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Effect of anchor installation on settlement of nearby structures in soft soils

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ABSTRACT: Most often, the effect of anchor installation on the ground movements is ignored. This paper, however, reveals that this effect will be considerable in soft clays if appropriate drilling technique and support for the drill hole is not used. A case history shows that more than 70% of the total ground settlement had occurred at the surface during the anchor installation. An attempt is made to back analyses the effect of anchor installation on the ground movement with the help of finite element method and analytical approach.

1 INTRODUCTION

The main concern of an engineer in designing a temporary support for an excavation in an urban area is to avoid excessive ground movement in order to secure safe working condition and to provide sufficient safety to the existing nearby structures. To arrive at this objective, it is required to study the factors that control the ground movements around and in an excavation. According to Manna (1978), these factors are classified as a) factors under designer control such as type and stiffness of support system, degree of wall embedment and degree of pre-loading of anchors and struts; b) factors partially under designer control such as method of support system construction, construction period, method of construction within excavation and size of surcharge load, and c) fixed parameters not subjected to designer control such as subsoil condition and properties, surrounding structures, excavation shape and depth. It is the effect of the method of support system construction that interest us in this paper. The factors related with construction include: overexcavation, delays and inadequate support, drilling and driving process, grouting, and dewatering. Several reports indicated that appreciable ground settlement occurred during boring and placing of diaphragm and bored pile walls and driving and pulling of sheet pile walls. Fujita (1994) reported that about 50% of the total ground settlement at the surface in a 14.65 m deep braced excavation was caused by driving and extracting of the sheet piles. Burland & Hancock (1977) had also reported that the vertical and horizontal ground movements outside the excavation due to the installation of the diaphragm walls and piling amounted to approximately 50% of the total movements recorded on the completion of the main design in London clay. Similarly, Lehar et al. (1993) indicated that about 60% of the total settlement at the ground surface was due to the installation of the diaphragm wall constructed in Salzburg lacustrine soft clay.

Likewise ground anchor installation also causes ground settlement at the surface. Its effect, however, is usually ignored since the hole required for placing the anchor is relative small. To date no report can be found on the effect of anchor installation in the literature. This paper presents a case history where anchor installation contributed to more than 70% of the total ground settlement at the surface of an excavation in soft lacustrine clay.

2 GENERAL DESCRIPTION OF THE EXCAVATION

2.1 *The site*

The excavation site is located in a built up area in southern Germany in the city of Constance near the lake Constance. It was intended for the basement of a multi-storey residential apartment and the construction work was completed in 1993. The site plan together with field instrumentation locations is shown in Figure 1. The excavation was 5.3 m to 7.0 m deep, and covered an area of 55 m x 60 m at the longer sides. In south, south-west, and west sides, the site is surrounded by 1- to 6-storey (one basement floor) residential buildings. All buildings are rested on mat foundation. At two sides (along MS2 and MS5) in particular, the excavation was very close (1.2 to 1.5 m) to the existing buildings.

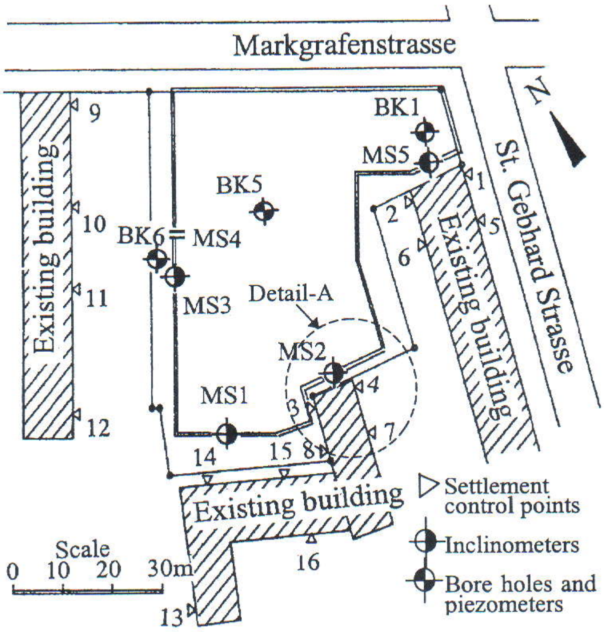

Figure 1. The site plan and locations of field measurement points and bore holes.

2.2 *Soil condition*

The site investigation revealed a ground comprising upper lacustrine silty clay of thickness 3 to 4 m with low to medium plasticity and soft to stiff consistency, overlying very soft lower lacustrine clay of thickness 5 to 7 m. Beneath is low plastic lacustrine clay in combination with boulder clay of thickness 3 to 4 m overlying moraine gravel. The ground water is located at about 1 to 2 m below the ground level. Soil profile and parameters are shown later in section 4.

