope stability is most commonly assessed by the limit equilibrium (LE) method, which results in a factor of safety (FS) against slope failure (Abramson et al., 2002). Stability analysis with LE involves calculation of forces and moments along a rotational slip surface, with the FS calculated as the ratio of forces resisting motion to forces driving motion along the failure plane (US Army Corps, 2003). Resisting forces at a given streambank include soil shear strength, confining water pressure exerted by the stream and any reinforcements such as plant roots or structural elements. Positive pore water pressure acts to reduce resisting forces by decreasing frictional resistance thereby lowering the effective shear strength (Duncan et al., 2014), while negative pore water pressure has been found to increase shear strength due to matric suction (Simon et al., 2000). Forces driving streambank failure include weight of the soil mass corresponding to the soil bulk density and the geometry of the bank, weight of the groundwater within the soil, and external loading applied to the slope.

Many LE analysis techniques have been developed, all of which assume a failure surface and account for either force equilibrium, moment equilibrium or a combination of the two. Widely accepted methods include Bishop's Modified, Janbu's Generalized, Morgenstern and Price, and Spencer's method (Duncan, 1996). The advent and ultimate ubiquity of personal computers has allowed slope stability analysis to be conducted quickly and with relative ease as compared to hand calculations (Duncan, 2013). Because of this development, many LE techniques can be applied in a single evaluation, allowing FS to be compared and assessed.

Duncan's (1996) work to compare the analysis techniques found an average of 12 percent difference between FS, suggesting fair reliability regardless of the technique selected.

Since the FS represents a margin of safety against slope failure, additional context is needed to interpret streambank stability. A FS less than 1 indicates instability, predicts imminent failure, and implies a necessity for remediation (Duncan et al., 2014). For FS above 1, stability determinations are dependent on the application (US Army Corps, 2003). In situations where loss of life and property would be catastrophic, a higher FS is required, but in locations where failure consequences are immaterial, a lower FS may be used. Some precedence exists for streambank applications, with general agreement that a FS value of 1.3 is acceptable in design and practice (USDA, 2007).

Streambank Stabilization

Stabilization of streambanks is typically an explicit or implied goal of stream restoration. Natural channel design principles dictate the use of a stable reference reach, which exhibits stable banks and other desirable channel features as a basis for design (Rosgen, 1998). When a channel is unstable due to hydrologic processes, sediment transport capacity and supply should be examined to understand the underlying cause of degradation. For instance, a decrease in shear stress along the bank could be achieved by reducing the channel slope or increasing channel roughness. Roughness can be increased by addition of vegetation or channel bed and streambank materials could be supplemented with larger diameter stones and rock, which also increase resistance to erosion.

Mechanical stability can be achieved through numerous means depending on the constraints and criteria of a restoration project. The most obvious tactic is the alteration of streambank geometry to reduce the bank slope angle, although this approach requires heavy construction and may disrupt the ecology of the stream. Another method to increase stability is the use of toe armoring with rocks or rip-rap, which act to protect the toe and add resisting force against rotational failure. Geotextile fabrics or structural elements like tie-backs and soil nails may be used to increase the shear strength of weak soils. Vegetation with dense root systems can add stability to soil, but research has shown the effects on slope stability to be marginal (Krzeminska et al., 2019).

Conclusions

Streambank instability is a complex problem that requires understanding of fluvial geomorphology, geotechnical soil mechanics, and hydrology. Evaluation of stability must consider both erosion from hydraulic forces and mechanical mass failures. Since processes at and near the streambank occur simultaneously a feedback loop can evolve, adding complexity to the problem. Careful and systematic examination of the hydraulic and mechanical processes can help to inform design of stable streambanks. A combination of geotechnical and channel morphology assessments can be used to inform design choices and watershed planning. Future work should focus on refining existing knowledge and developing a standardized method for streambank stability evaluation.

CHAPTER 3: SLOPE STABILITY ANALYSIS OF A SATURATED RIPARIAN BUFFER: A CASE STUDY

Modified from a paper published in the Proceedings of the Geo-Congress 2020: Geo-Systems, Sustainability, Geoenvironmental Engineering, and Unsaturated Soil Mechanics.

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Abstract

A relatively new solution to reduce nitrate export from agricultural drainage is to use existing riparian buffer zones along the field edge as media to provide storage volume by distributing drainage water to saturate the soil, commonly referred to as a "saturated riparian buffer" (SRB). Though previous research has proven the effectiveness of SRBs to reduce nitrate export, uncertainties about long-term impacts prevent widespread adoption of the practice. One significant uncertainty is the stability of the streambank after saturation, raising concerns about slope instability and erosion. Current design standards use conservative guidelines for minimum buffer width and maximum bank height to prevent bank failure from occurring, thereby limiting site eligibility for installation of SRBs. This study investigated the impact of SRB design parameters on the stability of the streambank at a site in Hamilton County, Iowa. Installation of the SRB did not substantially decrease the factor of safety against failure. Additionally, our model shows that a moderate reduction in buffer width decreases the factor of safety but does not lead to slope failure.

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Introduction

Nitrate exported via agricultural subsurface drainage is a major contributor to excessive nutrient concentrations found in surface waters. As much as 50% of the cropland in the U.S. Midwest has subsurface drainage (Kalita et al., 2007), which lowers the groundwater table to provide a well-aerated root zone for optimal corn and soybean production. Nitrate loss within subsurface drainage under conventional corn-soybean agricultural practices is typically high, with nitrate-nitrogen concentrations up to 40 mg L^{-1} observed in Iowa (Jaynes et al., 2001). Nitrate rich water exported via drainage degrades the quality of the receiving stream and contributes to downstream hypoxic zones.

Interest in preventing adverse effects of nutrient export led to the development of conservation practices aimed at reducing nitrate concentrations in water leaving croplands. A saturated riparian buffer (SRB) is a conservation practice installed along a field edge that routes drainage water through the soil beneath perennial vegetation in a riparian zone to allow denitrification and plant uptake to occur. Drainage water is intercepted by a water control structure and discharged into the soil through an underground distribution pipe. Use of the practice in Iowa has steadily increased since its introduction in 2010. Because SRBs cost less to install than most other conservation practices (Jaynes and Isenhart, 2014) and require little to no maintenance, they are an attractive option for farmers wishing to incorporate a conservation practice on their land.

A site suitable for an SRB would include a nearby stream or drainage channel, an existing or proposed vegetated riparian buffer between the field and stream, and suitable soils. Soils ideal for SRB placement must have sufficient organic matter and a restrictive layer to prevent water from leaching vertically rather than horizontally toward the receiving stream or channel. SRBs function best when site conditions allow the drainage water to maintain contact with rich organic soils near the surface and have sufficient residence time to allow denitrification to occur (Jaynes and Isenhart, 2014). The water level in the buffer is governed by use of an outlet control structure with flashboards, which can be adjusted based on site conditions. Up to 22% of drained cropland in the U.S. Midwest is appropriate for treating drainage water with SRBs, totaling 75,520 km of streambanks (Chandrasoma et al., 2019).

Though past research has shown that SRBs effectively reduce nitrate export from agricultural drainage, many questions about their design and long-term impacts remain. Currently, U.S. Department of Agriculture Natural Resources Conservation Service (USDA NRCS) design guidance Code 604 stipulates SRBs must be placed on a buffer with at least a 9.1 m width and shall not be installed at sites with an incised channel depth greater than 2.4 m without additional geotechnical investigation (USDA, 2016). These criteria aim to prevent slope failure due to installation of the SRB by enforcing conservative limits on the design. SRBs artificially elevate groundwater; therefore, it is important to study their effect on the slope stability of the streambank.

Slope stability depends on factors including soil shear strength, height of the slope, angle of inclination, porosity, unit weight of soil, hydraulic conductivity, and degree of saturation. Drainage of groundwater is often recommended to improve stability (Crosta and di Prisco, 1999; Simon et al., 1999), but no geotechnical studies have been identified for sites where soil is intentionally saturated. Because of the coupled effect of soil strength reduction and groundwater seepage on slope stability, both mechanisms must be incorporated into the analysis.

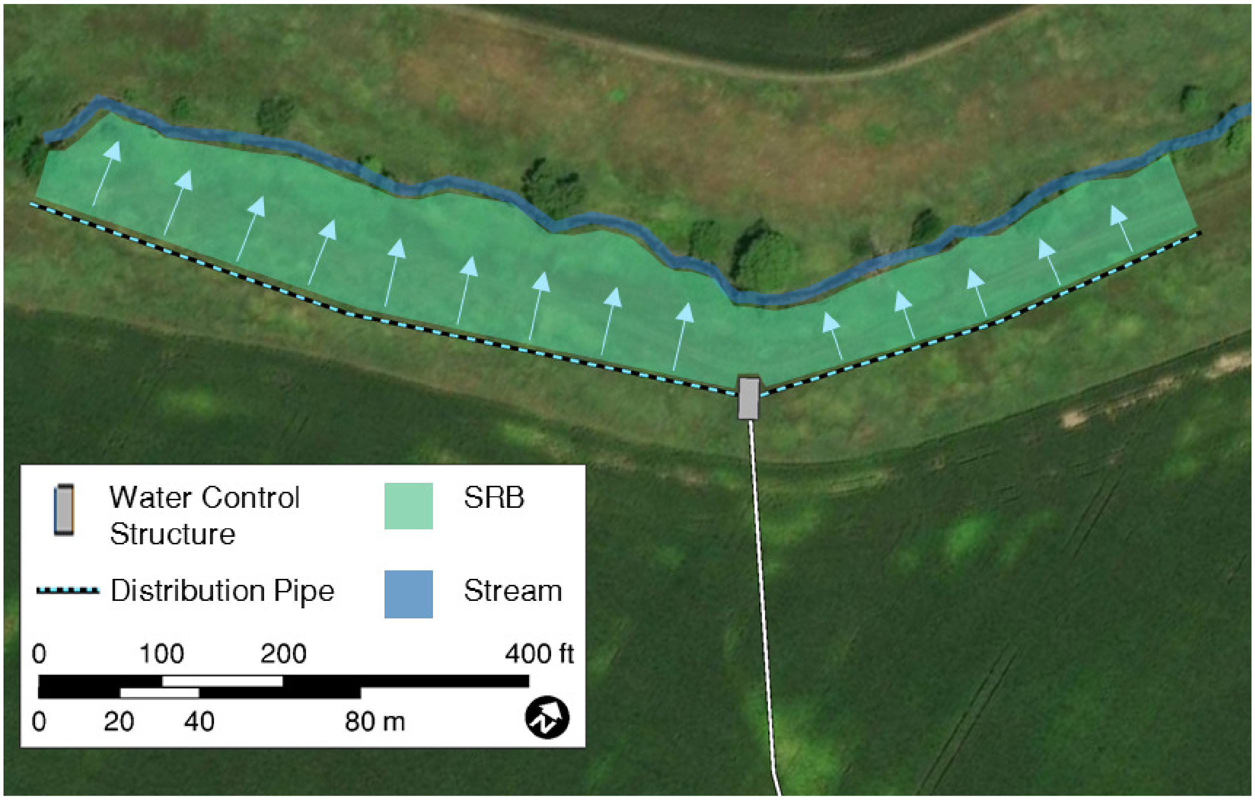
This research investigates the slope stability at an SRB site located in central Iowa. The site was selected because the incised depth of the stream channel is 2.8 m, greater than the 2.4 m maximum prescribed by NRCS Code 604. Groundwater seepage and slope stability were modeled using a finite element modelling software to solve for factor of safety against slope failure. Several conditions were modelled to examine SRB design elements and investigate questions about the effect of SRBs on slope stability.

Methods

Site Description

The site examined in this analysis is located along an unnamed tributary of the South Skunk River in Hamilton County, IA. The SRB was installed in 2013, and it measures an average width of 24 m with a distribution pipe length of 308 m (Figure 3.1). The 10 cm diameter distribution pipe was installed at a depth of 0.76 m below the soil surface. Adjustable boards in a water control structure set the water table elevation in the SRB. The site receives an average of 145 days with flow per year and has a removal rate of 84% of nitrate entering the SRB (Jaynes and Isenhart, 2018). Soils at the site were characterized as predominantly clay loam according to the USDA soil taxonomy system. A pollinator mix of CP42 was planted on top of the SRB as specified by NRCS Code 604 (USDA, 2016).

To model the behavior of the SRB, data was collected through surveying, slug testing, soil boring, and installation of groundwater level monitoring equipment. Elevations obtained from the survey showed a maximum incised channel depth of 2.8 m with the slope of the bank varying along the stream. Because of wet conditions during temperate months, a limited number of soil cores were collected, with most being of poor quality. Monitoring of groundwater levels provided daily data at a sample rate of every 3 hours, and stream level monitoring data were used to estimate an average stream stage of 1.0 m.



Imagery © 2019 DigitalGlobe, Inc.
Figure 3.1 Study site in Hamilton County, Iowa.

Model Overview

Seepage, groundwater flow, and slope stability were modelled using Geo-Studio SEEP/W and SLOPE/W softwares from Geo-Slope International Ltd. SEEP/W applies Darcy's law to govern groundwater flow in saturated soils, while in unsaturated soils, flow is governed by the relationship between volumetric water content and pore water pressure. Input requirements include soil stratigraphy, topography or geometry of the area of interest, soil material characteristics, and boundary conditions (Krahn, 2004). Once the groundwater flow and seepage are characterized, slope stability can be analyzed with SLOPE/W from Geo-Slope International Ltd. SLOPE/W calculates the factor of safety against slope failure by applying equations of limiting static equilibrium upon segments of soil. The analysis, known as the method of slices, calculates a factor of safety equivalent to the reduction in soil strength necessary to create a state of limiting equilibrium at the slip surface. The robust Morgenstern-Price method calculates interslice interactions, producing accurate results for slopes with complex seepage geometries (Krahn, 2004). Localized variability in soil strength is calculated within the model by use of modified Mohr-Coulomb soil strength theory (Krahn, 2004). Input parameters include soil stratigraphy, seepage forces, pore water pressure conditions, soil cohesion and internal friction angle, and slope geometry.

A simplified 2D model of the site was created using GeoStudio 2019 SEEP/W and SLOPE/W packages. First, site geometry obtained from the topographic survey was input to create a parent model representing transient seepage. A single material layer was used because information about soil layers at the site was not available. A secondary slope stability model was created using SLOPE/W with geometry and groundwater conditions obtained from the SEEP/W parent model. The slope modeled was 2.8 m high with a 45 degree angle of inclination, representing the steepest face of the stream bank at the site. The default mesh element size of 1 m was retained for analysis.

Soil properties used in the model are a combination of results from field testing and published data for similar Iowa soils (Table 3.1). Hydraulic properties used in SEEP/W were obtained from slug tests and soil analysis to determine saturated hydraulic conductivity and saturated water content. SEEP/W's internal volumetric water content and hydraulic conductivity functions were used to estimate unsaturated soil properties. Material properties used in SLOPE/W were found by reviewing published data for Iowa glacial tills and selecting low values within the range as a conservative estimate (Lohnes et al., 2001). Soil properties were assumed to be homogeneous and isotropic in the analysis.

Table 3.1 Dominant soil material and hydraulic properties.

USDA Texture	USCS Texture	Unit Weight	Cohesion	Friction Angle	Saturated Hydraulic Conductivity	Saturated Water Content
Clay Loam	CL	15 kN m^{-3}	5 kPa	26°	5.0×10^{-6} m s^{-1}	0.4

Model Conditions

First, a “natural” groundwater condition model was developed to assess slope stability at the site before installation of the SRB (Figure 3.2a). The natural water table elevation was estimated using an approximate depth of 1.8 m below the surface obtained from measurements of baseflow elevation in the stream. Although the actual depth of the groundwater table fluctuates, only one steady state condition was considered in the analysis. Constant head boundary conditions were used to represent the water table and the water level in the stream. The stream was modeled at a constant depth of 1.0 m, based on stream stage data obtained from the site. A SEEP/W analysis was conducted using these conditions, followed by a SLOPE/W analysis using the Morgenstern-Price method option.

Next, groundwater conditions were altered to represent the elevated water table at the site with the SRB, as set by the water control structure (Figure 3.2b). To ensure the most conservative results, the water table was assumed to be at or near the surface directly above the distribution pipe. This assumption was made to allow for additional water potentially infiltrating from precipitation above the SRB to be included in the analysis. A constant head boundary condition was applied at the surface directly above where the SRB distribution pipe would be located. A potential seepage face water flux boundary condition was applied to analyze for seepage along the bank face. The stream depth condition from the previous analysis was retained. With these conditions, the SEEP/W and SLOPE/W modules were run using the Morgenstern-Price method for slope stability analysis.

