A management tool to reduce the risk of damage caused by geotechnical groundworks

L Piciullo[1], Y Bekele[2], I Depina[2], F Nadim[1], J Langford[1]

[1] Norwegian Geotechnical Institute, Oslo, Norway
[2] SINTEF, Trondheim, Norway

luca.piciullo@ngi.no

Abstract. A qualitative risk management tool, developed in the R&D project "BegrensSkade" [1], was recently updated in the R&D "REMEDY"-project [2] to include quantitative risk analysis. The tool contributes to the main objective of REMEDY to reduce the risk of damage to neighbouring structures caused by groundwork, as well as developing practical tools for risk assessment and management for the industry, to aid decision making. The tool is programmed in Visual Basic for Applications (VBA) and implemented in Excel spreadsheet software to emphasize usability among non-experts. The risk methodology implemented in the tool is based on the risk management framework described in the ISO 31000 guidelines [3]. This paper provides a tool overview describing the qualitative and quantitative procedures. The tool has been employed in several projects. The recent upgrades further simplify and improve its use, hopefully also expanding the use amongst project stakeholders. The tool can be downloaded from the project web page: https://www.ngi.no/eng/Projects/BegrensSkade-II-REMEDY-Risk-Reduction-of-Groundwork-Damage/Risk-management-tools. Currently, only the qualitative procedure has been validated and is available for downloading. The quantitative procedure, after a test period, will be formally released and integrated into the tool.

1. Introduction

Society increasingly requires the engineer to quantify and manage the risk which people, property and the environment are exposed to [4]. The risk management should be an integral part of management and decision-making. It should be integrated into the structure, operations and processes of the organization [3]. The core of the risk management framework proposed by the ISO 31000:2018 is composed by three main phases: context definition, risk assessment and risk treatment. In the first step, the scope and understanding of context/environment are defined, with the purpose of customizing the procedure, enabling effective risk assessment and appropriate risk treatment measures. The risk assessment phase is composed of risk identification, risk analysis and risk evaluation. The aim of the risk identification is to define all possible sources of risk and their consequences on different sectors (e.g., environment, life and health, economy, etc..). In the risk analysis step, the probabilities and the potential consequences of the risk sources are quantified. Then, the risk is evaluated and compared with established criteria to evaluate if mitigation measures are required. Finally, the risk treatment aims at selecting and implementing actions for addressing and reducing the risk and, analyzing the potential benefits against costs.

The R&D project "REMEDY", financed by the Research Council of Norway and 18 partners from the private and public sectors, aims to include risk management procedures into decision-making

processes to reduce the risk of damage to neighbouring structures caused by groundwork (excavation and foundation works). The primary objective of REMEDY is to integrate foundation engineering and risk assessment, to reduce risk of damage caused by groundwork. The project has six work packages (WP) and WP5 deals with risk assessment and management. One task of WP5 is to test and further develop the risk management tool designed in the previous project BegrensSkade I [5, 6]. The tool is programmed in Visual Basic for Applications (VBA) and implemented in Excel spreadsheet to simplify user interaction and emphasize usability. The tool is developed to be used together with all the stakeholders of a construction project, to aid decision-making. Moreover, it can be used in all phases of a project: early planning, design and construction. This paper describes the tool.

2. Background and general structure of the tool

The risk methodology used to design this tool is based on the framework described in the ISO 31000:2018 risk management guidelines. The current version of the tool is composed of qualitative and quantitative procedures to quantify the risk due to undesired events generated by work-processes (i.e., risk sources). The tool procedure is organized into steps following the core scheme of the risk management process described in the ISO 31000:2018: context definition, risk identification, risk analysis and risk evaluation (Figure 1). In step 1, the purpose of the analysis and the consensus on the tolerable risk levels need to be clarified. In this step, the sources of uncertainty and the sectors where consequences may occur are defined (Figure 1). A maximum of ten categories of uncertainty sources and consequence sectors can be defined by the user within the tool. The probability that an undesired event may occur is classified into five classes (Table 1) according to the NS 5815 [7] -"Risk assessment of construction work". The consequences due to a risk source are also classified into 5 classes [7] depending on the severity level (Table 1).

Table 1: Probability and consequence classes.

