The Refne landslide, Halden, Norway: case history and use of risk assessment

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ABSTRACT

In 2014, a landslide in a steep slope beneath an apartment block in Refne in the city of Halden, Norway led to the evacuation of over 60 residents from their homes.

The landslide is assumed to have been triggered by unusually high levels of rainfall over the preceding months, leading to accumulative long-term rainfall not previously seen in the lifetime of the block. Raised groundwater level and increased pore water in the saturated and unsaturated (vadose) zones are assumed to have contributed to reduced stability of the slope.

An initial risk assessment was performed to aid communication with local authorities and stakeholders and to clarify necessary actions. Following the evaluation of potential scenarios affecting the structural integrity of the pile foundations, the risk to residents was found to be unacceptable, and evacuation was therefore maintained. In particular, the potential development of a quick clay slide would have had catastrophic consequences. In order to improve the basis for further risk analyses and allow the design of stabilising measures, geotechnical site investigations (SI) were undertaken. Following the SI results and the completion of stabilising measures, an updated risk analysis was issued. This concluded a reduced level of risk for all landslide scenarios previously evaluated, and that the risk to residents was adequately reduced.

This paper shows how the visualization of risk using diagrams for risk analysis enabled communication and understanding between the geotechnical and structural engineers, police, local authorities and other stakeholders throughout the project, and formed the basis for decisions regarding evacuations and necessary mitigation measures. Engineering judgment is essential when reviewing risks in any natural hazard situation. Graphical risk analysis tools allow experience to be quantified and communicated to both experts and laymen alike so that operational decisions regarding public safety can be taken.

Keywords: Landslide, risk assessment, risk communication.

1 INTRODUCTION

In 2014, a landslide in a steep slope beneath an apartment block in Refne in the city of Halden, Norway, led to the evacuation of over 60 residents from their homes.

This paper shows how the visualization of risk using diagrams for risk analysis enabled communication and understanding between the geotechnical and structural engineers, police and local authorities throughout the project, and formed the basis for decisions regarding evacuations and mitigation measures.

2 BACKGROUND

NGI was first contacted by local residents regarding cracks and displacements on top of a 16 m high, steep slope beneath the apartment block. An inspection was carried out by NGI and it was discovered that a large slope instability had developed. The slope had deformed visibly and a continuous crack had developed covering the full width of the slope beneath the apartment block. Along the crack, the slope had a vertical deformation of approx. 0,5-1 m. The southern part of the crack followed a ridge leading down to the Refne stream (Figure 2).

The deformations of the slope had uncovered the corner pile foundation, situated at the brink of the slope (Figures 1, 2 and 3).

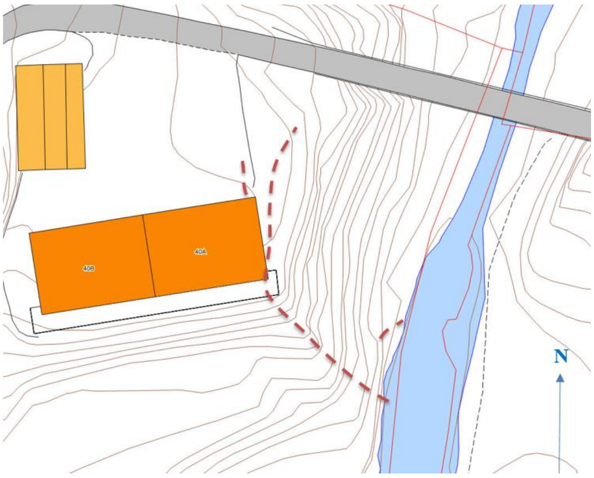

Figure 1 Location of the apartment block and approximate location of cracks in slope. The slope was 16 m high.

Figure 2 The backscarp of the slide. Vertical deformation 0,5-1 m.

Deformations along the side of the block were approx. 1,5-2 m. The backscarp of the slide coincided with the corner pile of the block partially exposed the corner pile foundation (Figure 3). The pile guided the crack in the way that the direction of the backscarp was forced outside the pile.

Following NGI's first inspection, grave concerns for the further development of the landslide and the structural integrity of the pile foundations were communicated to the municipality and the local police authority. Based on NGI's evaluation of the situation based on available data, the police decided to evacuate all residents from the building.