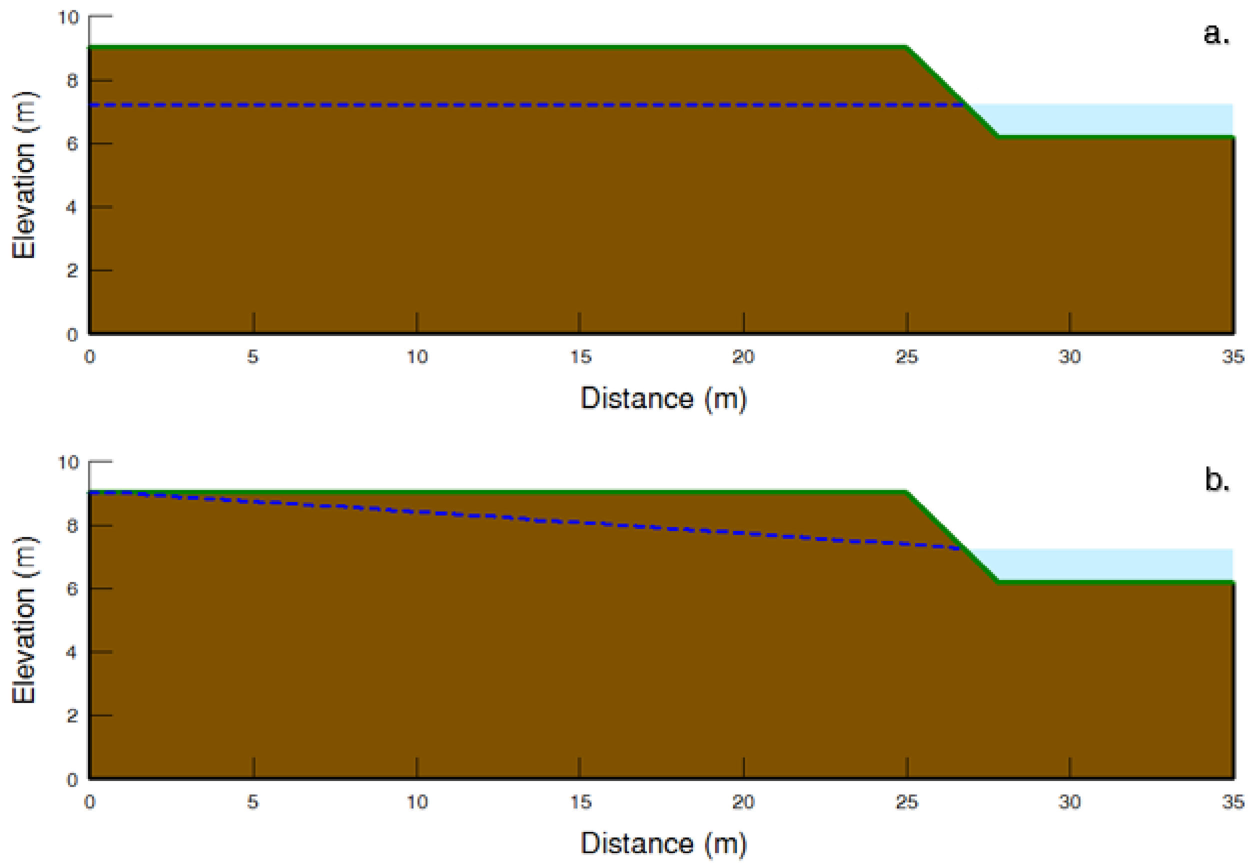


Figure 3.2 Slope stability model: a. Natural groundwater condition without SRB, b. SRB groundwater condition.

A parametric analysis was conducted to determine the effect of the width of the SRB on slope stability. The width of the SRB is equivalent to the distance from the distribution pipe to the stream. The average width at the study site is 24 m, which is larger than the NRCS Code 604 standard minimum width of 9.1 m (USDA, 2016). To assess the impact of reducing the width, the distribution pipe was incrementally moved closer to the stream in the model. Simulation of the narrower SRB was achieved by applying the constant head boundary condition for the distribution pipe at varying distances from the stream bank and running the SEEP/W and SLOPE/W modules.

Results and Discussion

Factors of safety were obtained for the “natural” condition with no SRB and the conditions with the SRB present. The factors of safety for the various configurations used in the parametric study were obtained and plotted against the distance of the hypothetical distribution pipe from the stream (Figure 3.3). The highest factor of safety, 1.62, was found to occur with the no-SRB condition. The lowest factor of safety found was 0.97, which occurred when the distribution pipe was located nearest to the streambank.

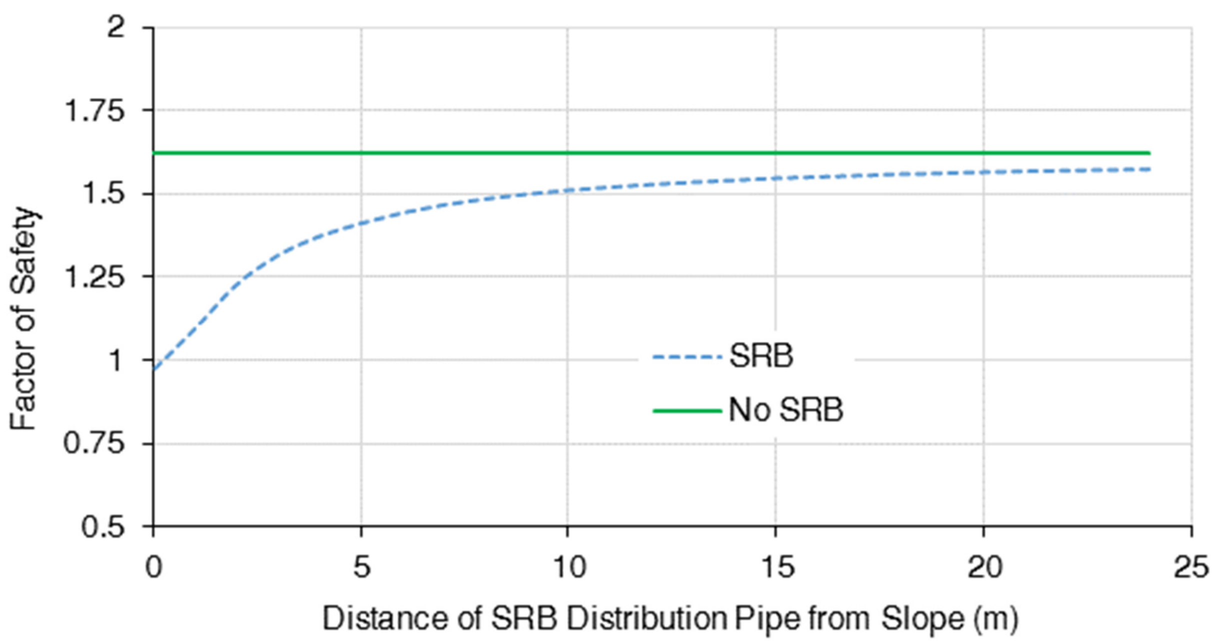


Figure 3.3 Factor of safety versus SRB width as compared to natural conditions.

While the SRB reduces slope stability, the effect is not enough to cause the slope to fail at this site. This finding corresponds to conditions at the site as the SRB has been in operation for 6 years under various flow conditions with no slope failure observed. When the distribution pipe was modeled at locations greater than 3 m away from the slope, the factor of safety was above

1.3, which is the threshold for slopes with low consequences of failure (Lohnes et al., 2001). The factor of safety for an SRB decreases by about 3% from the "natural" condition with no SRB, a relatively low value. In the worst case, with the distribution pipe placed very close to the stream, the factor of safety is 40% smaller than that for the "natural" condition. It is not likely that a condition with the distribution pipe placed so near the stream would ever occur in practice because nitrate removal depends on residence time as water flows through the buffer. For a more reasonable distance of 5 m, the reduction in factor of safety was found to be 13%, showing that SRBs may be installed closer to the stream where the factor of safety for the "natural" condition is large enough. The findings indicate the width of 9.1 m specified in NRCS Code 604 is overly conservative in terms of slope failure in this case.

Although the site used in this analysis has an incised channel depth greater than the maximum recommended by NRCS Code 604, the factor of safety found in the analysis indicates that placing the SRB along the deeper channel is not likely to cause slope failure. The streambank represented in the model had a depth of 2.8 m and a bank angle of 45 degrees. The interaction of the channel depth and angle of inclination was not assessed in this study, but it may play a significant role in slope stability. Further analysis of these factors would help to provide more guidance for SRB design and placement.

Conducting a slope stability analysis in order to determine the suitability of a site for an SRB is complicated by uncertainty regarding the soil properties. Several assumptions made in the analysis were conservative, with soil strength properties chosen at the low end of the known range and the SRB water table elevation assumed to be at the soil surface. The choice to model the slope as a single homogeneous and isotropic soil layer may not accurately portray conditions at the site. If additional information about soil layers becomes available, the model could be updated to fit site conditions. Explicit application of these findings to other sites may not be accurate as conditions are not likely to be the same elsewhere; however, general tendencies of groundwater and slope stability behavior at SRB sites may be inferred.

Conclusions

The SRB at a site in Hamilton County, IA does not greatly increase the likelihood of slope failure caused by artificial elevation of the water table. The reduction in the factor of safety caused by installation of the SRB at the site in 2013 is negligible. Predictably, placement of the SRB very close to the streambank does cause a greater reduction in the factor of safety, but this scenario is very unlikely to occur in practice. Additionally, the width of the SRB was found to moderately affect the factor of safety, but SRBs may be installed closer to the stream at sites where the "natural" condition of the slope is highly stable.

This analysis provides information about slope stability that is relevant to the soil properties, slope geometry, and assumptions used in the model. Alternative models should use the best information about soil properties and slope geometry corresponding to conditions at the site to achieve accurate findings. This study demonstrates that SRBs have a quantifiable effect on the factor of safety against slope failure and serves to provide guidelines for creating similar models to analyze slope stability at SRB sites.

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CHAPTER 4: SLOPE STABILITY ANALYSIS OF SATURATED RIPARIAN BUFFERS

Modified from a paper published in the Proceedings of the 20th Annual International Erosion Control Association Environmental Connection 2020 Conference.

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Abstract

A relatively new solution to reduce nitrate export from agricultural drainage is to use existing riparian buffer zones along the field edge as media to provide storage volume by distributing drainage water to saturate the soil, commonly referred to as a "saturated riparian buffer" (SRB). Though previous research has proven the effectiveness of SRBs to reduce nitrate export, uncertainties about long-term impacts prevent widespread adoption of the practice. One significant uncertainty is the stability of the streambank after saturation, raising concerns about slope instability and erosion. Current design standards use conservative guidelines for minimum buffer width and maximum bank height to prevent bank failure from occurring, thereby limiting site eligibility for installation of SRBs. This study investigated the impact of SRB design parameters on the streambank stability at five sites in central Iowa. Four of the five sites were found to have an adequate factor of safety against failure, and while the fifth site was unstable, the bank failure was not likely to be caused by installation of the SRB. Additionally, our model shows that a reduction in SRB width decreases the factor of safety but does not lead to slope failure.

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Introduction

Nitrate exported via agricultural subsurface drainage is a major contributor to excessive nutrient concentrations found in surface waters (Goolsby et al., 2001). As much as 50% of the cropland in the U.S. Midwest has subsurface drainage (Kalita et al., 2007), which lowers the groundwater table to provide a well-aerated root zone for optimal corn and soybean production. Nitrate loss within subsurface drainage under conventional corn-soybean agricultural practices is typically high, with nitrate-nitrogen concentrations up to 40 mg L^{-1} observed in Iowa (Jaynes et al., 2001). Nitrate rich water exported via drainage degrades the quality of the receiving stream and contributes to downstream hypoxic zones.

Interest in preventing adverse effects of nutrient export led to the development of conservation practices aimed at reducing nitrate concentrations in water leaving croplands. A saturated riparian buffer (SRB) is a conservation practice installed along a field edge that routes drainage water through the soil beneath perennial vegetation in a riparian zone to allow denitrification and plant uptake to occur. Drainage water is intercepted by a water control structure and discharged into the soil through an underground distribution pipe. Use of the practice in Iowa has steadily increased since its introduction in 2010. Because SRBs cost less to install than most other conservation practices (Jaynes and Isenhart, 2014) and require little to no maintenance, they are an attractive option for farmers wishing to incorporate a conservation practice on their land.

A site suitable for an SRB would include a nearby stream or drainage channel, an existing or proposed vegetated riparian buffer between the field and stream, and suitable soils. Soils ideal for SRB placement must have sufficient organic matter and a restrictive layer to prevent water from leaching vertically rather than horizontally toward the receiving stream or channel. SRBs function best when site conditions allow the drainage water to maintain contact with rich organic soils near the surface and have sufficient residence time to allow denitrification to occur (Jaynes and Isenhart, 2019). The water level in the buffer is governed by use of an outlet control structure with flashboards, which can be adjusted based on site conditions. Researchers have estimated that approximately 22% of drained cropland in the U.S. Midwest is appropriate for treating drainage water with SRBs, totaling 75,520 km of streambanks (Chandrasoma et al., 2019).

Though past research has shown that SRBs effectively reduce nitrate export from agricultural drainage (Jaynes and Isenhart, 2019), many questions about their design and long-term impacts remain. Currently, U.S. Department of Agriculture Natural Resources Conservation Service (USDA NRCS) design guidance Code 604 stipulates SRBs must be placed on a buffer with at least a 9.1 m width and shall not be installed at sites with an incised channel depth greater than 2.4 m without additional geotechnical investigation (USDA, 2016). These criteria aim to prevent slope failure due to installation of the SRB by enforcing conservative limits on the design. SRBs artificially elevate groundwater; therefore, it is important to study their effect on the slope stability of the streambank.

Slope stability depends on factors including soil shear strength, height of the slope, angle of inclination, unit weight of soil, hydraulic conductivity, and degree of saturation. Stability is often expressed in terms of the factor of safety (FS) against failure, which is calculated by determining the ratio of resisting to driving forces in a rotational failure surface along the slope. Drainage of groundwater is often recommended to improve stability (Crosta and di Prisco, 1999; Simon et al., 1999), but no geotechnical studies have been identified in the literature for sites where the soil is intentionally saturated. Because of the coupled effect of soil strength reduction and groundwater seepage on slope stability, both mechanisms must be incorporated into the analysis.

This research investigates the slope stability at SRB sites located in central Iowa. Five sites with varying slope geometries, stream conditions, soil properties, and buffer widths were studied. Groundwater seepage and slope stability were modeled using a finite element and limit equilibrium modelling software to solve for the FS against slope failure. Several conditions were modelled to examine SRB design elements and investigate questions about the effect of SRBs on slope stability.

Methods

Site Descriptions

The five SRBs examined in this analysis represent a range of design conditions. The sites are located in central Iowa (Figure 4.1). Each SRB consists of a 10 cm distribution pipe installed parallel to the stream approximately 0.75 m below the soil surface. Adjustable boards in a water control structure set the water table elevations in the SRB to ensure the water comes in contact with the carbon rich soils near the ground surface. Flow from the field tile enters the water control structure where it is diverted into the distribution pipe and subsequently enters the soil as shallow groundwater flowing toward the stream (Figure 4.2). Soils at the sites were characterized as predominantly clay loams according to the USDA soil taxonomy system. Geology of all five sites indicates glacial till as the underlying soil parent material. A pollinator mix of CP42 was planted on top of the SRBs as specified by NRCS Code 604 (USDA, 2016).

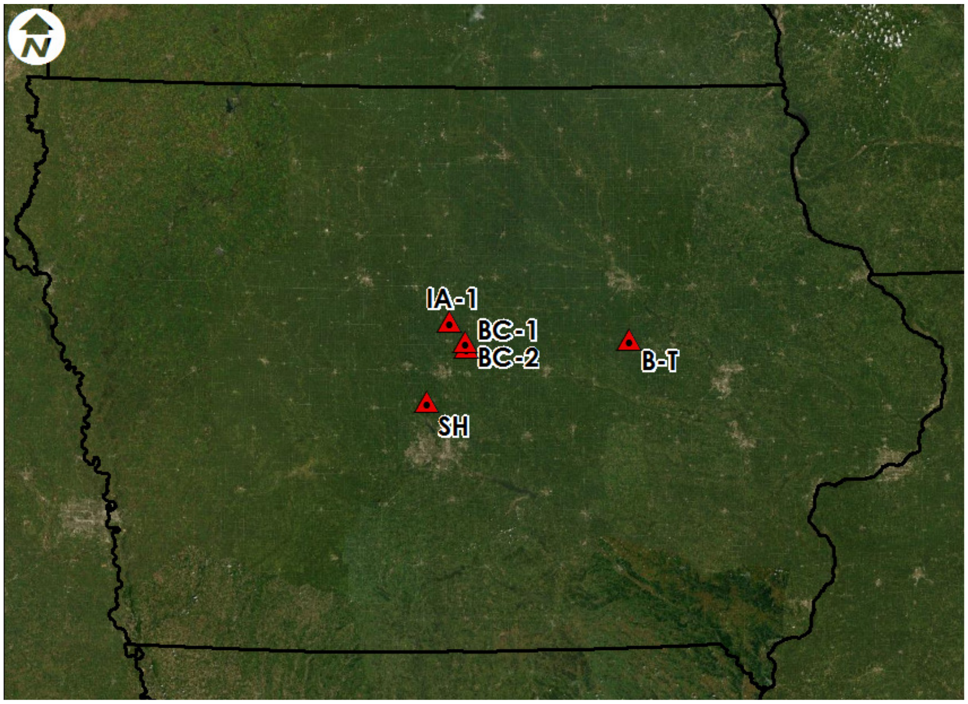

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Figure 4.1 SRB study sites in central Iowa.

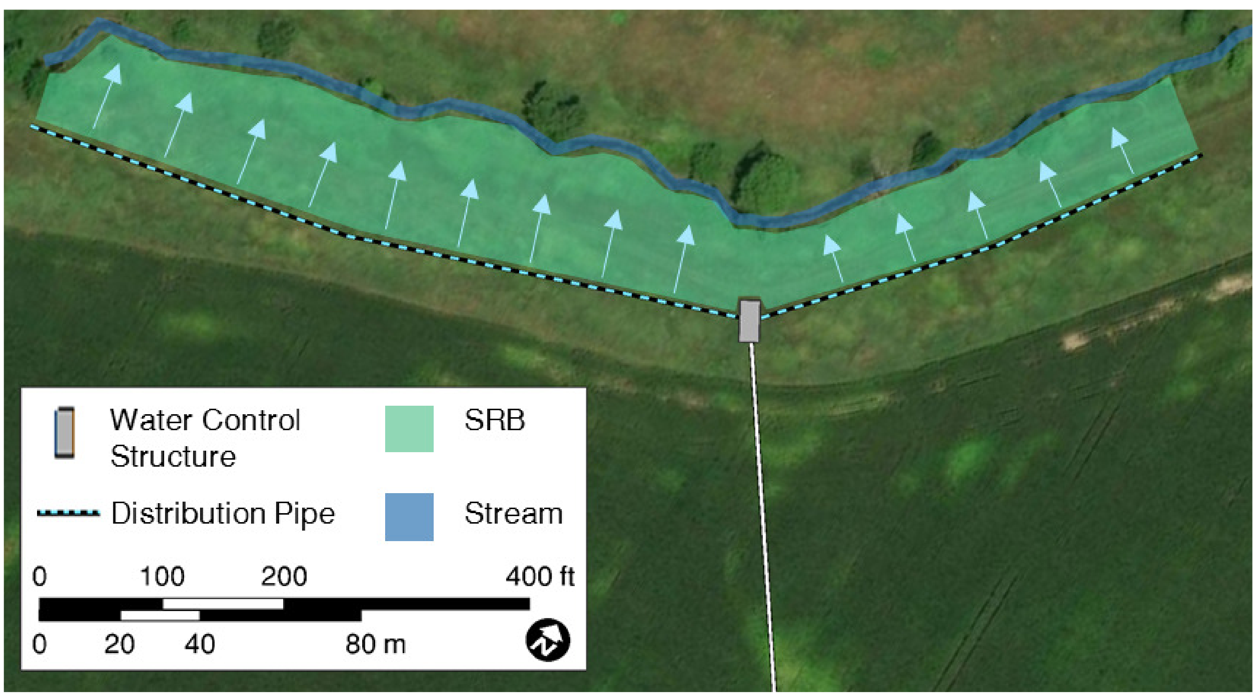

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Figure 4.2 Typical SRB configuration in Hamilton County, Iowa.

