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Difficulties of vibrodriving in till -causing cost intensive measures.

Difficultés de faire vibrer des moraines -entraînant des mesures coûteuses.

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ABSTRACT: This paper presents a brief background to Sweden's largest on-going infrastructure project E4 Stockholm Bypass and the difficulties of installing temporary retaining walls down to bedrock to facilitate deep excavations. Difficulties are attributed to the use of vibro-driven steel sheet piles into dense glacial till containing boulders, typical for the region Stockholm Mälardalen. Since the method is so cost effective, it's quite often the entrepreneur insist on applying the method an neglecting the risk of damaging the toe. Before realizing it's time to switch to drilled interlocked O-pile walls with down-the-hole technique. The consequence of a severely damaged toe is the unnecessary time- and cost intensive measures that needs to be implemented to ensure a stable and waterproof excavation. The aim of presented paper has been to invoke thoughts on mechanisms behind local buckling of toes and form the basis of a new stop criteria.

RÉSUMÉ: Ce document présente brièvement le plus grand projet d'infrastructure en cours en Suède, E4 Stockholm Bypass, et les difficultés rencontrées pour installer des murs de soutènement temporaires jusqu'à la roche en place afin de faciliter les excavations profondes. Des difficultés sont attribuées à l'utilisation de palplanches d'acier vibro-pilotées dans un till glaciaire dense contenant des blocs, typique de la région de Stockholm Mälardalen. Comme la méthode est si rentable, il est fréquent que l'entreprenur insiste pour l'appliquer en négligeant le risque d'endommager l'orteil. Avant de réaliser, il est temps de passer à des murs en O perforés imbriqués avec la technique du fond du trou. Un orteil gravement endommagé a pour conséquence des mesures coûteuses en temps et en argent qui doivent être mises en œuvre pour garantir une excavation à l'aide d'un couteau et imperméable. Le présent article avait pour objectif d'invoquer des idées sur les mécanismes à l'origine de la flexion locale des orteils et de constituer la base d'un nouveau critère d'arrêt.

Keywords: sheet pile, vibrodriving, local buckling, vibratory soil resistance to driving.

1 INTRODUCTION

A steel sheet pile (SSP) wall is the most common type of temporary retaining wall to facilitate deep excavations and the vibro-technique is the most cost-effective installation method. Civil engineering aspects such as “stability” and “waterproofed” facilitates analysis of prescribed depth of grade the SSP‘s are required to be driven to. In order to assess the vibro-driveability, it is necessary to review the existing ground conditions and perform a vibratory soil resistance to driving (VSRD) analysis.

In situations where hard driving is anticipated, damage to the SSP’s toe is a real risk that can occur. Especially when the slender SSPs enters a hard stratum such as till on bedrock or encounters blocks or boulders in the soil as it's driven. Damages to the toe, may go undetected with only indication that the SSP did not reach the prescribed depth below grade.

However, if the toe fails or buckle as illustrated in Fig.1, it leads to the need of extensive complementary work to achieve a stabile and waterproof retaining wall. Situations of hard driving leads to discussions if the vibro-method needs to be aided with pre-boring and/or switching to stronger SSP sections to minimize the complementary work.

Continued hard driving leads to the decision of abandoning the cost-effective type and installation method. In Stockholm Mälardalen such a decision often leads to the type; interlocked O-pile wall, installed with the drilling down-the-hole technique.

It's well know and documented in technical literatures; se Sponthandboken, that SSP's cannot be driven successfully through soil stratums such as hard till containing boulders.

2 VIBRODRIVABILITY ANALYSIS

Prior installation a VSRD-analysis needs to be performed to predict required vibro-equipment that's able to drive the SSP to planned elevation.

In (1995), Van Rompaey et al. presented a method that forms the basis of the VSRD-analysis. A method that defines the forces of the three main parts; i.e. capacity of vibro equipment F_d, SSP-profile, the dynamic soil resistance $R_s + R_t$ and clutch friction R_c in the interlock, se Eq.1.

$$F_d > R_s + R_t + R_c \tag{1}$$

This equation and several other design tools for SSP installation, all based on CPT investigations, can assists with selection of the appropriate sized equipment to drive the SSP to the predefined elevation in soft soils. However, the method has limitations when the maximum stress levels imparted to the driven SSP are of concern, se Fig.1., i.e. when hard driving and risk of local buckling of toe is anticipated.