Figure 3 Backscarp of the landslide restricted by the pile foundation. Concrete pile supporting the corner foundation visible.

3 STAKEHOLDERS

The evacuation of 65 residents involved numerous stakeholders with different requirements and relationships, a few of them mentioned below.

Østfold Police - Although NGI can notify the police of a concerning situation, the local police are ultimately responsible for making a decision regarding the need for evacuation, and when and whether it is safe to return.

Halden Kommune - The municipality is responsible for residents' safety and emergency housing, and have a communications officer for emergency situations.

Insurers and underwriters - Once an evacuation becomes a longer term situation, each resident's insurance policy would come into effect. A separate insurance policy concerned actual damage to the structure itself.

Residents co-ownership committee - The residents had an elected representative who served as NGI's client and who took part in meetings with NGI and other stakeholders.

Print and TV media - Local and national media were involved, most heavily in the early phases when there were more questions than answers.

All stakeholders looked to the engineers for answers on duration of evacuations and cause and effect, as well as future development, of the landslide. Many of the questions lay outside of NGI's mandate and responsibility, and it was therefore essential that communication was as clear as possible.

The day following the evacuation, all stakeholders (except the press) met on site for briefing and later in the town hall to conclude a first statement and suggested process for the further work, need of supplementary information and establishment of responsibilities, tasks and formal roles.

All subsequent results and reports from NGI were issued to the residents' representative who could distribute to other stakeholders.

In later stages the County Governor, the Norwegian Water Resources and Energy Directorate and several contractors were also involved.

4 EMERGENCY PHASE STRUCTURAL AND GEOTECHNICAL ASSESSMENT

4.1 Geology

Geological mapping (NGU, 2014) showed that the area consists of thick deposits of marine sediments, predominantly clay, and that undulating bedrock is locally exposed. Rivers and streams have formed steep ravines, such as the one past the apartment block, seen in Figure 1.

Combinations of slope geometry, river erosion, ground conditions and pore water pressures can reach critical states leading to triggering of small or large landslides. Two known landsides had occurred just upstream of the block in the previous three years. One of these was in a steep silt slope where NGI subsequently designed ground improvement measures.
There were no known quick clay zones in the area, but in areas with marine sediments, it must always be considered a possibility until an SI can document otherwise.

4.2 Foundations and structural sensitivity

The five story block was built in 1974 on driven concrete pile foundations. A sand fill of approx. 2 m was built at the construction site before the piles were driven (Figure 3). Information from construction workers taking part in the construction work in the 1970s indicated that soft, sensitive clay might have been encountered during installation of piles. Assumptions based on typical building methods, construction drawings from local archives and the geological setting formed the basis for the assessment of the block's sensitivity to ground movements and expected behaviour should any of the foundations fail. The early stage evaluation was that failure in any of the piles closest to the landslide could leave the block uninhabitable.

4.3 Geotechnical assumptions and first evaluation

At the initial stage, no ground investigations or detailed knowledge of the local ground conditions were available, however, assumed depth to bedrock under the block was known from construction drawings documenting installation of piles. Decisions in the early phase therefore had to be based on very limited information. Different stakeholders, such as local government employees and politicians, spokespersons for the residents, insurance companies and the police, were all involved in the discussions regarding the need for continued evacuation and required measures, as well as the geotechnical and structural engineers.

Based on results from preliminary geotechnical site investigations (SI) and evaluations, it was concluded that the stability of the slope was not acceptable and that stabilising measures would be required. The question to be answered from day to day was whether the evacuation of inhabitants from the block would remain, or whether people could move back in to all of, or parts of, the building. From a geotechnical point of view, there was no doubt that the slide would, with time, develop further if measures were not taken. However, with no visible damage on the building and a large number of inhabitants evacuated from the building, the pressure was high to allow people to move back into their homes.

There was an obvious need to aid the communication and enhance the common understanding of the actual risk, taking uncertainties at this early stage and potential consequences of the landslide into account. It was decided to illustrate the situation to the residents and local authorities through a risk assessment for the relevant scenarios.