Table 4.1 Study site characteristics.

Site Name	SRB Width (m)	Bank Height (m)	Slope Angle (˚)	Distribution Pipe Length (m)	USDA Soil Texture
BC-1	21	2.1	25.0	305	Coland clay loam
BC-2	22	2.6	69.0	168	Spillville-Coland complex
B-T	10	0.9	52.5	115	Colo silty clay loam
IA-1	24	2.3	47.3	308	Coland-Terril complex
SH	21	2.0	13.2	266	Coland-Spillville complex

To model the behavior of the SRBs, data were collected through surveying, slug testing, soil boring, installation of groundwater level monitoring equipment (Table 4.1). Soil textures were acquired from the USDA's Web Soil Survey database. Elevations obtained from the survey were used to create profiles of the maximum streambank sections at each site. Because of wet conditions during temperate months, a limited number of soil cores were collected, with most being of poor quality. Monitoring of groundwater levels and the stream stage provided daily hydraulic head data at a sample interval of every 3 hours.

Model Overview

Seepage, groundwater flow, and slope stability were modelled using Geo-Studio SEEP/W and SLOPE/W softwares from Geo-Slope International Ltd. SEEP/W applies Darcy's law to govern groundwater flow in saturated soils, while in unsaturated soils, flow is governed by the relationship between volumetric water content and pore water pressure. Input requirements include soil stratigraphy, topography or geometry of the area of interest, soil material characteristics, and boundary conditions (Krahn, 2004). Once the groundwater flow and seepage are characterized, slope stability can be analyzed with SLOPE/W from Geo-Slope International Ltd. SLOPE/W evaluates slope stability by applying equations of limiting static equilibrium upon segments of soil. The analysis, known as the method of slices, calculates a FS equivalent to the reduction in soil strength necessary to create a state of limiting equilibrium at the slip surface. The robust Morgenstern-Price method calculates interslice interactions, producing accurate results for slopes with complex seepage geometries (Krahn, 2004). Localized variability in soil strength is calculated within the model by use of modified Mohr-Coulomb soil strength theory (Krahn, 2004). Input parameters include soil stratigraphy, seepage forces, pore water pressure conditions, soil cohesion and internal friction angle, and slope geometry.

Simplified 2D models of the sites were created using GeoStudio 2019 SEEP/W and SLOPE/W packages. First, site geometry obtained from the topographic survey was input to create a parent model representing transient seepage. A single material layer was used because information about soil layers at the sites was not available. A secondary slope stability model was created using SLOPE/W with geometry and groundwater conditions obtained from the SEEP/W parent model. The default mesh element size of 1 m was retained for analysis.

Soil properties used in the models are a combination of results from field testing and published data for Iowa soils of the same geologic parent material (Table 4.2). Hydraulic properties used in SEEP/W were obtained from slug tests and soil analysis to determine saturated hydraulic conductivity and saturated water content. SEEP/W's internal volumetric water content and hydraulic conductivity functions were used to estimate unsaturated soil properties. Material properties used in SLOPE/W were found by reviewing published data for Iowa glacial tills and selecting low shear strength values within the range as a conservative estimate (Lohnes et al., 2001). Soil strength properties were assumed to be homogeneous and isotropic in the analysis.

Table 4.2 Soil properties used in slope stability analysis.

Geologic Parent Material	Unit Weight	Cohesion	Friction Angle
Glacial Till	15 kN m^{-3}	3 kPa	27°

Model Conditions

First, models were developed to assess slope stability of the SRBs in the as-built condition (Figure 4.3). Constant head boundary conditions were used to represent the elevated water table at the sites, as set by the water control structure. To ensure the most conservative results, the water table was assumed to be at or near the surface directly above the distribution pipe. This assumption was made to allow for additional water potentially infiltrating from precipitation above the SRB to be included in the analysis. A potential seepage face water flux boundary condition was applied to analyze for seepage along the bank face. The stream was modeled at a constant depth, based on stream stage data obtained from monitoring equipment at the sites. A SEEP/W analysis was conducted using these conditions, followed by a SLOPE/W analysis using the Morgenstern-Price method option.

A parametric analysis was conducted to determine the effect of the width of the SRBs on slope stability. The width of the SRB is equivalent to the distance from the distribution pipe to the stream. The average width for the study sites ranges from 10 to 24 meters, which is larger than the NRCS Code 604 standard minimum width of 9.1 m (USDA, 2016). To assess the impact of reducing the width, the distribution pipe was incrementally moved closer to the stream in each site model. Simulation of smaller SRB widths was achieved by applying the constant head boundary condition for the distribution pipe at varying distances from the stream bank and running the SEEP/W and SLOPE/W modules.

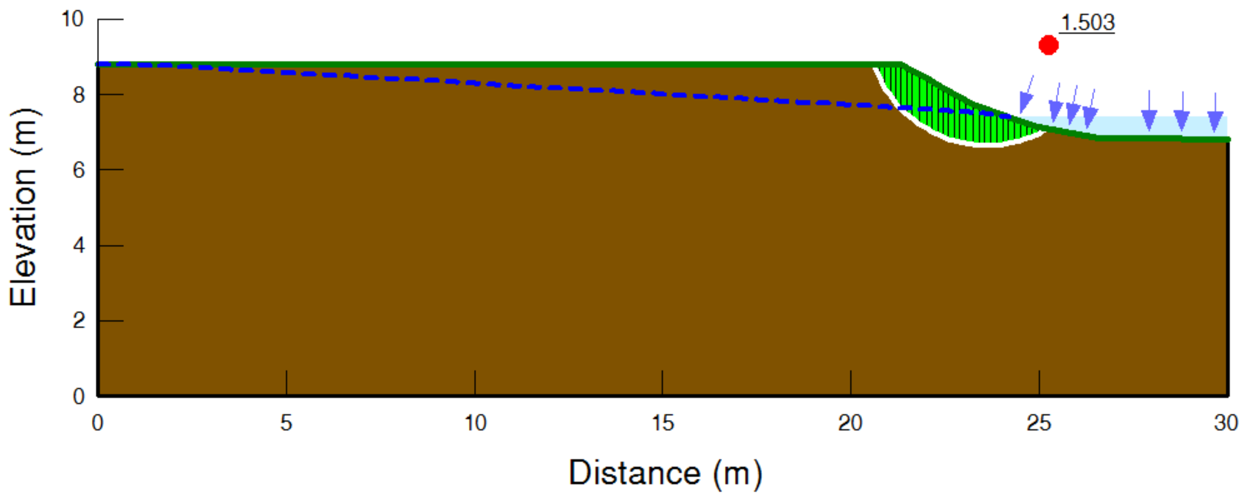

Figure 4.3 Typical SRB slope stability model. The blue line signifies groundwater flow to the stream from the SRB, the green circle represents the failure slip surface, and the red dot signifies the FS against failure.

Results and Discussion

Slopes become less stable as the buffer width decreases (Figure 4.4). The acceptable threshold FS for natural slopes with minimal consequences of failure is 1.3 at worst-case conditions (Lohnes et al., 2001). A general trend of decreasing slope stability as the distribution pipe is moved closer to the stream is observed, with FS falling below the minimum when the pipe is modeled very close to the stream.

While the SRBs influence slope stability, the effect is not enough to cause the slope to fail for all sites except BC-2. This finding corresponds to observed site conditions at BC-1, B-T, IA-1, and SH as the SRBs have been in operation for up to 6 years under various flow conditions and no slope failures have occurred. When the distribution pipes for these sites were modeled at locations greater than 3 m away from the streambank, the FS were above 1.3. The FS for all sites falls below the threshold when the distribution pipe is placed very close to the stream, signifying instability caused by the SRB. It is not likely that a condition with the distribution pipe placed so near the stream would ever occur in practice because nitrate removal depends on residence time as water flows through the buffer. For a more reasonable distance of 5 m, all sites except BC-2 have an FS above the minimum. These findings indicate that the width of 9.1 m specified in NRCS Code 604 is overly conservative in terms of slope failure at these sites.

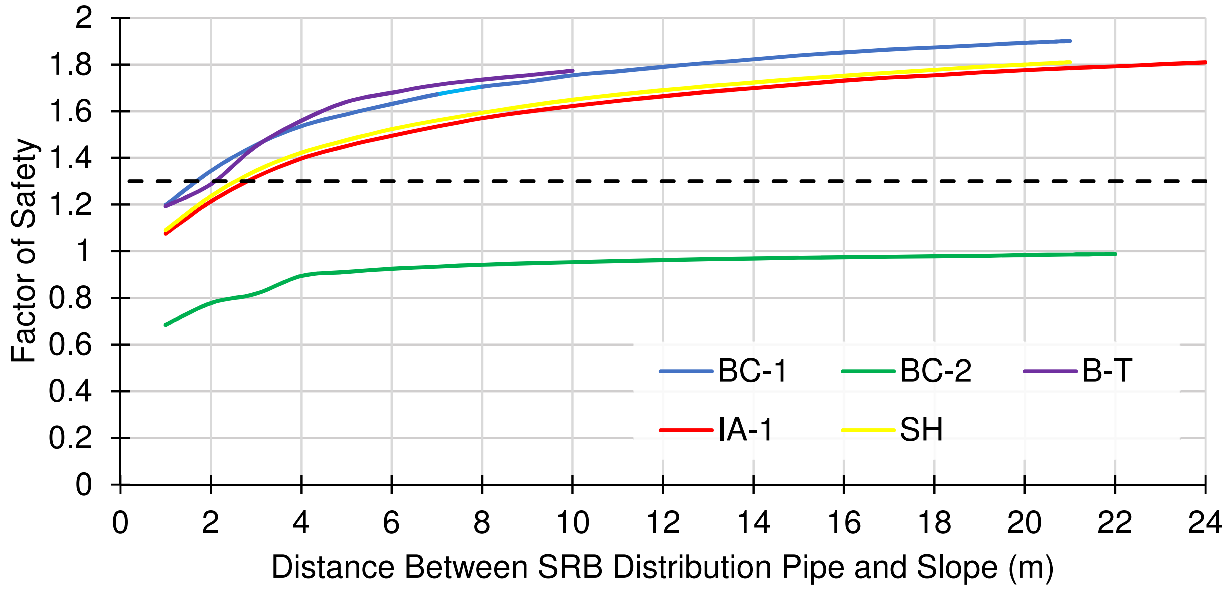

Figure 4.4 FS versus SRB width. The dotted black line signifies the threshold FS of 1.3.

Only one site, BC-2, has an incised channel depth greater than the maximum recommended by NRCS Code 604. Visual observation of conditions at BC-2 indicates instability of the streambank with downcutting and bank incision occurring during the study period. The bank at the site is steep with a slope angle of 69˚, and when combined with the relatively large bank height of 2.6 m the model shows an FS below 1 for all SRB design conditions. In fact, a bank failure at the site was recorded in spring 2019, verifying the model results. Geomorphology of the site suggests the stream may be in Stage 4 of the Channel Evolution Model, corresponding to degradation and widening of the channel caused by fluvial processes (Simon and Rinaldi, 2006). Additional modeling of the slope at this site results in an FS below 1 for conditions with no groundwater flow, confirming instability at the site is not caused by the SRB.

Conducting a slope stability analysis in order to determine the suitability of a site for an SRB is complicated by uncertainty regarding the soil properties. Several assumptions made in the analysis were conservative, with soil strength properties chosen at the low end of the known range and the SRB water table elevation assumed to be at the soil surface. The choice to model the slopes as a single homogeneous and isotropic soil layer may not accurately portray conditions at the sites. If additional information about soil layers becomes available, the models could be updated to fit site conditions. Explicit application of these findings to other sites may not be accurate as conditions are not likely to be the same elsewhere; however, general tendencies of groundwater and slope stability behavior at SRB sites may be inferred.

Conclusions

Four of the five sites evaluated in this study have a low likelihood of slope failure with the as-built SRB. SRB widths smaller than the minimum required in Code 604 were modeled and found to be stable when greater than 3 m. Predictably, placement of the distribution pipe very close to the streambank creates an unstable condition, but this scenario is very unlikely to occur in practice. Additionally, the width of the SRB was found to affect the stability of the streambank, but SRBs may be installed closer to the stream at sites where the in-situ condition of the slope is highly stable.

One site, BC-2, exhibited instability for the as-built condition and all simulated SRB widths. Further investigation shows the site is unstable regardless of groundwater flow, which suggests the influence of fluvial and geomorphological processes is of greater consequence than the SRB installation. This finding emphasizes the contribution of stream dynamics as a substantial cause of streambank erosion which is not considered in the mechanical stability of the slope.

This analysis provides information about slope stability that is relevant to the soil properties, slope geometry, and assumptions used in the models. Alternative models should use the best information about soil properties and slope geometry corresponding to conditions at the site to achieve accurate findings. This study demonstrates that SRBs have a quantifiable effect on the FS against slope failure and serves to provide guidelines for creating similar models to analyze slope stability at SRB sites.

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CHAPTER 5: SLOPE STABILITY OF STREAMBANKS AT SATURATED RIPARIAN BUFFER SITES

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Modified from a manuscript to be submitted to the Journal of Environmental Quality.

Abstract

Saturated riparian buffers (SRBs) reduce nitrate export from agricultural tile drainage by infusing drainage water into carbon-rich riparian soils where denitrification and plant uptake can occur. The water quality benefits from SRBs are well documented, but uncertainties about their effect on streambank stability have led to conservative design standards that prevent widespread implementation. In this study, the relationship between SRB design conditions and streambank stability was examined through numerical slope stability modeling. A comparison of no-flow and SRB flow conditions showed the addition of SRB flow did not cause instability in 96.5% of simulated cases. The simulations provide no evidence to support excluding potential sites based on bank height alone. Dimensionless parameters identified in the analysis were used to predict the FS as a function of the SRB site and design conditions, allowing designers to assess the stability of a potential site. Results of this study alleviate the need for extensive geotechnical evaluations at future SRB sites and will help to increase the implementation of SRBs by expanding the range of eligible sites.

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Introduction

Nitrate rich water exported via agricultural tile drainage in the Midwestern United States degrades water quality and contributes to excessive nutrient concentrations in downstream surface waters. Tile drainage turns waterlogged hydric soils into well-aerated and productive cropland; however, drainage systems also facilitate the export of nitrate, which is readily leached from fertilized soils. Surface waters with high concentrations of nitrate undergo eutrophication leading to hypoxic zones that harm aquatic organisms. Most notably, an extensive hypoxic zone in the Gulf of Mexico, known as the "dead zone," is linked to nutrient export from the production of corn and soybean crops in heavily drained watersheds of the Midwest (Goolsby et al., 2001).

Strategies to reduce the export of nutrients in agricultural drainage typically focus on a combination of in-field source reduction and edge-of-field water quality treatment practices. A saturated riparian buffer (SRB) is an edge-of-field water quality treatment practice in which tile drainage water is routed through soil at the field edge adjacent to a stream or drainage ditch. SRBs use a hydraulic water control structure and perforated distribution pipe to infuse drainage water into carbon-rich soil where microbial denitrification, immobilization, and plant uptake can occur (Jaynes and Isenhart, 2014). A hydraulic gradient, governed by water level set at the control structure, is used to induce flow towards the stream where water exits after achieving adequate residence time for nitrate removal. Jaynes and Isenhart (2019) found nitrate removal effectiveness of up to 92% at SRB sites in Iowa, with an average cost of approximately $3.00 per kilogram of nitrate removed. SRBs can be incorporated into an existing riparian buffer without removing additional land from production and require little to no maintenance by landowners. The effectiveness, low cost, and limited maintenance requirements have made SRBs a desirable option for farmers looking to incorporate a water quality conservation practice on their land.

Since SRBs function by artificially elevating the groundwater level, their effect on the stability of the streambank is a concern. High groundwater levels can induce excessive pore water pressures leading to slope failure (Jia et al., 2009). Streambank failures degrade water quality and can disrupt sensitive riparian and aquatic ecosystems (Palmer et al., 2000), counteracting potential water quality improvements from the SRB. In the Upper Mississippi River Basin, streambank materials are the primary source of suspended sediment rather than upland erosion (Belmont et al., 2011), a surprising revelation that stresses the validity of concerns regarding streambank stability.

Current SRB design standards reflect these concerns by establishing conservative guidelines; the U.S. Department of Agriculture Natural Resources Conservation Service's (USDA NRCS) Saturated Buffer Conservation Practice Standard (Code 604) requires a minimum 9.1 m setback from the SRB distribution pipe to the streambank and precludes siting SRBs along streams with channels deeper than 2.4 m without an extensive geotechnical slope stability evaluation (USDA NRCS, 2016). Geotechnical evaluations are expensive and could more than double the installation cost of an SRB. These limitations, though well-intentioned, may lead to a reduction in the implementation of SRBs if otherwise suitable sites are excluded.

Streambank stability at SRB sites can be evaluated with a geotechnical slope stability analysis to determine the factor of safety (FS) against mechanical slope failure. In this application, slope stability depends on three primary elements: soil properties including unit weight γ_s and shear strength parameters of effective cohesion c' and friction angle ϕ', slope geometry from bank height h_b and slope angle θ, and seepage conditions determined from the water level h_0 set in the control structure, the width L_b of the buffer defined as the linear distance from the distribution pipe to the streambank, and the stream water level h_w (Figure 5.1). The limit equilibrium method is most commonly used to determine the FS by calculating the ratio of resisting to driving forces about a two-dimensional failure surface (Abramson et al., 2002). Resisting forces at a given streambank include soil shear strength, confining water pressure exerted by the stream, and any reinforcements such as plant roots or structural elements. Forces driving streambank failure include weight of the soil, weight of the groundwater within the soil, and external loadings applied to the slope. Although bank height is germane to slope stability, determination of the FS depends on the combination of all elements at a given site and cannot be deduced from a singular measurement.