2.1 *VSRD-profile prediction*

When SSPs are vibrodriven into the ground they experience resistance from the ground, named as vibratory soil resistance to driving (VSRD). The VSRD is calculated by a combination of skin friction and toe resistance in a similar way to static capacity. The results of the VSRD calculation provides input to the VSRD-analysis. Similar to SRD-analysis do to pile driveability programs such as GRLWEAP or TNOWAVE.

The difficult part boils down to define the dynamic soil resistance profile of the hard sub-soil stratum, i.e. till or moraine. The difficulty relates to phenomenon occurring during vibro-installation, not yet completely understood nor well documented or published, which is to quantifying the magnitude of the VSRD.

In Sweden the hard sub-soil profile is mostly characterized by field methods such as; weight sounding (Vim), dynamic soil/rock probing (Jb) and dynamic probing with stress wave measurements (Hfa).

If the soil characterization indicates presence presences of blocks, defined as having a size D

Figure 1 Photo's above show example evidence of local buckling of steel sheet pile toes, two photo's below show unearthed toe of sheet pile wall. Photo: P. Björgúlfsson & K. Viking.

in the range of 0.2 < D < 0.630 m. The boulder content (AB) can be analyzed according to the following: AB > 1.4/[0.4 + (L_{tot}/L_{bloc})] described in the Swedish Commission on Pile Research, Report 103.

If AB is analyzed to be high, i.e. > 20%, then it's recommended to analyze how a stop driving criteria should be defined. With purpose to minimize the probability of causing local buckling of the SSP toe, as shown in Fig.1.

2.2 *SSP damage*

Damage to vibrodriven SSP's has been observed before, however no research (known to the authors) as to the mechanisms and limit states behind the damage has been published. Limited research can however be found for impact driven large diameter-to-wall thickness steel piles in the field of offshore geotechnical engineering, as in Holeyman et al. (2015) and Randolph (2018). The study of Holeyman relates to *local buckling* as the driven pipe-pile encountered a boulder suspended in a stiff clay till. In study by Randolph (2018) damages was related to *extrusion buckling* (progressive deformation of pile during driving).

It's in the authors opinion obvious that the inherent slenderness and thus sensitivity to structural instability, of structures in named studies, suggest that the failure mechanisms may be similar

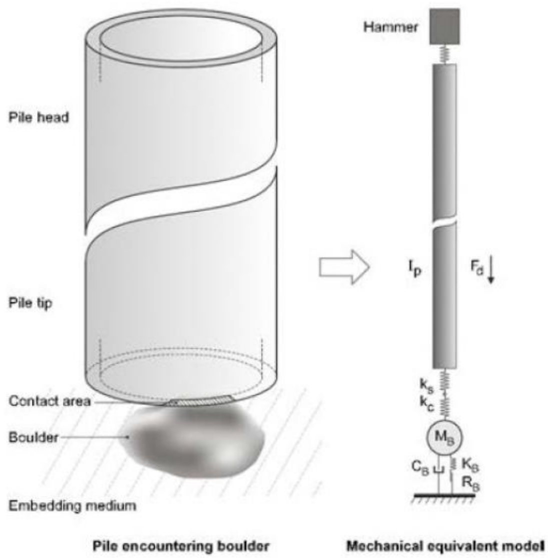

Figure 2 Model used by Holeyman et al. (2015).

to those as observed for the damaged SSP's in Fig.1.

2.3 *Limit states*

When a vibrodriven SSP, in the region of Stockholm Mälardalen, encounters the hard friction soil layer above bedrock. A complex situation occurs where different limit states can occur including the soil response as well. However, either the soil layer yields and the SSP can be driven into the hard soil layer. Or a boulder within the hard soil layer is encountered which is small enough that the SSP are able to move as it's driven into the soil. Or the soil layer is so stiff (dens) and/or the boulder so big it does not move.