5 RISK THEORY

Guidelines from the Norwegian Directorate for Civil Protection (DSB, 2011), were used as basis for deciding appropriate probability (return period) boundaries and categorising risk. No current standard or regulation exists for geotechnical stability of existing structures, however the Norwegian project NIFS (Natural hazards, Infrastructure, Flooding, Landslides) have recently suggested risk acceptance criteria (NIFS, 2014).

Table 1 Probability classes for landslide if no stabilising measures are taken

Probability class, P		**Description**
1	Unlikely	1/300 per year Or the scenario cannot occur
2	Less likely	1/50 per year Scenario can happen within 50 years
3	Likely	1/10 per year Scenario can happen within 10 years
4	Very likely	1/1 per year Scenario expected to happen within 1 year

The suggested upper probability before evaluation of measures is needed for existing structures is 1/300 per year (Table 1). In an emergency situation a higher probability could be acceptable for a limited time period but would have to be compensated by increased monitoring of the situation.

Probability classes based on return periods are well known to most people in the context of flooding and are, with some exceptions, translatable and relatable to landslides.

For the case of the apartment block, the consequences in terms of damage to the structure, and whether the block would be considered habitable with a certain level of damage, were considered based on landslide scenarios defining a certain damage to the pile foundations (Table 2).

Table 2 Consequence classes - Damage to structure

Consequence class, C		**Description of damage**	**Block habit-able?**
1	Negligible	Small deformations / lines	Yes
2	Moderate	Deformations / cracks	No
3	Critical	Large structural damage	No
4	Catastrophic	Complete failure	No

Table 3 Evaluating risk from probability and consequence

Risk of damage		Consequence, Table 2			
		1	2	3	4
Probability of scenario which will cause damage, Table 1	1	L	L	L	M
	2	L	L	M	H
	3	L	M	H	H
	4	M	H	H	H

Where risk classes are indicated by colours:

Green:	**L**ow. Acceptable risk
Yellow:	**M**oderate. Risk needs further assessment
Red:	**H**igh. Unacceptable risk

The evaluation of risk is the combination of probability and consequence (Table 3). Thus, an unlikely scenario with catastrophic consequences or a very likely scenario with negligible consequences can still be deemed unresolved and require further assessment.

6 EARLY STAGE EVALUATION AND COMMUNICATION OF RISK

6.1 Probability of given scenarios

Based on available SI results, structural evaluation and the development of the landslide in the early stage, five scenarios were evaluated, each resulting in a specified damage on the pile foundations due to further development of the landslide.

A. Quick clay slide:

If potential quick clay under the block was to slide, all piles would likely follow the slide, break or buckle (Figure 4). Soundings performed in the first phase of the SI did not indicate quick clay underneath the building, but the scenario could not be eliminated before samples were taken and analysed. However, it was deemed unlikely that quick clay could be exposed as a result of further development of the landslide, thereby triggering a major quick clay landslide involving the building, i.e. the lowest probability class P1 was assigned.

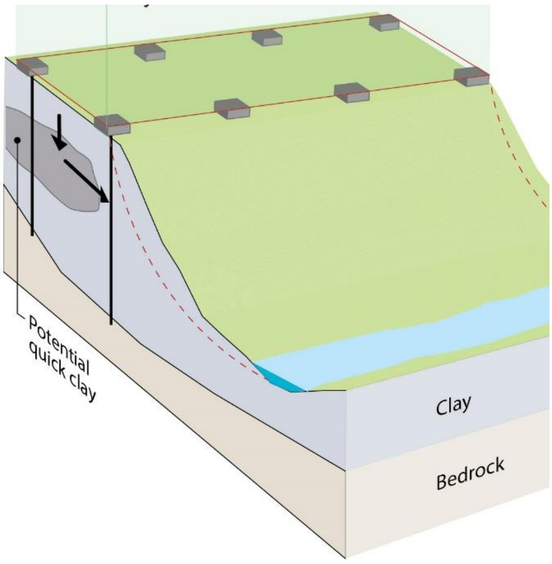

Figure 4 Scenario A - quick clay slide

B. Damage to corner pile:

One of the concrete piles under the block was partly exposed by the landslide (Figure 3). A further development of the landslide would increasingly expose the pile, leaving it vulnerable to excessive lateral loading or horizontal displacement (Figure 5). The probability of damage to the corner pile was evaluated to be in the highest probability class P4, i.e. damage to the pile was expected to occur within 1 year. Further movement of the landslide would certainly be expected in connection with heavy rainfall events.

