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Some aspects of The Norwegian Risk Evaluation System for Quick Clay based on recent landslide events

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Abstract: Mapping of landslide hazard zones in Norway started after the famous Rissa landslide in 1978. In the following decades, quick clay hazard zones were mapped for large areas. A semi-quantitative risk evaluation system has been established for prioritizing between the zones for more detailed geotechnical investigation and mitigation measures. Mapping of quick clay zones is still ongoing, however, the majority of already known zones have not yet undergone detailed examination. Together with the fact that the quick clay areas in Norway coincide with the most densely populated areas of the country, this means that quick clay landslides pose a considerable threat to the society. Risk is related to extent of hazards zones, to landslide triggering from natural and human factors, and from objects at risk within (known and unknown) hazard zones. The Plan and building code, geotechnical standards and guidelines give clear restrictions for new projects. However, for existing (older) residential areas, no legal requirements exist. In this paper, some aspects related to the methods used for assessing the landslide risk are discussed.Lines are drawn from the current risk assessment system to experiences from the last fatal quick clay landslide in Norway that occurred in Gjerdrum, 30th of December 2020.

Keywords: Quick clay; Hazard mapping; Risk evaluation; Gjerdrum quick clay landslide

1 Introduction

The risk potential of quick clay is connected to the potential of very large landslidesdeveloping rapidly after small initial disturbances. Mapping of landslide hazard zones in Norway started after the famous Rissa landslide in 1978, which was captured on amateur films (The Quick Clay Landslide at Rissa - 1978 (English commentary) - YouTube). The event developed from a small initial failure due to a landfill of a few hundred m^3, to a gigantic landslide with volume of about 6 million m^3(Gregersen, 1981).In the following decades, quick clay hazard zones were mapped for large areas. After year 2000, a semi-quantitative risk evaluation system has been established for prioritizing between the zones for more detailed geotechnical investigation and mitigation measures.The mapping of quick clay zones is still ongoing, and the majority of already known zones have not yet undergone detailed examination. This, together with the fact that the quick clay areas in Norway coincide with the most densely populated areas of the country, means that quick clay landslides pose a considerable threat to the society. Experiences from the fatal quick clay landslide in Norway that occurred at Ask in the municipality of Gjerdrum, 30th of December 2020, gives reason for reviewing the current risk assessment system as well as the risk management related to the quick clay landslide hazard.

2 Background

2.1 Quick clay properties and landslide mechanisms

Quick clay can be found below the marine limit and is widespread in large parts of Norway, but also in Sweden, Finland, Russia, Canada, and Alaska. Quick clayis clay originally deposited in sea or brackish water, and later lifted onshore in the isostatic uplift following deglaciation after the last ice age. The quick (collapsible) behaviour of the soil skeleton is attributed to reduced salt content in the porewater of the clay particles. Quick clay slides can be triggered by human activities (e.g., by increased loads on terrain due to landfills, excavations, vibrations from construction work and blasting), or by natural causes (e.g., by erosion of the toe of slopes in creeks or rivers or by destabilisation from high porewater pressure in aquifers resulting from surface water infiltration and ground water flow through bedrock). Erosion in rivers and creeks has been known as the primary natural triggering factor for quick clay landslides. It should however be underlined that erosion may be affected by urban development that increases surface runoff. This opens for a discussion on to what extent erosion is a purely natural triggering factor. Quick clay is characterized by being a "strain softening material"(Rosenquist, 1953).This implies that as the clay is sheared during undrained loading, it will first reach a peak in mobilized shear stress, and thereafter the shear stress will decrease. The peak value represents the material's undrained shear strength, while the reduced shear stress after peak corresponds to a loss in the material's shear strength and a collapse of the clay structure. The faster the material loses its strength after the peak, the more brittle the material is said to be. As full mobilization of the soil strength is approached in a strain softening material, the strains will localize in a shear band. The thickness of theshear band affects the brittleness of the material (the thinner the shearband, the more brittle the soil will be). To illustrate the concept of strain softening, the softening properties of three different materials are presented in Figure 1.

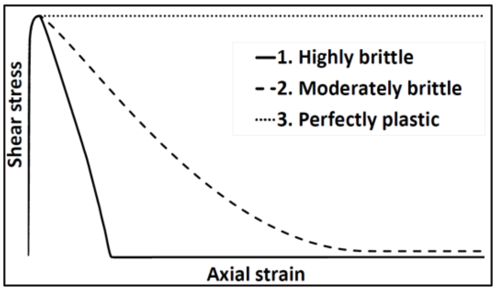

Figure 1. Degree of strain softening (brittleness)fromtypical active triaxial tests on three different materials.

