28th European Young Geotechnical Engineers Conference – EYGEC 2024
© 2024 Macedonian Association for Geotechnics, ISBN xxx-xxx-xx-xxxx-x

Assessment of the impact of soil degradation due to pile driving on slope stability in cohesive soil conditions

Yeganeh Attari[a,b], Gudmund Reidar Eiksund[b]

[a] *Multiconsult AS, Oslo, Norway*
[b] *Norwegian University of Science & Technology, Trondheim, Norway*

ABSTRACT

Piles are a common foundation solution to support buildings, bridge abutments and embankments in soft soil deposits to transfer structural loads to deeper more stable soil layers or bedrock. During pile driving adjacent to slopes, stability of the slope can be negatively affected due to excess pore pressure generation, dissipation of the excess pore pressure into the slope, induced displacements, and cyclic degradation of the soil among other possible factors. However, there is a lack of understanding of the failure mechanisms involved in this phenomenon; as well as methods to account for the temporary reduction in slope stability during pile driving. This paper provides an overview of this problem. Furthermore, the paper introduces a method which couples pile driving analysis using wave theory with numerical finite element analysis to obtain the extent of cyclic soil degradation due to pile driving. This could be further used to assess stability of a slope during pile driving.

KEYWORDS

Pile driving, Installation effects, Cyclic degradation, Slope Stability.

1. INTRODUCTION

1.1. Piles and pile driving

Piles are foundation elements that transfer structural loads from weak soil layers to deeper more competent strata or the bedrock. Piles can be classified into replacement or displacement piles according to their method of installation. Piles that are driven into the soil by a piling hammer and displace the adjacent soil during lie in the displacement pile category. The magnitude of the displacement depends on the pile size and type (open vs close ended). In Scandinavia, onshore piles are generally precast concrete piles. For building foundations, pile diameter of 300mm or quadratic cross section piles of 230 or 270 are common choices. Bridge foundations are commonly built with concrete in close ended 0.8m wide steep pipes. Offshore structures which require larger foundations can have piles with diameter up to 3m and length in the order of 50 to 100m.

Driving piles into clay generates high shear strains in the soil as the pile tip goes through the ground. Hence, the soil close to the pile undergoes a high degree of remoulding. This process is usually considered to be undrained, except in high-permeability silty clays where certain degree of drainage may occur. The act of pile driving pushes the soil away and generates an increase in total horizontal stresses which depend on the undrained shear strength of the soil (typically in the order of 4 to 6 times the undrained shear strength), (Randolph and Gourvenec, 2011). Furthermore, changes in pore pressure occurs which arises from two different mechanisms: Firstly, an increase in pore pressure occurs in response to increase in total stress and secondly (and to a smaller degree of contribution), a change in excess pore pressure occurs due to undrained shearing of the soil (Randolph and Gourvenec, 2011). This change can be positive or negative with respect to the type of clay. Stiff clays show a dilative behavior during shearing and generate suction, whereas soft clays tend to contract and result in an increase in the pore pressure (Burns and Mayne, 1999).

1.2. Slope stability and pile driving in slopes

Addressing stability issues in natural or engineered slopes presents significant challenges in engineering design and construction. Various factors, such as changes in groundwater table due to heavy rainfall or rapid drawdown, seismic forces, and construction activities can lead to slope failure (Broms and Wong, 1991). Typically, slope failure occurs when the average shear stresses along the slip surface exceeds the shear strength of the soil or rock material (Broms and Wong, 1991). However, this isn't always the sole cause, particularly in the case of a progressive failure mechanisms -where a local failure can trigger a general slope failure. Preventing such incidents requires a comprehensive understanding of failure mechanisms, investigative and predictive tools, as well as stabilization measures (Abramson et al., 2001). The primary objective of slope stability analysis is to ensure safety for individuals, structures, and infrastructure, while also contributing to the economically and safely designed and constructed structures (Chowdhury, 1978).

Pile driving in clay induces rapid undrained soil behavior due to clay's low permeability (Randolph and Gourvenec, 2011). Early studies by Bjerrum et al. (1958) were among the first to address excess pore pressures around piles driven in clay. Subsequent research by Bjerrum and Johannessen (1960) highlighted that the increase in pore pressure during pile driving, followed by its dissipation, temporarily reduces the undrained shear strength and decreases the factor of safety of nearby slopes. The soil properties near the pile wall are influenced during the driving process, leading to the formation of plastic and elastic zones, as defined by Karlsrud and Nadim (1990). Zone I, characterized by high shear-induced and displacement-induced pore pressures, is confined to the immediate vicinity of the pile. Conversely, the elastic zone, representing excess pore pressure due solely to displacement, extends further and decays exponentially with distance. This elastic zone can be subdivided into zones II and III. In zone II, pore pressure decreases after pile driving ceases, while in zone III, dissipation of excess pore pressure leads to a delayed increase in pore pressure and subsequently a delayed reduction in effective stress (see Figure 1). The effects of the pore pressure migration into various zones in the slope is explained in detail in Attari et al. (2023). This paper aims to provide some insight into the cyclic effects of pile driving on slope stability.