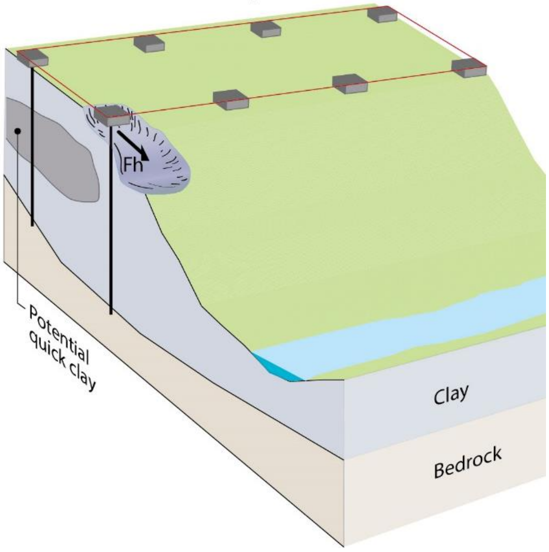

Figure 5 Scenario B - Damage to corner pile

C. Damage to several piles in the pile row closest to the slope:

Should the landslide develop along the length of the slope, more of the piles in the pile row closest to the slope could be exposed or affected (Figure 6).

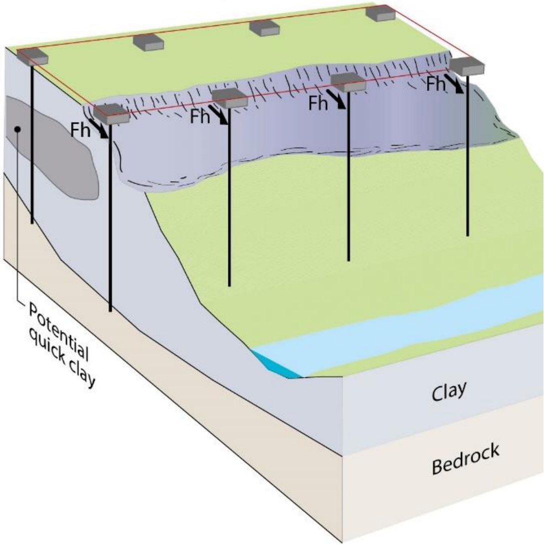

Figure 6 Scenario C - Damage to several piles in 1st row

Due to the orientation of the building not quite parallel to the slope (Figure 1), the distance from the closest piles to the slope edge increases slightly towards the north. This makes a scenario damaging several piles slightly less probable than damage to the corner pile. For this scenario, the second highest probability class P3 was therefore assigned.

D. Damage to piles in the second pile row from the slope:

The distance between the rows of piles was approx. 6 m. Based on the SI it was considered less likely that the landslide would develop backwards to that extent and cause direct damage on the piles in the second row (Figure 7), i.e. the second lowest probability class P2 was assigned.

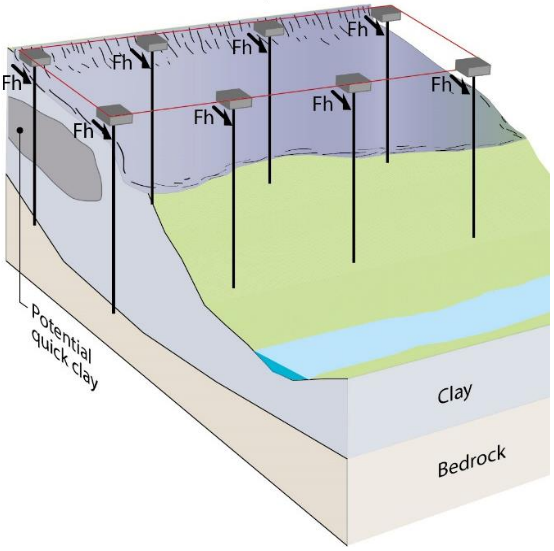

Figure 7 Scenario D - Damage to several piles in 2nd row

E. "Domino effect" – failure of all piles:

A "domino effect" may occur from redistribution of horizontal and vertical loads. It is a relevant scenario if failure of one or several piles leads to deformations that cause additional load on, and potential failure of, the next row of piles (Figure 8). The second highest probability class P3 was assigned for this scenario.