2.3 *Support system*

The excavation was supported by three types of wall support systems. The larger part of the excavation: north-east, north west and part of the south-east sides (Fig. 1) was supported by soldier piles with timber sheeting. The pile, made of HEB 600 H-section steel, was placed in a pre-bored 0.9 m diameter concrete footing 3 m inside the gravel layer. The piles were located at a spacing of 2 and 2.5 m and were supported by ground anchors inclined at 40° below the horizontal. In south-west side, the excavation was supported in a similar way as above with soldier piles, but one 0.75 m diameter reinforced concrete piles and two 0.62 m diameter concrete piles(Fig. 2) were placed between the soldier piles instead of the timber sheeting. These piles penetrated 2 m below the excavation depth. The rest of the excavation were supported by 0.9 m diameter tangent bored concrete piles (see Figure 3). The piles penetrated 2 - 3 m into the gravel layer and were supported with ground anchors inclined at 40° below horizontal at a 0.9 m spacing. The anchors extended 5-6 m deep into the gravel layer. All anchors were supposed to be pre-stressed to a load of 80-100% of their design load. The walls were supported by struts at all internal corners.

2.4 *Anchor installation*

The rotary type of drilling in the soft soil layer and percussion drilling in the gravel layer were employed to drill a hole (shaft of 0.101 m diameter with expendable drilling bit (≈ 0.120 m)) for the installation of the anchors between the pile no. 44 and 65 (Fig. 3). Wash water was pressured through the casing to enhance the drilling and it came out of the hole through the external side of the shaft, which makes the hole a bit larger than the bit diameter. After the completion of the boring, the tendons were inserted, the hole along the bonded length was grouted with cement mortar, and finally the hole along the unbonded length of the anchor was filled with cement-bentonite slurry while pulling out the casing. It is during this anchor installation process that an excessive settlement had occurred under the existing building. The extent of the damage on the nearby building at the outer side is shown in Fig. 4. 3-4 cm crack was observed throughout the height of the 4-storey building and along the staircase.

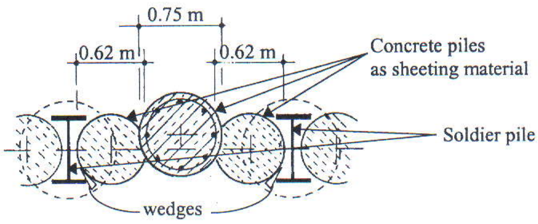

Figure 2. Concrete piles as sheeting material between soldier piles.

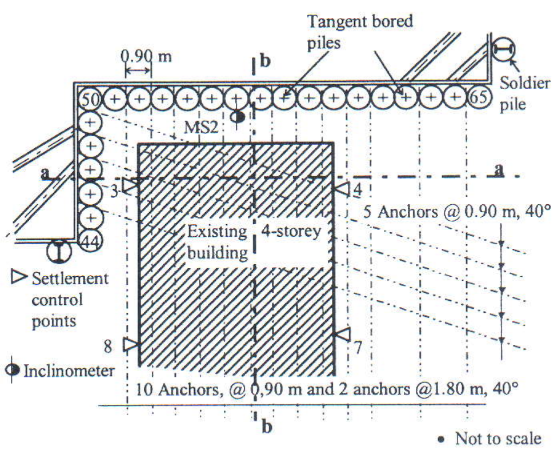

Figure 3. Overlapping of anchors at one of the external corners (Detail-A in Figure 1).

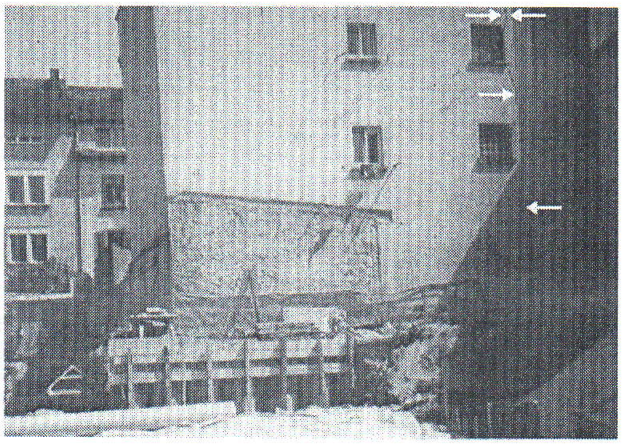

Figure 4. Damage on the nearby building during the anchor installation.

