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Calculation of soil volume loss caused by drilling of anchors

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ABSTRACT: Accurate prediction of ground settlements related to deep supported excavations or foundation works are key in risk assessments of vulnerability of neighboring assets. Several studies show that rotary percussive duplex drilling of casings for tieback anchors and piles can cause substantial local soil volume loss (cavities) around the casings resulting in ground settlements. This paper presents FE back-analysis of a well-documented deep supported excavation in soft clay to investigate the influence from such soil volume loss on the surrounding ground. The analysis demonstrates a simple approach to estimate potential installation effects from overburden drilling by modelling volume loss in specified soil clusters. The method can be implemented in early-planning risk assessments in building projects to assess influence areas and suitability of drilling methods.

Keywords: overburden drilling; tieback anchors; settlements; back analysis

1 INTRODUCTION

Assessment of potential detrimental impacts on adjacent buildings and infrastructure due to groundworks are essential in the design and planning of construction projects in urban environments. The effects from deep excavations on the surrounding ground have been studied extensively by among others Peck (1969), Mana and Clough (1981), Long (2001), Kung et al. (2007) and Karlsrud and Andresen (2008). Langford et al. (2015) analyzed several well-documented case records of deep supported excavations in soft clay in Norway. The study showed that initial and secondary effects from drilling of tieback anchors and foundation piles from within the excavation resulted in ground settlements up to 3-4 % of the total excavation depth (H). These values largely exceed expected values of δ_v/H which generally are observed to be less than 2 % for soft clays (Peck, 1969; Moorman, 2004).

The existing methods for predicting ground displacements due to deep excavations focus mainly on the support system stiffness and the shear induced deformations of the support wall and soil behind the wall and below the bottom of the excavation. Despite some research on the effects from overburden drilling (Ahlund and Ögren, 2016; Asplind, 2017; Lande et al., 2021) there are no well established methods to estimate ground displacements, hence this is hardly ever accounted for in the design.

Tieback anchors and foundation piles that are drilled into bedrock are normally preferred in areas with limited depths of soft soils overlying solid bedrock. The anchor tendons or piles are often installed by drilling a continuous permanent casing to support the borehole through varying soils (i.e. overburden) and with an embedment into bedrock. This methodology is called overburden drilling and is often carried out by rotary percussive duplex drilling (FHWA, 2005).

Results from field tests (Lande et al., 2020; Ahlund and Ögren, 2016) and case records (e.g. Sandene et al., 2021; Asplind, 2017; Bredenberg, 2014; Küllingsjö, 2007; and Konstantakos et al., 2004) have shown that drilling with air flushing to run the percussive hammer and transport drill cuttings may cause considerable ground displacements and excess pore pressures in the surroundings. The studies indicate that settlements occurred immediately (i.e. within a few days) when drilling through silty and sandy soils using air flushing causing erosion and loss of soil volumes.

This paper presents results from a numerical investigation of ground displacements induced by overburden drilling of casings for tieback anhors for a deep excavation in soft clay in Oslo, Norway. A case study previously reported by Sandene et al. (2021) is used to back-analyse the effects of local soil volume loss adjacent to the casings for tieback anchors.

2 BACKGROUND

2.1 *Effects from overburden drilling*

The studies by Langford et al. (2015) identified three main contributions to ground displacements caused by deep supported excavations in soft to medium stiff clays. In addition to the horizontal displacements of the sheet pile wall (A), contributions also come from installation effects from drilling of tieback anchors and/or piles (B) and leakage of groundwater through or along casings causing reduced pore pressure and consolidation of the clay (C). Displacements related to scenario (A) are widely recorded and studied in literature and scenario (C) may be calculated for a given scenario. For scenario (B) little reference material to estimate the effects is available.

2.2 *Erosion and loss of soil volume*

An air-lift pump is schematically illustrated in Figure 1(a): injection of compressed air at the bottom of a discharge riser tube submerged in water (e.g. casing) reduces the density of the air-water mixture in the riser tube, creating a lower pressure compared to the water pressure outside the riser tube. Figure 1(b) illustrates overburden drilling with air flushing in granular soil where the air-lift pump effect may induce ground water flow towards the drill bit resulting in considerable erosion and soil volume loss (i.e. cavities) around the casing. The Venturi effect as described by Bredenberg et al. (2014) is assumed to enhance the air-lift effect due to the high air flow velocity resulting in a lower static pressure around the drill bit than in the surrounding ground. The compressed air may also escape into the soil formation itself, flushing out the soil particles as it goes.

