Impact of blast vibrations on the release of quick clay slides

Impact des vibrations dues aux explosions sur les glissements de terrain dans les argiles sensibles

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ABSTRACT: Blast induced vibrations are suspected to be one of the triggering factors of quick clay slides. To better understand how such vibrations affect sensitive clays we have analyzed vibrations from blasts near quick clay deposits and performed numerical simulations. In addition, based on a set of cyclic laboratory tests on quick clay with anisotropic consolidation, a set of cyclic loading contour diagrams have been established. The diagrams are used to estimate the effect of cyclic loading on the clay from blasting in combination with the permanent stress in quick clay slopes. The above results were combined in a simplified method of estimating vibration velocities that could cause a local failure in a slope. The velocities are in the range of 57-110 mm/s depending on degree of strength mobilization in the slope and number of load cycles imposed by the blast vibration. Taking into account uncertainties, spatial variability and desired safety margins we recommend a vibration limit of 25 mm/s. We further recommend that vibration monitoring during blast operations should be performed at two separate locations, near the rock-clay boundary, with the highest vibration amplitude in any of the vertical and the two orthogonal horizontal directions should be lower than the vibration limit.

RÉSUMÉ : Les explosions génèrent des vibrations qui sont soupçonnées d’être un des facteurs déclencheurs des glissements de terrain dans les argiles sensibles. Pour mieux comprendre comment de telles vibrations affectent ces argiles, nous devons analyser les vibrations d’explosions proches des dépôts d’argile sensible et effectuer des simulations numériques. De plus, basé sur un ensemble de tests cycliques faits en laboratoire sur les argiles sensibles avec une consolidation anisotropique, un ensemble de diagrammes de contours de chargements cyclique a été établi. Ces diagrammes sont utilisés pour estimer les effets de chargement cyclique sur l’argile suite aux explosions et soumises aux stress permanents des argiles sensibles sur les pentes. Les résultats ci-dessus sont combinés dans une méthode simplifiée d’estimations des vitesses de vibrations qui peuvent causer une rupture locale de la pente. Les vitesses sont comprises entre 57 et 110 mm/s, dépendant du degré de la force de mobilisation dans la pente et de la charge de cycles imposé par les vibrations suite à l’explosion. En tenant compte des imprécisions, de la variabilité spatiale et des marges de sécurité désirée, nous recommandons une limite de vibration de 25 mm/s. Nous recommandons également de surveiller les vibrations durant les explosions à deux endroits différents prés de l’interface roche-argile avec enregistrement dans la direction verticale et les deux orthogonales pour s’assurer que les amplitudes des vibrations les plus importantes soient enregistrées

KEYWORDS: Quick clay, blast, vibration limit, cyclic loading, creep failure, local failure, global failure.

1 INTRODUCTION

In 2009, a large quick clay slide involving up to 500,000 m^3 soil, and affecting some 10 houses, was triggered by rock blasting for a road cutting in Kattmarka near the city of Namsos in Norway. For this event it was concluded the trigger was not the vibrations themselves, but a large block of rock that was punched in to the soil by the blast effect, due to unfavourable fault planes in the rock. The landslide did however reinitiate discussions on slope stability with respect to blast induced vibrations in the vicinity of sensitive soils. A brief literature survey showed that there are other events where vibrations may have been one of the triggering factors. Yet, prior to 2009, no regulations existed, and the understanding of blast induced landslide events was limited.

After the 2009 Kattmarka quick clay slide, a vibration limit of 25 mm/s was introduced in the Norwegian Public Roads Administration’s Handbooks (NPRA, 2011) based on engineering considerations of soil dynamics and general cyclic soil response. However, experimental data on cyclic behaviour of quick clay were sparse.

To improve the understanding of the effect of blast induced vibrations on the possible triggering of slides in sensitive clays, a research project was initiated at NGI, with financial support from NPRA, the Norwegian Government’s agency for railway services, and Norwegian Research Council. The goal of the project is to establish vibration limit values and vibration monitoring procedures to avoid landslides due to blast operations, without imposing more restrictions than necessary.

The research activity has involved a brief literature study of previous case histories, a set of laboratory tests and re-evaluation of relevant previous laboratory tests. We have also analyzed vibration measurements and performed numerical analyses. Finally we have combined the above in a simplified method of estimating vibration velocities that could cause a local failure in a slope.

