Assessment of the impact of pile driving on slope stability

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ABSTRACT

Driving piles near slopes can be challenging in terms of temporarily reducing slope stability, specifically in the presence of sensitive clay or lenses of sand and silt in the ground. There is currently no standard method for calculating the reduced safety factor of a slope due to pile driving, even though this has been the initiating cause for a few landslides in the Nordic countries, Canada, and the United States, among others. This paper investigates some of these cases of slope failure, looks into the possible failure mechanisms and assesses the traditional methods used to calculate the reduced factor of safety of the slope during pile driving. Finally, the paper provides suggestions for better evaluation of pile driving effects on slope stability based on the results of numerical analyses in Plaxis 2D Geotechnical finite element package, coupled with soil mechanics theory and project experience.

Keywords: Pile driving, Slope stability, Excess pore pressure, Finite Element Analysis

1. BACKGROUND

1.1. How can pile driving affect a slope negatively?

Pile driving, may be conducted adjacent to slopes for bridge abutments, port substructures or other objectives. Driven piles are also used as a method to stabilize slopes, specifically in areas prone to shallow slides where the generated lateral forces by the slide can be resisted by rows of piles (Abramson et al. 2001). However, installation effects may be sufficient to trigger slope instability during and shortly after driving. Such effects include induced displacements, excess pore pressure, vibrations, cyclic degradation of the soil and the possibility of progressive failure in a slope where a local failure can propagate into the slope and result in a massive landslide (see Figure 1 where the impact of pile driving in a slope are depicted).

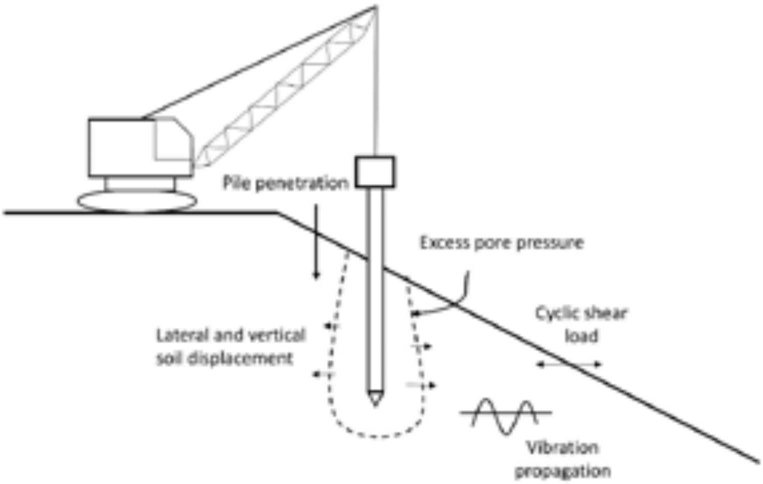

Figure 1 - Effects of pile installation in a slope (Attari et al., 2023)

It shall be noted that the lateral movements generated by pile driving tend to follow the direction towards the lower ground and in the case of a slope, accumulation of displacements towards the slope toe can also be dangerous and problematic (Vytiniotis et al., 2018). Furthermore, shear strains generated due to pile driving may be sufficient to exceed the peak shear strength point and hence, reduce the strength of the soil material in the failure surface to a post-peak value. In soft sensitive clays, after reaching a peak strain value, further straining of the material results in loss of shear strength, which is called strain-softening (see Figure 2). It can be inferred that increased displacements in the soil due to pile driving may cause a gradual progression of strain-softening behaviour throughout the slope which could ultimately lead to a global failure (Bernander 2011). Sensitivity of a clay material is the ratio between undisturbed shear strength and the shear strength of the soil in a remoulded state. Behavior of soft and sensitive clay is an important topic in Scandinavia due to the existence of large deposits of quick clays in this region (Rosenqvist 1953). Presence of soft sensitive soils in an area necessitate conducting slope stability analysis with regards to strain-softening behaviour as well as thorough risk assessments prior to construction on such deposits. Design codes require higher safety margins for construction in areas with the presence of sensitive and quick clays.