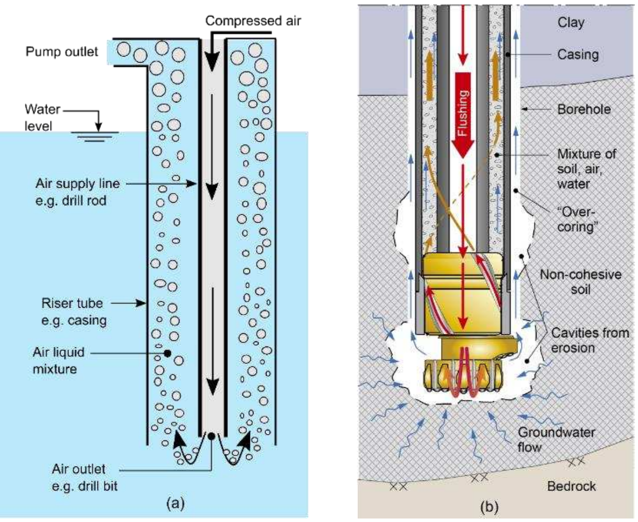

Figure 1. Illustration of (a) principles of an air-lift pump; and (b) erosion and loss of soil volume from drilling with air flushing.

2.3 *Case record*

Sandene et al. (2021) presented monitoring results from an about 9 m deep excavation in mainly soft, low sensitive clay in Oslo, Norway. In two specific areas, excessive ground settlements were recorded behind the sheet pile wasll (SPW) during and right after drilling for the tieback anchors. The SPW was also observed to be pulled outwards from the excavation. Sandene et al. (2021) showed that the ground settlements were occuring mostly during and shortly after anchor drilling and were not related to consolidation settlements or retaining wall displacements. Figure 2 shows a plan view of the excavation pit and location of section B-B used in the following back-analysis.

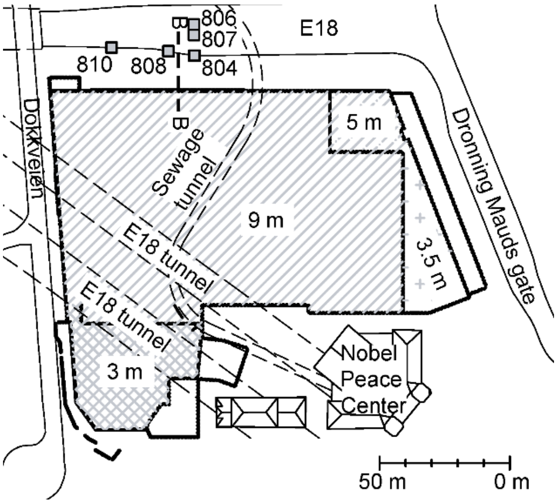

Figure 2. Plan view of the excavation pit from Sandene et al. (2021) including neighbouring structures, streets and the final excavation depths. Location of cross section B-B and relevant survey points also indicated

Soil layering and structures installed in cross section B-B is shown in Figure 3. Figure 4 also shows the spacing between anchors in each level R1 to R4, diameter of casing used and the prestressing force applied to each anchor before excavation to the next level. Three survey points on the road shoulder 804, 808 and 810 and two points in the middle of the road 806 and 807 were monitored during construction.

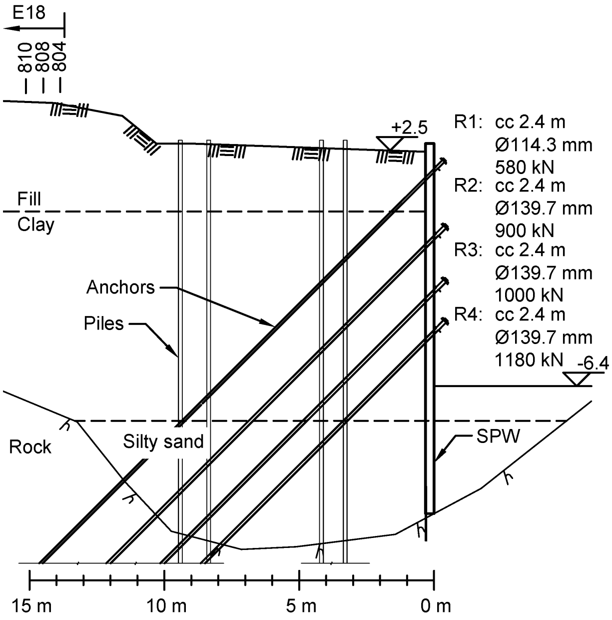

Figure 3. Cross section B-B from Sandene et al. (2021) including soil layering, tieback anchors, piles and settlement surveying points at the E18 road.