A small perturbation in a slope with quick clay might trigger a progressive development and thereby result in a large landslide. This occurs because the perturbation might locally overload the shear capacity, whereafter further shear strain will lead to a reduction in the shear strength of the soil. This implies that the stresses in the slope must be redistributed, leading to higher mobilization of the neighbouring soil. This process can lead to a progressive mobilization of the slope, leading to a lower average shear strength of the soil than what one could expect if the material would act as a perfectly plastic material (as would be the normal assumption in a limit equilibrium analysis of slope stability). The process could be compared to a "domino effect".The retrogressive evolvement of a quick clay slide can result in propagation both perpendicularly(backwards) and parallel (sideways) to the initial slope's direction. Studies of historical landslide events have shown that quick clay slides can propagate in terrains with low sloping angle (down to approx. 1:15), and that the backwards propagation of quick clay slides can be up to at least 15 x the height of the initial slope (Aas, 1979; Gregersen, 2008; L'Heureux & Solberg, 2013).Sideways propagation has been less studied, but several previous landslides have shown that large sideways propagation is possible, e.g.,the recent Kråknes landslide in 2020 (Gylland et al, 2021) and the Leksvikalandslide in 2018 (NGI, 2018).The final size of a quick clay slide depends on factors as topography of the terrain, distribution of quick clay in the ground, position of bedrock, brittleness of the clay and ability for the sliding material to be transported away from the release area.

2.2The quick clay slide at Ask, Gjerdrum, 30th December 2020

At approx. 4 a.m. in the morning of 30th December 2020 a large quick clay slide was triggered at Ask in the municipality of Gjerdrum, Norway(Figure 2). The release area was approx. 600 m wide and 300 m long, giving a total volume of approx. 1.3 million m^3(Ryan et al, 2021). The runout distance was approx. 2 km, and the thickness of the slide debris deposited in the lower part of the runout area was approx. 10-12 m.

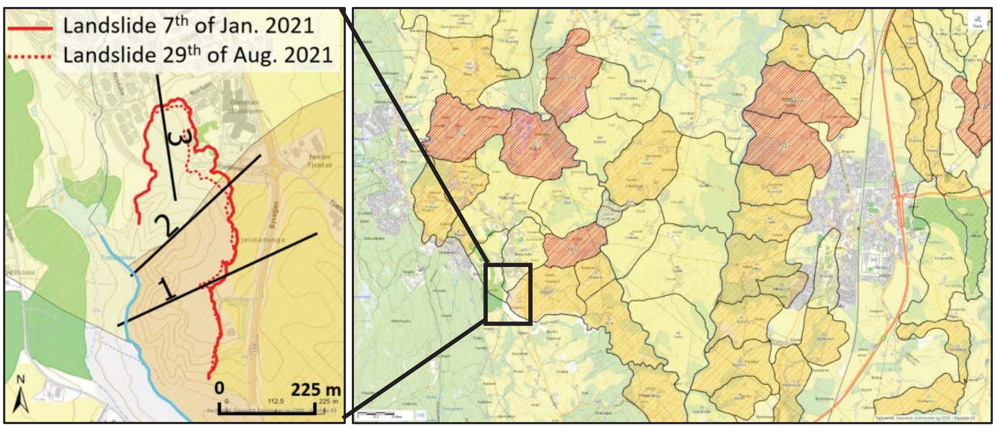

Figure 2. Left: Profiles through the Gjerdrum 2020 landslide pit representing main phases of slide event. Right: Quick clay zones coveringlarge continuous areas in the Romerikeregion, Norway. (Source: https://temakart.nve.no/tema/kvikkleire).

Analysis of the Gjerdrum landslide (Ryan et al., 2021) shows that the triggering factor was most likely erosion in a creek running through the area (Figure 2), along a known quick clay zone.The erosion occurred at the foot of a 30 m high clay slope with assumed low static stability prior to the event, and partly sideways into the foot of the slope (area of profile 1). After the triggering event, the slide is assumed to have developed towards the north (profile 2), and finally reached the populated area in the north (profile 3). Movement in each phase was in direction of the profiles. Sideways propagation of the landslide crossed a boundary between two quick clay zones (zone boundary indicated close to profile 2). The final phase of the landslide affected a residential area, and several houses were taken by the slide, resulting in a total of 11 fatalities including an unborn child.