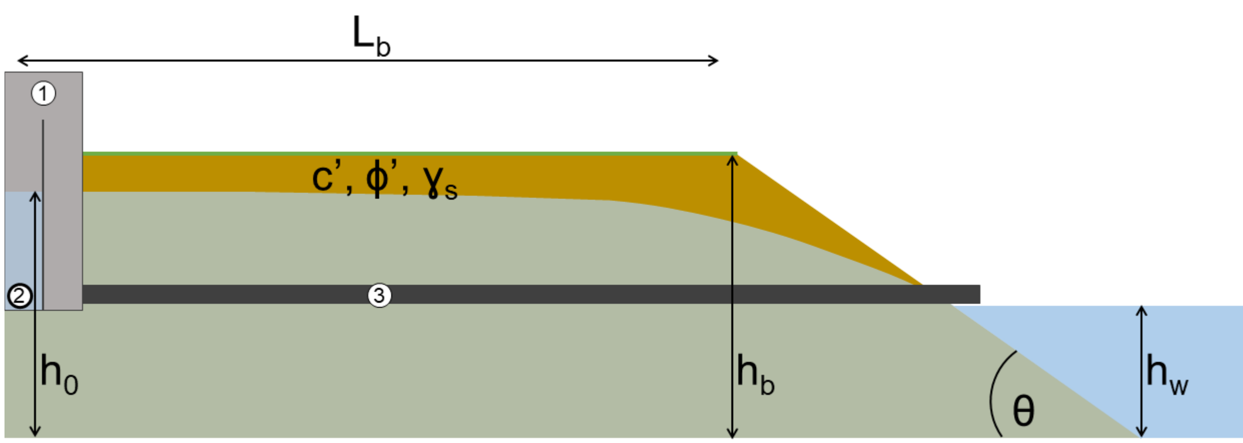

Figure 5.1 A simplified profile view of a saturated riparian buffer where the bottom of the stream channel is taken as the datum. The hydraulic control structure (1) is shown at the left edge, the distribution pipe (2) extends into the page, and the overflow outlet pipe (3) connects the control structure to the stream. The tile drainage main and field are not shown.

Pore water pressures induced near the streambank at an SRB site depend on the groundwater elevation, which is governed by the head difference between the level set by the control structure, the stream water level, and the distance between the distribution pipe and the stream. Positive pore water pressure acts to reduce resisting forces by decreasing frictional resistance, thereby lowering the effective shear strength (Duncan et al., 2014), while negative pore water pressure increases shear strength because of matric suction (Simon et al., 2000).

Work by McEachran et al. (2020a, 2020b) found flow in SRBs follows Darcy's Law and primarily travels horizontally towards the stream, therefore the groundwater level near the slope can be determined using Darcy's equations for steady one-dimensional flow.

Since the FS represents a margin of safety against slope failure, additional context is needed to interpret streambank stability at SRB sites. A FS less than 1 indicates instability, predicts imminent failure, and implies a necessity for remediation (Duncan et al., 2014). For FS above 1, stability determinations depend on the application (US Army Corps, 2003). In situations where slope failures could lead to loss of life and property, a higher FS is required, while low-risk situations may warrant the use of a lower FS. The risk to life and property at a typical SRB site is low; SRBs are located in agricultural fields devoid of structures and away from populated areas. The low risk combined with NRCS technical guidance for stream stabilization suggests that a FS equal to 1.3 is adequate at SRB sites (USDA, 2007).

In this study, the effect of SRBs on streambank stability was evaluated with the limit equilibrium method to determine the FS against slope failure. Five existing sites were examined to gain insight about typical SRB conditions and validate a simplified conceptual model. Groundwater seepage conditions generated by the SRB were compared to no-flow conditions at varying stream stages to compare stability at a site with and without an SRB. A range of potential SRB site conditions was considered to evaluate the design standards given in Code 604 and investigate conditions that cause bank instability. The results of the analysis were used in statistical analysis to create a regression equation that relates SRB design parameters to streambank stability. The implications of the results on SRB design are discussed.

Methods

Field Sites

Five existing SRB sites in central Iowa (BC-1, BC-2, B-T, IA-1, and SH) were studied to inform a conceptual model of SRB slope stability. The sites represent a range of slope geometries and seepage conditions (Table 5.1), but they are similar in basic design and function. Each SRB includes a hydraulic control structure that intercepts the tile drainage main and routes water to a 10 cm distribution pipe installed approximately 75 cm below the soil surface running parallel to the stream. The hydraulic head in the distribution pipe is set by the hydraulic control structure to ensure water encounters carbon-rich soils near the ground surface. Soils at the sites are poorly drained, free from extensive sand layers, and predominantly composed of clay loams classified under the USDA soil taxonomy system. Geology of all five sites indicates glacial till as the underlying soil parent material. Each SRB is vegetated with pollinator mix CP42 as specified in practice standard Code 604 (USDA, 2016).

Table 5.1 SRB site characteristics.

Site	θ, °	h_b, m	h_0, m	h_w, m	L_b, m	USDA Soil Texture
BC-1	25	2.10	1.80	0.42	21	Coland clay loam
BC-2	69	2.60	1.79	0.22	22	Spillville-Coland complex
B-T	53	0.95	1.66	0.47	10	Colo silty clay loam
IA-1	47	2.30	2.03	0.23	24	Coland-Terril complex
SH	13	2.00	1.70	0.11	21	Coland-Spillville complex

Site characteristics were determined through field measurements, monitoring, and review of past research. Topographic surveys conducted at each site were used to determine the SRB width, bank height, and slope angle associated with the maximum section of the streambank. Groundwater levels were monitored with pressure transducers (Solinst 3001) installed in wells located throughout the SRB. The wells were also used for slug testing to determine the saturated hydraulic conductivity of the soil, as explained in further detail by McEachran et al. (2020a). Soil boring with a hydraulic soil probe (Giddings Machine Co, Model GSRTSA) was attempted, though undisturbed samples at an adequate depth were not obtained because of field conditions during the study period. Because of the challenges obtaining undisturbed soil samples, the soil strength parameters of unit weight, effective cohesion, and friction angle were estimated from a range of published values corresponding to Iowa glacial tills (Table 5.2). A back-analysis of a slope failure that occurred at site BC-2 was undertaken to determine exact values by incrementally adjusting the parameters of effective cohesion and friction angle until a FS of 1 was achieved in the model.

Table 5.2 Geotechnical soil characteristics used in the analysis of study sites†.

γ_s, kN/m^3	c', kPa	ϕ', °
19	4	28

†Values from the range for glacial tills determined by Lohnes et al., 2004.

Slope Stability Modeling

Numerical analyses of groundwater seepage and slope stability were undertaken using Geo-Studio SEEP/W and SLOPE/W software from Geo-Slope International Ltd. In SEEP/W, Darcy's law is applied to saturated and unsaturated flow through the soil medium to calculate pore water pressures in the soil (Krahn, 2004). In SLOPE/W, static equilibrium equations are applied to segments of soil along potential slip surfaces near the slope to compute the FS for both force and moment equilibrium (Krahn, 2004). Input requirements for the simulations include soil characteristics, slope geometry, and groundwater and stream boundary conditions. Simplified, two-dimensional representations of SRBs were used in the seepage and stability analyses. Site topography was abstracted to a flat portion of ground representing the SRB and a simple slope delineating the streambank. Soil properties for the seepage and stability analyses were assumed to be homogeneous in the analysis. Trees and plants were not incorporated into the model, though they are typically present at SRB sites and could increase the soil strength along the slope.

In the seepage analysis, steady-state SRB flow was simulated by incorporating model elements to represent operating conditions. Pore water pressure depends on the water level in the soil as determined from boundary conditions independent of the saturated hydraulic conductivity; therefore, a constant value of 1 m/day was used for analysis. The ratio of the vertical and horizontal saturated hydraulic conductivities was taken to be 0.1. Constant head boundaries were applied to represent the water level at the edge of the SRB where the distribution pipe is located and the water level in the stream at a baseflow condition. A potential seepage face boundary condition was used along the unsaturated portion of the streambank. Negative pore water pressures induced by matric suction were not considered in the analysis.

Boundary conditions used in the analysis were chosen to obtain conservative FS values while accurately representing SRB function. Although the water in the level in SRB can exceed the level set at the hydraulic control structure, monitoring data from the field sites indicate that this condition rarely occurs and is not sustained for long periods. Since the control structure has an overflow outlet, the distribution pipe will function as a drain when water levels in the SRB surpass the level set in the structure. During low flow periods, the water level in the SRB can be lower than the level set in the control box, but since the worst case for stability occurs when the water level is high in the soil, the SRB boundary condition was set to the reflect the higher level set by the structure. Additionally, the baseflow stream level was used as the boundary condition because it corresponds to a worst case when the water level is high in the soil and low in the stream. Stream stage and SRB flow are dependent on precipitation at the site; thus, if the stream went completely dry, there would be little to no flow in the SRB.

Slope stability was evaluated with the Morgenstern-Price general limit equilibrium method to determine the FS against failure. In the Morgenstern-Price method, a potential sliding mass is divided into discrete slices, and equations of static equilibrium are applied from left to right across the sliding mass (Krahn, 2004). Interslice forces were calculated with the half-sine function in SLOPE/W. Pore water pressures were determined from the results of the seepage analysis, and the soil strength was represented by the Mohr-Coulomb function for effective strength. The failure surface corresponding to the lowest FS was identified through an iterative routine where an entry and exit range along the slope was specified, and thousands of potential slip surfaces were generated. A minimum slip surface depth of 10 cm was specified to exclude very shallow failures from the analysis.

Simulated Model Conditions

The methods described previously were used to determine the FS against failure for the five field sites and a range of additional potential SRB conditions. Since SRBs are relatively new, a diverse range of site conditions was not available for study, thereby limiting the ability to examine their effect on stability. To overcome this limitation, models representing hypothetical future SRBs were created by varying soil conditions, slope geometry, buffer width, and water levels (Table 5.3). The ranges chosen for the hypothetical conditions were informed by knowledge of SRB siting requirements, review of published literature, and physical constraints. Since SRBs treat agricultural tile drainage water, they are located in regions with primarily poorly drained soils composed of clays and silts limiting the range of soil properties and excluding the consideration of sands. A range of soil strength combinations determined by Lohnes et al. (2001) were used in the analysis. Bank height is of particular interest in this study; thus, the range of bank heights was determined by focusing on typical SRB installations that occur along drainage ditches or small streams rather than large rivers. The stream water level was varied by incrementally increasing the level from zero up to the corresponding bank height. The SRB water level was varied by depth, starting from the ground surface down to just above the stream water level to maintain a flow gradient in the direction of the stream. Since the seepage conditions near the streambank depend on the hydraulic gradient, the buffer width was also varied in the simulations.

In addition to determining the FS for an existing or potential SRB site, the effect of the SRB installation on the stability of the streambank was evaluated. Because slope stability depends largely on soil conditions and slope geometry, sites may be unstable prior to and regardless of SRB installation, which only alters groundwater flow conditions. To understand the change in FS caused by SRBs, two conditions were simulated: "no flow" antecedent of SRB installation in which the constant head boundary at the edge of the buffer was equivalent to the water in the stream and "SRB flow" where the constant head boundary at the edge of the buffer was set at the level in the hydraulic control structure representing sites after SRB installation (Figure 5.2). Comparing FS from the two conditions allows the reduction in stability caused by the SRB to be assessed.

Table 5.3 Range of conditions used in simulations.

Parameter		Range simulated
Soil	c', kPa	0.5 - 10
	ϕ', °	22 - 38
	γ_s, kN/m^3	10 - 25
Geometry	h_b, m	0.9 - 5
	θ, °	10 - 75
	L_b, m	0 - 24
Seepage	h_0, m	0.2 - 5
	h_w, m	0 - 4

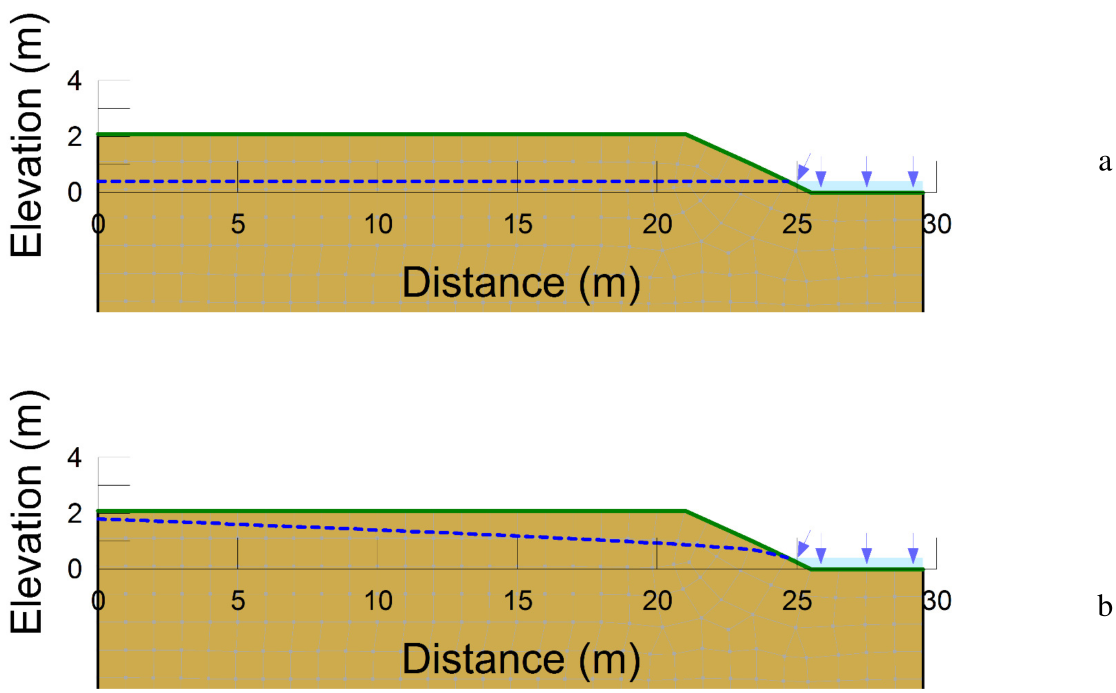

Figure 5.2 Example of no flow (a) and SRB flow (b) conditions at site BC-1. The blue line indicates the groundwater level used to calculate pore water pressures in the slope stability analysis.

Multivariate Analysis

Streambank stability was related to site conditions to inform decisions related to the siting and design of future SRBs. Though many hypothetical SRB conditions were modeled in this study, nearly infinite combinations of differing soil types, bank geometry, and flow conditions are possible. To reduce complexity, dimensional analysis of the parameters was undertaken. The dependence of FS on the parameters can be expressed as

$$FS = f_1\left(c', \phi', \gamma_s, \gamma_w, \theta, L_b, h_b, h_0, h_w\right) \quad [5.1]$$

where γ_w is the unit weight of water. Equations for flow in an unconfined aquifer can be used to estimate the height of the groundwater in the soil at the beginning of the slope h_g

$$h_g = \left(h_0^2 - \left(h_0^2 - h_w^2\right)\frac{L_b}{L_x}\right)^{\frac{1}{2}} \quad [5.2]$$

where L_x is the linear distance between h_0 and h_w determined from the slope geometry:

$$L_x = L_b + \frac{h_b - h_w}{\tan\theta} \quad [5.3]$$

Substituting h_g and adding L_x gives

$$FS = f_2(c', \phi', \gamma_s, \gamma_w, \theta, L_b, h_b, h_g, L_x) \quad [5.4]$$

which can be further simplified by inspecting the FS equation from a simple limit equilibrium analysis such as the method of ordinary slices (Fellenius, 1936) and grouping terms accordingly. Four dimensionless parameters were identified:

$$\mathrm{FS} = f\left(\frac{\tan\phi'}{\tan\theta}, \frac{c'}{\gamma_s h_b \sin\theta}, \frac{\gamma_w\left(h_g - h_w\right)\tan\phi'}{\left(\gamma_s - \gamma_w\right)h_b \sin\theta}, \frac{L_b}{L_x}\right) = f\left(\Pi_1, \Pi_2, \Pi_3, \Pi_4\right) \quad [5.5]$$

The first term involves the stability of dry cohesionless soil; the second term relates effective cohesion to the slope geometry and soil mass; the third accounts for pore water pressure near the slope; and the final term incorporates the geometry of the SRB.

Statistical analysis was performed to gain insight into the relationship between SRB site conditions and the stability of the streambank. Regression analysis was conducted using the general linear model (GLM) procedure with Python Stats Model API (Hastie et al. 2006). The relationship between individual parameters and the FS was evaluated with Pearson's correlation coefficient *r,* which ranges from -1 to +1 where perfect correlation corresponds to -1 or +1.

An equation to predict the FS as function of the dimensionless parameters (Eq. [5.5]) was developed with the GLM procedure. A sample (N = 375) of data corresponding to simulations resulting in a FS less than 3.5 was used to bias the model towards more critical values, and the study sites were excluded. Train/test splitting and cross validation were performed. Model fit was assessed with the coefficient of determination R^2, where a value of 1 corresponds to an ideal fit. An alpha value of 0.05 was used to determine statistical significance.

Results

Effect of SRB Flow

At the five study sites, the FS decreased with the addition of SRB flow, but the effect was not enough to induce failure at a previously stable site (Figure 5.3). Site SH experienced the greatest reduction in FS, though both the SRB flow and no-flow conditions are highly stable. Site BC-2 experienced the smallest reduction in the FS; however, both conditions are unstable with FS values indicating imminent failure. At the study sites, which are located in the same geologic region of Iowa and were assumed to have the same soil strength properties, the magnitude of the reduction in stability caused by the SRB flow is correlated (r = - 0.86) to slope angle θ where the

FS reduction decreases with increasing slope angle. However, under all simulated conditions (N = 256), the correlation between bank angle and stability reduction does not hold (r = 0).

Stability at an SRB site is strongly correlated to the stability of the existing streambank prior to installation (Figure 5.4). Under most of the simulated conditions, SRB flow does not cause a stable streambank to fail. In 3.5% of cases, a previously stable streambank became unstable when SRB flow was added. Two conditions were associated with the cases were the stability condition changed: soils with effective cohesion less than 2 kPa and sites with buffer widths less than 2 m. Under all simulated conditions (N = 256), the magnitude of the reduction in the FS was most strongly correlated to the groundwater level near the slope estimated by Eq. [5.2] (r = 0.62) where the reduction in stability increases with the water level.

