Predicted and measured settlements due to installation and removal of sheet piles

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ABSTRACT

At a construction site in the centre of Rotterdam, several sheet piles had to be installed. Preliminary calculations based on the method of Hergarden showed that large soil settlements at the location of an underground water duct could cause damage to it. Measurements of the soils settlement have been taken during both the vibratory installation and removal of sheet piles. Two types of prediction of these effects have been carried out: an advanced and a straightforward method. The predicted settlements at groundlevel have been compared to the measurements carried out during construction. The results show that the advanced method is conservative although easy to use. The calculated settlements seem to be consistent with the soil profiles. The straightforward method can be used for preliminary calculations.

RÉSUMÉ

Pour la construction d'un tunnel en centre-ville de Rotterdam, des palplanches devaient être installées. Des calculs préliminaires ont été effectués basés sur la méthode de Hergarden. Les résultats obtenus ont montrés que la conduite d'eau potable située à quelques mètres du chantier pourrait être endommagée par les tassements du sol causé par l'installation et l'enlèvement en mode vibratoire des palplanches. Deux types de méthodes de calculs de ces tassements ont été utilisés. L'une est avancée et l'autre plutôt directe. Les résultats des prédictions ont été comparés aux mesures prises durant l'exécution des travaux. Ces résultats montrent que la méthode utilisant des modèles avancés bien que facile à utiliser, est conservative. Cette méthode semble cohérente avec le profil du sol. La méthode directe est facile à utilisée et peut être utilisée pour des calculs préliminaires.

Keywords : Prediction, settlement, vibratory driven, vibratory installation, vibratory removal, sheet piles, measurements

1 INTRODUCTION

Various methods are available to predict settlement due to vibratory driving of sheet piles. However, in practice, quantified experience is scarce. 'Field' data are needed to evaluate these methods objectively and to understand the soil behaviour better. In the centre of Rotterdam, the building of two open tunnels, the Weena tunnels, presented a good opportunity to obtain a large set of measurements in that respect.

Most relevant in this study is the building of the southern Weena tunnel near the existing open tunnel and an underground water duct. The latter lies at a distance of 5 m from the projected sheet piles.

In this paper, predictions and measurements will be analysed. Specials attention will be paid to a method that can be easily used in practice.

2 CALCULATION MODELS

2.1 *Overview*

A number of methods have been developed to calculate the compaction of a sand layer due to vibrations. In Table 1 an overview of some of these methods is given. Also the main parameters for the calculation are given.

The methods have different origins. Meijers (2007) indicates that for a given situation several methods can lead to very different results. Massarch (1992) is an empirical method. Hergarden's method is based on the work of Barkan (1962). The result depends on the frequency of the vibrations, in other methods this parameter is not relevant. Drabkin & al. (1996) developed an empirical method based on results of cyclic tests on dry and moist sand. The method of Lukas and Gill (1992) determines the settlement from the shear strain caused by the peak acceleration. The method chosen to predict the settlement at groundlevel at a certain distance from the sheet pile wall was in this case the Hergarden method, because it is a practical and straightforward method, with reasonable accuracy.

Table 1. Overview of methods and calculation models

Method	Main parameters
Barkan (1962)	Acceleration, damping factor
Massarch (1992)	Acceleration, cone resistance
Hergarden (2000)	Acceleration, frequency, relative density
Drabkin, Kim & al. (1996)	Velocity
Gill & Lukas (1992)	Acceleration

Meijers (2007) proposes to combine different methods for propagation and densification for the calculation of the settlement. In his TRILDENS3 program a Barkan type relation is available for the propagation. The densification part is calculated with the methods according to Hergarden (2000) or Sawicki (1989). Also the volume loss during extraction of the sheet pile is taken into account.