3 Quick clay mapping in Norway – hazard, consequence and risk evaluation

Mapping of quick clay hazard zones in Norway started after the famous Rissa landslide in 1978 (Gregersen, 1981). In the following decades, quick clay hazard zones were mapped for large areas. After year 2000, a semi-quantitative risk evaluation system has been established for prioritizing between the zones for more detailed geotechnical investigation and mitigation measures (Gregersen, 2008; Moholdt, 2020). As of 23rdof February 2021, a total of 2310 quick clay zones have been mapped in Norway (Havnen et al., 2021). In several regions quick clay zones cover large continuous areas (Figure 2).Mapping of quick clay landslide hazard starts with geological mapping to determine areas below the marine limit. From this starting point, the mapping procedure of the quick clay hazard zones consists of three main stages:

1. In the first stage, areas susceptible to quick clay slides are delimited by analyzing an area's topography, geomorphology, and limited geotechnical data (around 1-2 drillings per quick clay zone).
2. In stage two, quick clay zones, defined in stage one,are classified with respect to hazard, consequence, and risk. This stage helps illuminate which zones are the most critical, and which should be prioritized for further geotechnical analysis.
3. In stage three, extensive geotechnical ground investigations are conducted, and the data is analyzed to better assess the risk of quick clay slides occurring within the zone. Stability calculations for most critical slopes are performed, and the need for mitigation measures is assessed.

The geometry of a quick clay zone is mainly determined by assessing an area's topography together with knowledge of the spatial distribution of quick clay in the ground (Moholdt et al., 2020). If little geotechnical data is available, the extent of the zone in the direction perpendicular to the slope is set to approx. 15 x the slope height (H).The extension of a zone can be shrunk/adjusted if extensive geotechnical ground investigations and evaluations are conducted.For example, for a thin quick clay layer, the extension of the zone can be reduced from 15 x H to 5 x H, according to the Norwegian guideline for quick clay mapping (NVE, 2020). Lateral boundaries of the zone are typically determined by ravines/valleys, rivers, bedrock outcrops or ground investigations proving absence of quick clay. One hazard zone should represent the maximum size of a landslide triggered somewhere inside the zone, and a landslide triggered within a zone should not develop across zone borders. Also, the system does not allow that release areas of zones overlap.

The hazard class of a quick clay zone is based on geotechnical, geological, hydrogeological, and geomorphological criteria, and determined by evaluating the factors presented in Table 1. The most aggravating factors with respect to hazard for quick clay slides are high porewater pressures, active erosion, and human interventions. The consequence of a potential quick clay slide is based on elements at risk within the quick clay zone, and the consequence class is determined by evaluating the factors presented in

Table *2*. Residential units and business buildings where people are staying are weighted highest. The risk score and corresponding risk class is determined as a product of the hazard and consequence scores (in percentage).

Table 1. Hazard evaluation for quick clay zones(modified after Moholdt (2020)).

Factors		Weight	Hazard, score			
			3	2	1	0
Previous landslide activity		1	High	Some	Low	None
Slope height (H) [m]		2	>30	20-30	15-20	<15
OCR		2	1.0-1.2	1.2-1.5	1.5-2.0	>2
Porewater pressure:	Excess pressure [kPa]	3	>30	10-30	0-10	Hydrostatic
	Pressure deficit [kPa]	-3	<-50	-(20-50)	-(0-20)	
Thickness of quick clay layer		2	>H/2	H/2-H/4	<H/4	Thin layer
Sensitivity		1	>100	30-100	20-30	<20
Erosion		3	Active	Some	Little	None
Human	Improving situation	-3	Large	Some	Small	None

activity:	Aggravating situation	3	Large	Some	Small	
Total			51	34	16	0
% of max			100%	67%	33%	0%
Low hazard = 0-17 points; Medium hazard = 18-25 points; High hazard = 26-51 points						

Table 2. Consequence evaluation for quick clay zones(modified after Moholdt (2020)).