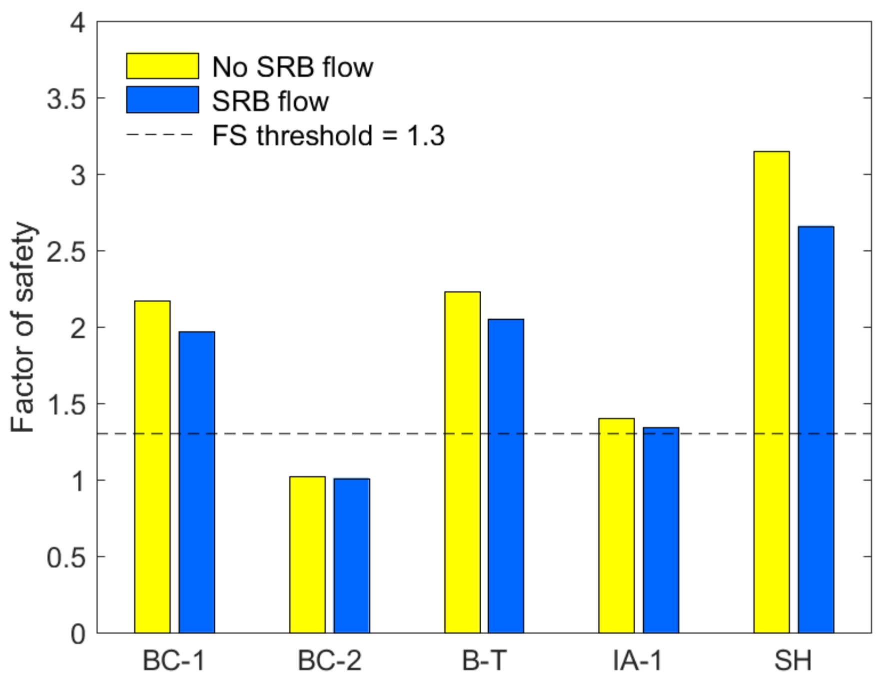

Figure 5.3 Factors of safety for study sites with and without flow.

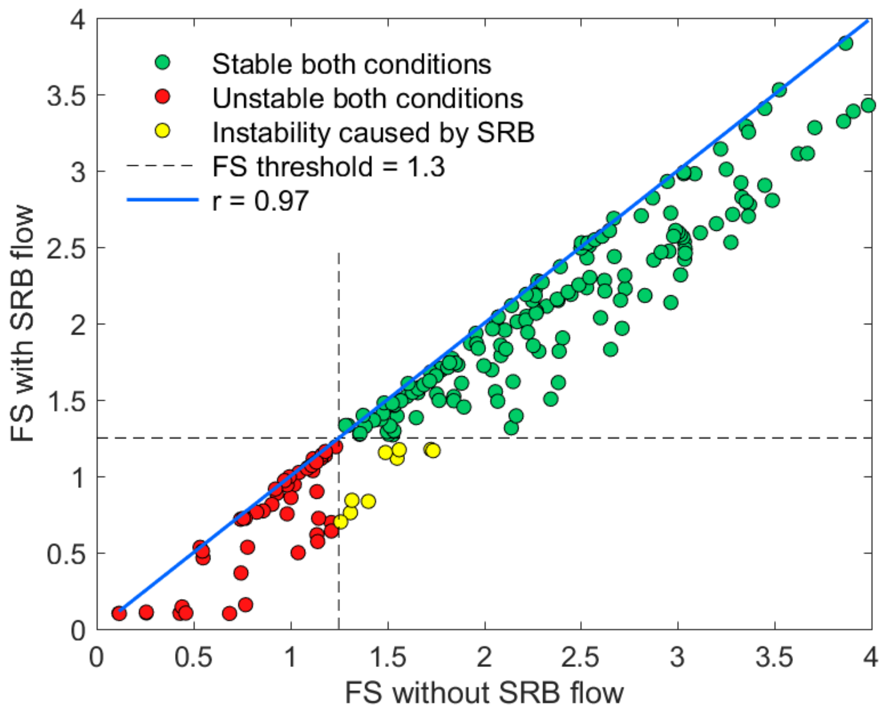

Figure 5.4 Factor of safety with and without SRB flow for all simulated cases grouped by stability condition. The line of equality is shown in blue.

Bank Height

Sites with streambanks higher than Code 604's limit of 2.4 m can be stable with SRB flow (Figure 5.5). The only study site with a bank height that exceeds the limit is BC-2, which has a low FS indicating streambank instability. In simulated cases with a streambank higher than 2.4 m (N = 288), 39% were stable while 61% were unstable. SRB simulations with bank heights below the Code 604 bank height limit (N = 91) also exhibit instability in 47% of cases. An increase in bank height reduces stability if all other factors remain constant (Figure 5.6). However, bank height does not have a statistically significant effect ($P = 0.864$) on the FS when all parameters given in Eq. [5.4] are included. The second dimensionless term in Eq. [5.5], which relates soil cohesion to the bank height and slope angle, was found to have a much stronger correlation to the FS (r = 0.92 and $P < 0.0001$), indicating the overall geometry of the slope is more critical to the stability of the streambank.

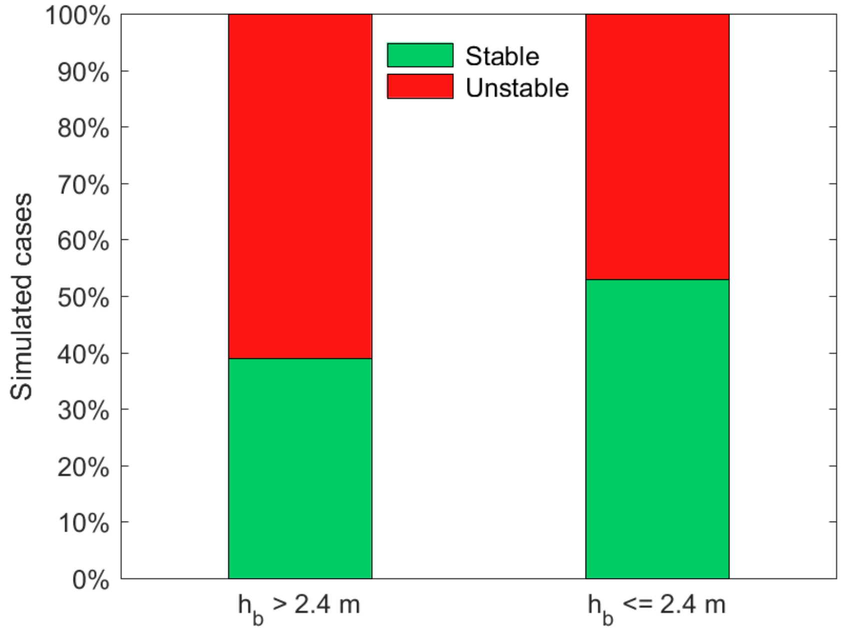

Figure 5.5 Stability categories for all simulated SRB flow conditions grouped by bank height. Code 604 currently prohibits SRB installations at sites with bank heights greater than 2.4 m.

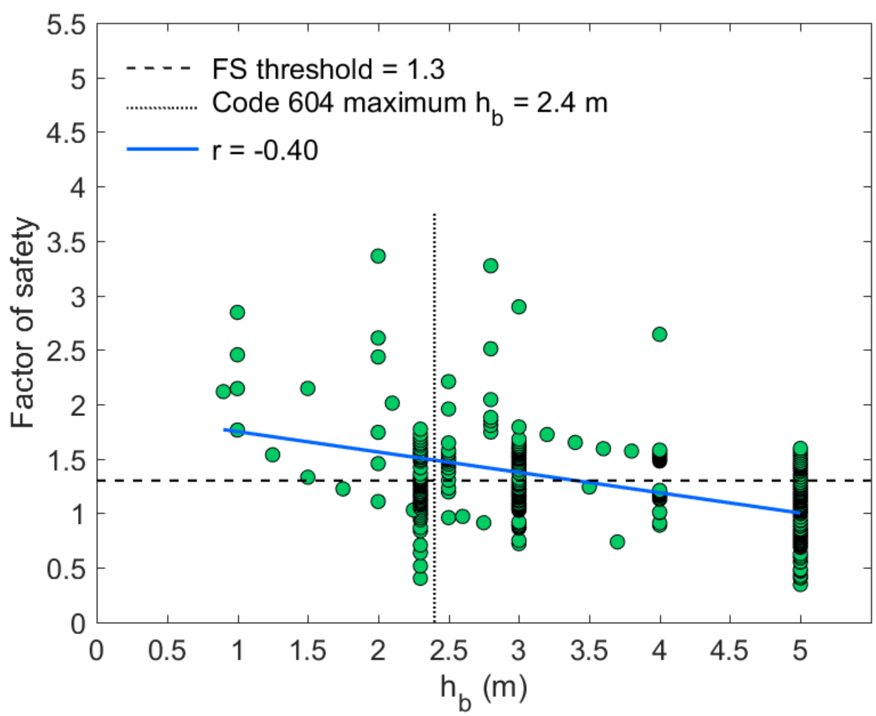

Figure 5.6 SRB factor of safety as a function of bank height. The linear fit is shown in blue, with r = -0.4.

FS Prediction at SRB Sites

The predicted FS calculated from the GLM (Table 5.4) fit the FS observed in the numerical simulations (N = 375) well. In 98% of cases the stability determination from the GLM agreed with the result of the numerical simulation; however, in 1% of cases the GLM overpredicted the FS–that is, predicted a stable condition at an unstable site (Figure 5.7). Comparison of the FS found in simulations of the study sites versus the GLM prediction shows a weaker fit (Figure 5.8), with the GLM results often overpredicting the FS at highly stable sites. The mismatch between the fit of the simulated cases versus the study sites is likely due to the small sample size (N = 5) and the choice to bias the analysis towards critical factors of safety near the stability threshold and exclude highly stable sites. Although the GLM has a less robust fit to the study sites, the stability condition predicted for all sites matches the stability condition determined in the numerical analysis.

Table 5.4 Result of GLM giving the estimated FS as a function of the dimensionless terms.

Term	Coefficient	Standard error	z score	*P*	95% confidence interval	
π_1	0.497	0.040	12.5	< .0001	0.420	0.574
π_2	6.459	0.153	41.6	< .0001	6.164	6.754
π_3	-0.454	0.066	-7.6	< .0001	-0.581	-0.327
π_4	0.326	0.017	20.6	< .0001	0.293	0.359

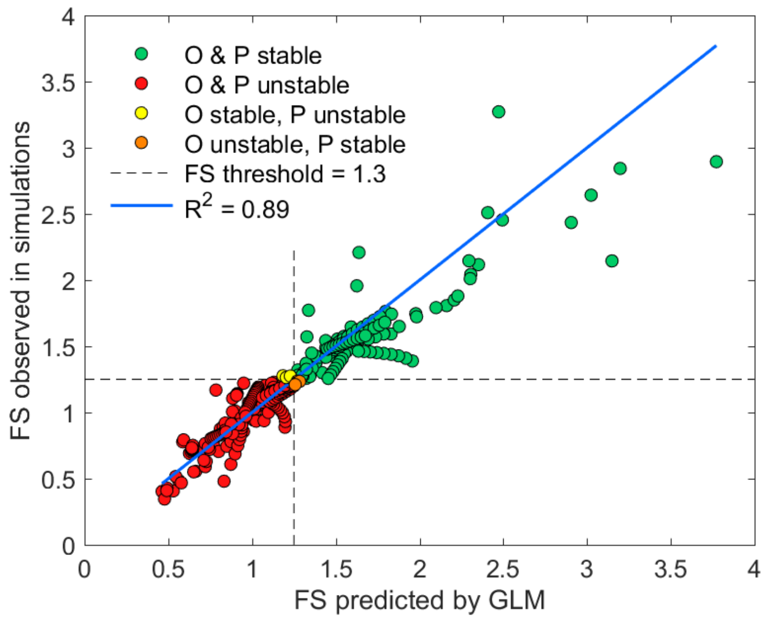

Figure 5.7. Evaluation of FS from the generalized linear model (P) with observations from numerical simulations (O). Results are grouped by stability category. The line of equality is shown in blue.

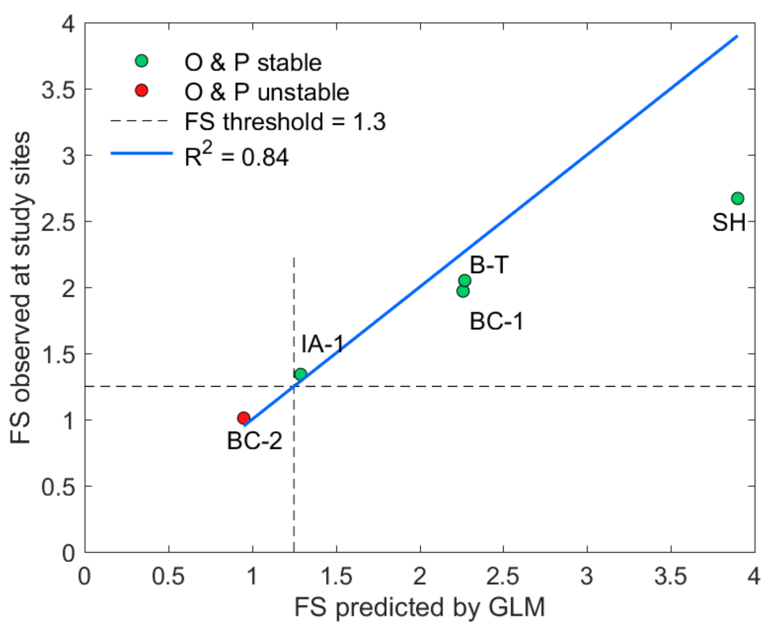

Figure 5.8. Evaluation of FS from the generalized linear model (P) with simulated FS corresponding to the study sites (O). The line of equality is shown in blue.

Discussion

In most of the simulated cases, the SRB flow did not decrease stability from the no-flow condition enough to induce failure. Of the few simulated cases where SRB flow did induce failure, soil cohesion was very low, or the buffer width was very small. Neither of these conditions is likely to occur in practice; SRBs are sited in poorly drained regions with tile drainage where soils are comprised of cohesive clays and silts, and SRB function relies on maintaining an adequate hydraulic residence time for nitrate removal which is largely controlled by buffer width. In a study of the same sites by McEachran et al., the optimal widths for maximizing nitrate removal were all well above the 2 m width associated with failure induced by SRB flow (2020a).

Although bank height does affect the stability at a site, there is not enough evidence to support restricting SRB installation at sites with banks higher than 2.4 m as mandated by Code 604. Bank height was not found to be a significant determinant of stability for the range of conditions simulated; however, the significance of the second dimensionless term in Eq. [5.5] shows the overall slope geometry is an important factor. The influence of slope geometry, typically expressed as the vertical to horizontal ratio corresponding to slope steepness, on stability is well understood – steeper slopes are less stable. Design standards for simple slope applications often specify a slope inclination based on soil type or fill material without the need for extensive geotechnical stability analysis. Since SRBs increase the complexity by adding groundwater flow, the GLM equation found in this analysis (Table 5.4) gives a more comprehensive method to estimate stability.

Uncertainty in the FS determined for the study sites arises from the uncertainty in the soil properties used in the analysis. Because deep soil boring could not be conducted, the shear strength parameters were chosen based on a back analysis of a failure that occurred during the study period at site BC-2. The back-analysis method provides validation of the parameter choices used in the simulations. Soils at the study sites were also assumed to be homogeneous without substantial layering, which may be an adequate approximation since the largest component of the slip surface is in a relatively narrow band of soil near the bottom of the slope. If information about layering is available, it is most conservative to use soil characteristics corresponding to the weakest soil layer.

In this study, the impact of SRBs on mechanical slope stability was evaluated; however, the overall stability of the streambank also depends on fluvial processes in the stream. Erosion of bank material by streamflow can create high and steep cut banks thereby inducing subsequent mechanical failure and creating a destructive feedback loop (Simon et al., 2000; Springer et al., 1985; Turner et al. 2010). A geomorphological assessment of the stream reach can give insight into the overall stability at an SRB site. The Channel Evolution Model (CEM), first developed by Simon and Hupp (1987), classifies six stages of channel morphology corresponding to states of channel degradation, widening, aggradation, or equilibrium. The CEM is particularly useful because it allows for the prediction of future changes to the stream form, which could inform decisions related to SRB design. For example, if a site is found to be in Stage IV of the CEM (degradation and widening) slope failure is likely to occur regardless of the addition of an SRB. The importance of the CEM stage was observed at site BC-2, where the FS indicated failure for conditions with and without SRB flow. Since natural streams are not static and bank failures can contribute to channel equilibrium, the question of whether to exclude degraded channels as potential SRB sites arises. However, that determination was not made in this study; rather, it may be a consideration for future work.

Expanding eligible SRB sites will increase implementation and provide water quality improvements. In Iowa, where agricultural tile drainage is common, streambank heights range from 0.2 to 5.2 m, which indicates many potential SRB sites could be identified if Code 604's restriction on bank height is lifted (USGS, 1993). Although the addition of flow from SRB installation was not found to cause failure at a previously stable site, without numerical modeling it may be difficult for designers to assess the existing stability condition at some potential sites. In cases where stability is uncertain, the GLM equation can be used to relate site conditions and SRB design options to the FS. At sites where bank failure has occurred or appears to be likely, a geomorphological assessment such as the CEM can help to understand the interaction between streambank stability and channel processes.

Conclusions

We have assessed the relationship between streambank stability and SRB design conditions and described a method to determine the stability at a potential SRB site. Although the bank height is involved in calculating the FS, the effect on stability was not significant when all other factors were considered. The proposed changes to Code 604 and the method we outline will allow more SRBs to be implemented while reducing the risk of streambank failure. Challenges remain in balancing the water quality improvements of SRBs with the risk of bank failure at sites where in-stream processes cause instability.

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CHAPTER 6: GENERAL CONCLUSIONS

Water quality can be improved through the increased implementation of SRBs that effectively remove nitrate through plant uptake, denitrification, and immobilization; however, concerns about the impact of SRB flow on streambank stability have led to restrictive design standards that impede their utilization. An extensive geotechnical slope stability evaluation of SRB design conditions was undertaken to gain insight into the conditions that lead to streambank failure and improve the design of SRBs. A method was proposed to predict the streambank stability at future SRB sites.