Figure 4 shows typical grain distribution curves from the clay layers and the silty sand layer. D_{60} and D_{10} values for the silty sand are 0,244 mm and 0,012 mm respectively. Cone penetration tests (CPTs) performed before after the installation of the anchors indicated a possible change in properties from loose to dense sand. Before installation the cone penetrated the whole layer without problems, but afterwards it was unable to penetrate more than 1-2 m. Table 1 summarizes results of cone resistance q_c and interpreted (after Mayne, 2014) friction angle φ' and relative density D_R.

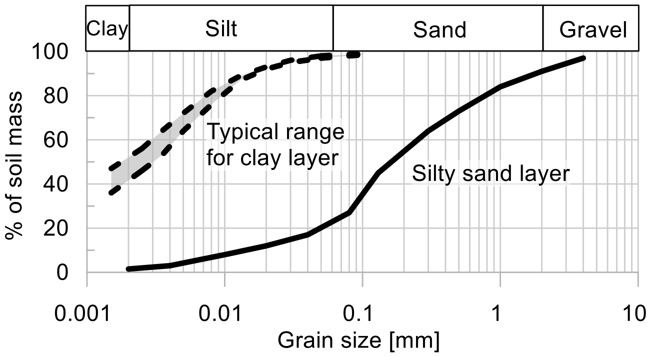

Figure 4. Grain size distribution of clay and silty sand layer

Table 1. CPT results and interpreted parameters

Parameter	Before	After
q_c (MPa)	1-5	8-22
φ' (°)	22-23	38-42
D_R (%)	0-40	40-75

Ground settlements occurred behind the sheet pile wall during and immediately after the tieback anchors were drilled into bedrock as shown in Figure 5. During drilling operations compressed air with water and soil was observed flushing out along the casing, from neighboring casings previously installed, through casings for rock dowels mounted on the SPW and through various weak or erodable zones in the soil. Based on the observations, it is likely that the use of air driven down-the-hole (DTH) hammer have caused significant erosion and cavities around the anchor casings in the silty sand layer.

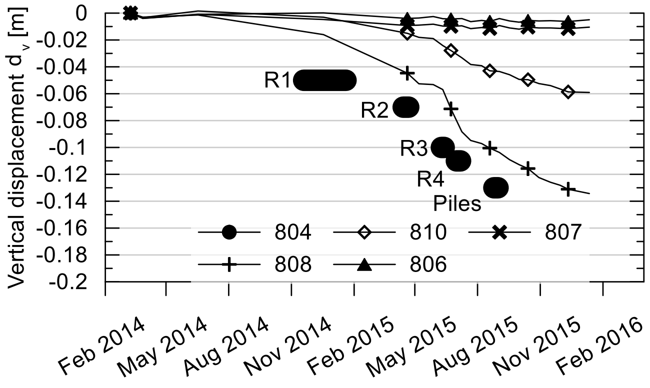

Figure 5. Measured ground displacements on settlement points located in cross section B-B during the groundworks.

3 FE MODELLING OF GROUND DISPLACEMENTS FROM OVERBURDEN DRILLING

3.1 General

Finite element modelling (FEM) have been carried out using Plaxis 2D version 22.02 (Bentley Systems, 2022). To model the effects of soil erosion and soil volume loss from drilling, a volumetric strain (ε_{vol}) is assigned to a soil cluster were the soil loss is assumed to take place in the ground. This technique has previously been used to model similar effects of soil volume loss from ground anchor installation (Konstantakos et al., 2004; Lande, 2009) and for processes as compensating grouting around tunnels (Schweiger and Falk, 1998). The volumetric strain levels (i.e. soil volume loss) in the back-analysis is adjusted by trial and error to reach similar ground and SPW displacements as observed in the field.

3.2 Plaxis 2D model

Figure 6 show the Plaxis 2D model of cross section B-B including terrain and bedrock topography, interpreted soil layers (clusters) and excavation and anchor levels. The figure also indicates the soil clusters around the theoretical location of the anchor casing in the silty sand layer where volumetric strains are applied. These soil clusters have a width of about 200 mm in the model, which is a rough estimate of the zone most affected by the drilling process. The simulation focuses on the displacements caused by drilling of the inclined anchors and not the piles, although they probably also caused some additional displacement (see Figures 3 and 5). Groundwater level corresponds to the sea level nearby at about el. 0.0 m.