Factors	**Weight**	**Hazard, score**			
		3	2	1	0
Residential units [number]	4	Dense > 5	Scarce > 5	Scarce < 5	None
Business buildings [persons]	3	>50	10-50	< 10	None
Other buildings [value]	1	Large	Considerable	Limited	None
Road [vehicles per day]	2	>5000	1001-5000	100-1000	<100
Train line [use]	2	People	Goods	Normally no traffic	None
Electric power line	1	Central	Regional	Distribution	Local
Damming/flooding	2	Serious	Medium	Small	None
Total		45	30	15	0
% of max		100%	67%	33%	0%
Less serious = 0-6 points; Serious = 7-22 points; Very serious = 23-45 points					

The landslide risk is calculated from the product of the two scores, expressed as percentages of the the total hazard and consequence points, respectively. If both hazard and consequence have the maximum score(100 %), the resulting risk points consequently are 10.000. The risk is classified according to Table 3.In the process of quick clay hazard mapping, it has generally been recommended to perform closer evaluation of zones with high risk (classes 4 and 5) and/or high hazard (class 3), including more detailed ground investigations. So far, this has been done only for a limited number of zones.

Table 3. Risk classification (modified after Moholdt (2020)).

Risk class	**Points**
1 (lowest risk)	0-170
2	171-630
3	631-1.900
4	1.901-3.200
5 (highest risk)	3.201-10.000

4 Weaknesses of the mapping system

4.1 Determination of quick clay hazard zone boundaries

One of the biggest challenges with the current mapping system is to determine the boundaries of the quick clay hazard zone. Two different uncertainties exist when the hazard zone boundaries are studied: First, the primary uncertainty will be the actual distribution, layering and mechanical properties of quick clay within the zone, i.e., an epistemic uncertainty. Second, the backwards and sideway extension involves an aleatoric uncertainty of the phenomenon itself, i.e., the retrogressive behaviour of the landslide, which is not readily solved with current knowledge.

*Quick clay distribution, layering and properties:*The lack of sufficient data for a proper evaluation may prioritizing funding for improved ground investigations and geotechnical evaluations. The spatial distribution, soil layering, soil properties andthe slope stability may then be evaluated properly, reducing the factual uncertainty of the site.

*Retrogression of potential quick clay landslides:*Empirically based methods for evaluating backwards propagation of potential quick clay landslides exist, but methods for assessing the lateral propagation potential are lacking. Lateral zone boundaries are usually based on topographical conditions, such as ravines or flat terrain, or geological limitations, such as bedrock outcrops, or proven non-sensitive clay in the ground. The "engineering judgment" is hence very important when determining the lateral boundaries of quick clay zones. It is emphasized that evaluation of sideways landslide propagation has always been an integrated part in the evaluation of quick clay hazard zones. However, it may sometimes be virtually impossible to draw an exact boundary.E.g., for a steep slope with constant topography and ground conditions along the slope, the sideways propagation could be indefinite.This is the situation along rivers, shorelines, and valley sides with constant geometry.When new buildings and/or infrastructure are planned, it is required to assess the quick clay landslide hazard and the need of mitigation measures (TEK17, 2017). The developer is however only required to secure areas within the same zone as the new constructions are planned. Hence, the quick clay zone's geometry is very important.The Gjerdrum landslide illustrates the importance of zone boundaries, as the landslide was initiated in one quick clay zone and propagated into the neighbouringzone. The houses that were taken by the first main phase of the landslide were situated in the latter zone (Figure 2).To avoid such events, definition of very large quick clay zones is the "safer option". This however leads to administrative challenges: Development of projects in quick clay areas is often expensive, and the larger the zones, the larger the costs of mitigation measures. Hence, quick clay zones should not be designed larger than "necessary", given the topographical and geotechnical properties of an area.

*Retrogression of the Gjerdrum 2020 landslide:*The retrogression of the landslide at Ask, Gjerdrum, has been evaluatedfor 3 profiles in the landslide, representing the initial phase (Profile 1), the sideways retrogression (Profile 2) and the final backward retrogression into the residential area(Profile 3). The relations L/H varies from approximately 6.5 in Profile 1, to 9 in profile 2, and 10 in profile 3. These values are within the expected values for maximum landslide propagation. However, without detailed information about the situation before the landslide, discussions on effects of thickness of the quick clay deposit may not be done in detail.After the initial failure of the high and steep, and consequently highly mobilized, slope around Profile 1, the landslide developed towards the North, and crossed an assumed previous landslide scar (Profile 2). An important feature is however the fact that the failure along Profile 2 opens a gate for a secondary effect, where the landslide direction changes from East-West along Profile 2 to a North-Southdirection along Profile 3. Profile 2 lies in the vicinity of the zone boundary, which indicates that a landslide was not expected to cross this line, and thereby retrogress towards the North into the residential area. However, this what was happened. Increased focus on potential sideways retrogression across zone boundaries should be a major point of learning from the Gjerdrum landslide for future risk mapping in quick clay areas, as well as increased attention to erosion protection in known hazard areas. A relatively modest mitigation measure in the release area would probably have prevented the initial failure resulting in the development of the disastrous landslide.

