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Observations on densification of soil during vibratory sheetpiling

Observations sur densification de sol pendant palplanche vibratoire

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ABSTRACT

Vibratory sheetpiling may result in temporary excess pore pressures and settlement in the adjacent soil. These effects may result in damage to surrounding structures like buildings, highway embankments, railroad embankments, pipelines and dikes. In order to make a well balanced decision for the use of vibratory sheetpiling insight in the amount of settlement to be expected is needed. In order to assess the expected soil response a numerical model is being developed.

The paper first describes the sheetpiling process, with special attention for the aspects relevant for the loading of the adjacent soil. Discussed are the friction at the interface sheetpile-soil (including the effect of large excess pore pressures) and the possible contribution of the tip force on the cyclic loading of the soil. The developed model is briefly described. Attention is paid to the used densification model. Observed settlements in a large scale field test are presented and discussed.

RÉSUMÉ

Le vibro-fonçage des palplanches peut avoir comme conséquence des surpressions interstitielles provisoires et des tassements du sol adjacent. Ces effets peuvent entraîner des dommages aux structures environnantes comme les bâtiments, les routes et les chemins de fer construits sur remblais, les canalisations et les digues. Afin de prendre une décision appropiée pour l'usage du vibro-fonçage des palplanches, il est nécessaire de bien estimer les tassement. Afin de connaître la reponse du sol, un modèle numérique est développé.

L'article décrit d'abord le processus du fonçage des palplanches, avec une attention particulière concernant le chargement du sol adjacent.

Le frottement à l'interface palplanche-sol est discuté (incluant l'effet d'importantes surpressions interstitielles) et la contribution possible de la force en pointe de la palplanche sur le chargement cyclique du sol. Le modèle développé est brièvement décrit. Une attention particulière est prêtée au modèle utilisé de densification. Les tassements observés dans un champ de test à grand échelle sont présentés et discutés.

1 INTRODUCTION

Installation or removal of sheetpiles by vibrating causes settlement in the surrounding. These settlements may result in damage to adjacent buildings, pipelines, highways and railroads. In practice the amount of settlement is still hard to predict and large uncertainties are present.

In the last decade several researchers tried to predict the settlement during vibratory sheetpiling like Massarch (1992), Drabkin et al (1996), Bement and Selby (1996) and Hergarden (2001). The researchers developed empirical models to predict the amount of densification, given a vibration level. The models are simple in nature. Meijers and van Tol (2004) compared some of these models for a reference case. A large difference in predicted amount of settlement between the different methods was observed. This indicates a low accuracy of the presently available models. The cause for the low accuracy may be either an incorrect densification model, the use of inappropriate empirical constants in the densification model, an incorrect description of the mechanisms involved, neglecting important mechanisms or a combination of these aspects.

As the amount of settlement is still hard to predict cautious designers, supervisors and contractors, afraid of unpredictable settlements, may decide to use another building method (e.g. diaphragm walls) in order to avoid all risk of damage. However, as the use of vibrated steel sheetpiles is very economical, alternatives are normally significant more expensive. Therefore a need for a more accurate model to predict the settlements is sensed.

Two approaches can be used to derive a new model. One is to compile a large database with measured settlements and using Artificial Intelligence or a Neural Network. The second approach is to describe the physical process in detail. The first approach is outlined in section 2, the last in the section 3 to 5.

2 EMPIRICAL OBSERVATIONS

In the literature reported data on observed settlements are limited. Examples of measured settlements are shown in e.g. Clough, Chameau (1980), Lacy, Gould (1985) and Fujita (1994). These data are insufficient to draw general conclusions.