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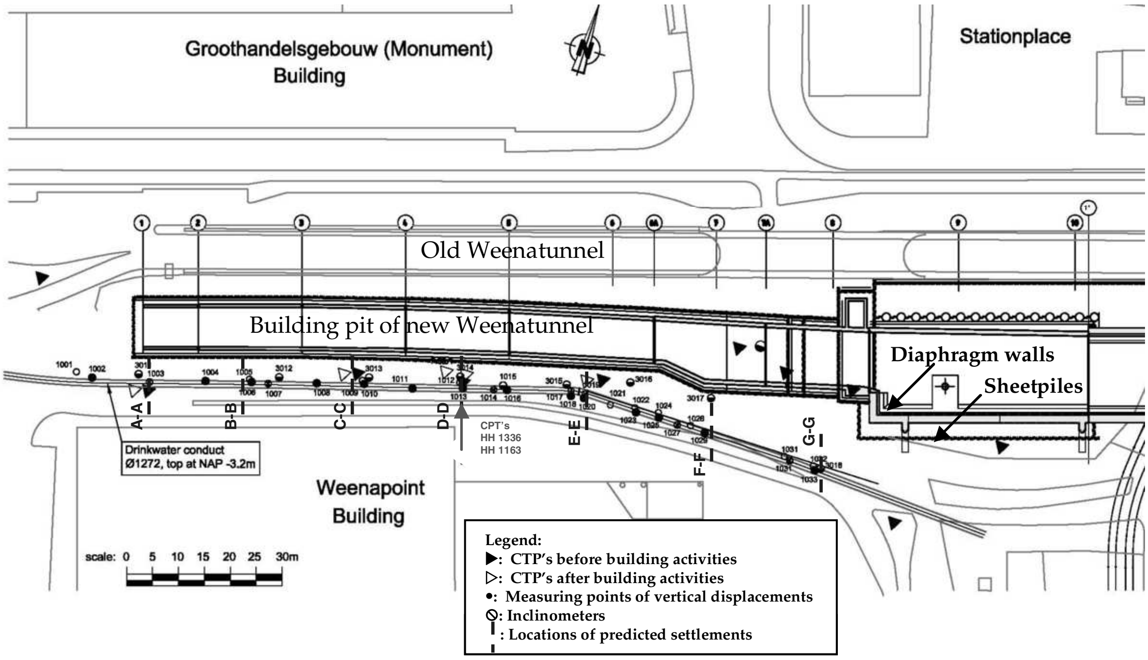


Figure 1. Situation at the Weena

2.2 *Used calculation models*

The method used in this study is that of Hergarden. In this method, the following aspects are taken into account separately: attenuation; change in relative density; vertical summation of settlement due to densification; vertical summation of summation of lateral variation of setttement due to the volume of a sheet pile.

2.2.1 *Transport of vibrations*

The attenuation of the waves is described using a Barkan type relation, which depends on the distance to the sheet pile. In this relation, the parameter α describes the soil damping.

$$a_r = a_0 \sqrt{\frac{r_0}{r}} \cdot \exp\left(-\alpha\left(r - r_0\right)\right) \qquad (1)$$

where a_r and a_0 are accelerati ons at distances r and r_0, respective ly.

2.2.2 *Densification*

The model of Barkan (1962) is used to quantify densification

$$\eta_0 = \frac{\ln(1 - I_{D,0})}{-\alpha_B} \qquad (2)$$

where : η_0 : threshold acceleration, $\eta = a / g$

$I_{D,0}$: initial relative density; a : acceleration; g : earth gravity

α_B : empirical parameter, depending on soil strength and stress level

The change in relative density is given in the following equation:

$$\Delta I_D(\eta, t) = \left[\exp(-\alpha_B \eta_0) - \exp(-\alpha_B \eta)\right] \times \left[1 - \exp(-\beta\ t)\right]$$

where β is an empirical parameter.

(3)

The settlement is calculated from:

$$\varepsilon_{vol} = \Delta I_D \frac{e_{\max} - e_{\min}}{1 + e_0} \qquad (4)$$

where: ε_{vol} = volumetric loss of volume, e_{max} and e_{min} are the maximum and minimum void ratio, and e_0 = initial void ratio.

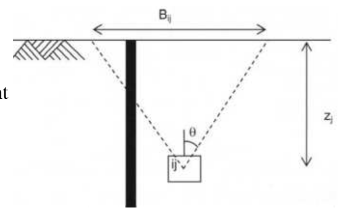
The settlement is calculated from:

$$\Delta z = \varepsilon_{vol}\, h \qquad (5)$$

where: Δz = settlement and h= thickness of the sand layer.

2.2.3 *Vertical summation of settlement*

$$\Delta z_{ij} = \frac{\varepsilon_{vol} A_{ij}}{B_{ij}} \qquad (6)$$



where :

Δz_{ij} : contribution to surface settlement due to densification of point i

ε_{vol} : volume strain at point ij;

A_{ij} : representative area of point ij

B_{ij} : influence width at surface

The method of Hergarden is represented graphically in Figure 2.