Probability Classes		Consequence Classes	
S1	extremely unlikely	K1	harmless
S2	very unlikely	K2	dangerous
S3	unlikely	K3	critical
S4	likely	K4	very critical
S5	very likely	K5	catastrophic

The meaning of each class of probability and consequence is defined by the user accordingly with the information at hand. To help the user in the process some suggested values are shown in the tool using an excavation example. In the Risk identification (step 2) the user needs to define all project processes, and their sub-processes that may cause undesired events or potential threats.

After risk identification, the user can choose, accordingly with the information at hand, to perform a quantitative or a semi-qualitative risk analysis (Figure 1).

2.1 Qualitative analysis

In the qualitative procedure risk sources are quantified with a value ranging from 1 to 5 (step 3), in agreement with the probability and consequence classes previously described. In step 4, Risk evaluation, the user has the possibility to select which risk source (i.e. project sub-process), uncertainty type and consequence sector, should be included in the risk analysis. Then, a final risk matrix is evaluated, and each risk source is plotted in a 5×5 risk matrix (Figure 2) where probability is plotted against consequences. Each risk source is then displayed in the matrix with the following code:

#P: #S-K

where the code is interpreted as follows:
- #P = Project process number;

- #S = Sub-process number;
- K = Code of the consequence type. For risk sources that generate multiple consequences in different sectors, multiple letters are plotted (see Figure 2).
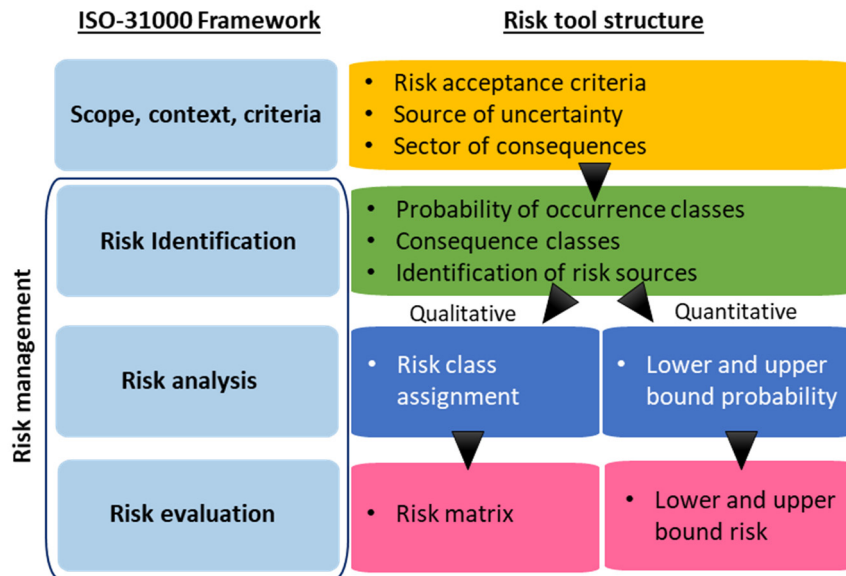

Figure 1: ISO 31000:2018 Risk management framework and risk tool structure.

The risk is not explicitly measured in the qualitative procedure. However, the matrix identifies the processes causing intolerably high level of risk, for which mitigation measures are necessary (Figure 2).
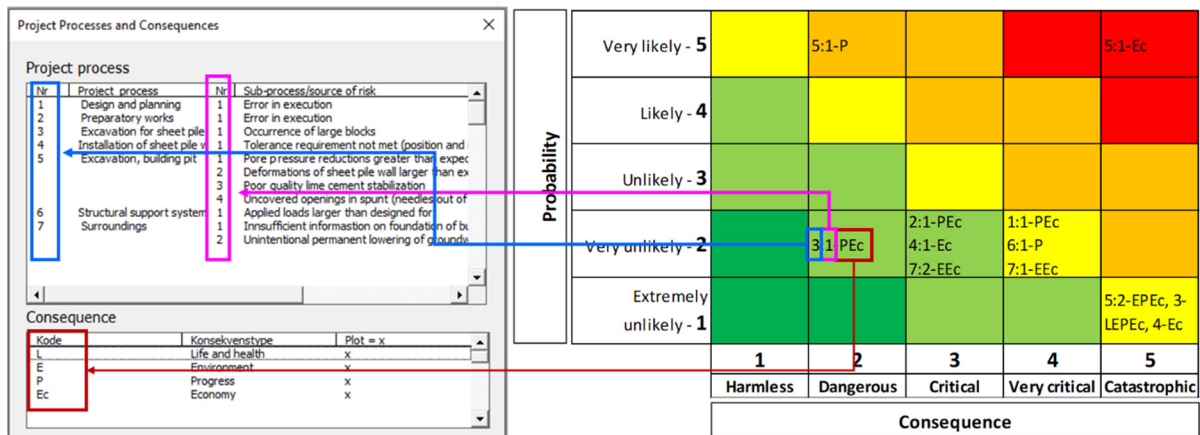