2 CASE HISTORIES

There seem to have been a common opinion in the Norwegian geotechnical community that vibrations from rock blasting do not have a high probability of trigging slides, even near quick clay slopes. This has however been questioned in connection with the Norwegian slides in Finneidfjord (NGI, 1997) and Kattmarka (NTNU, 2009). In 1973 a large slide in Fröland, Uddevalla in Sweden was triggered by liquefaction of thin sand and silt layers due to vibration from blasting at an adjacent stone quarry (Bjurström and Broms, 1973). Similar layers are also found in Finneidfjord and Kattmarka, and are considered common in most Norwegian quick clay deposits.

Very recently, in 2011, a slide occurred in a small ravine with quick clay more than 100 meters from ongoing road works near Lödöse in Sweden, involving rock blasting. The last round had been fired less than 24 hours before (Ekström, 2012). The peak vibration velocity has been estimated (frequency unknown) to some 30 mm/s at the upper edge of the slide with help of post slide measured blast vibrations.

The literature review further indicates that if blast vibrations are assumed to have triggered a slide it is often in combination with other adverse factor such as low stability prior to blasting, higher than normal ground water level due to high precipitation, erosion at the slope base, temporary placement of fill masses, etc. In addition, the existence of thin sand or silt layers within the clay are confirmed in many cases, and are hence assumed to have played a crucial role. In some cases the observed failures have occurred some hours after the blasting indicating a possible creep failure mechanism.

3 TRANSFER OF VIBRATIONS FROM ROCK TO SOIL DEPOSIT

Data from rock blasting induced surface vibration in quick clay deposits at a few locations in Norway have been analyzed (see Figure 1). The blasting induced vibration amplitude (Peak Particle Velocity) in the soil depends on a number of parameters, such as the explosive charge size, distance from blast location to the soil deposit, the geometry and material properties of the rock and soil. There is considerable variability in measured vibration amplitudes, sometimes horizontal vibrations are larger and sometimes the vertical ones. The data show the dominant frequencies of the soil vibration are between 15 and 35 Hz.

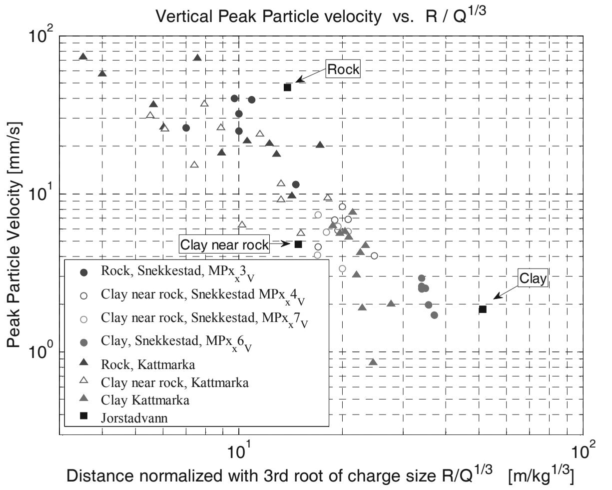

Figure 1 Vertical peak particle velocity vs. distance normalized with third root of explosive charge size.

Numerical simulations have been performed to better understand the transfer of vibration from rock into the clay. Axi-symmetric models, with simplified geometries with rock on the left and beneath a clay deposit, based on case histories have been used as shown in Figure 2 . The ground vibration do not depend very much on the slope of the soil surface, therefore all models have horizontal surfaces. Velocity time histories from the above field observations were used to calibrate the numerical simulations to compute time histories of cyclic shear strains and stresses at various locations within the clay deposit. Focus has been on the relation between surface vibration amplitude and shear strain in a homogeneous clay deposit to study the effects of 1) Different stiffness within the clay and 2) a thin layer with lower stiffness than the surrounding clay, and 3) different dip-angles of the rock-clay boundary.

Simulations show that there is a 2-3 m high by some 10 m wide zone at the clay surface next to the rock-clay boundary that is most affected by the blast vibrations.

Field vibration data and numerical results show the most important factor of reduction of vibration amplitude is distance attenuation, e.g. a reduction of almost one magnitude in vibration amplitude at blast distances of 10 m and 50 m is observed.

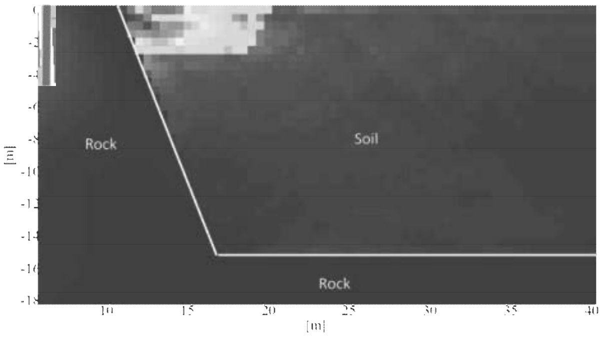

Figure 2 Maximum shear strain occurs in an area near the rock-clay boundary. Explosion loading at upper 4 m of left side, marked with red line.