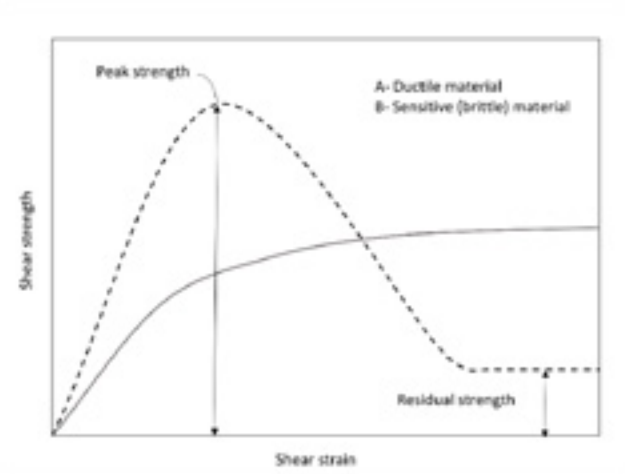

Figure 2 - Illustration of shear stress vs. shear strain behaviour in different types of soil, based on a figure by Bernander (2011)

In Norway, there is no standard method recognized by the industry to account for reduction in safety factor for slope stability as an effect of mass displacement and pore pressure build-up during pile installations. In practice, to account for reduced stability of the soil, pore pressures are monitored during construction and limits are set on maximum allowable pressure levels to avoid slope failure (Tefera et al., 2013). This allowable limit is normally based on previous experience and does not have a fixed theoretical base. The time required for the dissipation and continuation of the piling operation is not accurately specified either when a group of piles are installed. Moreover, the costs for waiting time or for moving pile-driving machines to different locations to allow for pore pressure dissipation can be large. Therefore, there is a strong need for further research to develop a standard approach to account for pile installation effects on slope stability in a reliable manner and understand the probable failure mechanisms involved.

2. RESEARCH METHODOLOGY AND OUTCOMES

2.1.Cases of slope failure

The research strategy to address this research gap consists of a combination of investigating cases of slope failure in the literature where pile driving was considered to be an initiating factor for the landslide as well as numerical simulations. Table 1 summarises cases of slope failure that were associated with pile driving.

Table 1 Cases of slope failure due to pile driving

Location	Description	Reference
Drammen, Norway	Piling activity for a factory building triggered a large landslide at which approximately 1000 m2 of the site subsided and slid out into the nearby River.	(Aas, 1975)

Fredrikstad, Norway	Pile driving for a bridge foundation (Værstebrua) caused excessive ground movements and resulted in misaligning of already-driven piles and disruption in construction activities.	Norwegian project report by Geovita AS (2013) 'Værstebrua, bysiden rapport'
Sandvika, Norway	Foundation installation for an embankment during construction of E18 road in Mustadjordet which included 150 number of concrete piles, resulted in a landslide volume of 5,000m3.	Norwegian project report by Veglaboratoriet (1963)
Quebec, Canada	A landslide occurred due to driving of three friction piles which resulted in a loss of life.	(Carson, 2011)
Portland, USA	During construction of a wharf facility, an underwater slope failed during dredging and subsequent driving of piles through the slope.	(LaGatta and Whiteside, 1984)
Trøndelag, Norway	In a harbour projects, a slide occurred in an engineered embankment during its construction, which was attributed to the movements induced by pile driving.	(Thakur et al., 2008)
Shanghai, China	A riverbank dike was damaged by pile driving in very soft Shanghai clay. Severe deformation and cracks of bank slope occurred during pile driving for the reinforcement of Shanghai Bailianjing port.	(Shen et al., 2005)
Gothenburg, Sweden	A slide took place due to pile driving for a family house, which slid away 31 houses in the area.	(Bernander, 2011)
Rollsbo Kungälv, Sweden	Pile driving for a family house resulted in a slope failure.	(Bernander, 2011)
Rävekärr, Mölndal, Sweden	Driving of pipes for sand drains resulted in a landslide.	(Bernander, 2011)

Investigating into the cases summarised in Table 1 has suggested that the speed of pile driving can affect slope stability. In some cases, excessive (vertical or lateral) displacements of the slope was regarded as failure without development of a slip surface, for instance in a case of slope failure induced by pile driving in Norway, ground movements accounted to 70 cm and pile installation was stopped Geovita AS (2013). In another case, during pile installation for a bridge, the accumulated displacements resulted in movement of the slope towards and into the adjacent river and this was considered as a landslide.