After experiencing the unpredicted ground settlement due to anchor installation between piles no. 44 and 65 (Fig. 3), measures had been taken in the installation of the rest of the anchors. Such measures include to use rotary drilling in all layers with the help of water flush and insertion of 0.133 m diameter plastic pipe to support the hole permanently in the soft soil layer. The plastic casing was pushed and partly rotated into the soft soil layer before the drilling had started. The drilling then continued with the water flushed out of the hole through the inner side of the plastic casing. The next step was similar as before. No appreciable settlement due to anchor installation was recorded at these locations.

3 DISCUSSION ON FIELD OBSERVATIONS

In order to monitor the soil movements resulting from construction activities several settlement points and inclinometers were installed. The ground settlement at the surface was recorded at and between each construction stages at 16 settlement control points around the excavation. A plot of the construction time and the corresponding ground settlement at points 3, 4, 7 and 8 (Figs 1, 3) are shown in Figure 4. From this figure and Table 1, it can be seen that 60 to 72% of the total settlement was caused due to anchor installations. A maximum settlement of 56.2 mm was recorded at settlement control point 3.

Two reasons can be given to the main cause of the large settlement at the ground surface during the anchor installation:

a) The vibration produced during the percussion drilling in the gravel layer, driving and pulling of the casing might be large enough to cause disturbance in the soft soil layer. This disturbance might have led to the settlement at the surface.

b) Cement-bentonite slurry, a thixotrophy material that gains its strength with time, has almost zero strength and stiffness in its fresh state. Hence, it is hard to expect the bentonite slurry to support the soft soil under ground water condition in its fresh state The failure of the bentonite slurry to support the drill hole might lead to a plastic failure of the soft soil around the hole that consequently results in the ground settlement at the surface.

Table 1. Percentages of the settlements at various construction stages.

Settlement point	percentage of the ground settlement [%]		
	bored pile installation	anchor installation	excavation
No. 3	9	70	21
No. 4	18	71	10
No. 7	3	72	25
No. 8	4	61	35

After a corrective measure in the installation of the anchors at the other sides had been made, no appreciable settlement was observed around these sides. A typical settlement record at settlement control points 13, 14, 15 and 16 is shown in Figure 6.

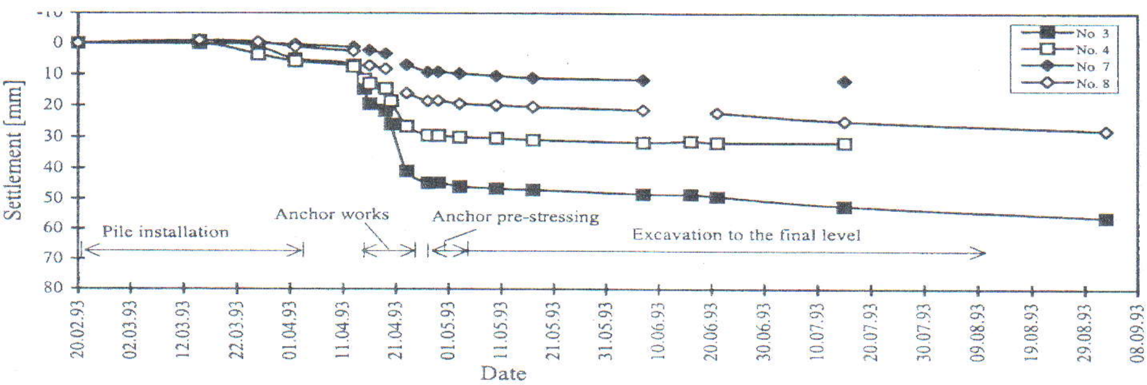

Figure 5. Time-settlement diagram for settlement control points 3, 4, 7 and 8.

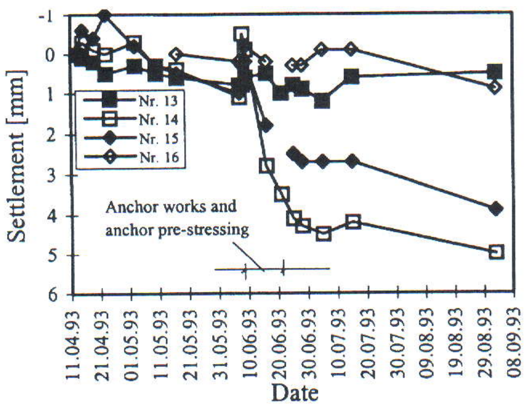

Figure 6. Time-settlement diagram at settlement control points 13, 14, 15, and 16.