The numerical analyses further show a doubling of vibration amplitudes in a zone near the boundary between the rock and soil. This amplification has however not been observed in the field, one reason may be that the vibration sensor are not put close enough to the rock-clay boundary. The vibrations decay sharply from the location of the peak value. The simulations show that the peak value is reduced to about 30% five meter away from the location of the peak.

Results so far indicate larger amplification with lower dip-angle of rock-clay boundary. The maximum cyclic shear strains occur from the boundary between rock and clay to point at a depth of about 1-2 m below the point at the surface where the highest vibration amplitude are computed. This depth corresponds to about half a wave length i.e. it depends on the dynamic soil properties and vibration frequency.

The surface vibration amplitude turns out to be a good indicator of the maximum shear strain the soil due to blast operation. The numerical simulations confirm that the maximum shear strain γ_{max}, can be estimated with good accuracy as

$$\gamma_{max} = \frac{v}{c_s} = \frac{v}{\sqrt{\frac{G}{\rho}}} \qquad (1)$$

where v is the peak particle velocity of the vibration, c_s, G, and ρ are the soils shear wave velocity, shear modulus, and density respectively. Equation (1) shows that if the shear modulus is reduced to half, the shear strain increases with a factor of $\sqrt{2}$ for the same vibration particle velocity at the surface. However, also the particle velocity will depend on the modulus of the clay for a given blast.

The numerical results so far show that within thin soft layers the strain does not decay as quickly with distance as in a homogenous clay deposit.

4 CONTOUR DIAGRAMS FOR CYCLIC AND CREEP LOAD

There is a lot of knowledge about cyclic behaviour of clays, however much less is so far known about quick clay subjected to cyclic loading. Therefore two series of static and cyclic laboratory tests were run on specimens from block samples taken from representative quick clay deposits near Trondheim, Norway. Index properties are given in Table 1.

The samples were consolidated with different ratios between shear stress and vertical effective stress, τ_c/σ'_{vc}, in order to simulate various slope angles.

The tests were run undrained by first applying stress controlled cyclic loading to reach a specified permanent shear strain, followed by creep to large shear strains. The initial shear modulus, G_{max}, was measured on all samples after consolidation. The test results showed that the rate of creep was influenced by the cyclic loading. The creep rate increased with increasing permanent shear strain at the end of the cyclic loading and increasing shear stress ratio, τ_c/σ'_{vc}.

Table 1 Mean parameters for the two test series.

Parameter	Samples 2007/08	Samples 2011
Water content, w_i (%)	39.5	32
Clay content (%)	38	36
Plasticity index, Ip (%)	11	8
Liquid limit, w_l (%)	31	24.5
Plastic limit, w_p (%)	20	16.5
s_u (Fall Cone) (kPa)	34	17
Sensitivity (Fall cone)	100	140
OCR	~1.5	Uncertain
G_{max}/σ_{vc}' for $\tau_c=0$	236	252 (one test)
G_{max}/σ_{vc}' for $\tau_c>0$	236	220

The test results were compiled in two different types of contour diagrams. The first type defines average and cyclic shear strains as functions of average and cyclic shear stresses, both normalized with undrained shear strength. The diagrams were established for different number of cycles and load periods. This type of diagram is illustrated by an example for 100 cycles and a load period of 0.1 s in Figure 3. (The average shear strain is defined as the average shear strain in a cycle, and the permanent shear strain is defined as the shear strain at the end of a cycle. For the test conditions that are relevant herein, the average and the permanent shear strains can be assumed to be the same). Andersen, 2009, gives a more detailed description of definitions and this type of diagram.