Clay layers are modelled undrained using the anisotropic NGI-ADP soil model (Grimstad et al., 2011) with key parameteres summarized in Table 2. Drained layers of frictional materials are modelled using the Hardening Soil (HS) soil model (Schanz, 1998) with key parameters summarized in Table 3.

Table 2. Key NGI-ADP model parameters for clay layers

Parameter	Clay 1	Clay 2	Clay 3	Clay 4
γ (kN/m^3)	18.0	18.0	18.5	18.5
G_{ur}/s_u^A (-)	400	400	400	400
$s_u^A{}_{ref}$ (kPa)	30	30	26	36
y_{ref} (m)	0	0	-3.5	-7.0
$s_u^A{}_{inc}$ (kPa/m)	0	0	2.86	2.86
ν_u (-)	0.495			
γ_f^C (%)	1.2			
γ_f^E (%)	4.0			
γ_f^{DSS} (%)	2.4			
s_u^P/s_u^A (-)	0.45			
s_u^{DSS}/s_u^A (-)	0.70			

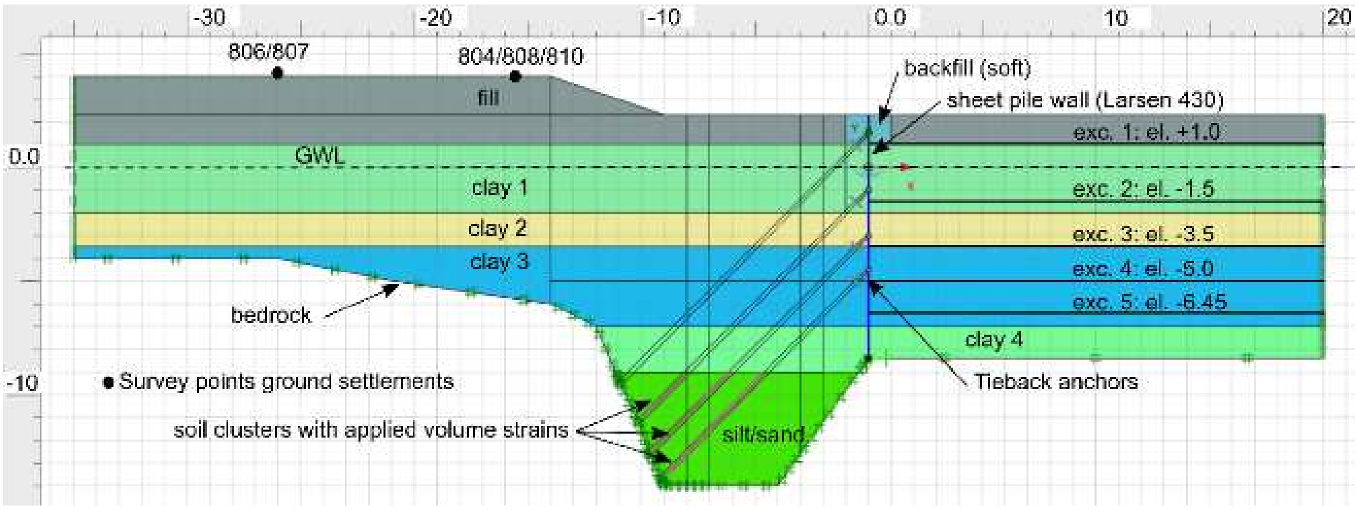

Figure 6. Plaxis 2D model of cross-section B-B showing soil layering, bedrock surface, elevation of the tieback anchors and excavation stages.

Table 3. Key HS model parameters for drained layers

Parameter	Fill	Backfill	Silt/sand
$\gamma_{sat}/\gamma_{unsat}$ (kN/m^3)	19/22	19/22	20/20
E_{50}^{ref} (kN/m^2)	10 000	5 000	10 000
E_{oed}^{ref} (kN/m^2)	10 000	5 000	10 000
E_{ur}^{ref} (kN/m^2)	30 000	15 000	30 000
ν_{ur} (-)	0.2	0.2	0.2
power (m)	0.5	0.5	0.5
c_{ref} (kN/m^2)	0	0	2.0
φ' (°)	35	35	35
ψ (°)	0	0	0

The sheet pile wall installed was a Larssen 430 profile modelled with bending stiffness EI = 483.6*10^3 kNm^2/m and axial stiffness EA = 5.99*10^6 kN/m. The tip of the sheet pile wall is fixed to bedrock with a rock dowel and is assumed to have negligibledisplacement. Fixed end anchors are modelled with length and stiffness according to reported values from the contractor.