Figure 2: Explanation of the risk code meaning within the matrix.

2.2 Quantitative analysis

In addition to the functionality for a qualitative risk analysis, the developed tool also supports quantitative risk analysis. It expresses the risk in a quantitative (e.g., monetary) way for an explicit risk assessment. The quantitative risk analysis procedure is integrated in the tool to allow for a seamless transition from qualitative to quantitative analysis (see Figure 1). Custom functions were developed to convert qualitative values into quantitative ones. Quantitative estimates for probabilities and consequences are obtained based on the corresponding classes that are specified in the qualitative analysis. The result of this procedure is an interval-based risk analysis. An interval-based quantitative risk analysis is able to take into account uncertainties, commonly associated with risk analysis, and to

provide a more flexible approach. The workflow and the main elements of the quantitative risk analysis procedures are presented in the following sections.

The quantitative risk analysis starts with the risk identification step. The user has the possibility to proceed to quantitative risk analysis, integrating the data from the qualitative risk analysis procedure. The context and risk identification data are the same for the two procedures (see Figure 1). Thus, the project processes and sub-processes (i.e., risk sources), defined in the qualitative procedure, are imported into the quantitative analysis by clicking a specific button. The import button also reads the probability and consequence classes (see Section 2) of each sub-process, from the qualitative analysis and, it automatically provides initial probability and consequence estimates for the quantitative analysis. Lower and upper bound probability estimates are assigned. The initial value assigned for the lower bound probability of to the lowest probability class (i.e., class 1) is assumed as 0.0001 to provide an initial estimate, which the user can modify as desired. Similarly, the initial values assigned for the upper bound probability of to the highest probability class (i.e., class 5 in this example) is assumed as 0.2. These values are set arbitrarily and can be edited by the user as desired, while providing continuous and non-overlapping intervals. In a similar way, lower and upper bound monetary estimates are assigned to the consequence classes. For the sake of simplicity, the implementation is simplified by taking the average value from the interval as the corresponding value for a given consequence class. In the risk analysis step, the data are summarized to give an indication of the overall risk in the project. Based on the data imported in the risk identification step, the data are summarized and updated. The summary table shows the project processes and sources of risk together with their respective estimated lower and upper bound risks (Figure 3.1). The expected risk interval for a certain source of risk is determined based on the lower and upper bound probabilities. The risk interval for each sources of risk is visualized in a bar chart (Figure 3.2), with the risk sources being grouped in processes. A visualization of the relative risk contribution of each risk source to the total project risk is shown in terms of a tree-map chart (Figure 3.3). The main project processes are identified using a single colour while the individual sub-processes are shown as partitions with labels corresponding to the sub-process number.
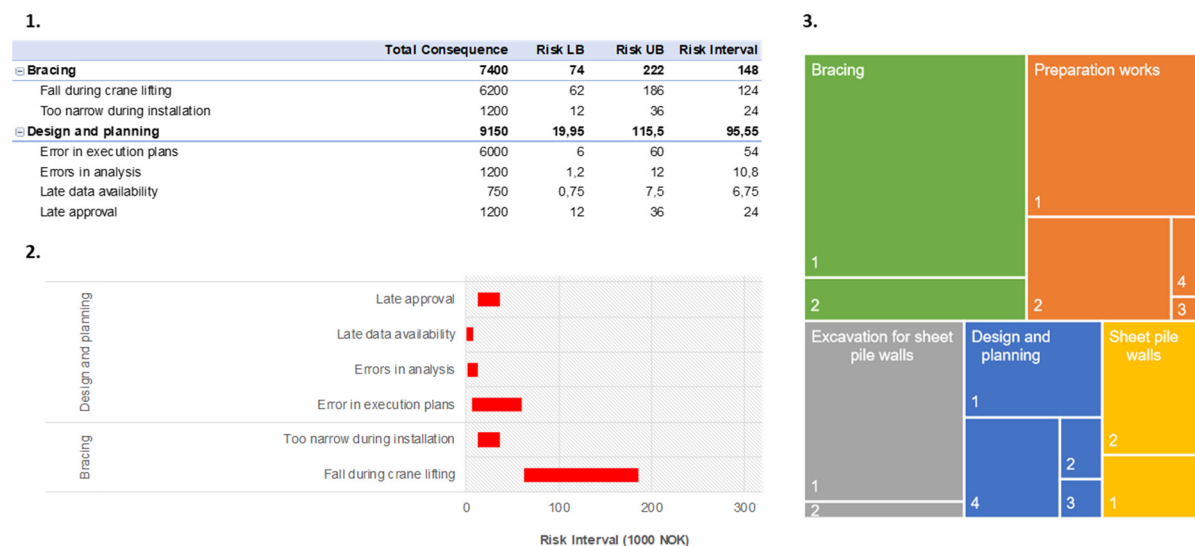