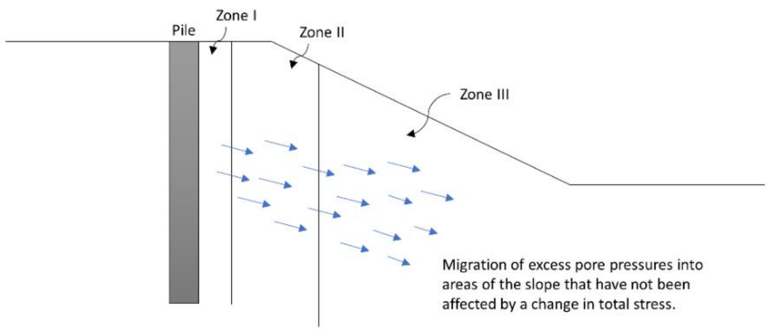

Figure 1. Affected zones around the pile wall due to pile driving, with regards to pore pressure generation and dissipation (Attari et al., 2023)

1.3. Cyclic loading and soil degradation due to cyclic loading

The response of soil to cyclic loading in clay differs from that in sandy materials due to the influence of time-dependent creep and preconsolidation periods (Yasuhara et al., 1992). Early investigations into clay behavior under cyclic loading were conducted by Sangrey et al. (1969), who performed triaxial tests on saturated clay samples. Their findings revealed the presence of a specific critical cyclic stress for each consolidation history, beyond which failure occurred. Subsequent studies by Andersen et al. (1976) extensively examined the behavior of Drammen clay under cyclic loading. Andresen et al. (1976)

have developed calculation procedures to evaluate the impact of cyclic loading on various soil types, based on extensive laboratory testing of clay samples and resulting contour diagrams. An example of these diagrams is presented in Figure 2.

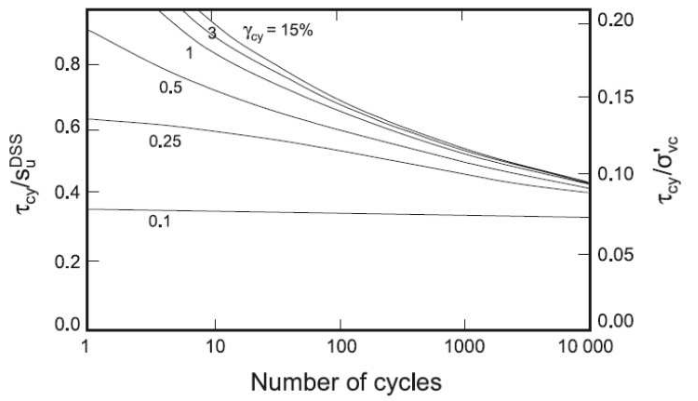

Figure 2 Extent of cyclic degradation of soil based on cyclic shear stress to undrained shear strength ratio, according to the number of cycles (Andresen et al., 1976).

2. SUGGESTED METHODOLOGY

2.1. Pile driving analysis

Pile driving transfers kinetic energy from the hammer to the top of the pile. Several hammer blows are required until the desired depth of the pile is reached (Woods, 1990). A compression body wave is generated in the pile by the hammer. As the wave travels down towards the pile toe, part of it is reflected in the pile and part of it transmits to the surrounding soil (Selby,1991). The energy transmitted to the soil from the pile depends on the pile and hammer characteristics. The elastic soil deformation due to this impact is propagated in the soil as elastic waves.
Pile driving analysis evaluates the ability of a hammer with a certain energy to safely drive a pile down to the required design depth into the soil (Stevens et al., 1982). A pile driveability analysis takes into account the pile geometry, type and energy of the hammer, as well as soil properties, which quantifies the soil's resistance to driving (Stevens et al., 1982). Pile driving analysis is typically performed using Wave Theory by means of software such as GRLWEAP.

For the purposes of the analysis, a pile driving analysis was conducted in GRLWEAP using a typical size onshore concrete pile, as delineated in the introduction. The pile driving analysis provides the number of blows among other results. The displacement versus time history related to one hammer blow in this case was accordingly used as input in the numerical model generated in the next step.

2.2. Finite element analysis and post-processing using cyclic degradation curves

A wished-in-place pile is modelled in Plaxis 2D, axisymmetric model (see overview of the model in Figure 3).