Some case studies such as the submarine landslide in Portland (LaGatta and Whiteside, 1984) have concluded that high speed of the pile driving suite to be a contributing factor to slope failure. In many cases, limiting the speed of pile driving per day or limiting the number or volume of piles per area/day could contribute to safe installation. In some cases, such as in Værstebrua, noticeable rise in excess pore pressure was observed prior or after the landslide (Geovita AS, 2013). However, in other cases, no significant changes were reported which indicates that the absence of high excess pore pressure does not guarantee safety of the slope during pile driving. Pore pressure monitoring is nevertheless recommended during piling in soft cohesive soils as its generation and dissipation can provide insight to the changes happening in the soil's stress state. Location and installed depth of the piezometers may also highly affect these results. Placing the piezometers in governing location/depths can provide more useful/relevant output with regards to continuing pile driving. Sand and silt lenses are present in most of the failed cases reported. It may be concluded that presence of sand and silt layers can be problematic, as these deposits may be prone to liquefaction due to vibrations caused by pile driving. The liquified lenses could induce displacements and stresses in the areas with low shear strength and generate failure. Furthermore, these layers with higher permeability could facilitate lateral dissipation of excess pore pressures and cause reduction of effective stresses in areas not affected by pile driving. Pile driving can initiate a local failure which can in turn develop into a global failure of the slope even when external forces are not sufficient (based on conventional stability analyses not accounting for the effect of strain softening) to cause instability.

2.2. Current methods of analysis

This section briefly summarises three methods that are commonly used to assess slope stability during pile driving in clay. It shall be noted that pile driving, which has an undrained rapid loading mechanism in cohesive soils, results in generation of excess pore pressures. One method considers the generated pore pressures to reduce the effective stresses, assuming no change in total stresses due to pile driving. The excess pore pressure profiles calculated based on empirical methods are then introduced into an effective-stress-based Limit Equilibrium Method (LEM) which result in a reduced factor of safety compared to the original slope’s factor of safety.

Another approach also uses estimations of excess pore pressures due to pile driving based on empirical methods. If no change in total stresses is assumed, this increase results in reduction of vertical effective stresses. The reduced values of effective stresses are then applied in a SHANSEP (Stress History and Normalized Soil Engineering Properties) formula to reduce the undrained shear strength of soil. SHANSEP technique which assesses the effect of stress history on the shear strength of soil was developed by Ladd & Foott (1974). This concept is based on a series of laboratory tests which establish undrained shear strength as a function of OCR and accordingly, calculates the undrained shear strength using the in-situ vertical effective stress, using Equation 1.

$$S_u = S(OCR^m)(P_0^{'})$$

Equation 1

Where Su is the undrained shear strength, P'_0 is the in-situ vertical effective stress, S is undrained shear strength ratio in normally consolidated state (OCR=1) and m is a constant dependent on the type and Plasticity Index (Ip) of clay. Using the SHANSEP principle in a pile driving scenario will provide reduced shear strength values (Kirkebø et al., 2006), (see Equation 2). Using these reduced strength values in an undrained slope stability analysis will then result in a lower factor of safety during pile driving.

$$(S_{u1}) = \left(\frac{S_u}{P_0'}\right) OCR^m (P_1') = \left(\frac{S_u}{P_0'}\right)\left(\frac{P_0'}{P_0' - \Delta u}\right)^m \left(P_0' - \Delta u\right)$$ *Equation 2*

Another method which is developed by Aas (1975) takes into account the effect of mass displacement due to pile driving by applying a horizontal load equal to the vertical pressure of clay in a vertical plane along the pile length. An increase in horizontal stresses corresponding to the coefficient of horizontal pressure (Kh) equal to 1 is assumed in this method. This increase can be applied as a driving force in a total or effective stress-based LEM analysis to provide a reduced factor of safety due to pile driving. A more in-depth summary of these methods can be found in Attari et al. (2023).

2.3.Numerical analysis

The effect of pile driving on slope stability was examined using the finite element package Plaxis 2D. A series of finite element analyses using three different constitutive soil models were conducted. The purpose of these analyses was to show the limitations of the methods discussed in Section 2.2. and provide a better understanding of the failure mechanisms that pile driving may initiate in a slope. In some cases, layers of silt can be present between layers of clay. The effect of these more permeable layers was simulated by applying a higher horizontal permeability in the soil material to show the effect of quicker pore pressure dissipation into the slope.