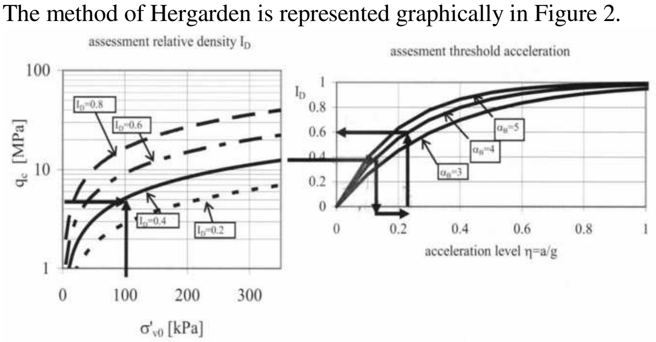


Figure 2. Graphical determination of increase relative density

The combinations of calculation models used for the predictions are given in Table 2.

Table 2. Combinations of models used

Combination	Model of Propagation	Model of Densification	Model of Summation
1	Barkan	Hergarden*	Linear approx.
2	Barkan	Hergarden Advanced	Vertical spreading with time

(*) no effect of volume of the sheet pile

The so called 'linear approximation' in Table 2 consists of deriving the total settlements by summing up the settlement of every sand layer where densification occurs. The latter is derived from the changed relative density and the thickness of a sand layer. The standard model of Hergarden assumes that the time of vibration is sufficiently large for *exp(-βt)* to become nearly zero. Hergarden advanced model takes the lateral spreading of the settlement with time into account (β ≠ 0).

3 CASE STUDY

3.1 *Project description*

The construction of the new Weena tunnel took place in a busy area of the city of Rotterdam. At a distance of about 20 m from the construction site, there were office and hotel buildings, a high rise building and a large building of historical interest. An inventory of objects in the neighbourhood of the excavation showed the presence of a 1.2 m diameter drinking water duct made of steel at 2 to 3 m below groundlevel from 1940's and still in use. The sheet pile walls came close to this duct (distance 5 m). Attention had to be paid to deformations of this duct during the installation and removal of the sheet piles.

3.2 *Soil characterization*

Figure 3 shows the result of a CPT test at the location of the construction site before building activities. The groundlevel lies at NAP-0.5 m (NAP = Dutch datum level). Below the soil surface, there is a sand fill down to about NAP -5 m. From that level downwards, Holocene peat and clay layers are found. The Pleistocene sand layer is present from about NAP -17 m. The phreatic groundwater level layes at about NAP -2 m. CPT's show that the soil profile is variable.

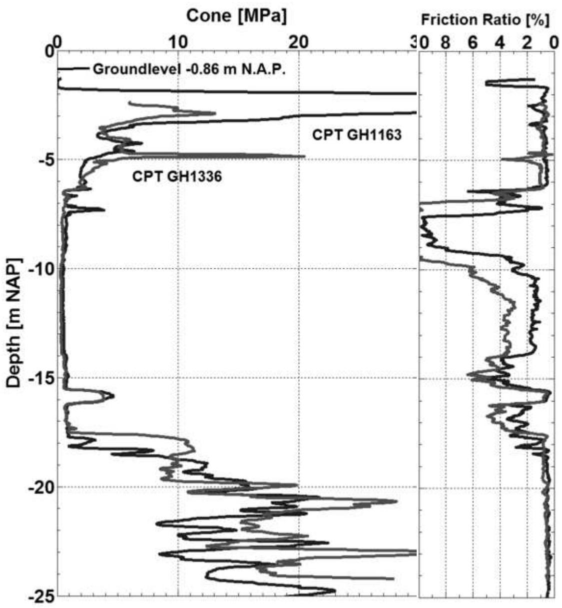


Figure 3. Cone penetration tests before (GH1163) and after (GH1336) construction

3.3 *Construction*

Construction considered of this phases: Phase 1: Installation of short sheet piles near the diaphragm walls. Phase 2: Installation of piles; installation of sheet piles: west end, then alternating between north and south sides of the projected excavation until reaching the sheetpile wall of Phase 1; dry excavation; construction of the tunnel; removal of the sheet pile walls. Sheet piles were installed from west to east.