The analysis is carried out with gravity loading followed by activation of sheet pile wall and interface elements. The stepwise excavation is simulated in the following stages:

- Excavation to anchor level
- Drilling of anchor (volumetric strains applied)
- Activation and prestressing of anchor

The process is repeated until the final excavation level of el. -6.45 is reached. A volumetric strain ε_{vol} = -50 % is applied to the casing zone in the sandy silty layer for all anchor levels. For the 200 mm wide zone, this implies a reduction of soil volume about 0.1 m^3 pr meter of anchor and length of wall. With the given spacing this will correspond to about 0.24 m^3 soil loss for each drilling meter of anchor. This is about 15-16 times higher than the volume of the casing itself (about 0.015 m^3/m).

During the drilling phase of the 3rd anchor row the material properties of clay layers 3 and 4 are changed to a softer behaviour, with G_{ur}/s_u^A reduced to 250 and failure strain γ_f^P increased to 6 % to simulate some disturbance caused by the drilling in the deeper clay.

3.3 *Calculation results*

Figure 7 shows the calculated final vertical ground displacements as contours of total displacements. It is evident that the bedrock topography has an influence on the calculated displacements at ground level, and is probably the main reason why excessive displacements are not observed at further distance from the sheet pile wall. It is worth noticing that calculated displacements are in the order of 300 mm directly above the anchor zone, while they are about 120-140 mm maximum near the surface.

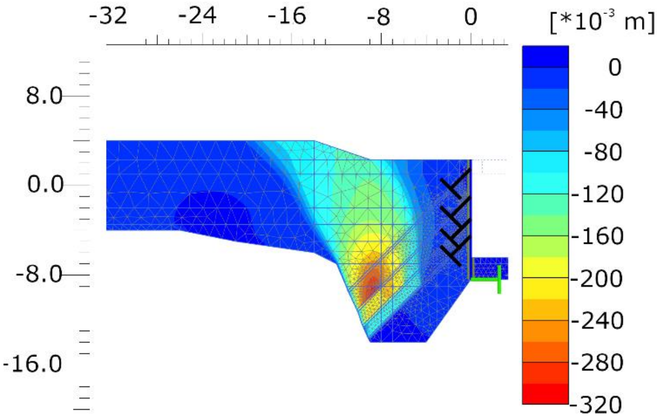

Figure 7. Calculated contours of vertical displacement u_y after final excavation phase.

Figure 8 shows the measured and calculated vertical displacements δ_v at terrain level with distance from the sheet pile wall. The figure also shows results from a calculation where no volumetric strains are applied (dashed lines). Calculations without the volumetric strains indicate a terrain heave behind the wall, which is caused by too high prestressing loads on the anchors and outwards movement of the wall. When volumetric strains are applied however there is a dramatic increase in observed displacements. The calculation results from each phase does not fit very well with the measured terrain settlements but the final phase fits quite well with the measured displacements at points 804 and 808. There has probably been different drilling machine operators and execution, slight differences in ground conditions etc. which may explain the differences between each phase. This study, however, focuses on the average overall effects of the drilling rather than precise simulation of each construction stage. For this purpose, the results are considered acceptable and ε_{vol} = -50 % for the 200 mm wide zone a reasonable average.

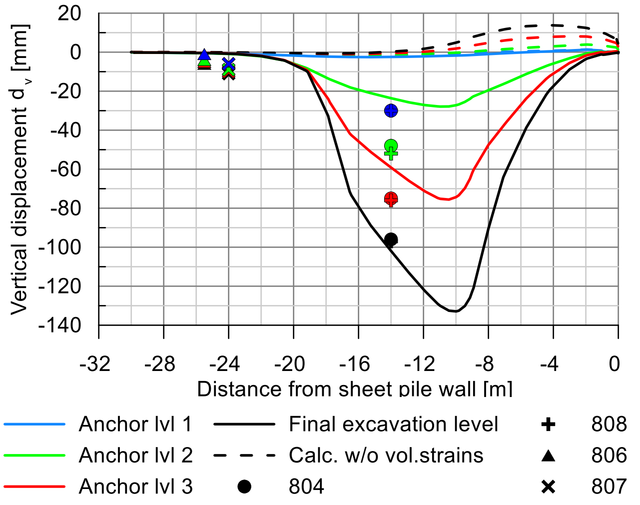

Figure 8. Measured and calculated vertical ground displacement with distance from sheet pile wall for different phases of construction.