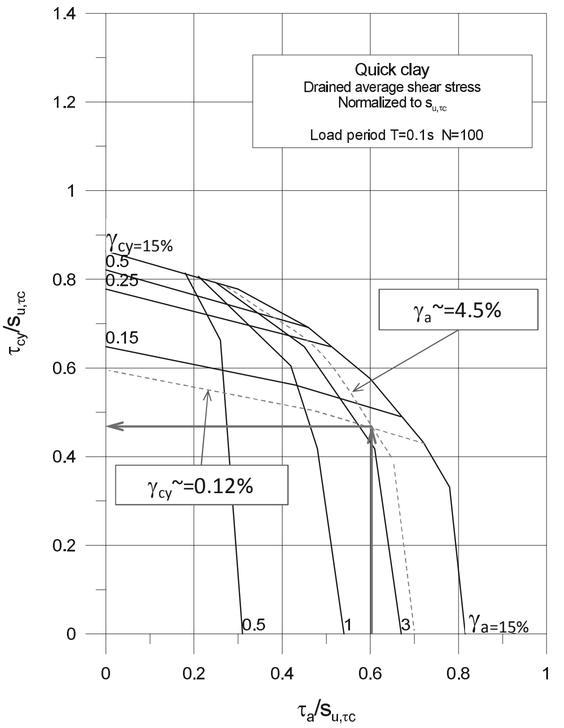

Figure 3 Contour diagram for N=100 and load period of 0.1 s for determining cyclic stresses and strains.

The second type of contour diagram is a time-to-failure diagram shown Figure 4 that relates the time to creep failure to the permanent shear strain at the end of cyclic loading and the normalized average shear stress (=degree of mobilization).

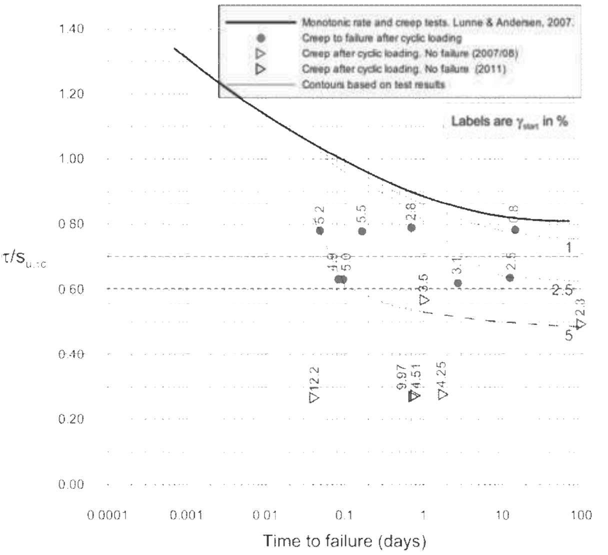

Figure 4 Time-to-failure diagram. Green dashed lines show to degrees of mobilisation 0.6 and 0.7 that were used in calculations.

5 VIBRATION AMPLITUDE TO CAUSE LOCAL FAILURE

The vibration velocity necessary for local failure of the soil in the zone near the rock-clay border that are subjected to the largest vibrations are estimated with help of equation (1) and the two contour diagrams described above. The following example illustrates the procedure.

We assume the soil density and initial shear wave velocity to be 1800 kg/m^3, and 80 m/s, respectively, giving an initial shear modulus, G_0 of 11.5 MPa. These values are typical for soft Norwegian quick clays.

As the first step the permanent shear strain that will almost cause creep failure is read off from the time-to-failure diagram in Figure 4. (Permanent shear strains are the shear strains at the start of creep and are termed γ_{start} in Figure 4). Permanent strains of 2.5% and 1.5% are close to causing failure for mobilization degrees (τ_a/s_u) of 0.6 and 0.7 (corresponding to factors of safety of 1.7 and 1.4 for infinitely long slopes).

In the next step we want use the contour diagram in Figure 3 to estimate cyclic shear strains, γ_{cy}. This diagram is based on averages strains, γ_a (that are almost the same as permanent strains). However the average strains used in Figure 3 include the shear strains during consolidation, γ_c. Therefore the shear strain during consolidation has to be added to the permanent shear strains determined from Figure 4. The shear strain during consolidation can be determined from the average shear strains along the horizontal axis in Figure 3. The resulting average strains to be used in Figure 3 thus become 4.5% and 6% for mobilization degrees of 0.6 and 0.7, respectively. The strains are shown in Table 2.

Table 2 Shear strains that would cause creep-failure in laboratory.

Mobilization degree	*0.6*	*0.7*
Permanent strain at end of cyclic loading, γ_p [%] (from Figure 4)	2.5	1.5
Consolidation shear strain, γ_c [%]	2.0	4.5
Resulting average strain, γ_a [%] (to be used in Figure 3)	4.5	6.0

The duration of a typical blast vibration time history is about 3 seconds and contains three to five cycles at the highest strain level, which is relevant to pore pressure build-up. During a blast operation there are three to five blasts, thus the number of cycles, N, are estimated to 15-25. Since the dominant frequencies of blasting vibrations in the soil are in the range 15-

35 Hz. Therefore it is relevant to use contour diagrams for a load period of 0.1s and with N=10 and N=100, respectively.

For a degree of mobilization of 0.6, 100 load cycles, and an average strain of 4.5%, Figure 3 give a cyclic strain, γ_c of 0.12% and a normalized cyclic stress τ_{cy}/s_u of 0.47.