3.4 *Execution of activities*

Because of obstacles in the underground, most of the sheet piles were vibratory driven. The vibrator used had the following specifications: loading force: 2000 kN; pulling force: 500 kN; frequency 38 Hz. The sheet piles used varied from AZ26, AZ36, AZ48 to AZ50, from west to east. The installation depths varied from NAP -22 m to NAP -25 m.

3.5 *Monitoring*

The monitoring program for the water duct consisted of measuring vertical displacements of the duct and of soils at the bedding depth of the water duct (NAP -4.5 m). These were conventionally measured using rods and plates. During the vibratory installation of the sheet piles close to the water duct, the measurement frequency was raised from once to twice a day for all measuring points. The water duct was taken out of service at the end of the installation of the sheet piles of phase 2. After that, measurements of soil settlement were only taken at two points. These were the most eastern ones 1028 and 1030.

4 PREDICTIONS

The predictions were carried out in accordance with the soil profiles of 7 locations (A-A to G-G) as indicated in Figure 1. Settlements were calculated according to the combination Barkan-Hergarden-linear approximation (1) and Barkan-Hergarden advanced-Vertical integration and spreading with time (2) using the program TRILDENS3 (see Table 2). The parameters used were: the damping factor obtained from field measurements α= 0.03.; the value of the Barkan factor α_B= 4; the relative densities are derived from the cone resistances according to Lunne (1983); the values of the oedometric modulus E_{oed} are estimated from available data. The other parameters are derived either from relative densities or E_{oed} using empirical relations (Meijers 2007). Figure 4 shows results of calculations using the soil profile and soil parameters derived from CPT GH1163 (Figure 3).

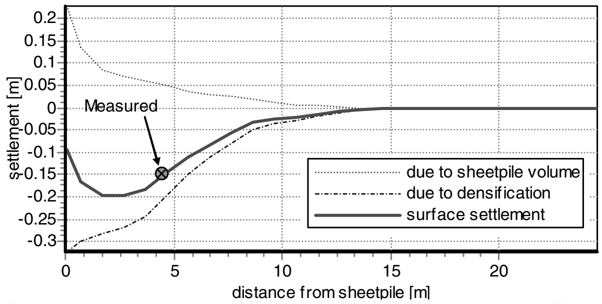


Figure 4. Calculated settlements at NAP -4.5 m due to vibratory installation, using TRILDENS3, location D-D

5 VIBRATORY INSTALLATION OF SHEET PILES

In Figure 5, the measured soil settlement at the bedding depth of the duct is presented at the start and at the end of the vibratory installation of the sheet piles in Phase 2. Each of the grey (settlement at groundlevel) and blue (at NAP -4.5 m) squares (see Figure 5) is determined as shown in Figure 4.

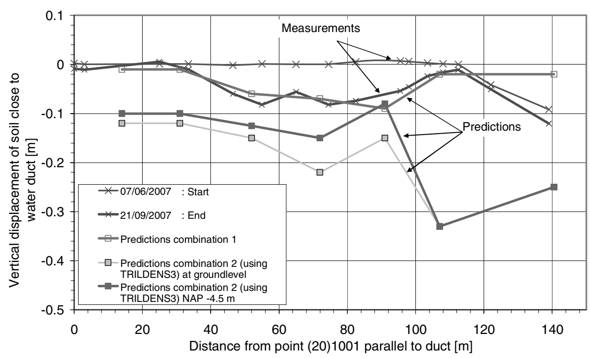


Figure 5. Measured and predicted settlements at vibratory installation in Phase 2

The discrepancy in settlements at locations A-A and B-B can be attributed to the presence of obstacles in the underground.

The results obtained show that the soil at NAP -4.5 m settles less than predicted. The advanced method (combination 2) tends to overestimate the settlement with a maximum error of about 40 %. At location D-D, the measured and calculated settlements were in agreement. The predicted settlement of both methods seems to follow the trend of the measurements. Combination 1 seems to provide rather correct predictions although in this method, the densification of the Pleistocene sand layer was deliberately underestimated. This assumption seems to be not correct as shown by the CPT's performed at nearly the same location before and after the construction of the tunnel, see Figure 3. The most noticeable changes of the cone resistances are found in the Pleistocene sand layer (below NAP -17) and not in the upper layers at about NAP -4.5 m and at NAP -16 m. In the predictions of settlement at NAP -4.5 m using TRILDENS3, the densification of sand layers above that level was not taken into account.