A typical sign in the field of such situation is abrupt change or decrease of the penetrative speed of the driven pile. Another indicative sign is sudden change (increase) of lateral movement of the slender SSP.

The limit states of the vibrodriven SSP is off course defined by the limiting stresses given by the elasticity theory. There is no published guides of limits related to damaging toe of vibro-driven SSP. However, guidance of maximum permissible load Q_t, before generating a local dent, can be found in a report by HSE (2001), assuming pure axial load and shell buckling.

$$Q_t = 1.2\ f_y\ t^2 \quad (2)$$

Guidance to the maximum permissible lateral and near axial forces at the pile tip, before causing a local dent, can also be found in Aldridge et al. (2005).

$$Q_{lat} = 1.4\ f_y\ t^2 \quad (3)$$

$$Q_{ax} = 2.8\ f_y\ t^2 \quad (4)$$

where f_y is the yield stress and t is the wall thickness.

The limit states of vibrodriving SSP's into glacial till containing different sizes of boulder is another aspect that needs to be considered.

Dense, heavily preconsolidated glacial till is a relatively incompressible soil that occurs throughout most of the Stockholm Mälardalen region. Geotechnical properties of such dens till is normally not thoroughly investigated, however known to have a Modulus of Elasticity in the range of; dense 150–720 MPa, very dense 500–1440 MPa. Rock types vary by region, however Scandinavian boulders made out of granite has a uniaxial compressive strength in the order of 200 MPa, a Young's modulus of ~70 GPa with an average value of the Poisson's ratio of ~0.24, according to the Swedish Nuclear Fuel and Waste Management report No. R-05-83.

2.4 *Simple analysis*

As mentioned, the difficult part of a VSRD-analyses in the Stockholm Mälardalen region boils down to the dynamic soil resistance of the hard sub-soil stratum, i.e. very dense till that frequently contains boulders.

Driving stresses at the SSP toe will depend on the total resistance the area proportion of the toe resisted in end bearing as well as the vibro-equipments driving force.

The driving capacity of a modern leader mounted vibro, has a capacity above F_d > 1000 kN. The contact force of the vibrodriven SSP to the right in Fig.1 have encountered a boulder of a size equally them with of the SSP web, i.e. roughly 300 mm. When the driving force of the vibro is compleatly resisted at the toe, the static toe stress of a web with a thickness of 10 mm, can be statically calculated to ~ 300 MPa. Although the estimated stress at the toe is not in excess of static yield stress (assumed to 330 MPa for the 10 mm thick web material), the dynamic yield stress is off course much higher.

However, if the entrepreneur do not observe that the toe have encountered a boulder of granite (and just continue driving), the toe will end up looking like the SSP's in Fig.1.

On the other hand, if the entrepreneur is observant, damages of pile toe can be limited to a minimum, as illustrated in Fig.3.

Figure 3 Damaged toe, from Guillemet (2013).

Furthermore, the analysis of when the SSP toe ends up damaged, have been initially studied in a thesis work at Div. of Geotechnical Engineering, Lund University, Sweden. A study that intends to be followed up by another thesis work at Div. of Soil- and Rock Mechanics, Royal Institute of Technology (KTH). With the aim to invoke thoughts on mechanisms behind damaged SSP toes and form the future specifications for how an end-of-vibrodriving analysis can be defined. Which in the end could form the future basis of a new definition of stop criteria for vibrodriven steel sheet piles in heavily preconsolidated glacial till found in the region of Stockholm Mälardalen.

3 PROJECT DESCRIPTION

The ongoing project E4 Stockholm bypass is a new route for the European highway E4 past the Swedish capital. The bypass is Sweden’s largest on-going infrastructure project of all time featuring the world’s second longest road tunnel in the proximity of a city. The road tunnel consists of two parallel tunnels travelling in opposite directions, each tunnel having three lanes, increasing to four at the six interchanges along the route. At their deepest, the tunnels are almost 100 meters below ground, as illustrated in Fig.4. With all entry and exit ramps and access tunnels, gives a total excavated length of 54 km.