4.2"Expiring date" of existing quick clay zones

The risk assessment method used in Norway for quick clay areas is qualitative and static and provides a "snapshot" of the time when the assessment was carried out. The method does not capture any subsequent changes, e.g.,changes in erosion processes along a watercourse, agricultural related measures such as re-grading of the terrain or other interventions within the zone. The zones themselves are thus in practice not static but change gradually.The evaluation factors in Table 1are important for the determination of the hazard class of the zone, which again governs the safety requirements for protection against quick clay slides for new construction projects in a zone. It is therefore utmost important that previous quick clay zone assessments are evaluated carefully before being "reused" when new activity in a zone is planned. For other common types of natural hazards in Norway, as debris flows, snow avalanches, rock falls etc., it is common to demand that a new evaluation is performed when new projects are considered in an area, if the current hazard evaluation is considered outdated. A period of 10 years could be applicable as interval for reevaluation of zones where the landslide hazard class is 3 (high), or where the landslide risk class is 4 or 5. Also, in areas affected by new urban development, reevaluation should be done considering both effects of topographic changes and effects of increased surface water runoff on erosion along natural waterways.

5 Risk management

5.1 New buildings and infrastructure

Of several thousands of already mapped quick clay zones in Norway, only a minor fraction has been secured. The reason behind this is partially Norwegian regulations and laws, which only demands implementation of mitigation measures to prevent quick clay slides when new buildings and/or infrastructure is planned (TEK17, 2017). If the geometry and/or hazard class of the quick clay zone where activity is planned are evaluated incorrectly, necessary mitigation measures may be omitted.It is therefore of utmost importance that experienced geotechnical engineers perform the assessment of quick clay hazard and risk. As the Norwegian population is growing, and urbanization is increasing, the need of new housing and infrastructure is high (Statistics Norway, 2020).This puts a pressure on the need for new areas for development, and it is not possible to avoid areas with quick clay. There is also a high demand for geotechnical engineers, which the industry is struggling to meet.

5.2Existing buildings

As mentioned above, only new projects impose the obligation of securing areas prone to quick clay slides. However, municipalities are obliged to perform overview mapping when new areal plans are developed (TEK17, 2017). This gives the municipality an overview of the hazard picture in their areas, and they can use this as a tool to plan how to best plan the use of their land. In addition to the mapping performed by the municipality themselves, detailed geotechnical mapping of quick clay hazard in conjunction to development projects (of a certain size) often leads to new information on the risk also outside the areas that are affected by the planned development. This information must by law be communicated to the municipality in which the project is located (TEK17, 2017).According to Kalsnes et al. (2021), 45 000 buildings are at risk for quick clay slides in Norway today. The responsibilities for securing existing areas against landslides is not well defined, and may be attributed to landowners, municipalities, and other stakeholders. Even though the municipalities are not obligated to secure areas at risk, it is at their and their inhabitants' best interest to do so anyhow. However, municipalities often have limited free resources to perform necessary mitigation measures. Another challenge can be that most municipalities do not dispose of the right competence to evaluate whether a given situation involves a risk or not, and therefore won't take necessary actions. A proper evaluation of the hazard requires both geotechnical competence and ground investigations, which are costly. On the other hand, the risk of erosion triggered landslides may be reduced by relatively modest measures, if built before a landslide occurs. The municipalities may apply for funding from the Norwegian Water and Energy directorate to perform mitigation measures towards existing buildings and infrastructure in areas exposed to the highest quick clay landslide risk. The amount is however far from enough to secure all known areas at risk.