In Figure 5, the effects of the installation of the sheet piles in construction Phase 1 are only measured at points 1028 and 1030. At these locations, the soils were sensitive to settlement because of the presence of various sand layers between NAP -5 and -8 m and NAP -18 and -20 m although the sheet piles were at a distance of approx. 8 and 12 m from the measuring points. Combination 2 did not predict correctly the settlements at the locations F-F and G-G (see Figure 1) while Combination 1 did it rather well. The sites of the CPT's used for the calculations were about 15 m away from the locations at stake. This may also explain the discrepancy between the various results.

6 VIBRATORY REMOVAL OF SHEET PILES

The measurements of soil settlement at points (20)1028 and (20)1030 have been carried out from construction Phase 1 until the excavation and the removal of the sheet piles of Phase 2, see Figure 7. Settlements due to the vibratory removal are derived from these results. The measured settlements due to the removal of the sheet piles only are about 65 mm (F-F=1028) and 30 mm (G-G=1030) whereas at installation, they are about 90 mm and 40 mm at the same locations, respectively. This means that by removing the sheet piles, settlements increased with approx. 42 % (compared to installation).

In Combination 1, the effects of vibratory removal of the sheet piles were not taken into account. TRILDENS3 considers the effects of installation and those of removal of sheet piles separately. In Figure 6, the settlement calculated using combination 2 shows that the volume of the removed sheet piles increases the settlement of the soil surface whereas at installation, the volume of the sheet piles reduces it (see Figure 4). In these calculations, the parameters used were the same as those for the vibratory installation. It was not possible here to account for the effects of installation.

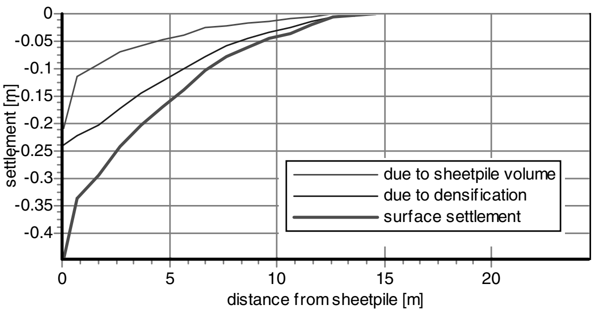


Figure 6. Calculated settlements due to vibratory removal, using TRILDENS3, location D-D

In the advanced model of Hergarden (2000), the effects of the volume loss of a sheet pile at removal is considered in a sand layer. In practice, the removed sheet pile can be coated with a layer of cohesive soils (clay or peat), which was the case at the Weena. Therefore the actual settlements due to the removal of the sheet piles are large and not easy to predict.

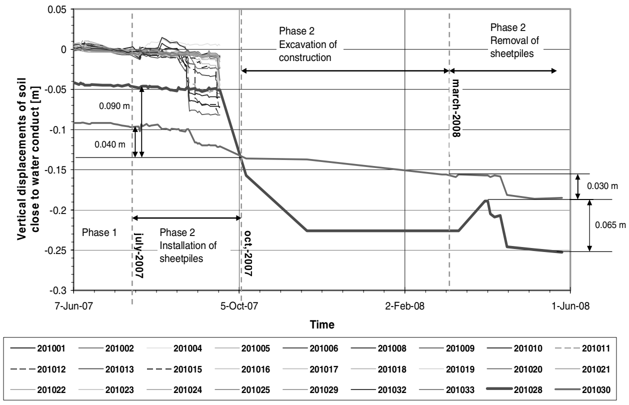


Figure 7. Measured settlements versus time

7 CONCLUSIONS AND RECOMMENDATIONS

From the results obtained, the following conclusions can be drawn: both methods Barkan-Hergarden-Linear summation (1) Barkan-Hergarden-Vertical spreading (2) show the same trend as the measured settlements when sheet piles are vibratory installed. Combination 2 overestimates the settlement with a maximum of 40 % error. Combination 1 is suitable for preliminary calculations. Combination 2 can be used to estimate the effects of vibratory removal of sheet piles; the settlement due to vibratory removal of sheet piles is about 42 % of those caused by vibratory installation.

To improve the calculation methods, it is recommended: to investigate quantitatively the densification of the Pleistocene sand because its densification is significant; to make it possible to read CPT's in TRILDENS3 so that calculations can be performed in a more systematic way; to implement vibratory removal after installation of sheet piles in order to obtain intermediate and total settlements.

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