The project have been divided into the following procurements: -six rock tunnels, -six interchanges and -one mechanical & electrical installation, as described in TrV (2006).

The awarded contracts for construction of the six interchanges comprises scopes such as cut-and-cover concrete tunnels, bridges, underpasses, concrete troughs and upgrading existing structures. Several of the interchange sub-projects consists of works that include large-scale sheeting and shoring measures for the excavation works from ground surface to bed-rock. And scope of this paper covers the knowledge transfer of the experienced installation problems of vibro-driven SSP‘s in dense preconsolidated glacial till.

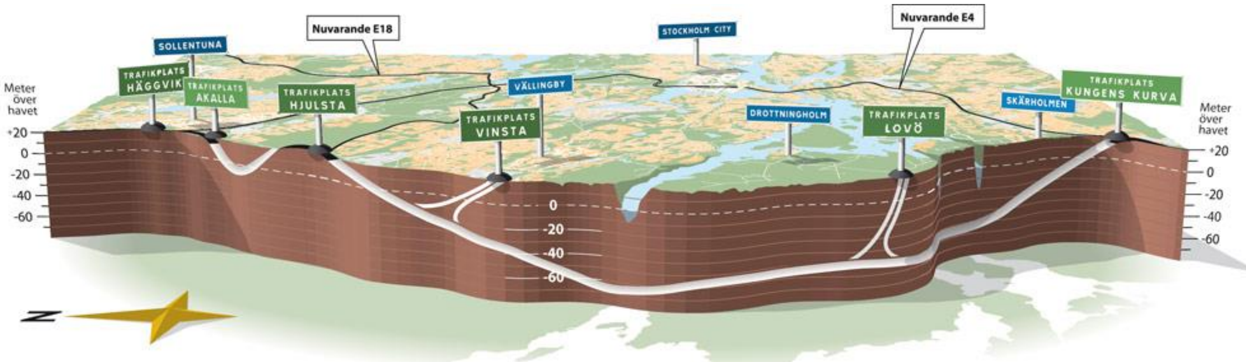

Figure 4 Construction lots of E4 Stockholm bypass project, green signs represents position of the six interchanges along the route, TrV (2006).

4 RESULTS AND DISCUSSIONS

Result illustrated in Fig.5 shows a damaged SSP toe after being vibrodriven into a large boulder of Scandinavian granite. The results are taken from a 3D FEM modeling of the experiences in the field of a vibro-driving a Larsen 603 SSP into dense preconsolidated glacial till containing boulders. With the purpose of parametric evaluate when local buckling of a SSP toe occur.
Results comes from a ongoing M.Sc. thesis work by Lund Tebäck (2019) at Div. of Geotechnical Engineering, Dept. of Construction Sciences, Faculty of Engineering at LTH,

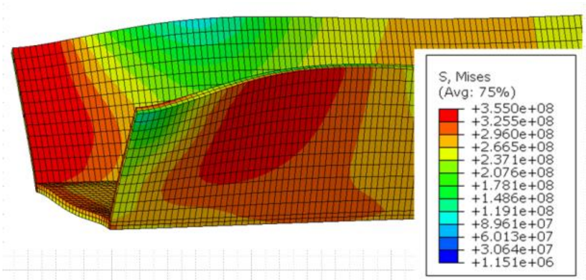

Figure 5 Numerical analysis of local buckling of a vibrodriven SSP toe, Lund Tebäck (2019).

5 SUMMARY AND CONCLUSIONS

This paper presented a brief background to the ongoing project E4 Stockholm Bypass and the experiences of the difficulties of installing temporary retaining walls to facilitate deep excavations. Furthermore a simple methodology of how to minimize damages is presented.

Damage to vibrodriven SSP toes is a known phenomenon, possibilities of predicting these damages do exist, but if these analyzes are carried out at all, it only occurs after the injury has occurred.

6 ACKNOWLEDGEMENTS

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It's also important to mention that due to contractor confidentiality, the authors have abstained from providing further details regarding project location and properties of the superstructure.

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