Figure 3: 1. Lower and upper bound risk in monetary value for each sub-process; 2. Interval-based quantitative risk assessment based on lower and upper bound probabilities; 3. Tree-map chart showing the contribution of each source of risk to the total project risk. The number labels correspond to the sub-process number

3. Discussion on risk acceptance criteria, sensitivity and cost-benefit analyses

3.1 Risk acceptance criteria for the qualitative analysis
The user has the possibility to any risk acceptance criterion that meets the requirements or conditions of the project at hand. In the qualitative procedure some functions have been implemented to assist in this process. The tool gives the possibility to characterize the risk matrix choosing among different risk criteria, risk aversion options, and numbers of risk levels. Currently, the user can choose among three different pre-configured risk criteria:

a) **Stair**: the boundaries between the different colors in the matrix look like a staircase;
b) **Hyperbola**: the boundaries between the five different colors in the matrix are hyperbolas;
c) **Consequence Aversion**: The acceptance of many single events with minor injuries/losses will be greater than the acceptance of one major event with high damage/loss, although the total loss over a given time span interval is the same for the two cases. Basically, in this case there is a low tolerability towards the occurrence of major/catastrophic events and, mitigation measures are needed, even for low occurrence probabilities.

The second option for characterizing the risk matrix is related to the selection of the risk aversion levels. Three levels of risk aversion are included in the Excel tool: 1) **Low***;* 2) **Medium***;* 3) **High**.
A high-risk aversion means a lack of willingness to take risks. However, it is important to mention that in a cost/benefit perspective, risk-taking can give a profit, and the willingness to take risk will often depend on the impact and the extent of the potential consequences. The third function is related to the choice of the risk levels number. The user can choose among 3, 4 or 5 levels of risk.

