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Evaluation of slope safety during pile driving in clay

Évaluation des risques lors du battage de pieux dans des pentes argileuses

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ABSTRACT: Pile driving adjacent to or in slopes can trigger landslides, specifically in marginally stable slopes and in the presence of sensitive soil deposits. Slope failure incidents due to pile driving have been reported in countries such as Norway, Sweden and Canada where soft sensitive clay deposits are prevalent. However, the failure mechanisms involved in such incidents are not well studied nor understood. Furthermore, the methods currently used to estimate the reduction in the slope's factor of safety during pile driving lack scientific consensus. This paper describes how pile driving can reduce slope stability by means of empirical relations and analytical solutions from soil mechanics as well as numerical analysis.

RÉSUMÉ: Le battage de pieux à proximité ou dans des pentes argileuses peut déclencher des glissements de terrain, particulièrement dans des pentes peu stables et en présence de sols mout et sensible. Des glissements de terrain dus au battage de pieux ont été répertoriés dans différents pays comme la Norvège, la Suède et le Canada, pays dans lesquels les argiles sensibles. Cependant, les mécanismes de rupture qui explique ces incidents ne sont pas clairement identifiés ni compris. De plus, les méthodes actuellement disponibles pour quantifier les coefficients de sécurité des pentes durant le battage de pieux manque de précision scientifique. Cet article décrit comment le battage de pieux peut affecter la stabilité de la pente.

Keywords: Pile driving; slope stability; excess pore pressure; strain softening; numerical modelling.

1 INTRODUCTION

Pile driving generates stresses, strains, excess pore pressures and vibrations in the soil (Seed and Reese, 1957). Pile driving in clay is an undrained type of loading where multiple hammer-blows generate excess pore pressure in the adjacent soil which may lead to cyclic degradation of the soil (Randolph and Gourvenec, 2011). These effects are visually depicted in Figure 1. As a result, characteristics of the soil (such as plasticity index and strength among others) in the vicinity of the pile change during and for a period after the pile driving. These changes are usually temporary, and the soil regains its initial strength to some extent (Karlsrud and Nadim 1990). But this process can take many months depending on the properties of the soil, mainly permeability and stiffness of the soil material.

In some cases, these temporary changes in the soil can lead to a reduction in the factor of safety of a slope and lead to excessive movements or initiate a landslide. Understanding the mechanisms involved and methods to account for this reduction in the safety factor can help reduce risks related to pile driving conducted in slopes.

There are not many reported and documented cases of landslides due to pile driving in the literature (Attari et al., 2023). Reviewing the few numbers of reported cases shows that this type of slope failure is more common in Norway, Sweden and Canada where sensitive and brittle clay materials are present in the soil (Attari et al., 2023). For instance, a large landslide occurred in 1950 in the Gota river valley area, located nearby Gothenburg city in Sweden. The landslide affected 240,000 m^2 of the area and swept away 31 family houses and resulted in a loss of life (Bernander, 2011). At the time of the landslide, pile driving was being conducted at the top of the slope. A landslide took place in 1966 a few hours after completion of driving 50 wooden piles into soft sensitive clay (Broms and Bennemark, 1967). Another landslide occurred in Quebec, Canada in 1978 while pile driving was in operation for an electrical tower (Carson, 2011). The results of grain size analysis and drilling reports indicated lenses of sand and silt in the deposit and the investigating committee report concluded that the vibrations induced by pile driving have resulted in the liquefaction of these sand lenses, causing the surrounding clay to lose part of its shear strength, resulting in continuation of the movements even after pile driving had stopped (Carson, 2011).

A list of slope failure incidents due to pile driving is provided in Attari et al. (2023). In some of these cases, noticeable rise in pore pressure was observed prior or after the landslide and a lot of the soil investigation reports indicate lenses of silt and sand between the clay layers. Despite the significance of this problem, there is still not a standard method developed to accurately account for the reduced stability of a slope due to pile driving (Langford et al., 2021).