In Chapter 3, the stability of an SRB site in Hamilton County, IA was assessed. The no-flow condition was compared to the SRB flow condition, which showed the SRB flow did not change the stability condition of the streambank. The FS was found to decrease by 3% because of the change in the groundwater level from the SRB. This study helped to achieve objectives (1) and (2) by providing a conceptual model of SRB function based on an existing SRB site, and the results were helpful in developing the methods used in Chapter 5.

In Chapter 4, the effect of the SRB width on stability was examined to achieve objective (3). At all five sites included in the analysis, the streambank became less stable at smaller buffer widths. In four of the five sites, instability was observed at widths of 3 m or less. The fifth site was unstable regardless of the buffer width. SRB sites can be stable with buffer widths lower than the Code 604 minimum.

In Chapter 5, the relationship between SRB design conditions and streambank stability was assessed. This study addressed objectives (4) and (5) by investigating the relationship between streambank height and slope stability and providing evidence to recommend improvements to SRB design guidance. In 96.5% of simulated cases, the flow from the SRB did not reduce the stability by enough to cause a previously stable to fail. Over the simulated range of conditions, the bank height did not have a significant effect on streambank stability. Dimensional parameters derived from the site conditions were used to create a regression model that predicts the FS. The model can be used in the design of future SRB sites. The bank height restriction in Code 604 can be eliminated, which will allow greater SRB implementation.

Future work should focus on determining if the risk of streambank failures at SRB sites outweigh the potential water quality benefits. Since the SRB flow generally does not change the stability condition at a site, it may be worthwhile to consider allowing SRB placement at sites that are already unstable. A site may be in a state of instability created by fluvial in-stream processes and will experience future streambank failures until a state of equilibrium is achieved. In such a case, installation of an SRB will not change the stability condition but would potentially provide water quality benefits.

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APPENDIX A: SOIL STRENGTH PARAMETERS

Geologic parent material	c' , kPa		ϕ' , °		γ_s , kN/m³	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Glacial till	7.65	5.59	28	1.2	19.1	1.7
Friable loess	5.21	4.00	25	1.4	18.2	1.1
Plastic loess	6.91	4.19	29	4.2	18.7	1.4
Alluvium	2.28	1.90	31	1.3	19.0	1.1

[†]Values determined by Lohnes et al., 2004.

APPENDIX B: SIMULATED SRB CONDITIONS

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
8	10.0	28	4	19	1	0.7	0.4	0.3	0.508	11.403	3.015	1.212	0.354	0.702	4.662	9.399
8	10.0	28	4	19	2	1.7	0.8	0.9	1.294	14.806	3.015	0.606	0.807	0.540	3.361	5.225
8	10.0	28	4	19	3	2.7	1.2	1.5	2.172	18.208	3.015	0.404	1.060	0.439	2.895	3.773
8	10.0	28	4	19	4	3.7	1.6	2.1	3.094	21.611	3.015	0.303	1.220	0.370	2.642	3.025
22	13.2	26	4	19	2	2	0.6	1.4	1.066	27.969	2.079	0.461	0.531	0.787	2.609	4.027
9	25	22	3	18	1	1	0.25	0.75	0.452	10.608	0.866	0.394	0.232	0.848	2.145	3.149
10	25.0	28	5.5	19	1	1	0.35	0.65	0.479	11.394	1.140	0.685	0.174	0.878	4.994	5.198
10	25.0	28	5.5	19	2	2	0.7	1.3	1.120	12.788	1.140	0.342	0.282	0.782	2.435	2.906
21	25.0	26	4	19	2.1	2.1	1	1.1	1.159	23.359	1.046	0.237	0.094	0.899	2.011	2.303
10	25.0	28	5.5	19	2.8	2.8	1E-07	2.8	1.715	16.005	1.140	0.245	0.823	0.625	1.746	1.978
10	25.0	28	5.5	19	2.8	2.8	0.7	2.1	1.665	14.503	1.140	0.245	0.463	0.689	1.807	2.162
10	25.0	28	5.5	19	2.8	2.8	0.9	1.9	1.687	14.075	1.140	0.245	0.377	0.711	1.850	2.207
10	25.0	28	5.5	19	2.8	2.8	1	1.8	1.704	13.860	1.140	0.245	0.338	0.721	1.880	2.229
10	25.0	28	5.5	19	2.8	2.8	1.4	1.4	1.821	13.002	1.140	0.245	0.202	0.769	2.043	2.306
10	25.0	28	5.5	19	2.8	2.8	2.1	0.7	2.204	11.501	1.140	0.245	0.050	0.869	2.510	2.408
10	25.0	28	5.5	19	2.8	2.8	2.8	0	2.800	10.000	1.140	0.245	0.000	1.000	3.272	2.473
10	25.0	28	5.5	19	3	3	1	2	1.844	14.289	1.140	0.228	0.378	0.700	1.792	2.098
10	25.0	28	5.5	19	3.2	3.2	1	2.2	1.990	14.718	1.140	0.214	0.416	0.679	1.723	1.982
10	25.0	28	5.5	19	3.4	3.4	1	2.4	2.142	15.147	1.140	0.201	0.451	0.660	1.650	1.879
10	25.0	28	5.5	19	3.6	3.6	1	2.6	2.298	15.576	1.140	0.190	0.484	0.642	1.593	1.785
10	25.0	28	5.5	19	3.8	3.8	1.2	2.6	2.469	15.576	1.140	0.180	0.448	0.642	1.571	1.737
10	25.0	28	5.5	19	4	4	1.4	2.6	2.643	15.576	1.140	0.171	0.417	0.642	1.554	1.693
0	25	28	5	19	5	5	1	4	5.000	8.578	1.140	0.125	1.074	0.000	1.106	0.884
1	25	28	5	19	5	5	1	4	4.743	9.578	1.140	0.125	1.005	0.104	1.221	0.950
2	25	28	5	19	5	5	1	4	4.524	10.578	1.140	0.125	0.946	0.189	1.073	1.004

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
3	25	28	5	19	5	5	1	4	4.334	11.578	1.140	0.125	0.895	0.259	1.119	1.050
4	25	28	5	19	5	5	1	4	4.167	12.578	1.140	0.125	0.851	0.318	1.158	1.089
5	25	28	5	19	5	5	1	4	4.020	13.578	1.140	0.125	0.811	0.368	1.191	1.123
6	25	28	5	19	5	5	1	4	3.889	14.578	1.140	0.125	0.776	0.412	1.218	1.154
7	25	28	5	19	5	5	1	4	3.770	15.578	1.140	0.125	0.744	0.449	1.242	1.180
8	25	28	5	19	5	5	1	4	3.663	16.578	1.140	0.125	0.715	0.483	1.264	1.204
10	25.0	28	5.5	19	5	2	1.8	0.2	1.884	16.862	1.140	0.137	0.023	0.593	1.594	1.635
10	25.0	28	5.5	19	5	2.2	1.8	0.4	1.973	16.862	1.140	0.137	0.046	0.593	1.574	1.624
10	25.0	28	5.5	19	5	2.4	1.8	0.6	2.065	16.862	1.140	0.137	0.071	0.593	1.553	1.613
10	25.0	28	5.5	19	5	2.6	1.8	0.8	2.162	16.862	1.140	0.137	0.097	0.593	1.531	1.601
10	25.0	28	5.5	19	5	2.8	1.8	1	2.261	16.862	1.140	0.137	0.124	0.593	1.509	1.589
10	25.0	28	5.5	19	5	3	1.8	1.2	2.363	16.862	1.140	0.137	0.151	0.593	1.485	1.576
10	25.0	28	5.5	19	5	3.2	1.8	1.4	2.468	16.862	1.140	0.137	0.179	0.593	1.460	1.564
10	25.0	28	5.5	19	5	3.4	1.8	1.6	2.574	16.862	1.140	0.137	0.208	0.593	1.443	1.551
10	25.0	28	5.5	19	5	3.6	1.8	1.8	2.682	16.862	1.140	0.137	0.237	0.593	1.406	1.538
10	25.0	28	5.5	19	5	3.8	1.8	2	2.792	16.862	1.140	0.137	0.267	0.593	1.385	1.524
10	25.0	28	5.5	19	5	4	1.8	2.2	2.904	16.862	1.140	0.137	0.297	0.593	1.359	1.511
10	25.0	28	5.5	19	5	4.2	1.8	2.4	3.017	16.862	1.140	0.137	0.327	0.593	1.333	1.497
10	25.0	28	5.5	19	5	4.4	1.8	2.6	3.131	16.862	1.140	0.137	0.357	0.593	1.308	1.483
10	25.0	28	5.5	19	5	4.6	1.8	2.8	3.245	16.862	1.140	0.137	0.388	0.593	1.283	1.469
10	25.0	28	5.5	19	5	4.8	1.8	3	3.361	16.862	1.140	0.137	0.419	0.593	1.257	1.455
10	25.0	31	2	15	5	5	1.8	3.2	3.478	16.862	1.289	0.063	0.902	0.593	0.480	0.832
10	25.0	31	2	16	5	5	1.8	3.2	3.478	16.862	1.289	0.059	0.756	0.593	0.608	0.873
10	25.0	31	2	17	5	5	1.8	3.2	3.478	16.862	1.289	0.056	0.651	0.593	0.687	0.898
10	25.0	31	2	18	5	5	1.8	3.2	3.478	16.862	1.289	0.053	0.571	0.593	0.749	0.914
10	25.0	31	2	19	5	5	1.8	3.2	3.478	16.862	1.289	0.050	0.509	0.593	0.795	0.925
10	25.0	31	2	20	5	5	1.8	3.2	3.478	16.862	1.289	0.047	0.459	0.593	0.828	0.931
10	25.0	31	2	21	5	5	1.8	3.2	3.478	16.862	1.289	0.045	0.418	0.593	0.857	0.935
10	25.0	31	2	22	5	5	1.8	3.2	3.478	16.862	1.289	0.043	0.384	0.593	0.883	0.938

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	25.0	26	4	15	5	5	1.8	3.2	3.478	16.862	1.046	0.126	0.732	0.593	0.888	1.196
10	25.0	31	2	23	5	5	1.8	3.2	3.478	16.862	1.289	0.041	0.355	0.593	0.905	0.939
10	25.0	26	4	16	5	5	1.8	3.2	3.478	16.862	1.046	0.118	0.614	0.593	0.932	1.199
10	25.0	26	4	17	5	5	1.8	3.2	3.478	16.862	1.046	0.111	0.528	0.593	0.968	1.193
10	25.0	26	4	18	5	5	1.8	3.2	3.478	16.862	1.046	0.105	0.464	0.593	0.997	1.182
10	25.0	26	4	19	5	5	1.8	3.2	3.478	16.862	1.046	0.100	0.413	0.593	1.018	1.169
10	25.0	26	4	19	5	5	1.8	3.2	3.478	16.862	1.046	0.100	0.413	0.593	1.018	1.169
10	25.0	26	4	20	5	5	1.8	3.2	3.478	16.862	1.046	0.095	0.373	0.593	1.036	1.156
10	25.0	26	4	21	5	5	1.8	3.2	3.478	16.862	1.046	0.090	0.340	0.593	1.051	1.142
10	25.0	26	4	22	5	5	1.8	3.2	3.478	16.862	1.046	0.086	0.312	0.593	1.062	1.128
10	25.0	26	4	23	5	5	1.8	3.2	3.478	16.862	1.046	0.082	0.288	0.593	1.073	1.114
10	25.0	26	4	18	5	5	1.8	3.2	3.478	16.862	1.046	0.105	0.464	0.593	1.151	1.182
10	25.0	26	4	19	5	5	1.8	3.2	3.478	16.862	1.046	0.100	0.413	0.593	1.164	1.169
10	25.0	26	4	20	5	5	1.8	3.2	3.478	16.862	1.046	0.095	0.373	0.593	1.174	1.156
10	25.0	26	4	21	5	5	1.8	3.2	3.478	16.862	1.046	0.090	0.340	0.593	1.182	1.142
10	25.0	26	4	22	5	5	1.8	3.2	3.478	16.862	1.046	0.086	0.312	0.593	1.189	1.128
10	25.0	28	7.65	15	5	5	1.8	3.2	3.478	16.862	1.140	0.241	0.798	0.593	1.389	1.957
10	25.0	28	7.65	16	5	5	1.8	3.2	3.478	16.862	1.140	0.226	0.669	0.593	1.410	1.918
10	25.0	28	5.5	19	5	5	1.8	3.2	3.478	16.862	1.140	0.137	0.451	0.593	1.417	1.441
10	25.0	28	7.65	17	5	5	1.8	3.2	3.478	16.862	1.140	0.213	0.576	0.593	1.428	1.874
10	25.0	28	7.65	18	5	5	1.8	3.2	3.478	16.862	1.140	0.201	0.506	0.593	1.439	1.830
10	25.0	28	7.65	19	5	5	1.8	3.2	3.478	16.862	1.140	0.191	0.451	0.593	1.446	1.787
10	25.0	28	7.65	20	5	5	1.8	3.2	3.478	16.862	1.140	0.181	0.406	0.593	1.452	1.745
10	25.0	28	7.65	21	5	5	1.8	3.2	3.478	16.862	1.140	0.172	0.370	0.593	1.457	1.706
10	25.0	28	7.65	22	5	5	1.8	3.2	3.478	16.862	1.140	0.165	0.340	0.593	1.461	1.669
10	25.0	28	7.65	23	5	5	1.8	3.2	3.478	16.862	1.140	0.157	0.314	0.593	1.463	1.634
10	25.0	28	7.65	18	5	5	1.8	3.2	3.478	16.862	1.140	0.201	0.506	0.593	1.593	1.830
10	25.0	28	7.65	19	5	5	1.8	3.2	3.478	16.862	1.140	0.191	0.451	0.593	1.595	1.787
10	25.0	28	7.65	21	5	5	1.8	3.2	3.478	16.862	1.140	0.172	0.370	0.593	1.596	1.706

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	25.0	28	7.65	20	5	5	1.8	3.2	3.478	16.862	1.140	0.181	0.406	0.593	1.596	1.745
10	35.0	22	2	19	3.7	3.7	1	2.7	2.129	13.856	0.577	0.050	0.229	0.722	0.737	0.738
10	35.0	24	3	19	4	3.7	1	2.7	2.192	14.284	0.636	0.069	0.247	0.700	0.912	0.877
10	35.0	25	5.21	23	4	3.7	1	2.7	2.192	14.284	0.666	0.099	0.180	0.700	1.158	1.115
10	35.0	25	5.21	22.5	4	3.7	1	2.7	2.192	14.284	0.666	0.101	0.187	0.700	1.162	1.126
10	35.0	25	5.21	22	4	3.7	1	2.7	2.192	14.284	0.666	0.103	0.195	0.700	1.167	1.137
10	35.0	25	5.21	21.5	4	3.7	1	2.7	2.192	14.284	0.666	0.106	0.203	0.700	1.172	1.149
10	35.0	25	5.21	21	4	3.7	1	2.7	2.192	14.284	0.666	0.108	0.212	0.700	1.176	1.161
10	35.0	25	5.21	20.5	4	3.7	1	2.7	2.192	14.284	0.666	0.111	0.222	0.700	1.180	1.174
10	35.0	25	5.21	20	4	3.7	1	2.7	2.192	14.284	0.666	0.114	0.233	0.700	1.185	1.187
10	35.0	25	5.21	19.5	4	3.7	1	2.7	2.192	14.284	0.666	0.116	0.245	0.700	1.190	1.200
10	35.0	25	5.21	19	4	3.7	1	2.7	2.192	14.284	0.666	0.120	0.259	0.700	1.195	1.214
10	35.0	25	5.21	18.5	4	3.7	1	2.7	2.192	14.284	0.666	0.123	0.274	0.700	1.200	1.228
10	35.0	25	5.21	18	4	3.7	1	2.7	2.192	14.284	0.666	0.126	0.290	0.700	1.205	1.242
10	35.0	25	5.21	17.5	4	3.7	1	2.7	2.192	14.284	0.666	0.130	0.309	0.700	1.210	1.257
10	35.0	28	7.65	23	4	3.7	1	2.7	2.192	14.284	0.759	0.145	0.206	0.700	1.480	1.449
10	35.0	28	7.65	22.5	4	3.7	1	2.7	2.192	14.284	0.759	0.148	0.214	0.700	1.488	1.466
10	35.0	28	7.65	22	4	3.7	1	2.7	2.192	14.284	0.759	0.152	0.222	0.700	1.496	1.484
10	35.0	28	7.65	21.5	4	3.7	1	2.7	2.192	14.284	0.759	0.155	0.232	0.700	1.505	1.502
10	35.0	28	7.65	21	4	3.7	1	2.7	2.192	14.284	0.759	0.159	0.242	0.700	1.513	1.521
10	35.0	28	7.65	20.5	4	3.7	1	2.7	2.192	14.284	0.759	0.163	0.254	0.700	1.522	1.541
10	35.0	28	7.65	20	4	3.7	1	2.7	2.192	14.284	0.759	0.167	0.266	0.700	1.530	1.562
10	35.0	28	7.65	19.5	4	3.7	1	2.7	2.192	14.284	0.759	0.171	0.280	0.700	1.540	1.583
10	35.0	28	7.65	19	4	3.7	1	2.7	2.192	14.284	0.759	0.175	0.295	0.700	1.550	1.605
10	35.0	28	7.65	18.5	4	3.7	1	2.7	2.192	14.284	0.759	0.180	0.312	0.700	1.560	1.628
10	35.0	28	7.65	18	4	3.7	1	2.7	2.192	14.284	0.759	0.185	0.331	0.700	1.570	1.652
10	35.0	28	7.65	17.5	4	3.7	1	2.7	2.192	14.284	0.759	0.191	0.352	0.700	1.580	1.676
10	45.0	28	5.5	19	0.5	0.2	0.1	0.1	0.106	10.400	0.532	0.819	0.009	0.962	5.088	5.862
10	45.0	28	5.5	19	1	0.7	0.3	0.4	0.341	10.700	0.532	0.409	0.033	0.935	2.844	3.198