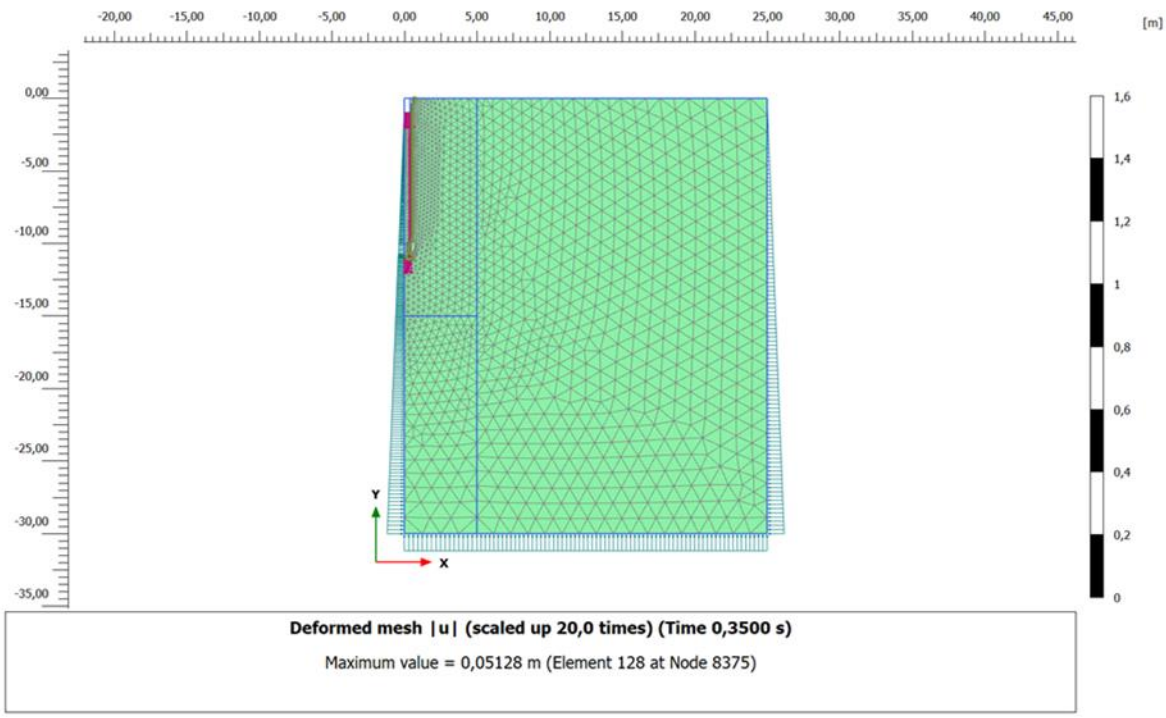

Figure 3 Overview of the Plaxis model.

The HSSs constitutive model is used for this analysis and a soil strength profile of Su=20+2z kPa, where undrained moel B is used. The displacement in dynamic time generated in the previous stage is used as a dynamic prescribed displacement in the Plaxis 2D model. Required boundary conditions and interface properties are considered accordingly. Among the results of this analysis, shear stresses generated in different points in the soil are looked at (See Figure 4, where X is the lateral distance between pile and considered output point, and Y denotes the vertical distance). The accumulation of the shear stress in the soil body is then calculated based on the piling layout. These results are used to assess the extent of the cyclic shear degradation (generation of cyclic shear strains and cyclic excess pore pressure).

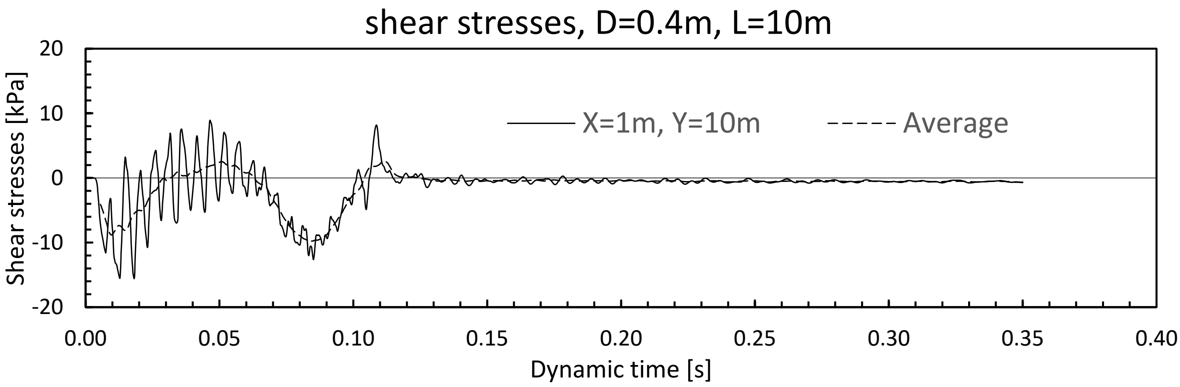

Figure 4 Shear stresses in the soil in dynamic time (related to one hammer blow)