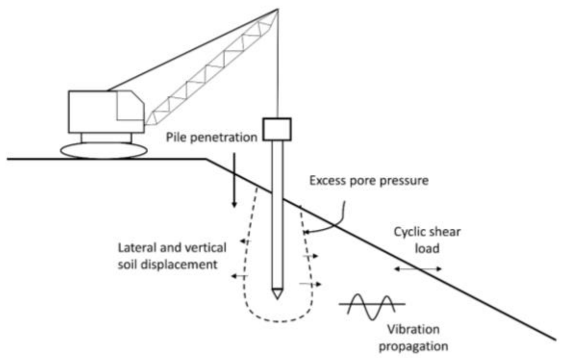

Figure 1. Effects of pile installation in a slope (Attari et al., 2023).

Common practice in Norway to account for reduced stability of a slope during pile driving, is to monitor pore pressures during construction. Limits are set on maximum allowable pore pressure levels to avoid slope failure. Piling operations are stopped when these limits are exceeded and are continued where pore pressures return to allowable rates (Tefera et al., 2013). However, the basis for obtaining these limiting values is not accurate. Moreover, the costs for waiting time or for moving pile-driving machines to different locations to allow for pore pressure dissipation can be large and there are a lot of uncertainties in the installation/construction phase, which usually infers extra costs. Therefore, there is a strong need for further research to develop an approach to account for pile installation effects on slope stability in a more reliable manner.

2 REVIEW OF THE BASIS OF THE TRADITIONAL METHODS

The basis for the currently used methods in practice together with measuring of pore pressures is that soil strength is dependent on effective stresses (Ladd & Foott, 1974). The 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 Overconsolidation Ratio (OCR) and accordingly, calculates the undrained shear strength based on the in-situ vertical effective stress, using Equation (1).

$$S_u = S.OCR^m.P' \quad (1)$$

$$P' = P - \Delta u \quad (2)$$

where S_u is the undrained shear strength, P is the *in-situ* vertical stress, P’ is the *in-situ* vertical effective stress, Δu is pore pressure, S is undrained shear strength ratio in normally consolidated state (OCR=1) and m is a constant dependent on the type and Plasticity Index of clay. Using the SHANSEP principle in a pile driving scenario will provide reduced shear strength values (Kirkebø et al., 2008) due to the reduction in P’ given by Equation (2). The methods assume that the excess pore pressure results in reduced effective stresses in the soil adjacent to the pile, and as given by the SHANSEP formula, the undrained shear strength reduces. Accordingly, the reduced Su results in a lower safety factor of the slope.

However, these assumptions do not consider that pile driving is an undrained loading mechanism in clay (considering the low permeability of clays) which increases the total stresses. Thus, according to equation (2), which is the basis of the effective stress concept by Terzaghi (1943), the change in effective stresses is dependent on both total stress and excess pore pressure which are both increasing. A more in-depth evaluation of these methods can be found in Attari et al. (2023).

3 NUMERICAL ANALYSIS

It is a complex task to simulate pile driving using Finite Element Analysis (FEA). For the purpose of this study, it was deemed suitable to only take into account the effect of the lateral push that is generated due to driving a pile in the slope, 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 the finite element code Plaxis, where in a 2D setting, lateral strains are applied to a wished-in-place pile modelled as a soil cluster. This volumetric strain feature expands or contracts a soil cluster equal to the applied strain (Brinkgreve et al., 2021). This change in strains will then affect the surrounding soil until equilibrium is reached between all clusters. Application of prescribed volumetric strains on the pile cluster, generates lateral displacements in the soil similar to the 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 soil (Hunt, 2000). Although this method disregards the changes in vertical stresses during pile driving, it still provides good estimates of stresses, displacements and excess pore pressures in the soil due to pile penetration (Hunt, 2000). The accuracy of the results in these analyses are highly dependent on the choice of the constitutive soil model. For instance, a simple soil model such as Mohr-Coulomb cannot simulate several important effects of pile driving (stress dependent stiffness, strain softening) and are therefore not able to capture the reduction of the safety factor of the slope. More advanced constitutive models such as Soft Soil can provide better estimates of, for example, the excess pore pressure and, accordingly, provide a better understanding of the extent of undrained shear strength mobilization in the soil after pile driving.