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	45.0	28	5.5	19	1.5	1.2	0.46	0.74	0.572	11.040	0.532	0.273	0.060	0.906	2.146	2.295
10	45.0	28	5.5	19	2	1.7	0.6	1.1	0.819	11.400	0.532	0.205	0.088	0.877	1.743	1.832
10	45.0	28	5.5	19	2.5	2.2	1E-07	2.2	0.984	12.500	0.532	0.164	0.316	0.800	1.543	1.439
10	45.0	28	5.5	19	2.5	2.2	0.63	1.57	1.047	11.870	0.532	0.164	0.134	0.842	1.551	1.536
10	45.0	28	5.5	19	2.5	2.2	0.75	1.45	1.095	11.750	0.532	0.164	0.111	0.851	1.575	1.549
0.25	45.0	28	5.5	19	2.5	2.2	0.8	1.4	2.074	1.950	0.532	0.164	0.409	0.128	1.196	1.178
0.5	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.971	2.200	0.532	0.164	0.376	0.227	1.232	1.226
1	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.812	2.700	0.532	0.164	0.325	0.370	1.304	1.295
2	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.603	3.700	0.532	0.164	0.258	0.541	1.376	1.381
3	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.469	4.700	0.532	0.164	0.215	0.638	1.417	1.432
4	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.376	5.700	0.532	0.164	0.185	0.702	1.452	1.467
5	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.306	6.700	0.532	0.164	0.162	0.746	1.475	1.491
6	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.252	7.700	0.532	0.164	0.145	0.779	1.492	1.510
7	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.209	8.700	0.532	0.164	0.131	0.805	1.500	1.525
8	45.0	28	5.5	19	2.5	2.2	0.8	1.4	1.173	9.700	0.532	0.164	0.120	0.825	1.511	1.536
10	45.0	28	5.5	19	2.5	2.2	1	1.2	1.225	11.500	0.532	0.164	0.072	0.870	1.577	1.572
10	45.0	28	5.5	19	2.5	2.2	1.25	0.95	1.388	11.250	0.532	0.164	0.044	0.889	1.646	1.591
10	45.0	28	5.5	19	2.5	2.2	1.875	0.325	1.896	10.625	0.532	0.164	0.007	0.941	1.957	1.626
10	45.0	28	5.5	19	2.5	2.2	2.2	0.00	2.200	10.300	0.532	0.164	0.000	0.971	2.209	1.638
10	45.0	28	5.5	19	3	2.7	0.9	1.8	1.391	12.100	0.532	0.136	0.131	0.826	1.449	1.355
1	45	28	7.65	19	3	3	1.02	1.98	2.516	2.980	0.532	0.190	0.400	0.336	1.301	1.418
2	45	28	7.65	19	3	3	1.02	1.98	2.236	3.980	0.532	0.190	0.325	0.503	1.401	1.506
3	45	28	7.65	19	3	3	1.02	1.98	2.051	4.980	0.532	0.190	0.276	0.602	1.467	1.561
4	45	28	7.65	19	3	3	1.02	1.98	1.917	5.980	0.532	0.190	0.240	0.669	1.507	1.599
5	45	28	7.65	19	3	3	1.02	1.98	1.816	6.980	0.532	0.190	0.213	0.716	1.537	1.627
6	45	28	7.65	19	3	3	1.02	1.98	1.736	7.980	0.532	0.190	0.192	0.752	1.558	1.648
7	45	28	7.65	19	3	3	1.02	1.98	1.672	8.980	0.532	0.190	0.174	0.780	1.575	1.665
8	45	28	7.65	19	3	3	1.02	1.98	1.619	9.980	0.532	0.190	0.160	0.802	1.589	1.679
9	45	28	7.65	19	3	3	1.02	1.98	1.573	10.980	0.532	0.190	0.148	0.820	1.605	1.690

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	45.0	22	2	19	3	3	1.02	1.98	1.535	11.980	0.404	0.050	0.105	0.835	0.721	0.746
10	45.0	24	3	19	3	3	1.02	1.98	1.535	11.980	0.445	0.074	0.115	0.835	0.909	0.922
10	45.0	25	5.21	23	3	3	1.02	1.98	1.535	11.980	0.466	0.107	0.084	0.835	1.141	1.155
10	45.0	25	5.21	22.5	3	3	1.02	1.98	1.535	11.980	0.466	0.109	0.087	0.835	1.151	1.169
10	45.0	25	5.21	22	3	3	1.02	1.98	1.535	11.980	0.466	0.112	0.091	0.835	1.162	1.183
10	45.0	25	5.21	21.5	3	3	1.02	1.98	1.535	11.980	0.466	0.114	0.095	0.835	1.174	1.198
10	45.0	25	5.21	21	3	3	1.02	1.98	1.535	11.980	0.466	0.117	0.099	0.835	1.185	1.214
10	45.0	25	5.21	20.5	3	3	1.02	1.98	1.535	11.980	0.466	0.120	0.104	0.835	1.196	1.230
10	45.0	25	5.21	20	3	3	1.02	1.98	1.535	11.980	0.466	0.123	0.109	0.835	1.208	1.247
10	45.0	25	5.21	18	3	3	1.02	1.98	1.535	11.980	0.466	0.136	0.136	0.835	1.258	1.324
10	45.0	25	5.21	17.5	3	3	1.02	1.98	1.535	11.980	0.466	0.140	0.144	0.835	1.271	1.345
10	45.0	25	5.21	18.5	3	3	1.02	1.98	1.535	11.980	0.466	0.133	0.128	0.835	1.274	1.303
10	45	28	5	19	3	3	1.02	1.98	1.535	11.980	0.532	0.124	0.138	0.835	1.282	1.275
10	45.0	28	7.65	23	3	3	1.02	1.98	1.535	11.980	0.532	0.157	0.096	0.835	1.488	1.505
10	45.0	28	7.65	22.5	3	3	1.02	1.98	1.535	11.980	0.532	0.160	0.100	0.835	1.502	1.526
10	45.0	28	7.65	22	3	3	1.02	1.98	1.535	11.980	0.532	0.164	0.104	0.835	1.517	1.548
10	45.0	28	7.65	21.5	3	3	1.02	1.98	1.535	11.980	0.532	0.168	0.108	0.835	1.532	1.570
10	45.0	28	7.65	21	3	3	1.02	1.98	1.535	11.980	0.532	0.172	0.113	0.835	1.549	1.594
10	45.0	28	7.65	20.5	3	3	1.02	1.98	1.535	11.980	0.532	0.176	0.118	0.835	1.566	1.619
10	45.0	28	7.65	20	3	3	1.02	1.98	1.535	11.980	0.532	0.180	0.124	0.835	1.583	1.645
10	45.0	28	7.65	19.5	3	3	1.02	1.98	1.535	11.980	0.532	0.185	0.131	0.835	1.600	1.671
10	45	28	7.65	19	3	3	1.02	1.98	1.535	11.980	0.532	0.190	0.138	0.835	1.619	1.700
10	45.0	28	7.65	19	3	3	1.02	1.98	1.535	11.980	0.532	0.190	0.138	0.835	1.619	1.700
10	45.0	28	7.65	18.5	3	3	1.02	1.98	1.535	11.980	0.532	0.195	0.146	0.835	1.638	1.729
10	45.0	28	7.65	18	3	3	1.02	1.98	1.535	11.980	0.532	0.200	0.155	0.835	1.659	1.760
10	45.0	28	7.65	17.5	3	3	1.02	1.98	1.535	11.980	0.532	0.206	0.165	0.835	1.681	1.793
10	45.0	25	5.21	19.5	3	3	1.02	1.98	1.535	11.980	0.466	0.126	0.115	0.835	1.222	1.265
10	45.0	25	5.21	19	3	3	1.02	1.98	1.535	11.980	0.466	0.129	0.121	0.835	1.235	1.284
10	45.0	28	5.5	19	3.5	3.2	1.05	2.15	1.703	12.450	0.532	0.117	0.150	0.803	1.241	1.213

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	45.0	28	5.5	19	4	3.7	1.2	2.5	2.030	12.800	0.532	0.102	0.166	0.781	1.141	1.104
10	45.0	28	5.5	19	5	2	1.8	0.2	1.850	13.200	0.532	0.082	0.008	0.758	1.191	1.036
10	45.0	28	5.5	19	5	2.2	1.8	0.4	1.905	13.200	0.532	0.082	0.017	0.758	1.182	1.032
10	45.0	28	5.5	19	5	2.4	1.8	0.6	1.962	13.200	0.532	0.082	0.026	0.758	1.173	1.028
10	45.0	28	5.5	19	5	2.6	1.8	0.8	2.023	13.200	0.532	0.082	0.036	0.758	1.163	1.024
10	45.0	28	5.5	19	5	2.8	1.8	1	2.087	13.200	0.532	0.082	0.046	0.758	1.153	1.019
10	45.0	28	5.5	19	5	3	1.8	1.2	2.153	13.200	0.532	0.082	0.057	0.758	1.142	1.014
10	45.0	28	5.5	19	5	3.2	1.8	1.4	2.222	13.200	0.532	0.082	0.068	0.758	1.129	1.009
10	45.0	28	5.5	19	5	3.4	1.8	1.6	2.293	13.200	0.532	0.082	0.079	0.758	1.116	1.004
10	45.0	28	5.5	19	5	3.6	1.8	1.8	2.366	13.200	0.532	0.082	0.091	0.758	1.101	0.999
10	45.0	28	5.5	19	5	3.8	1.8	2	2.440	13.200	0.532	0.082	0.103	0.758	1.086	0.993
10	45.0	28	5.5	19	5	4	1.8	2.2	2.517	13.200	0.532	0.082	0.115	0.758	1.073	0.988
10	45.0	28	5.5	19	5	4.2	1.8	2.4	2.594	13.200	0.532	0.082	0.128	0.758	1.059	0.982
10	45.0	28	5.5	19	5	4.4	1.8	2.6	2.674	13.200	0.532	0.082	0.140	0.758	1.044	0.976
10	45.0	28	5.5	19	5	4.6	1.8	2.8	2.754	13.200	0.532	0.082	0.153	0.758	1.029	0.970
10	45.0	28	5.5	19	5	4.8	1.8	3	2.835	13.200	0.532	0.082	0.166	0.758	1.015	0.965
10	45.0	31	2	15	5	5	1.8	3.2	2.918	13.200	0.601	0.038	0.359	0.758	0.691	0.626
10	45.0	31	2	16	5	5	1.8	3.2	2.918	13.200	0.601	0.035	0.301	0.758	0.703	0.637
10	45.0	31	2	17	5	5	1.8	3.2	2.918	13.200	0.601	0.033	0.259	0.758	0.713	0.643
10	45.0	31	2	18	5	5	1.8	3.2	2.918	13.200	0.601	0.031	0.228	0.758	0.719	0.645
10	45.0	31	2	19	5	5	1.8	3.2	2.918	13.200	0.601	0.030	0.203	0.758	0.724	0.646
10	45.0	31	2	20	5	5	1.8	3.2	2.918	13.200	0.601	0.028	0.183	0.758	0.726	0.645
10	45.0	31	2	21	5	5	1.8	3.2	2.918	13.200	0.601	0.027	0.167	0.758	0.728	0.644
10	45.0	31	2	22	5	5	1.8	3.2	2.918	13.200	0.601	0.026	0.153	0.758	0.730	0.642
10	45.0	31	2	23	5	5	1.8	3.2	2.918	13.200	0.601	0.025	0.141	0.758	0.732	0.640
10	45.0	26	4	23	5	5	1.8	3.2	2.918	13.200	0.488	0.049	0.115	0.758	0.803	0.755
10	45.0	26	4	22	5	5	1.8	3.2	2.918	13.200	0.488	0.051	0.124	0.758	0.809	0.765
10	45.0	26	4	21	5	5	1.8	3.2	2.918	13.200	0.488	0.054	0.135	0.758	0.814	0.776
10	45.0	26	4	20	5	5	1.8	3.2	2.918	13.200	0.488	0.057	0.148	0.758	0.820	0.787

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	45.0	26	4	19	5	5	1.8	3.2	2.918	13.200	0.488	0.060	0.165	0.758	0.826	0.799
10	45.0	26	4	19	5	5	1.8	3.2	2.918	13.200	0.488	0.060	0.165	0.758	0.826	0.799
10	45.0	26	4	18	5	5	1.8	3.2	2.918	13.200	0.488	0.063	0.185	0.758	0.833	0.811
10	45.0	26	4	17	5	5	1.8	3.2	2.918	13.200	0.488	0.067	0.210	0.758	0.840	0.824
10	45.0	26	4	16	5	5	1.8	3.2	2.918	13.200	0.488	0.071	0.244	0.758	0.846	0.835
10	45.0	26	4	15	5	5	1.8	3.2	2.918	13.200	0.488	0.075	0.292	0.758	0.852	0.844
10	45.0	28	5.5	19	5	5	1.8	3.2	2.918	13.200	0.532	0.082	0.179	0.758	1.001	0.959
10	45.0	28	7.65	23	5	5	1.8	3.2	2.918	13.200	0.532	0.094	0.125	0.758	1.113	1.062
10	45.0	28	7.65	22	5	5	1.8	3.2	2.918	13.200	0.532	0.098	0.135	0.758	1.128	1.085
10	45.0	28	7.65	21	5	5	1.8	3.2	2.918	13.200	0.532	0.103	0.147	0.758	1.144	1.110
10	45.0	28	7.65	20	5	5	1.8	3.2	2.918	13.200	0.532	0.108	0.162	0.758	1.162	1.136
10	45.0	28	7.65	19	5	5	1.8	3.2	2.918	13.200	0.532	0.114	0.179	0.758	1.182	1.165
10	45.0	28	7.65	18	5	5	1.8	3.2	2.918	13.200	0.532	0.120	0.201	0.758	1.204	1.196
10	45.0	28	7.65	17	5	5	1.8	3.2	2.918	13.200	0.532	0.127	0.229	0.758	1.230	1.229
10	45.0	28	7.65	16	5	5	1.8	3.2	2.918	13.200	0.532	0.135	0.266	0.758	1.255	1.264
10	45.0	28	7.65	15	5	5	1.8	3.2	2.918	13.200	0.532	0.144	0.318	0.758	1.282	1.299
24	47.3	26	4	19	2.3	2.3	1	1.3	1.097	25.200	0.450	0.125	0.030	0.952	1.326	1.325
10	52.5	26	4	19	0.9	0.9	0.1	0.8	0.237	10.614	0.374	0.295	0.100	0.942	2.117	2.352
8	55	28	2	19	3	2.6	0.4	2.2	1.176	9.821	0.372	0.043	0.179	0.815	0.751	0.646
8	55	23	5	19	3	2.6	0.4	2.2	1.176	9.821	0.297	0.107	0.143	0.815	1.062	1.040
8	55	26	5	19	3	2.6	0.4	2.2	1.176	9.821	0.342	0.107	0.164	0.815	1.123	1.052
8	55	28	3	19	3	2.6	0.4	2.2	1.176	9.821	0.372	0.064	0.179	0.815	1.169	0.784
7	55	26	3	19	3	2.6	0.9	1.7	1.358	8.470	0.342	0.064	0.097	0.826	0.875	0.810
7	55	26	3	18	3	2.6	0.9	1.7	1.358	8.470	0.342	0.068	0.109	0.826	0.893	0.828
7	55	28	5	18	3	2.6	0.9	1.7	1.358	8.470	0.372	0.113	0.119	0.826	1.228	1.131
7	55	26	3	17.5	3	2.6	1.2	1.4	1.501	8.260	0.342	0.070	0.076	0.847	0.881	0.862
7	55	28	5	18	3	2.6	1.2	1.4	1.501	8.260	0.372	0.113	0.078	0.847	1.186	1.156
8	55	26	3	19	3	2.6	1.2	1.4	1.471	9.260	0.342	0.064	0.057	0.864	0.920	0.840
8	55	26	4	19	3	2.6	1.2	1.4	1.471	9.260	0.342	0.086	0.057	0.864	1.073	0.978

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
8	55	26	5	19	3	2.6	1.2	1.4	1.471	9.260	0.342	0.107	0.057	0.864	1.221	1.117
5	65.0	28	5.5	19	1	0.7	0.5	0.2	0.511	5.233	0.248	0.319	0.007	0.955	2.455	2.494
5	65.0	28	5.5	19	2	1.7	1	0.7	1.078	5.466	0.248	0.160	0.024	0.915	1.456	1.442
5	65.0	28	5.5	19	2.3	2	0	2	0.841	6.073	0.248	0.139	0.229	0.823	1.277	1.185
5	65.0	28	5.5	19	2.3	2	0.575	1.425	0.916	5.804	0.248	0.139	0.093	0.861	1.265	1.259
1	65.0	28	5.5	19	2.3	2	0.8	1.2	1.422	1.699	0.248	0.139	0.169	0.588	1.094	1.135
2	65.0	28	5.5	19	2.3	2	0.8	1.2	1.229	2.699	0.248	0.139	0.117	0.741	1.182	1.209
3	65.0	28	5.5	19	2.3	2	0.8	1.2	1.129	3.699	0.248	0.139	0.090	0.811	1.222	1.244
4	65.0	28	5.5	19	2.3	2	0.8	1.2	1.068	4.699	0.248	0.139	0.073	0.851	1.251	1.264
5	65.0	28	0.5	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.013	0.061	0.877	0.403	0.463
5	65.0	28	1	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.025	0.061	0.877	0.516	0.544
5	65.0	28	2	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.050	0.061	0.877	0.708	0.707
5	65.0	28	3	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.076	0.061	0.877	0.869	0.870
5	65.0	22	4	19	2.3	2	0.8	1.2	1.026	5.699	0.188	0.101	0.047	0.877	0.941	1.010
5	65.0	23	4	19	2.3	2	0.8	1.2	1.026	5.699	0.198	0.101	0.049	0.877	0.961	1.014
5	65.0	24	4	19	2.3	2	0.8	1.2	1.026	5.699	0.208	0.101	0.051	0.877	0.983	1.018
5	65.0	25	4	19	2.3	2	0.8	1.2	1.026	5.699	0.217	0.101	0.054	0.877	1.005	1.022
5	65.0	26	4	19	2.3	2	0.8	1.2	1.026	5.699	0.227	0.101	0.056	0.877	1.027	1.025
5	65.0	28	4	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.101	0.061	0.877	1.027	1.033
5	65.0	28	4	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.101	0.061	0.877	1.027	1.033
5	65.0	29	4	19	2.3	2	0.8	1.2	1.026	5.699	0.258	0.101	0.064	0.877	1.049	1.037
5	65.0	30	4	19	2.3	2	0.8	1.2	1.026	5.699	0.269	0.101	0.067	0.877	1.068	1.042
5	65.0	31	4	19	2.3	2	0.8	1.2	1.026	5.699	0.280	0.101	0.069	0.877	1.090	1.046
5	65.0	32	4	19	2.3	2	0.8	1.2	1.026	5.699	0.291	0.101	0.072	0.877	1.111	1.050
5	65.0	33	4	19	2.3	2	0.8	1.2	1.026	5.699	0.303	0.101	0.075	0.877	1.133	1.054
5	65.0	34	4	19	2.3	2	0.8	1.2	1.026	5.699	0.315	0.101	0.078	0.877	1.152	1.059
5	65.0	35	4	19	2.3	2	0.8	1.2	1.026	5.699	0.327	0.101	0.081	0.877	1.170	1.064
5	65.0	36	4	19	2.3	2	0.8	1.2	1.026	5.699	0.339	0.101	0.084	0.877	1.172	1.068
5	65.0	37	4	19	2.3	2	0.8	1.2	1.026	5.699	0.351	0.101	0.087	0.877	1.182	1.073