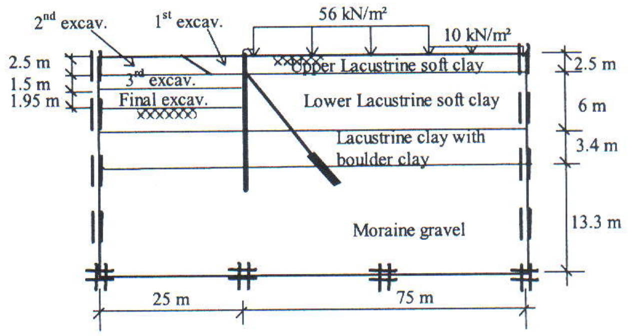

Figure 7. Cross section and soil profile along section b-b in Figure 3.

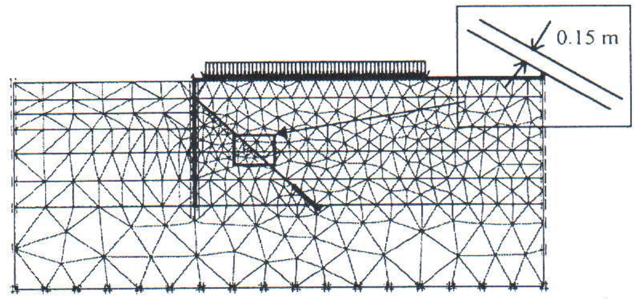

Figure 8. Finite element mesh.

4 BACK ANALYSIS

This excavation is a typical three-dimensional problem. At the external corners; the step by step excavation process at both sides, the overlap of anchors, and the strut support at the corners require a complete three dimensional modelling in order to predict or analyse its performance numerically. The effect of anchor installation on ground settlement can only be realistically simulated using three-dimensional analysis. However, with two dimensional plane strain finite element method and with the help of analytical approaches, the settlement progress at each construction stage can be estimated as described in the following sections.

4.1 *Finite element analysis*

Two sections (section a-a and section b-b in Figure 3) were selected for the back analysis using the finite element method. The geometry, the soil profile and the mesh used for section b-b are shown in Figures 7, 8. The parameters used in the finite element analysis are given in Table 2. The ground movement at any point is the sum of the combined effect of the performance of the excavation and other activities at both sides. The construction phases followed in the analysis are listed in Table 3. The material behaviour of the lacustrine soft clay was represented by soft soil model; the moraine gravel by hard soil model; and the cement-bentonite slurry by Mohr-Coulomb Model. Reference is given to Vermeer & Brinkgreve, 1998 for the description of the soil models.

The drill hole for anchor installation is modelled as plain strain rectangular slot of 0.15 m thick rather than the more realistic true three-dimensional circular hole with a diameter of 0.15 m. It was assumed that the diameter of the hole is widened to 0.15 m due to returning wash water through the external side of the drill shaft. The soil in the rectangular slot is replaced by cement-bentonit slurry after

Table 2. Soil and cement bentonite parameters.

Soft Soil Model

Soil layer	$\gamma_{wet}/\gamma_{dry}$	φ`	c`	λ^*	κ^*	K_0	ν_{ur}
	kN/m³	°	kN/m²	[x 10⁻³]	[x 10⁻³]	-	-
Upper und lower lacustrine soft clay	19/15.2	25	5	12.5	2.5	0.58	0.15

Hard Soil Model

Soil layer	$\gamma_{wet}/\gamma_{dry}$	φ`	c`	E_{50}^{ref} / E_{oed}^{ref} / E_{ur}^{ref}	K_0	P_{ref}	m
	kN/m³	°	kN/m²	MN/m²	-	kN/m²	-
Lacustrine and boulder clay	21/18.3	30	10	20/20/60	0.5	100	0.5
Moraine gravel	22/19.5	37.5	1	50/50/150	0.39	100	0.5

Mohr-Coulomb Soil Model

	$\gamma_{wet}/\gamma_{dry}$	φ`	c	E_{ref}	ν
	kN/m³	°	kN/m²	MN/m²	-
Cement-bentonite slurry	10/10	0	0.5	0.005	0.5

the 1st excavation and before stressing of the anchor. It was assumed that the slurry in its fresh state has very low undrained strength c = 0.5 kN/m² and stiffness E = 5 kN/m².