At GeoDelft empirical data from sheetpiling projects are collected in a systematic way (Hemmen (2004)). One of the collected data is the settlement close to the sheetpile. As the project just started the amount of data is still limited. From this database a first assessment of occurrence of settlements at 1 m in front of the sheetpile has been compiled and is shown in figure 1. This assessment is based on 35 projects. Unfortunately not for all projects the observed settlement is mentioned. For the interpretation it is assumed that in these cases the settlement is negligible. From this interpretation it is concluded that in about 20% of the projects a noticeable settlement occurs. In 5% of the projects the observed settlement even exceeds 0.5 m.

Well documented empirical data on the width of the settlement trough is not known to the authors. However it is the authors experience that in general at distances in excess of one time the embedment no surface settlement occurs.

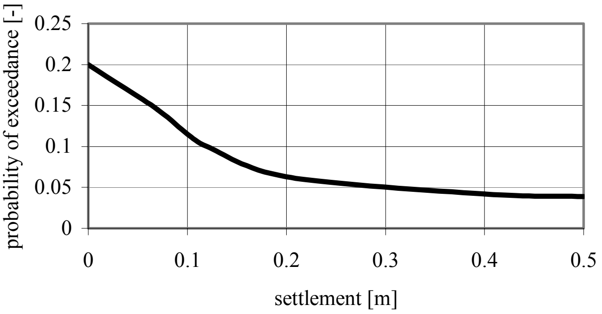

Figure 1: Probability of exceedance settlement at 1 m from the sheetpile due to vibratory sheetpiling

3 PROCESS OF VIBRATORY SHEETPILING

In order to develop a more accurate model first the process of vibratory sheetpiling is analysed. Figure 2 illustrates the process. A basic assumption in the description is that the densification is a consequence of the cyclic loading of the soil. A source-path-target approach is used to describe the different aspects. The source of the vibrations is of course the sheetpile with attached vibrator. From the (vibrating) sheetpile waves are emitted and will propagate in the surrounding soil. This results in a cyclic loading of the soil. In dry sand this will result in densification. In fully saturated sand however this densification cannot occur at the instance. First excess pore pressures will develop. Dissipation of these excess pore pressures in time will subsequently result in a volume decrease and thus a settlement.

From this description the following subprocesses can be distinguished:

- vibrating of the sheetpile
- transfer of vibrations at the interface sheetpile – soil
- propagation of vibrations
- densification of the soil/ generation of excess pore pressure
- dissipation of excess pore pressure
- deformation subsoil on local densification (volume decrease)
- compensation volume change due to sheetpile volume

The last subprocess accounts for the inserted or removed volume of the sheetpile on the surface settlement. It is considered as a separate process and will be present both in case of vibratory and of static sheetpiling.

Not all subprocesses will be described in this paper. In the next sections some considerations on two subprocesses, the behavior at the interface sheetpile-soil and the used densification model, will be mentioned.

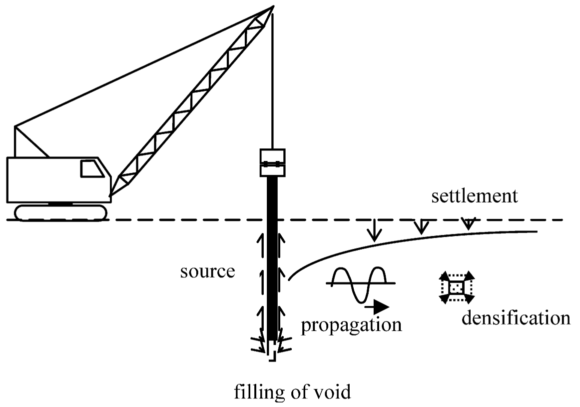

Figure 2: Situation (schematic) during vibratory sheetpiling

4 BEHAVIOUR AT INTERFACE

The purpose of vibrating is to install a sheetpile into to soil or to remove it from the soil. Therefore it may be assumed that in normal cases at the interface sheetpile-soil failure occurs. For the description of the process the actual amplitude of the sheetpile is not of interest. In exceptional cases (e.g. using a vibrator with insufficient capacity) this may not be true. As this involves an improper use of the system it is neglected here.