An arbitrary slope was modelled in Plaxis 2D, comprising of a slope and a pile row at the top of the slope, as is common for a bridge abutment. First, an elastic-perfectly plastic Mohr-Coulomb soil model was used. Secondly, more advanced soil models were used: Soft Soil that takes into account the excess pore pressure generated by the contraction of clay and NGI-ADPsoft that can simulate the strain softening in the soil. The soil parameters were selected in an arbitrary way to represent soft and brittle clay deposits. This is in detail presented in Attari et al., 2023).

For the purpose of this study, it was deemed suitable to only simulate the lateral push from pile driving on the slope stability, assuming the row of piles are installed simultaneously to full depth. For this reason, pile driving was simulated using the prescribed volumetric strain feature in Plaxis, where in a 2D setting, lateral strains are applied to a certain area. This function expands or contracts a soil cluster equal to the applied strain while maintaining the same stress levels (Brinkgreve et al., 2017). This change in strains will then affect the surrounding soil until an equilibrium is reached between all clusters. Application of prescribed displacements on the pile cluster, generates lateral displacements in the soil similar to expansion of a cylindrical cavity in a soil medium, which is widely used in combination with a constitutive soil model to simulate the effects of pile driving in the soil (Hunt, 2000).

All the analyses start with a Gravity Loading phase as a slope stability problem is dealt with. This is followed by a phase where lateral strains are applied to the defined pile row based on pile size and centre to centre spacing into the plane. In the Mohr-Coulomb analysis a phi-c reduction is conducted before and after pile driving simulation which shows the factor of safety of the slope in the two phases. In the Soft Soil analysis, pile driving was followed by a consolidation phase where excess pore pressure generated during pile driving is partially dissipating. The generated excess pore pressure contours are shown in Figure 3 for Mohr-Coulomb and Soft soil analysis.

The phi-c reduction phase is not representative in a soft soil model, but Figure 4 which depicts the relative mobilisation of shear strength in the slope after pile driving shows a situation very close to failure, where a significant part of the soil in the slope shows 90% mobilisation and higher. The mobilisation factor was higher after dissipation of the excess pore pressures into the slope.

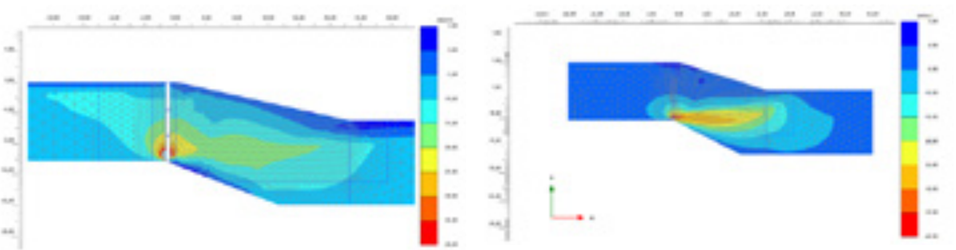

Figure 3 - Excess pore pressure field due to pile driving (Mohr Coulomb constitutive soil model on the left and soft soil model on the right.)

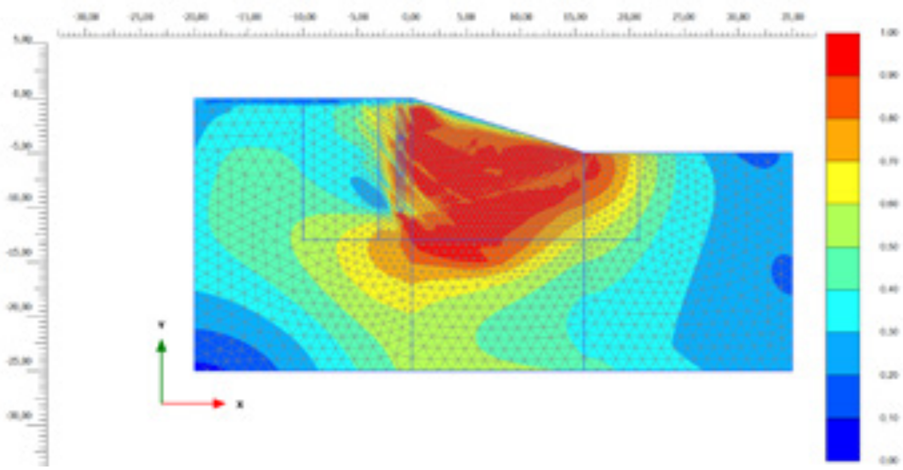

Figure 4 - Shear strength mobilisation in the slope after pile driving (during dissipation of the excess pore pressures into the slope)