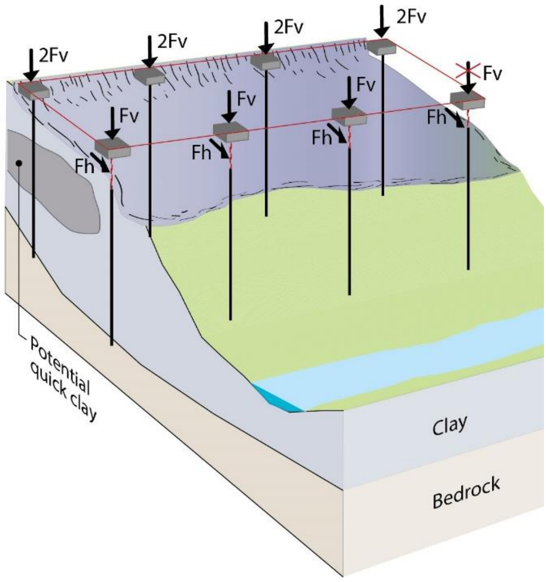

Figure 8 Scenario E - Domino effect - failure of all piles

6.2 Consequences of given scenarios

A structural engineer was engaged to evaluate the structural integrity and sensitivity at this initial stage, coupling landslide scenarios defined by NGI to consequences for the structural integrity of the foundations and the building (COWI, 2014), and a consequence class C1-C4 was assigned to each scenario.

For each of the scenarios, from damage on the corner pile to the quick clay slide, the conclusion from the structural engineer was that the described damage on the foundations would leave the block inhabitable. The expected damage to the building varied from total collapse to cracks or minor displacements, however, even for the smallest damage, moving back into the block under these circumstances was deemed not recommendable.

6.3 Risk

The probability of each identified scenario describing damage to the pile foundation was combined with the subsequent consequence to the block to produce the resulting risk to the block (Table 4). Based on the results in Table 4, all the scenarios were found to give unacceptable levels of risk of damage to the block before stabilising measures were in place.

Table 4 Risk of damage to the block from geotechnical failure scenarios. Green: Acceptable. Yellow: Risk needs further assessment. Red: Unacceptable.

Risk of damage		**Consequence (damage)**			
		1 Negligible	**2 Moderate**	**3 Critical**	**4 Catastrophic**
Probability of landslide (cause of damage)	**1 Unlikely**	🟩	🟩	🟩	🟨 Quick clay
	2 Less likely	🟩	🟩	🟨	🟥 Damage to piles in 2nd row
	3 Likely	🟩	🟨	🟥 Damage to several piles, 1st row	🟥 Domino effect
	4 Very likely	🟨	🟥	🟥 Damage to corner pile	🟥

The risk assessment and its supporting arguements was issued in a report (NGI, 2014a) to the residents' representative and other stakeholders. With the risk assessment as background, the stakeholders understood that the results of the SI alone would not improve the level of risk for all scenarios to an accepbable level, and that the mitigation measures required would take some time.

6.4 Benefits from risk assessment in communication with the media

In NGI's communicatio with the media, it was useful to be able to refer to conclusions from the risk assessment when faced with questions designed to create exciting headlines. For the journalists who are trying to pass on information to the public without having the technical background the nuances in our communication can easily be lost or interpreted the wrong way. The project therefore found it very useful to have graded the levels of probability and consequence so that all outwards communication was kept consistent.

7 GEOTECHNICAL ASSESSMENT POST SITE INVESTIGATIONS

7.1 Topography

Older maps of the area show that the slope beneath the block was as steep and tall before the block was constructed in 1975 as it was before the slide. The topography may have been slightly worsened by fill around the block for parking and walkways at the top of the slope, but the natural slope still had a total height of 16 m and inclinations of up to 40°.

7.2 Precipitation and ground water

A local metrological station in Halden has continuous precipitation data dating back to 1882, which can be accessed on web (MET, 2014). The measured monthly precipitation in February 2014 was almost 300% of the normal. The extreme monthly precipitation values for the months December, January and February from 1970 until 2013 have been collated (Table 5).