The calculated ground displacements shown in Figure 8 indicate that the maximum displacements were about 10 m behind the wall, a little more than the excavation depth (about 9 m). The location of the maximum displacement may however be influenced by the depth, thickness and general topography of the eroded layer and other soil and rock layers. Maximum vertical displacements calculated at the soil surface are just above 130 mm. If the effects of the first anchor row are neglected (it has a very short distance in the sand/silt layer), the maximum settlements observed at the surface can then be estimated to about 130/300 = 43 % of the soil volume reduction in the deep layer. Again, the bedrock topography might in this case contribute to arching and stress redistribution effects in the soil which may reduce the observed ground level displacements.

It can be seen from Figure 8 that the measured displacement at points 806 and 807 is larger than calculated. This indicates that there probably has been some erosion/disturbance in the clay layers as well which is not accounted for in the calculation. Because the simulation only accounts for volume loss in the silty sand layer, the rock topography in the model shades the location of 806 and 807 from the displacements, as shown in Figure 7.

Figure 9 shows results from calculated and measured horizontal displacements δ_h of the sheet pile wall. Horizontal displacements were measured using a manual probe in a casing welded to the sheet pile wall measuring the angle and calculating displacements for each 0.5 m. Both the measurements and calculations indicate that the prestressing loads used during construction are largely overestimated and that the wall is pulled outwards from the excavation (negative δ_h values). Measured and calculated values are generally in good agreement. As opposed to the case of vertical terrain displacements, the introduction of volumetric strain simulating the soil loss does not have the same dramatic influence on the horizontal sheet pile wall displacement. For the final excavation phase, however, the calculation with volumetric strains is closer to the measured values than the one without.

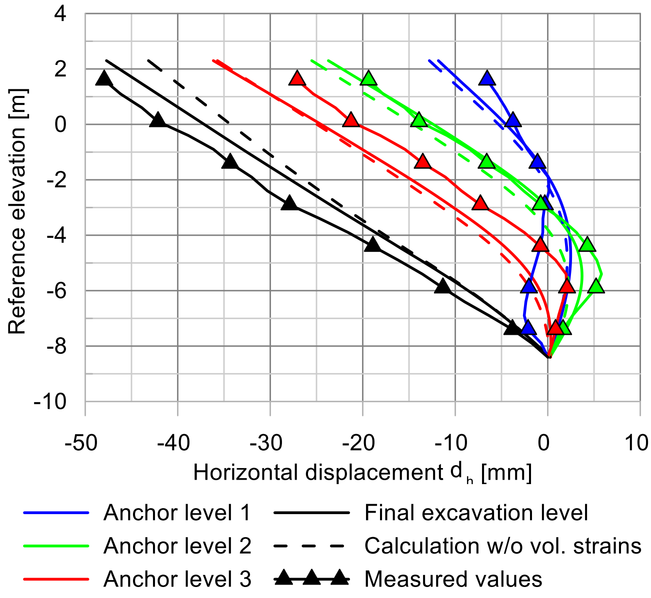

Figure 9. Measured and calculated horizontal displacement of the sheet pile wall for different phases of construction.

4 CONCLUSIONS

This paper presented a possible explanation to the unexpectedly large ground displacements which were observed behind a sheet pile wall in soft clay. By application of volumetric strains in a frictional soil layer, it has been shown that the loss of soil volume by flushing and erosion processes during anchor drilling is a highly likely cause of the displacements observed. In addition, the loss of soil volume is surprisingly large, calculated to be about 0.24 m^3 of soil volume loss for each meter of drilled anchor in the frictional soil layer. As indicated by the CPTs conducted before and after anchor installation, densification of the silty sand may also have contributed to the observed ground displacements. The drilling method does however not cause significant vibrations, and the densification mechanism may be related to the temporary air flow through the grain particles during drilling.

Maximum displacements calculated at ground surface are, in this case, about 40-45 % of the total volume loss and/or densification at a deeper level. The results of the analysis may be used as a rough estimate for future assessments of the effects of air flushed equipment in similar soil conditions. More importantly, the results show that the effects of compressed air flushing in certain soil conditions may have a significant impact on the surroundings. Further studies on analytical methods to estimate ground settlements from overburden drilling are currently ongoing.

5 ACKNOWLEDGEMENTS

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