These three functions are useful to characterize the risk matrix and they lead to 27 different risk matrix combinations (Figure 4.1). Alternatively, the user has the possibility to manually personalize the matrix by assigning to each cell a different level of risk.
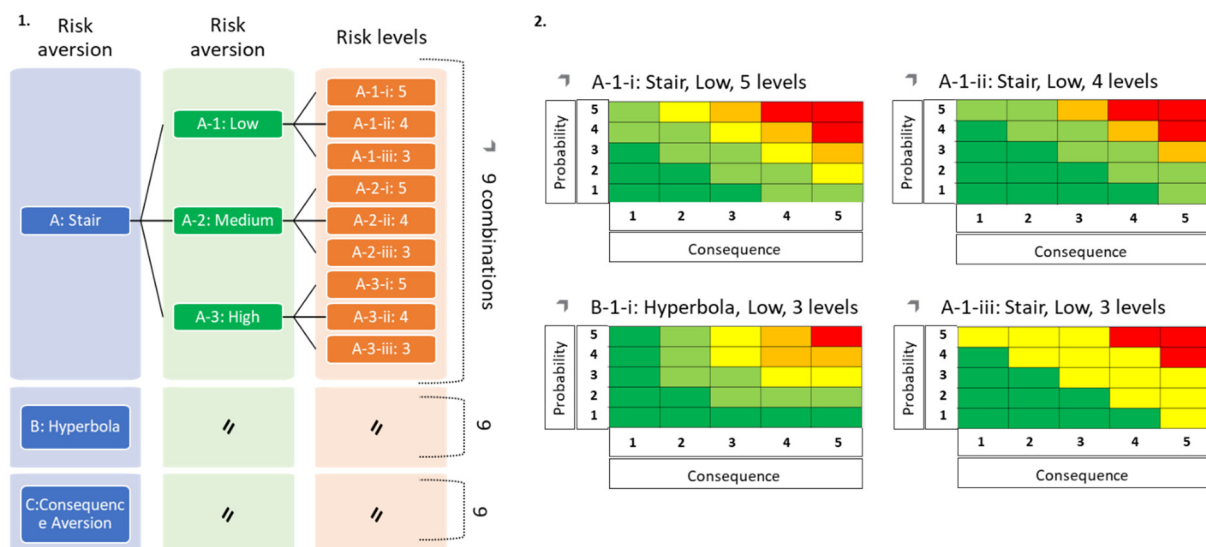

Figure 4: 1. Different possible combinations of the risk matrix as a function of the risk criterion, risk aversion, risk levels; 2. Four examples of risk matrices adopting different acceptance criteria.

3.2 Sensitivity analysis in the quantitative procedure
Sensitivity analysis enables identification of the most important and influential parameters in the analysed risk scenarios. Sensitivity analysis provides a basis to assess alternative parameters and decision options that may provide insights into the potential measures for risk treatment and robustness of the implemented approach. Sensitivity analysis is of great value in situations with large numbers of

risk sources as it provides a basis to aid decision-making on risk mitigation measures by identifying the threats having the highest influence on the overall risk assessment.

In the risk management tool, the user has the possibility to carry out a sensitivity analysis. The key parameters for the sensitivity analysis are the *risk change/reduction percentage* (a change of the occurrence probability or consequence) and the *acceptable risk threshold* (the maximum acceptable risk target). The values of these parameters are required as inputs from the user and may be entered directly in the specified cells or using a specific button. Sensitivity analysis helps to identify the sources of risk that have a higher effect on the overall project. The sensitivity analysis may be performed based on the lower, average or upper bound risks. The effect of these parameters on the project risks are reflected through:

- **Risk Reduction**: the level of risk reduced according to the risk change percentage
- **New Total Risk**: the total risk after a risk reduction measure to a given threat
- **Deviation**: the difference between the new total risk and the acceptable risk threshold
- **Deviation Percentage**: the change in risk compared to the initial total risk of the project item
- **Relative Change**: measures the effect of a given risk reduction on a certain threat in relation to all the threats in the project item. The relative change for all threats adds up to a 100%.

The results from sensitivity analysis indicate which sources of risk may be prioritized for risk mitigation. An example of the sensitivity of project threats to risk reduction is shown in Figure 5. The figure shows the relative change, in percentage, of the quantitative risk for project processes and sub-processes. The main project processes are identified with different colours while the sub-processes are shown using sub-process numbers. A higher relative change (wider area in Figure 5) indicates that a risk source is more sensitive to changes making it more suitable for risk mitigation.
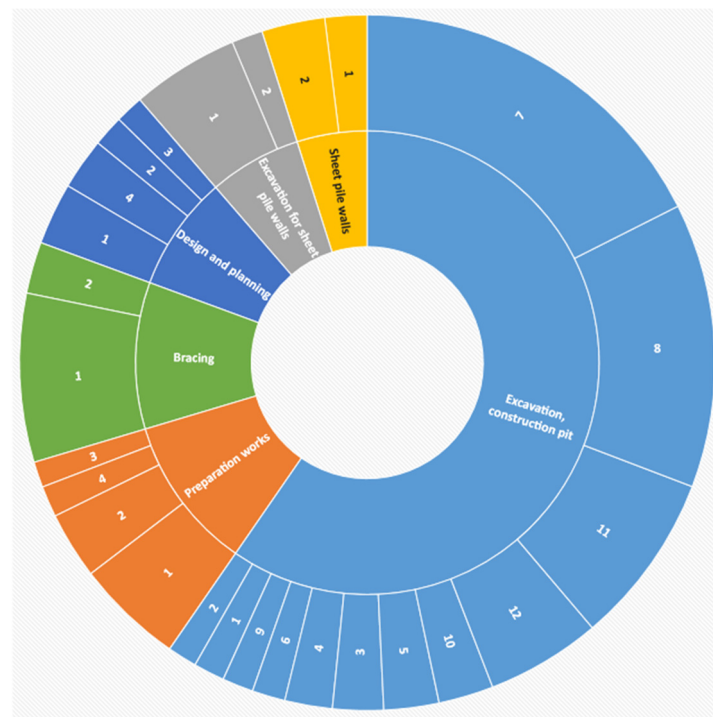