At the interface sheetpile-soil three aspects require some attention:

- deformation mode of the sheetpile
- the amplitude of the shear stress at the shaft
- behavior at the tip of the sheetpile

In general it is assumed that the sheetpile vibrates in a vertical mode. From this assumption it follows that the surrounding soil is mainly loaded in shear. Measurements by Viking (2002) however showed that a sheetpile also vibrates in a horizontal direction. This indicates that also compression waves are emitted from the sheetpile. The consequences of this aspect need further investigation.

For the model the main question is the amplitude of the shear stress at the interface sheetpile-soil. At the interface sheetpile-soil it can be assumed that shear failure will occur. The main reason to justify this assumption is that after all the sheetpile is to be driven into the soil or removed from the soil. In static situation shear failure occurs when

$$\tau = \sigma'_h \tan\delta = K_0 \sigma'_v \tan\delta \qquad (1)$$

where τ = shear stress at failure, σ'_h = horizontal effective stress, δ = angle of friction between sheetpile and soil, K_0 = ratio between horizontal and vertical effective stress and σ'_v = initial effective vertical stress.

When the excess pore pressure increases the effective stress decreases and eventually becomes zero. Using this approach his would imply that the shear stress becomes zero as well. Performed model tests (described in Meijers, van Tol (2002)) however showed that at complete liquefaction still vibrations are transmitted from the sheetpile. Most likely at the interface sheetpile-soil the soil behaves as a viscous fluid. In a liquefied soil the vibrations attenuate quite fast with distance. At some distance the behavior will transfer from a viscous behavior to an elastic soil behavior. As this process is difficult to describe numerically a practical approach has been followed.

In earthquake engineering attention is paid to the residual strength of a liquefied soil. The available data and discussions tend to use as strength of the liquefied soil a value of 5 to 10% of the initial effective vertical stress. This is in line when the approach by Holeyman (2000) for the liquefied strength would be used. Therefore as minimum yield shear stress at the interface sheetpile-soil 10% of the initial effective vertical stress is used.

The behavior at the tip of the sheetpile has been qualitatively investigated using videotapes made during a model test. In the model test a sheet was placed in a tank filled with saturated sand. One side of the tank consisted of a glass wall, allowing observing the behavior. The sheet was removed using a small vibrator. The soil movement was registered with a high-speed camera. Inspecting the resulting videotape revealed some interesting aspects. At the tip of the sheetpile it could be observed that P-waves were emitted. The amplitude of these body waves was quite high. Probably the amplitude of the sheetpile governs it. The amplitude however attenuates fast with the distance. At a few decimeters from the tip the movement could no longer be distinguished. The contribution of this mechanism to the total densification is expected to be limited. Further research on this aspect is however required.

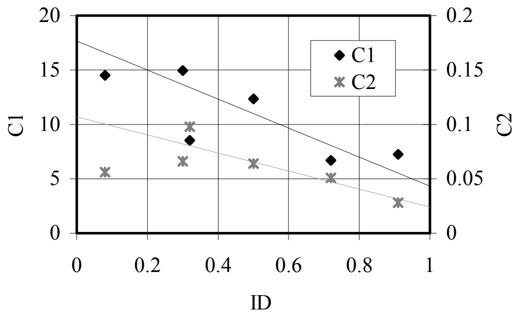

Figure 3: Empirical derived constants C/L model as function of relative density

5 DENSIFICATION MODEL

Interpretation of performed model tests showed that the settlement is more or less a function of the square of the vibration amplitude (see Meijers, van Tol (2002)). This is in line with the observation of Sawicki that the densification a function of the square of the shear strain amplitude. For the densification model the C/L model of Sawicki is therefore considered to be a suitable model.