More advanced constitutive models that can take into account strain-softening of the clay are further employed in FEA. Sensitive clays show a reduction in their undrained shear strength after the peak strength is reached in undrained conditions. This characteristic is referred to as strain-softening. A gradual progression of strain-softening behavior throughout the slope could ultimately lead to a global failure (Urciuoli et al., 2007). This type of failure is defined as progressive failure in sensitive deposits where a local disturbance may trigger a landslide Bernander (2011). The NGI-ADPSoft model is an elastoplastic constitutive soil model that can be used in total stress analysis of soils and can simulate the strain softening behaviour of sensitive clays and hence, can capture the reduction of the undrained shear strength in the soils as a function of strain level in undrained conditions. This could be used to calculate a representative factor of safety in the sensitive clay slope (see Figure 2). This representative factor of safety is obtained by increasing the unit weight of the soil int the analysis (instead of reducing the soil strength) until failure is reached. More information about this soil model can be found in Jostad et al. (2014) as well as Grimstad & Jostad (2012).

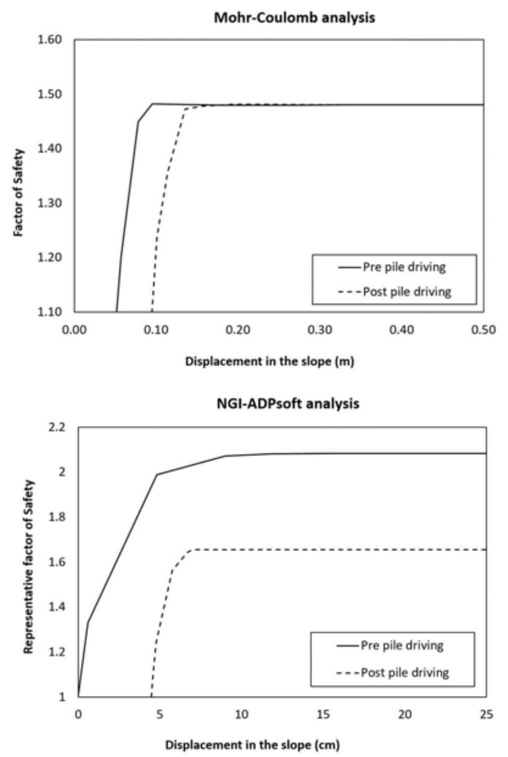

Figure 2. Comparison of factor of safety using different constitutive soil models in Plaxis (Attari et al., 2023).

4 CYCLIC SOIL DEGRADATION DUE TO PILE DRIVING

Soil response to cyclic loading is substantially different from the soil response under monotonic loading and depends on the mode, amplitude and frequency of the cyclic loading. To investigate if the cyclic loading generated due to pile driving can influence the stability of slopes due to cyclic degradation of the soil strength the following methodology is being investigated. A pile driving analysis is conducted to provide pile displacements in time by means of 1D stress wave analysis using the GRLWEAP software. The displacement versus time output can be used in a dynamic finite element analysis to estimate the extent and magnitude of the changes in stresses, strains and excess pore pressures due to the cyclic loading. These results can be used in combination with cyclic degradation contour diagrams developed by Andersen (2009) to determine the reduction in shear strength. These diagrams are developed for a great range of soils and are based on large numbers of laboratory tests on block samples (Andersen, 2009). The result of this study is planned to be included in future articles by the authors.

5 CONCLUSIONS

Throughout this study, changes occurring in clay due to pile driving have been briefly explained and their possible effect on the reduction of soil strength was pointed out. Subsequently, methods currently used by geotechnical engineers to take into account the reduction in the stability of a slope during pile driving were presented. It was pointed out that these methods lack theoretical consensus. Furthermore, examples of how numerical analysis can contribute to better understanding of this problem were outlined.

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