3. DISCUSSION & CONCLUSION

Pile driving adjacent to slopes can pose challenges with regards to slope stability. The cyclic loading resulting from the hammer blows can in some cases depending on the soil properties, pile geometry and piling layout cause excessive soil degradation which can generate excess pore pressure and affect soil strength. A methodology in the early phases is suggested for this purpose, where pile driving analysis is conducted to provide time-displacement input to a simplified numerical model that aims to calculate the shear stresses generated due to pile driving in each case. This can further on predict the magnitude of the generated excess pore pressure and evaluate the dynamic effects of pile driving on soil strength. This paper attempts to suggest a method to account for the cyclic degradation of soil due to pile driving in cohesive soil which could have the potential to be used with regards to slope stability problems. A challenge is to implement this into a slope where initially a degree of shear is being mobilized. This is being researched further and in more detail. It shall be noted that this is under development and final results will be presented in future publications.

ACKNOWLEDGEMENTS

This study was done within BegrensSkade (REMEDY) II research project financed by the Norwegian Research Council (grant 267674). The authors acknowledge the support of the research project leader, Dr. Jenny Langford at the Norwegian Geotechnical Institute. The authors also acknowledge the scientific support of Erik Sørlie at Multiconsult Oslo. The authors also appreciate the financial support provided by the Norwegian Geotechnical Society with regards to the conference attendance.

REFERENCES

Abramson, L. W., Lee, T. S., Sharma, S., and Boyce, G. M. (2001). Slope stability and stabilization methods. John Wiley & Sons.

Andersen, K. H., Brown, S. F., Foss, I., Pool, J. H., and Rosenbrand, W. F. (1976). Effect of Cyclic Loading on Clay Behaviour. In Nor Geotek Inst Publ, number 113, pages 1-6. Thomas Telford Publishing.

Attari, Y., Jostad, H. P., Grimstad, G., & Eiksund, G. R. (2023). Evaluation of Pile Driving Effe cts on Slope Stability in Clay. Geotechnical and Geological Engineering, 1-16.

Bjerrum L, Johannessen IJ (1960) Pore pressures resulting from driving piles in soft clay. Norwegian Geotechnical Institute. In: Pore pressure & suction in soils Conference, Londres.

Broms, B. B. and Wong, K. S. (1991). Landslides. In Foundation Engineering Handbook, pages 410-446. Springer.

Burns SE, Mayne PW (1999) Pore pressure dissipation behavior surrounding driven piles and cone penetrometers. Transp Res Rec 1675(1):17–23.

Chowdhury, R. N. (1978). Effective-Stress Parameters of Anisotropic Soil. Journal of the Geotechnical Engineering Division, 104(1):124-128.

Karlsrud K, Nadim F (1990) Axial capacity of offshore piles in clay. Offshore technology conference, OnePetro.

Matsui, T., Ohara, H., & Ito, T. (1980). Cyclic stress-strain history and shear characteristics of clay. Journal of the geotechnical Engineering Division, 106(10), 1101-1120.

Randolph M, Gourvenec S (2011) Offshore geotechnical engineering/Mark Randolph and Susan Gourvenec; with contributions from David White and Mark Cassidy. Abingdon, Spon Press, Oxon New York.

Sangrey, D. A., Henkel, D. J., & Esrig, M. I. (1969). The effective stress response of a saturated clay soil to repeated loading. Canadian Geotechnical Journal, 6(3), 241-252.

Stevens, Robert S., Wiltsie, Edward A., and Thomas H. Turton. (1982) Evaluating Drivability for Hard Clay, Very Dense Sand, and Rock. Paper presented at the Offshore Technology Conference, Houston, Texas, May 1982. doi: https://doi.org/10.4043/4205-MS.

Wood, D. M. (1990). Soil behaviour and critical state soil mechanics. Cambridge university press.

Yasuhara, K., Yamanouchi, T., & Hirao, K. (1982). Cyclic strength and deformation of normally consolidated clay. Soils and Foundations, 22(3), 77-91.

Yasuhara, K., Hirao, K., & Hyde, A. F. (1992). Effects of cyclic loading on undrained strength and compressibility of clay. Soils and Foundations, 32(1), 100-116.