The results of the gravity increase phase before and after pile driving phase, using NGI-ADPsoft constitutive soil model in Plaxis showed a reduction in the factor of safety of slope due to pile driving (see Figure 5). According to the provided results, an analysis using the Mohr-Coulomb soil model cannot simulate the reduction of the safety factor of the slope, as the excess pore pressures generated are (1) does not include shear induced pore pressure and a reduction in the mean effective stress, and (2) do not have an effect on soil strength in undrained stability analysis. This proves the shortcoming of the current methods (referred to in section 2.2.) where the excess pore pressures generated due to pile driving directly reduces the effective stresses in the surrounding soil and hence, reduce shear strength and factor of safety of the slope. However, the total stress increase due to pile driving does not affect the effective stresses and does not change the soil strength. With no change in soil strength, such simulations do not provide a reduction in the factor of safety of the slope during pile driving and cannot represent a triggering mechanism. This shows also that using an advanced soil model that can represent the drop in the undrained shear strength of the soil may provide realistic results in the presence of sufficient soil tests that can be used to model the strain-softening behaviour of the soil. A more in-depth evaluation of the analysis and results is available in Attari et al. (2023).

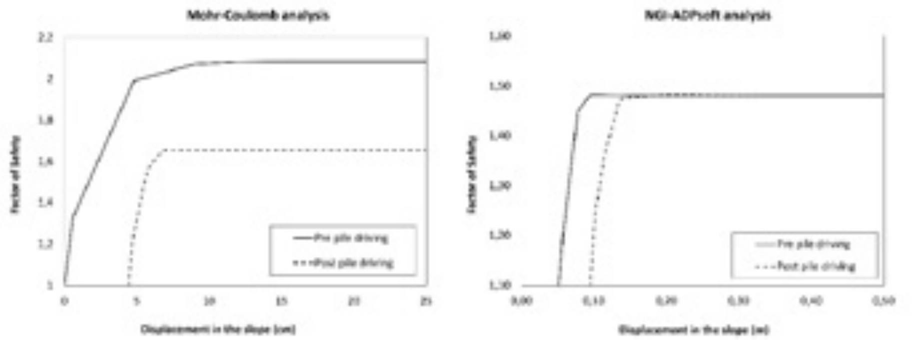

Figure 5 - Comparison of factor of safety using different constitutive soil models in Plaxis

SUMMARY AND CONCLUSIONS

The outcomes of this research can be summarised into the following points:

- There are limited number of reported cases of landslide that initiated due to pile driving. In many cases, sensitive clay deposits were present, or lenses of silt and sand were detected between the clay layers which could be subjected to liquefaction or facilitate migration of the excess pore pressures to parts of the slope where pile driving has not increased the total stress in the soil.
- In many reported cases of failure, limiting the speed of pile driving per day or limiting the number or volume of piles per area/day could contribute to safe installation.
- Current methods that estimate strength reduction due to increased pore pressure assuming no change in total stresses. This assumption is not correct as pile installation displaces the soil radially outwards which increases the total horizontal stresses in soils.

- Sensitivity and brittleness behaviour of soil are not considered in any of the methods. Hence, the possibility of a progressive failure which might occur in sensitive soil deposits is not considered.
- Applying a limit on measured pore pressure changes due to pile driving will not necessarily guarantee that failure cannot occur as excess pore water pressure can dissipate to other parts of slope that could trigger instability. The slope can be in a more critical situation during dissipation of the excess pore pressure, as seen in the results of the numerical analysis.
- An alternative to assess slope stability by means of LEM, is to use numerical methods such as the Finite Element Method (FEM), especially in the case of a brittle or quick clay deposit which increases the risk of a progressive type of failure. However, the effect of pile driving on slope stability cannot be simulated using a simple soil model such as Mohr-Coulomb. Reduced stability or failure may be predicted if a more advanced soil models that can simulate strain softening and shear induced pore pressure of the actual clay are used. In the presence of comprehensive information about the sensitivity and brittleness of the soil material, such constitutive soil models might be able to provide a more accurate prediction of the failure.

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