Table 5 Extreme values for monthly precipitation, the five highest from 1970 to February 2014 for station 1230, Halden, Norway (MET 2014)

Monthly precipitation (mm)					
	1	**2**	**3**	**4**	**5**
Dec. **(Year)**	**175** **2013**	168 1999	163 2006	145 2011	143 1972
Jan. **(Year)**	157 2008	136 1999	133 2002	128 1990	124 1988
Feb. **(Year)**	198 1990	**134** **2014**	118 1995	114 1988	104 2002

Table 5 shows that December 2013 had the highest recorded precipitation in December during the lifetime of the block and that February 2014 had the second highest February precipitation. The precipitation for January 2014 was not among the ten highest January recordings, but summing December to February, 2013/2014 gives the highest total precipitation recorded since 1975. In conclusion, the level of precipitation leading up to the landslide was unusually high.

Regional modelling of soil moisture from weather data and simulated water retention shows 80-100% saturation in the days prior to the landslide (NVE, 2014).

7.3 Geotechnical site investigation and laboratory results

The SI, consisting of rotary soundings, CPTUs, extraction of undisturbed samples and pore pressure measurements, was carried out in the week following the evacuation of residents. The interpretations of the SI formed the basis for further assessment of geotechnical stability, the potential for further development of the landslide and design of required stabilising measures.

The SI results show that the block was built on top of a 2-3 m fill layer of sand. The natural ground consists of silt with an increasing clay content with depth. Underneath the silt there is a layer of clay over bedrock. Depths to bedrock from the SI are between 7 m and 16 m, increasing towards the southeast and the base of the slope. The depth to bedrock is assumed to increase further towards the sea shortly south of the area. The thickness of the clay layer above bedrock is assumed to increase with the depth to bedrock.

Electrical piezometers were installed at the top and bottom of the slope for back-calculating the slope stability before the slide, as well as giving data for design and monitoring of stabilising works. At the base of the slope, artesian water pressures equivalent to 3 m above ground level were measured just above bedrock.

An undrained triaxial compression test gave an interpreted effective angle of friction, φ', of approx. 35°, which is less than the natural inclination of parts of the slope.

7.4 Causes of the landslide

Natural silt slopes can be very steep and seemingly stable, even with inclinations higher than the material's effective angle of friction. Stability thus relies on some cohesion. If pore pressure and saturation of such slopes increase due to ground water flow or infiltration, apparent cohesion may be lost and a slide may be triggered. The stability of such slopes is thus very dependent on climatic conditions.

Slopes respond differently to short-term and long-term precipitation, the soil type being significant for the response. Short-term, intense rainfall (from a few hours to a few days), could for silt slopes trigger shallow landslides, typically 1-2 m deep. As a result of more prolonged, less intense rainfall (from a few days to several months), deeper slides can occur, due to an increased ground water level and saturation of the soil above the ground water level to larger depth. Detailed assessment of triggering mechanisms thus requires application of unsaturated soil mechanics.

For the Refne landslide, it is likely that high long-term precipitation (Section 7.2), in combination with the high slope inclination, were the principal causes of the landslide. It is assumed that, in February 2014, critical levels of pore pressures and saturation with respect to slope stability were exceeded for the first time since construction of the block. Stability calculations (NGI, 2014b) show that the slope had a low factor of safety for slope stability even under 'normal' conditions, without extreme precipitation. A moderate change in negative direction would therefore be enough to trigger a slide.

7.5 Slope stability calculations and design of stabilising measures

The stabilising measure aimed at improving slope stability and ease of construction. The slope gradient had to be reduced to very top of the slope and along the full length of the apartment block along the river, to the base of the slope. The stream at the base of the slope needed to be moved a few metres to the east. The embankment was designed to give sufficient improvement to the slope, and at the same time not creating instability of underlying clay when the embankment was put out as undrained loading. The embankment would also serve as erosion protection from the stream.

Table 6 Revised risk assessement after SI and stabilising measures. Arrows indicate changes from the early stage assessment. Green: Acceptable. Yellow: Further assessment needed. Red: Unacceptable.