6 Conclusion

In this paper, some aspects related to the methods used in Norway for assessing the risk of quick clay landslides are discussed. Lines are drawn from the current risk assessment system to experiences from the last fatal quick clay landslide in Norway that occurred at Gjerdrum, 30th of December 2020. Today's system for mapping quick clay zones is appropriate,but is still dependent on the quality of the geotechnical engineers performing the evaluations. In particular a major uncertainty is that geotechnical data is often too scarce, and that the current knowledge on the mechanisms of sideways retrogression makes it difficult to properly define the quick clay zone's boundaries. In addition to the weak links in the mapping methods, backlogs of securing areas that have been revealed at risk is a severe problem. Also, quick clay zones are not revised over time, although major changes can develop related to topography and erosion conditions.

References

Aas, G. (1979). Kvikkleireskred. Forelesningsnotertil NIF-kurs "Skredfareogplanlegging". Lofthus Hardanger.

Gjelsvik, V. and L'Heurux (2019). The landslide in Leksvika 20. June 2018. Technical Note 20180577-02-TN, rev. 1, dated 2019-02-05 (in Norwegian).

Gregersen, O. (1981). The quick clay landslide in Rissa, Norway. The sliding process and discussion of failure modes.*10. ICSMFE, Stockholm 1981. Proc., Vol. 3*, pp. 421-426.

Gregersen, O. (2008). *Program for økt sikkerhet mot leirskred – Metode for kartlegging og klassifisering av faresoner, kvikkleire.*(20001008-2, 3. Revisjon 08.10.2008). NGI.

Gylland, A., Bjarghov, E., Nordal, S., L'Heureux, J.-S. and Degago, S. Quick clay landslide at Kråknes in Alta 3rdof June 2020. Evaluation of cause.Multiconsultreport 10220443-RIG-RAP-001, dated 22nd February 2021.

Havnen, I., Johnsen, M.H., Borge, A.F., Dalen, E.V., and Verhage, A. (2021) Kvikkleirekartlegging – metoder, status ogviderearbeid: rapport fra intern arbeidsgruppe. (NVE Rapport nr. 12/2021). Oslo: NVE.

Kalsnes, B., Solheim, A. Sverdrup-Thygeson, K., Dingsør-Dehlin, F., Warsrud, J., Indrevær, K., and Bergbjørn, K. (2021).*Flom og skred – sikringsbehov for eksisterende bebyggelse (FOSS): beskrivelse av metodikk og resultater.* (NVE Rapport nr. 20/2021). Oslo: Norgesvassdrags- ogenergidirektorat (NVE).

Locat, A. et al, The Saint-Jude landslide of 10 May 2010, Quebec, Canada: Investigation and characterization of the landslide and its failure mechanism, *Canadian Geotechnical Journal* (2017). DOI: 10.1139/cgj-2017-0085

L'Heureux, J. S. and Solberg, I. L. (2013). *Utstrekningogutløpsdistanse for kvikkleireskred basertpåkatalog over skredhendelseri Norge.* (rapport nr. 21/2013). NVEi et samarbeid med SVVogJernbaneverket.

NVE (2020). Guidelines No. 1/2019. Safety against quick clay landslides. ISBN: 978-82-410-2091-9. ISSN: 1501-0678

NVE (2020). Guideline for evaluation of safety towards landslides in steep terrain. (version 12.11.2020). https://www.nve.no/veileder-skredfareutredning-bratt-terreng, located on internet 23.06.2022.

Moholdt, R. (2020). *Oversiktskartleggingogklassifiseringavfaregrad, konsekvensogrisiko for kvikkleireskred: metodebeskrivelse.*(NVE Ekstern rapport nr. 9/2020). Oslo: Norges vassdrags- og energidirektorat (NVE).
Rosenquist, I. (1953). Investigations into the clay - electrolyte - water system. *NGI publication, 9.*
Ryan, I., Bruvoll, A., Foldal, K.M., Hæreid, G.O., Muthanna, T.M., and Ottesen, H. B., Solberg, I.L. (2021). *Årsakenetilkvikkleireskredeti Gjerdrum 2020.* (Y-0128 B). Oslo: Olje- ogenergidepartementet.
Statistics Norway (2020, 3rd of June). National population projections. Available from: https://www.ssb.no/befolkning/befolkningsframskrivinger/statistikk/nasjonale-befolkningsframskrivinger
TEK17 (2017) Byggeteknisk forskrift (TEK17) med veiledning (15.09.17). Available from: https://dibk.no/byggereglene/byggteknisk-forskrift-tek17/.