Figure 5: Sensitivity of project threats to risk reduction with a specified acceptable risk threshold.

3.3 Cost-benefit analysis in the quantitative procedure

Cost-benefit analysis provides a basis for a systematic consideration of all decisions in a project. It aims to identify and optimize among decisions that are worth taking (i.e., where the benefits outweigh the costs). The lower bound, average or upper bound risks may be used for cost-benefit analysis. The risks are retrieved from the risk analysis step according to the selected level (e.g., lower bound) for analysis. The next step in performing the cost-benefit analysis is to provide risk mitigation inputs. The inputs required from the user during this step are:

- **Action Description**: description of a risk mitigating measure to reduce the risk
- **Cost of Action**: the estimated cost of the specified risk mitigating measure/action
- **Risk After Action**: the estimated risk after applying a risk mitigating measure/action

These inputs may be provided directly in the data table (Figure 6) or by using the dedicated button and navigating through each of the sources of risk. Based on entries regarding the risk mitigation parameters, cost-benefit analysis indicators are automatically calculated. These cost benefit indicators are:

- **Benefit**: the difference between the initial risk and the risk after a mitigation measure/action
- **Net Present Value (NPV)**: the difference between the benefit and cost of an action
- **Benefit-Cost Ratio (BCR)**: the ratio of the benefit to the cost

See **Error! Reference source not found.** for an example of the risk mitigation user inputs and cost-benefit indicators for a selected number of project threats. The columns containing the Benefit, NPV and BCR are colour formatted to indicate the worthiness of the risk mitigation action using green, yellow and red colours. **Green** indicates that the risk mitigation action results in a positive effect on the source of risk while **Red** implies a negative effect, with respect to the Benefit, NPV and BCR. **Yellow** indicates that either there was no risk mitigation action or that the mitigation action has a neutral effect on the source of risk. Customizable visualization of the results from cost-benefit analysis is provided in the tool. **Error! Reference source not found.** shows the initial risk (green bar), risk after action (blue bar) and cost-benefit indicators (NPV in grey, Benefit in yellow) for selected project processes and sub-processes.

Risk Mitigation			Cost-benefit Indicators			
Action Description	Cost of Action	Risk After Action	Benefit	NPV	BCR	
Improve planning	10	20	13	3		1.30
Improved management	4	2	5	1		1.15
Additional personnel	10	5	-1	-11		-0.09
Improved planning	15	20	4	-11		0.27
Improved quality control	25	50	22	-3		0.88
No action	0	5	32	32		N/A
Improved communication	5	0	2	-3		0.40
No action	0	6.6	0	0		N/A

Figure 6: Risk mitigation user inputs and cost-benefit indicators for selected project processes and sub-processes.

4. Applications

The qualitative procedure of the tool has been applied to several projects in Norway. An extension of the current Viking museum is planned in Bygdøy, Oslo. The museum has one of the largest collection of Viking artefacts and ships in the world. The new museum is planned as a circular building, which will be attached to the north and west wings of the existing museum [8]. A qualitative risk assessment was undertaken to identify and evaluate the risk of damage for the Viking museum collection caused by vibrations from the planned construction activities. Construction activities were identified the project which could cause a threat to the Viking museum collection: construction traffic, excavation,

groundworks for water and waste water system, backfill and vibro-compaction. Detailed results for this case study can be found in [8].