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
5	65.0	38	4	19	2.3	2	0.8	1.2	1.026	5.699	0.364	0.101	0.090	0.877	1.203	1.078
5	65.0	28	5	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.126	0.061	0.877	1.203	1.196
5	65.0	28	5.5	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.139	0.061	0.877	1.264	1.278
5	65.0	28	6	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.151	0.061	0.877	1.334	1.360
5	65.0	28	7	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.177	0.061	0.877	1.517	1.523
5	65.0	28	8	19	2.3	2	0.8	1.2	1.026	5.699	0.248	0.202	0.061	0.877	1.642	1.686
6	65.0	28	5.5	19	2.3	2	0.8	1.2	0.995	6.699	0.248	0.139	0.053	0.896	1.277	1.288
7	65.0	28	5.5	19	2.3	2	0.8	1.2	0.972	7.699	0.248	0.139	0.047	0.909	1.288	1.295
8	65.0	28	5.5	19	2.3	2	0.8	1.2	0.954	8.699	0.248	0.139	0.042	0.920	1.294	1.301
9	65.0	28	5.5	19	2.3	2	0.8	1.2	0.939	9.699	0.248	0.139	0.038	0.928	1.300	1.305
10	65.0	22	2	19	2.3	2	0.8	1.2	0.927	10.699	0.188	0.050	0.026	0.935	0.638	0.712
10	65.0	24	3	19	2.3	2	0.8	1.2	0.927	10.699	0.208	0.076	0.029	0.935	0.840	0.884
10	65.0	25	5.21	23	2.3	2	0.8	1.2	0.927	10.699	0.217	0.109	0.021	0.935	1.082	1.105
10	65.0	25	5.21	22.5	2.3	2	0.8	1.2	0.927	10.699	0.217	0.111	0.022	0.935	1.094	1.120
10	65.0	25	5.21	22	2.3	2	0.8	1.2	0.927	10.699	0.217	0.114	0.023	0.935	1.106	1.136
10	65.0	25	5.21	21.5	2.3	2	0.8	1.2	0.927	10.699	0.217	0.116	0.024	0.935	1.119	1.152
10	65.0	25	5.21	21	2.3	2	0.8	1.2	0.927	10.699	0.217	0.119	0.025	0.935	1.133	1.170
10	65.0	25	5.21	20.5	2.3	2	0.8	1.2	0.927	10.699	0.217	0.122	0.026	0.935	1.147	1.188
10	65.0	25	5.21	20	2.3	2	0.8	1.2	0.927	10.699	0.217	0.125	0.027	0.935	1.162	1.207
10	65.0	25	5.21	19.5	2.3	2	0.8	1.2	0.927	10.699	0.217	0.128	0.029	0.935	1.177	1.227
10	65.0	25	5.21	19	2.3	2	0.8	1.2	0.927	10.699	0.217	0.132	0.030	0.935	1.198	1.248
10	65.0	25	5.21	18.5	2.3	2	0.8	1.2	0.927	10.699	0.217	0.135	0.032	0.935	1.237	1.270
10	65.0	25	5.21	18	2.3	2	0.8	1.2	0.927	10.699	0.217	0.139	0.034	0.935	1.256	1.294
10	65.0	25	5.21	17.5	2.3	2	0.8	1.2	0.927	10.699	0.217	0.143	0.036	0.935	1.304	1.318
10	65.0	28	5.5	19	2.3	2	0.8	1.2	0.927	10.699	0.248	0.139	0.035	0.935	1.305	1.309
10	65.0	28	7.65	23	2.3	2	0.8	1.2	0.927	10.699	0.248	0.160	0.024	0.935	1.477	1.447
10	65.0	28	7.65	22.5	2.3	2	0.8	1.2	0.927	10.699	0.248	0.163	0.025	0.935	1.494	1.470
10	65.0	28	7.65	22	2.3	2	0.8	1.2	0.927	10.699	0.248	0.167	0.026	0.935	1.513	1.493
10	65.0	28	7.65	21.5	2.3	2	0.8	1.2	0.927	10.699	0.248	0.171	0.027	0.935	1.531	1.518

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
10	65.0	28	7.65	21	2.3	2	0.8	1.2	0.927	10.699	0.248	0.175	0.028	0.935	1.552	1.543
10	65.0	28	7.65	20.5	2.3	2	0.8	1.2	0.927	10.699	0.248	0.179	0.030	0.935	1.571	1.570
10	65.0	28	7.65	20	2.3	2	0.8	1.2	0.927	10.699	0.248	0.183	0.031	0.935	1.594	1.599
10	65.0	28	7.65	19.5	2.3	2	0.8	1.2	0.927	10.699	0.248	0.188	0.033	0.935	1.623	1.628
10	65.0	28	7.65	19	2.3	2	0.8	1.2	0.927	10.699	0.248	0.193	0.035	0.935	1.645	1.659
10	65.0	28	7.65	18.5	2.3	2	0.8	1.2	0.927	10.699	0.248	0.198	0.037	0.935	1.670	1.692
10	65.0	28	7.65	18	2.3	2	0.8	1.2	0.927	10.699	0.248	0.204	0.039	0.935	1.697	1.727
10	65.0	28	7.65	17.5	2.3	2	0.8	1.2	0.927	10.699	0.248	0.210	0.041	0.935	1.725	1.763
5	65.0	28	5.5	23	2.3	2	1.15	0.85	1.258	5.536	0.248	0.115	0.020	0.903	1.171	1.149
5	65.0	28	5.5	22	2.3	2	1.15	0.85	1.258	5.536	0.248	0.120	0.022	0.903	1.202	1.182
5	65.0	28	5.5	21	2.3	2	1.15	0.85	1.258	5.536	0.248	0.126	0.024	0.903	1.237	1.218
5	65.0	28	5.5	20	2.3	2	1.15	0.85	1.258	5.536	0.248	0.132	0.026	0.903	1.274	1.257
5	65.0	28	5.5	19	2.3	2	1.15	0.85	1.258	5.536	0.248	0.139	0.029	0.903	1.316	1.301
5	65.0	28	5.5	19	2.3	2	1.15	0.85	1.258	5.536	0.248	0.139	0.029	0.903	1.316	1.301
5	65.0	28	5.5	18	2.3	2	1.15	0.85	1.258	5.536	0.248	0.147	0.033	0.903	1.362	1.349
5	65.0	28	5.5	17	2.3	2	1.15	0.85	1.258	5.536	0.248	0.155	0.037	0.903	1.418	1.403
5	65.0	28	5.5	16	2.3	2	1.15	0.85	1.258	5.536	0.248	0.165	0.044	0.903	1.495	1.463
5	65.0	28	5.5	15	2.3	2	1.15	0.85	1.258	5.536	0.248	0.176	0.052	0.903	1.559	1.530
5	65.0	28	5.5	19	2.3	2	1.725	0.275	1.740	5.268	0.248	0.139	0.004	0.949	1.571	1.327
5	65.0	28	5.5	19	2.3	2	2	0	2.000	5.140	0.248	0.139	0.000	0.973	1.772	1.337
10	65.0	28	5.5	19	3	1.1	1	0.1	1.009	10.933	0.248	0.106	0.002	0.915	1.145	1.108
10	65.0	28	5.5	19	3	1.15	1	0.15	1.014	10.933	0.248	0.106	0.003	0.915	1.146	1.107
10	65.0	28	5.5	19	3	1.2	1	0.2	1.019	10.933	0.248	0.106	0.004	0.915	1.143	1.107
10	65.0	28	5.5	19	3	1.25	1	0.25	1.024	10.933	0.248	0.106	0.005	0.915	1.143	1.107
10	65.0	28	5.5	19	3	1.3	1	0.3	1.029	10.933	0.248	0.106	0.006	0.915	1.142	1.106
10	65.0	28	5.5	19	3	1.35	1	0.35	1.034	10.933	0.248	0.106	0.007	0.915	1.141	1.106
10	65.0	28	5.5	19	3	1.4	1	0.4	1.040	10.933	0.248	0.106	0.008	0.915	1.140	1.105
5	65.0	28	5.5	19	3	2.7	1.5	1.2	1.694	5.699	0.248	0.106	0.040	0.877	1.086	1.078
5	65.0	28	5.5	19	4	2.2	2	0.2	2.033	5.933	0.248	0.080	0.005	0.843	1.142	0.911

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
5	65.0	28	5.5	19	4	2.3	2	0.3	2.050	5.933	0.248	0.080	0.008	0.843	1.139	0.910
5	65.0	28	5.5	19	4	2.4	2	0.4	2.068	5.933	0.248	0.080	0.011	0.843	1.133	0.909
5	65.0	28	5.5	19	4	2.5	2	0.5	2.087	5.933	0.248	0.080	0.014	0.843	1.129	0.907
5	65.0	28	5.5	19	4	3	2	1	2.188	5.933	0.248	0.080	0.029	0.843	1.010	0.900
5	65.0	28	5.5	19	4	3.7	2	1.7	2.350	5.933	0.248	0.080	0.055	0.843	0.891	0.889
5	65.0	28	5.5	19	4	4	2	2	2.426	5.933	0.248	0.080	0.067	0.843	1.006	0.883
5	65.0	28	5.5	19	5	4.7	2.5	2.2	3.041	6.166	0.248	0.064	0.068	0.811	0.762	0.769
22	69.0	26	4	19	2.6	2.6	1	1.6	1.075	22.614	0.187	0.087	0.016	0.973	0.971	0.963
8	75.0	28	4	19	1	0.5	0.4	0.1	0.402	8.161	0.142	0.218	0.001	0.980	1.764	1.797
8	75.0	28	4	19	1.25	0.75	0.5	0.25	0.508	8.201	0.142	0.174	0.004	0.975	1.537	1.513
8	75.0	28	4	19	1.5	1	0.6	0.4	0.615	8.241	0.142	0.145	0.006	0.971	1.331	1.323
8	75.0	28	4	19	1.75	1.25	0.7	0.55	0.726	8.281	0.142	0.125	0.009	0.966	1.224	1.186
8	75.0	28	4	19	2	1.5	0.8	0.7	0.838	8.322	0.142	0.109	0.011	0.961	1.108	1.083
8	75.0	28	4	19	2.25	1.75	0.9	0.85	0.953	8.362	0.142	0.097	0.014	0.957	1.030	1.002
8	75.0	28	4	19	2.5	2	1	1	1.069	8.402	0.142	0.087	0.016	0.952	0.960	0.937
8	75.0	28	4	19	2.75	2.25	1.1	1.15	1.188	8.442	0.142	0.079	0.019	0.948	0.913	0.883
8	75.0	28	5.5	19	3	1.2	1.2	0	1.200	8.482	0.142	0.100	0.000	0.943	1.065	1.023
8	75.0	28	5.5	19	3	1.3	1.2	0.1	1.206	8.482	0.142	0.100	0.001	0.943	1.064	1.023
8	75.0	28	5.5	19	3	1.4	1.2	0.2	1.212	8.482	0.142	0.100	0.002	0.943	1.062	1.022
8	75.0	28	5.5	19	3	1.5	1.2	0.3	1.219	8.482	0.142	0.100	0.004	0.943	1.060	1.021
8	75.0	28	5.5	19	3	1.6	1.2	0.4	1.226	8.482	0.142	0.100	0.005	0.943	1.059	1.021
8	75.0	28	7.65	25	3	1.6	1.2	0.4	1.226	8.482	0.142	0.106	0.003	0.943	1.078	1.059
8	75.0	28	7.65	24	3	1.6	1.2	0.4	1.226	8.482	0.142	0.110	0.003	0.943	1.093	1.087
8	75.0	28	7.65	23	3	1.6	1.2	0.4	1.226	8.482	0.142	0.115	0.004	0.943	1.112	1.118
8	75.0	28	7.65	22	3	1.6	1.2	0.4	1.226	8.482	0.142	0.120	0.004	0.943	1.156	1.151
8	75.0	28	7.65	21	3	1.6	1.2	0.4	1.226	8.482	0.142	0.126	0.004	0.943	1.219	1.188
8	75.0	28	7.65	20	3	1.6	1.2	0.4	1.226	8.482	0.142	0.132	0.005	0.943	1.275	1.228
8	75.0	28	7.65	19	3	1.6	1.2	0.4	1.226	8.482	0.142	0.139	0.005	0.943	1.321	1.273
8	75.0	28	7.65	18	3	1.6	1.2	0.4	1.226	8.482	0.142	0.147	0.006	0.943	1.371	1.323

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
8	75.0	28	7.65	17	3	1.6	1.2	0.4	1.226	8.482	0.142	0.155	0.007	0.943	1.428	1.378
8	75.0	28	7.65	16	3	1.6	1.2	0.4	1.226	8.482	0.142	0.165	0.008	0.943	1.488	1.440
8	75.0	28	7.65	15	3	1.6	1.2	0.4	1.226	8.482	0.142	0.176	0.009	0.943	1.555	1.511
8	75.0	28	5.5	19	3	1.7	1.2	0.5	1.234	8.482	0.142	0.100	0.007	0.943	1.056	1.020
8	75.0	28	5.5	19	3	1.8	1.2	0.6	1.242	8.482	0.142	0.100	0.008	0.943	1.054	1.019
8	75.0	28	5.5	19	3	1.9	1.2	0.7	1.250	8.482	0.142	0.100	0.010	0.943	1.052	1.019
8	75.0	28	5.5	19	3	2	1.2	0.8	1.259	8.482	0.142	0.100	0.012	0.943	1.049	1.018
8	75.0	28	5.5	19	3	2.1	1.2	0.9	1.268	8.482	0.142	0.100	0.013	0.943	1.047	1.017
8	75.0	28	5.5	19	3	2.2	1.2	1	1.278	8.482	0.142	0.100	0.015	0.943	1.040	1.016
8	75.0	28	5.5	19	3	2.3	1.2	1.1	1.288	8.482	0.142	0.100	0.017	0.943	1.037	1.015
8	75.0	28	5.5	19	3	2.4	1.2	1.2	1.298	8.482	0.142	0.100	0.019	0.943	1.036	1.014
8	75.0	28	4	19	3	2.5	1.2	1.3	1.309	8.482	0.142	0.073	0.021	0.943	0.864	0.837
8	75.0	28	5.5	19	3	2.5	1.2	1.3	1.309	8.482	0.142	0.100	0.021	0.943	1.032	1.013
8	75.0	28	5.5	19	3	2.6	1.2	1.4	1.320	8.482	0.142	0.100	0.024	0.943	1.028	1.012
3	75	30	5	20	5	5	1	4	2.705	4.072	0.155	0.052	0.196	0.737	0.486	0.562
6	75	28	3	20	5	5	1	4	2.153	7.072	0.142	0.031	0.122	0.848	0.428	0.492
9	75	22	2	18	5	5	1.75	3.25	2.236	9.871	0.108	0.023	0.049	0.912	0.346	0.477
9	75	30	2	18	5	5	1.75	3.25	2.236	9.871	0.155	0.023	0.070	0.912	0.410	0.491
9	75	22	7	18	5	5	1.75	3.25	2.236	9.871	0.108	0.081	0.049	0.912	0.744	0.849
9	75	22	8	18	5	5	1.75	3.25	2.236	9.871	0.108	0.092	0.049	0.912	0.795	0.923
9	75	22	10	18	5	5	1.75	3.25	2.236	9.871	0.108	0.115	0.049	0.912	0.937	1.072
3	75	28	3	20	5	5	3	2	3.380	3.536	0.142	0.031	0.040	0.848	0.407	0.529
3	75	28	5	20	5	5	3	2	3.380	3.536	0.142	0.052	0.040	0.848	0.555	0.663
9	75	22	3	18	5	5	3	2	3.146	9.536	0.108	0.035	0.015	0.944	0.468	0.577
9	75	22	4	18	5	5	3	2	3.146	9.536	0.108	0.046	0.015	0.944	0.551	0.652
9	75	22	5	18	5	5	3	2	3.146	9.536	0.108	0.058	0.015	0.944	0.629	0.726
9	75	22	6	18	5	5	3	2	3.146	9.536	0.108	0.069	0.015	0.944	0.705	0.800
9	75	22	7	18	5	5	3	2	3.146	9.536	0.108	0.081	0.015	0.944	0.780	0.875
9	75	22	8	18	5	5	3	2	3.146	9.536	0.108	0.092	0.015	0.944	0.856	0.949

L_b	θ	ϕ'	c'	γ_s	h_b	h_0	h_w	h_d	h_g	L_x	π_1	π_2	π_3	π_4	Actual FS	GLM FS
9	75	22	9	18	5	5	3	2	3.146	9.536	0.108	0.104	0.015	0.944	0.934	1.023
9	75	22	10	18	5	5	3	2	3.146	9.536	0.108	0.115	0.015	0.944	1.000	1.097
6	75	30	5	20	5	5	4	1	4.048	6.268	0.155	0.052	0.006	0.957	0.590	0.720
6	75	30	5	20	5	5	4	1	4.048	6.268	0.155	0.052	0.006	0.957	0.765	0.720
6	75	28	3	19.5	5	5	4	1	4.048	6.268	0.142	0.032	0.005	0.957	0.778	0.586
6	75	28	3	19	5	5	4	1	4.048	6.268	0.142	0.033	0.006	0.957	0.793	0.591