The lab tests show that ratio of the initial shear modulus, G_0, to the undrained shear strength, s_u, is approximately 800, giving a cyclic stress, τ_{cy} of 6.8 kPa.

To account for the cyclic strain level the shear modulus was reduced from initial value of 11.5 MPa to a value 5.6 MPa. The reduced shear modulus corresponds to a local shear wave velocity of 56 m/s.

With the determined cyclic strain to cause failure and the reduced shear wave velocity, the necessary vibration velocity on the surface to cause local failure in the clay is calculated, by using Eq. (1), to

$$v = \gamma_{max} \times c_s = 1.2 \times 10^{-3} \times 56 = 67\ mm/s. \tag{2}$$

The same procedure has been applied for other mobilization degrees and number of loading cycles and Table 3 summarizes the resulting cyclic strains and corresponding vibration amplitudes that will lead to local failures in the clay.

Table 3 Vibration velocities to cause local failure for two different mobilization degrees, number of cycles and initial shear wave velocity, c_s, of 80 m/s.

Mobilization degree, (τ_a/s_u)	0.6		0.7	
Number of cycles, N	10	100	10	100
Cyclic shear strain, γ_{cy} [%]	0,22	0,12	0,13	0,1
Normalized shear stress, τ_{cy}/s_u	0,68	0,47	0,47	0,4
Shear modulus corresponding cyclic strain [MPa]	4,5	5,6	5,2	5,8
Vibration amplitude [mm/s] to cause local failure in clay.	110	67	70	57

6 DISCUSSION

The vibration amplitudes in Table 3 is the basis for developing recommended vibration limits for safe blast operations, to avoid initiation of sliding in low stability quick clay slopes. In this process it is necessary to take into account that there are uncertainties and simplifications in the performed analysis, some are conservative and some are non-conservative.

There is a lack of knowledge of how large a local failure zone must be to initiate a progressive global failure and to initiate a quick clay landslide. Therefore a conservative choice was made to set the limit as to avoid a local failure.

Conservative aspects are:

- If a local failure of certain extent could be accepted, higher vibration amplitudes could be allowed.
- The estimated vibration velocities correspond to failure during the creep phase of the laboratory tests. For local failure to take place during the cyclic loading phase, a 20-30% higher vibration amplitude and/or higher mobilization degree is necessary.
- The maximum shear strain occurs only in part of the highly affected zone in the clay. The mean cyclic strain in the highly affected zone are about half of the maximum strains used in the analysis.

Non-conservative aspects are:

- When measuring the vibrations in the field during blast operations it is unlikely that the sensor is put at the location of the peak value, and since the vibrations reduce quickly with distance from the rock-clay boundary, the measured amplitudes are lower than the peak value.
- The effect of thin soft sand and silt layers often present in quick clays have not been considered when estimating the velocities.
- The mobilization degrees were selected to correspond to overall factors of safety, in reality the mobilization degree can be higher closer to the rock-clay boundary and then the estimated vibration velocities are on the high side.
- The whole calculation procedure does not contain any safety margins.

7 CONCLUSIONS AND RECOMMENDATIONS

There is a lack of knowledge of how large a local failure zone must be to initiate a progressive global failure and to initiate a quick clay landslide. Therefore a conservative choice was made to set the limit as to avoid a local failure.

Taking into account uncertainties and simplifications in the analysis, spatial variability of vibrations and desired safety margins we recommend a vibration limit of 25 mm/s.

Peak value monitoring during blast operations of vibrations on quick clay deposits should be done in two locations e.g. at distances of 5 and 10 m from the rock-clay boundary and the highest vibration amplitude in any of the vertical and the two orthogonal horizontal directions should be lower than the vibration limit.

Since blasting vibration amplitudes show a large variability it is important to use vibration monitoring actively during blast operations to adjust the blast design to avoid exceeding the vibration limit.

To better understand the behaviour of quick clay with thin silt and sand layers, it is recommended to perform further laboratory tests and also to perform more numerical simulations with more realistic soil profiles looking at the effect of such silt layers, soil stiffness increasing with depth, a stiff dry crust etc. This could improve our understanding and possibly allow for further adjusting vibration limits, probably to somewhat higher values.

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