This method is described in different publications by Sawicki, (e.g. in Sawicki et al (1998)). The method has been developed for dry sand and assesses directly the plastic volume strain. The compaction follows from:

$$\Phi = C_1 \ln(1 + C_2 z) \tag{2}$$

$$z = JN = \frac{1}{4}\gamma_0^2 N \tag{3}$$

where Φ = compaction, C_1, C_2 = empirical constants, J = second invariant of strains, γ_0 = shear strain amplitude and N = number of cycles.

The relation between the compaction Φ and the plastic volume strain ε^p_{vol} is

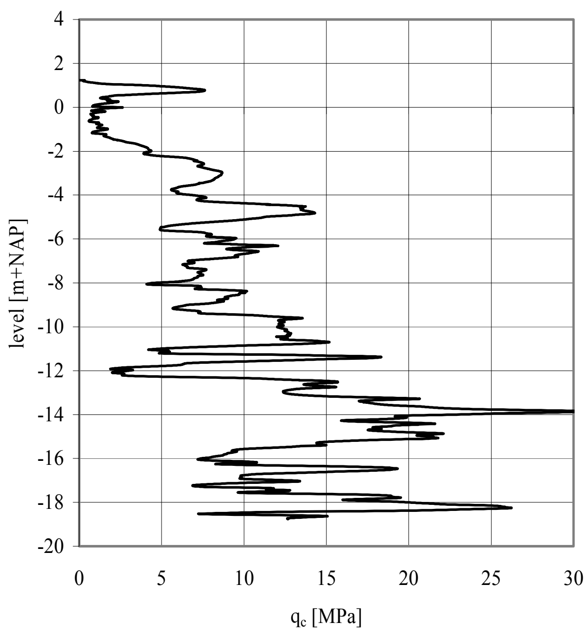

Figure 4: Representative CPT result at Raamsdonksveer test site

$$\Phi = -\frac{1-n_0}{n_0}\varepsilon^p_{vol} \tag{4}$$

where n_0 = initial porosity [-] and ε^p_{vol} = plastic volume strain.

The empirical parameters C_1 and C_2 are to be determined from cyclic tests, e.g. cyclic simple shear tests. Using the data given by Sawicki and Sliwinski (1989) for two sands and shown graphically in figure 3 a tentative relation can be derived.

$$C_1 = 17.67 - 13.33 * I_D \tag{5}$$
$$C_2 = 0.107 - 0.083 * I_D \tag{6}$$

The model is derived for dry sand. It can be used for saturated undrained sand as well using the following relation between densification and stress.

$$\Delta u = M * \varepsilon^{el}_{vol} = -M * \varepsilon^p_{vol} \tag{7}$$

where M = constrained modulus.

In this way the method can be used to assess the generation of excess pore pressure as well. The actual volume change follows from dissipation of the excess pore pressure.

6 FIELD TEST RAAMSDONKSVEER

In order to check the validity of the proposed model a field test has been performed on installation and removal of sheetpiles. The test was performed at Raamsdonksveer, The Netherlands. The subsoil consisted mainly of sand. The top 1 m is of anthropogenic sand. Between 1 m and 2.5 m below ground level clay and occasionally peat was encountered. Figure 4 shows a representative CPT result of the site. The installed length of the steel sheetpiles was 14.25m and 14.75 m.

During the test different parameters were measured. Among them the settlement at surface, at 6.5 m below surface and at 11 m below surface. The surface settlement after installation and after removal is shown in figure 6. Before start of the test the expected settlement at surface, using the densification model described in chapter 5, at surface was 0.12 cm after installation and an increase with 0.05 cm after removal. The measured settlement after installation is thus below the expected settlement. Predicting the settlements after installation using alternatives for this densification model (as described in Meijers, van Tol (2004)) gives a range of 0.04 m to 0.3 m.