Figure 7: Initial risk, risk after action and cost-benefit indicators for selected project processes and sub-processes.

The qualitative procedure of the tool has also been employed for the Svalbard Global Seed Vault. It is a seeds bank located on the island of Svalbard in Norway built to secure different plant seeds. The aim of the vault is to store seeds during national and/or global crises and to provide them to restore plants accidentally lost during catastrophic events. The tool has been used for the risk assessment of some construction aspects. Unfortunately, no more information can be described since the project is covered by confidentiality.

The quantitative procedure of the tool will be formally released and integrated into the tool and after a validation period where it will be applied to real cases.

5. Conclusions
This paper describes the current version of the Excel VBA risk management tool. The tool was developed for a R&D project and it has been recently updated. The integrated qualitative and quantitative tool for the risk management of groundwork damage is intuitive and easy to use. The user is required to provide risk identification data only once in the qualitative analysis tool.

The qualitative analysis produces a 5×5 risk matrix plotting the probability classes of each risk source (i.e. sub-process) against consequence classes. The risk matrix compares the defined risk level of each sub-process with risk acceptance criteria to determine whether risk mitigation measures are necessary. However, it is important to point out that the risk sources that require action are ultimately not just a

technical decision. Furthermore, the user has the possibility to define the risk acceptance criteria setting the options for the risk classification criterion, the risk aversion and the risk levels that better match the needs of the analysis and the willingness to take risks. It is recommended that the definition of the risk sources is performed by technicians aware of the project processing techniques under investigation. Then, as the project progresses, and new information becomes available, the spreadsheet should be revised and the tool re-run.

The data from qualitative analysis can be subsequently used to perform quantitative analysis in a seamless manner. Based on the data entries provided by the user, the quantitative risk analysis tool provides useful insights on the project processes and sub-processes in terms of risk management. The interval-based quantitative risk assessment gives an indication of which project threats have the highest expected risk interval in monetary value, while also showing the relative difference in comparison with other project threats. Further analyses based on sensitivity studies using given risk change/reduction and acceptable risk threshold criteria give the user an insight into which projects threats may be prioritized for risk mitigation. Moreover, the cost-benefit analysis step provides an indication to the user on the worthiness of risk mitigation actions (based on the action, the cost of the action and the risk after action) to specific project threats in terms of cost-benefit indicators such as the benefit-to-cost ratio and the net present value.

The semin-quantitative tool has been already employed to several projects and the recent upgrades further simplify and improve the use, hopefully also expanding the field of operation. The semi-quanitative tool can be downloaded at the following link: https://www.ngi.no/eng/Projects/BegrensSkade-II-REMEDY-Risk-Reduction-of-Groundwork-Damage/Risk-management-tools. The quantitative tool is to be further developed before releasing it.

6. References

[1] Web site: https://www.ngi.no/Prosjekter/BegrensSkade
[2] Web site: https://www.ngi.no/eng/Projects/BegrensSkade-II-REMEDY-Risk-Reduction-of-Groundwork-Damage
[3] ISO 31000 (2018) Risk management - Principles and guidelines. International Standard, 2018.
[4] Lacasse S. (2016). Hazard, Reliability and Risk Assessment-Research and Practice for Increased Safety. Proc. of the 17th Nordic Geotechnical Meeting Challenges in Nordic Geotechnic, Icelandic Geotechnical Society, Reykjavik, Island: 17-42.
[5] Kalsnes B, Vangelsten B.V., Eidsvig U. (2016). Risk analysis in excavation and foundation work. Proc. of the 17th Nordic Geotechnical Meeting Challenges in Nordic Geotechnic, Icelandic Geotechnical Society, Reykjavik, Island: 487-494.
[6] Langford J., Karlsrud K., Lande E. J., Baardvik G., Engen A. (2016). Begrensskade – limitation of damage caused by foundation and ground works.
[7] Norwegian Standard, NS 5815 (2006). Risikovurdering av anleggsarbeid.
[8] Langford J., Norén-Cosgriff K., Lacasse S., Sørgjerd T., Brekke A., Koelsch G. (2019). Risk assessment of vibrations caused by groundworks. Proceedings of the XVII ECSMGE-2019 Geotechnical Engineering foundation of the future ISBN 978-0-7277-6067-8

www.manaraa.com