Risk of damage		**Consequence (damage)**			
		1 Negligible	**2 Moderate**	**3 Critical**	**4 Catastrophic**
Probability of landslide (cause of damage)	**1 Unlikely**	🟩	🟩	🟩 Damage to several piles, 1st row ↑ ↑Damage to corner pile	🟨 Damage to piles in 2nd row ↑ ↑Domino effect
	2 Less likely	🟩	🟩	🟨	🟥 ●
	3 Likely	🟩	🟨	🟥 ●	🟥 ●
	4 Very likely	🟨	🟥	🟥 ●	🟥

Slope stability calculations showed an improved factor of safety of at least 15 % for both drained and undrained analyses. The slope stability was considered satisfactory after the completion of the stabilising embankment. The factor of safety is, however, still lower than the requirement from Eurocode 7 for new builds. When modelling the slope stability prior to the landslide, all calculations resulted in a safety factor FS < 1.0, i.e. the slope should theoretically fail. The slope had, however, remained stable with this topography, through periods with high levels of precipitation for 40 years without failing.

This indicates that the applied model does not capture the slope behaviour. For silty slopes, unsaturated soil mechanics is necessary to include the effect of soil moisture in the vadose zone on soil strength. With a "standard geotechnical approach" we will not know the true improved safety factor of the slope, but an improvement can nevertheless be documented.

8 RE-EVALUATION AND COMMUNICATION OF RISK

The evacuation order remained in place while the geotechnical design and the construction of stabilising measures were completed. In total, the residents remained evacuated from their homes for just over five weeks (which in reality is not long for this kind of operation). In the same way as the risk of a landslide was conveyed to them and other stakeholders, it was important to communicate the improved situation which allowed them to move home again. It was important that they would feel safe and there were also concerns around resale values of the property after the media coverage the landslide.

The improvement to the slope stability documented through calculations was again converted into to classifications of risk. For the scenarios defined, the consequence remains the same. The probability, however, had been adequately reduced for the risk to be considered acceptable.

In the re-evaluation of risk, the first scenario regarding quick clay was discounted, as no quick clay was found in the SI. The four remaining scenarios all showed an improved risk classification as a result of the stabilising measures (Table 6) and were all considered to have a probability of P<1/300 per year, in accordance with guidelines (NIFS, 2014).

The scenarios which remain in the yellow zone are, based on NGI's evaluation, at an acceptable risk level. The probability of these scenarios will be lower as the distance from the top of the slope to the foundations increases away from the corner.

As discussed in section 7.5, the true behaviour of the silt slope and its safety factor against failure, are not easily modelled. The results of the SI, geotechnical calculations and constructed stabilising embankment therefore give the basis for relative, rather than definitive, answers. This was illustrated in the risk assessment matrix through improved risk classification.

The re-evaluated risk assessment was issued to the residents' representative (NGI, 2014b) as a part of a final report. This gave the right authorities the technical documentation they needed to make decisions regarding the safety of residents and whether they would be allowed to move home.

9 DISCUSSION OF THE USE OF RISK EVALUATION

The initial phase of this project involved many stakeholders with many questions, relying on engineers for immediate answers. This raised the need for a structured analysis of knowns and unknowns, with the gaps filled in by engineering judgement.

Communicating all the aspects taken into consideration in such an analysis to residents, authorities and the media can be a challenge. Through defining scenarios covering both geotechnical and structural failure mechanisms, some of the complexity of the situation could be described. Pairing this with probability in a risk assessment provided a matrix that could be referred to and a guideline terminology for our communication that, hopefully, reduced the potential for misunderstandings. The risk assessment places the results of engineering judgement from geotechnical and structural engineers in a non-technical framework, which allows for a non-technical discussion.

"Do you think the block will end up in the sea?". No, but potentially it could. "Will it collapse in the next week or month?". Probably not. "When can we move back?". We can't say. These are all examples of frustrating communication. Grounded in the risk assessment, these vague answers could be replaced with the explanation that even if something is considered not very likely, the consequence would be so great that the risk is nonetheless unacceptable. Likewise, the probability of any scenario will never be fully eliminated, and thus neither will the risk.

The use of risk assessment aided this project, where all the stakeholders waiting for a geotechnical assessment and report had no background in geotechnical engineering. For the most simplistic of analyses, stakeholders could choose to relate to just three terms; high, moderate or low risk. As engineers working with the public, it is important to strive for this level of communication, and to create a common platform from which operational decisions can be made.

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