Figure 5: Execution of the test

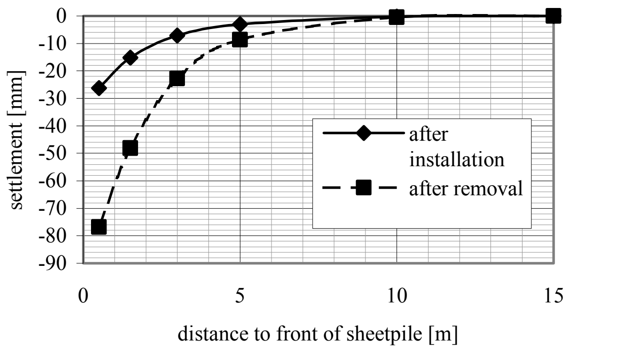

Figure 6: Settlement at surface after installation and after removal of sheetpiles

The area of the settlement through is respectively 2*0.0786 m^2/m and 2*0.2344 m^2/m. This suggests that most settlement occur during sheetpile removal. For assessing the amount of densification the values are to be corrected with the volume of the sheetpile of 0.272 m^2/m. This gives that during installation the decrease in soil volume is 0.157 + 0.272 = 0.429 m^2/m. During removal the change in soil volume is (0.469 – 0.157) – 0.272 = 0.040 m^2/m. It should be noted however that during removal some sand was sticking to the sheetpile. The actual removed volume is thus in excess of the net steel volume. Taking this into account it is concluded that during removal hardly any soil densification occurs.

From this comparison it follows that the soil densification occurs during vibratory installation and for removal the removed volume of the sheetpile governs the settlement. However one should take into account that at the test site the situation is different from the situation in practice. At the test the sheetpiles were installed and removed after just two days. No loading of the sheetpile has been performed in between. In practice however mostly at one side of the sheetpile the soil will be excavated and refilled. Due to the excavation the sheetpile will deform. The soil behind the sheetpile will become more or less in an active state. This deformation results in a loss of structure gained during the densification. Cyclic triaxial tests by Vaid et al (1989) and Oda et al (2001) showed that static axial loading and subsequent unloading of the sand decreases the resistance to cyclic loading. Thus it may be expected that in practice the actual densification during removal may be more compared to the situation during installation.

Other aspects that may influence the settlement on removal are stretching of the deformed sheetpile during pull and adjustment of differences in horizontal stresses at both sides of the sheetpile

Figure 7 shows the measured settlement at the surface and at depth after installation. The measurements show that at depth

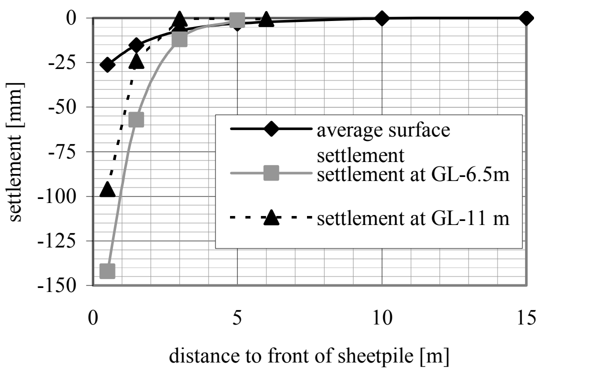

Figure 7: Settlement at surface and at depth after installation.

the settlement close to the sheetpile is in excess of the settlement at the surface. At a distance of 1 to 2 m the settlement at the surface is in excess of the settlement at depth. This phenomenon can be explained from the limited zone with densification. The volume decrease at depth spreads towards the surface, resulting in a wider through with reduced depth. At depth this effect is less pronounced, resulting in a deeper but less wide through.

7 CONLUSIONS

The behavior between vibrator-sheetpile-soil is quite complex. Published models for assessing the densification during vibratory sheetpiling are relative simple. A new model has been developed to assess the soil densification. This model takes into account the whole process during vibratory sheetpiling.

For validation of the model a large scale sheetpile test has been performed. From the measured settlements it was concluded that the effect of the volume of the sheetpile on the settlements cannot be neglected. The test results did not clarify the question if most densification will occur during installation or during removal.

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