The analysis using 0.15 m rectangular slot in a plane strain is far from the reality. Hence, in order to estimate the effect of a single anchor settlement at the surface, a section in the out of plane direction with the width equal to the anchor spacing (0.9 m) was selected. An analysis had then been made to study the relationship between the settlement due to 0.15 m thick and 0.9 m wide rectangular slot (Fig. 9a) and 0.15x0.15 m square hole (Fig. 9b) at different depths and points. The 0.15 m diameter circular

Table 3. Construction stages.

Construction stage	Section a-a	Section b-b
0	Initial stress	Initial stress
1	Applying external load	Applying external load
2	Activating the wall and 1st & 2nd excavations	Activating the wall and 1st excavation
3	Anchor installation	Anchor installation
4	Pre-stressing the anchor	Pre-stressing the anchor
5	3rd excavation	2nd excavation
6	final excavation	3rd excavation
7	-------------	final excavation

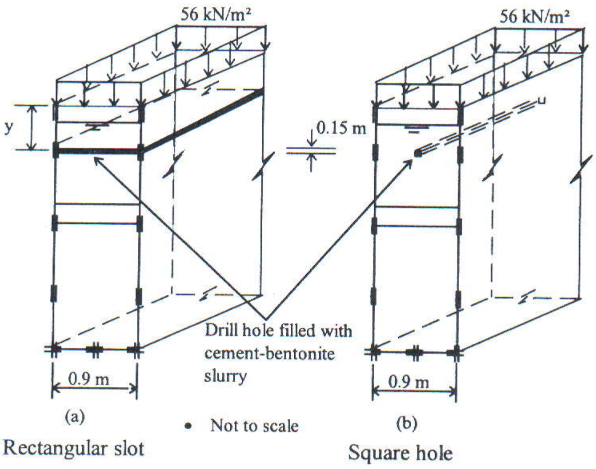

Figure 9. Sections in out of plane direction for comparative finite element analysis.

Table 4. Factors to determine the maximum settlement due to a single drill hole for the anchor installation.

depth below ground level	Settlement		Factor
	0.15 m thick rectangular slot (Fig. 4.3a)	0.15 x 0.15 m square hole (Fig. 4.3b)	col. 3 / col. 2
m	mm	mm	
1	2	3	4
4.92 (under point 3&4, section b-b)	28.24	1.360	0.0482
10.8 (under point 7&8, section b-b)	48.31	0.575	0.0119
3,7 (under point 3&8, section a-a)	25.13	1.330	0.0529
9,58 (under point 4&7, section a-a)	44.58	0.569	0.0128

drill hole is approximated by a 0.15 x 0.15 m square hole. From this comparative finite element analysis the factors at four different depths under settlement control points 3, 4, 7 & 8 were determined and are listed in Table 4. These factors relate the settlements at the ground surface due to the rectangular slot and square hole. The maximum settlement at a point on the ground surface due to a single anchor can now be estimated by multiplying the settlement from the plane strain FE-analysis by the corresponding factor. For example, the settlement at 3.24 m away from the wall (such as along points 3 & 4 in section b-b) from the finite element analysis is 50.71 mm. This value multiplied by 0.0482 (Table 4) will give approximately the maximum settlement (= 2.444 mm) due to a single anchor.

4.2 *Analytical approach*

The settlement trough at ground surface due to a tunnel construction (Fig. 10) can be estimated using the Gaussian distribution (Powrie 1997) as follows:

$$S = S_{max} \cdot e^{-x^2/2 \cdot i^2}$$

where S is the settlement at surface at any distance x from the centre of the tunnel, S_{max} is the maximum settlement at x = 0 above the centre line of the tunnel, i is a parameter which defines the width of the settlement zone and is given by $i = 0.5 \cdot z_0$ at the surface, and z_0 is the depth to the centre line of the tunnel.

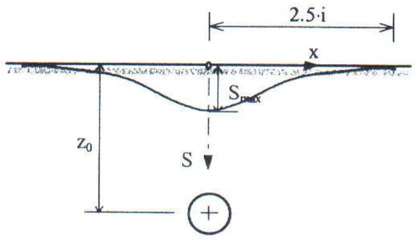

Figure 10. Settlement trough above a tunnel (after Powrie 1997).

The maximum settlement at the surface due to a single anchor installation is already estimated above using the finite element method . The contribution of each anchor hole to the total settlement at each settlement control points can now be approximated using the tunnel principle and method of superimposition. For example, the total settlement at point A in Figure 11 can be defined as the sum of the settlements due to holes 1 to 4. That is

$$S_{max,A} = S_{1A} + S_{2A} + S_{3A} + S_{4A}$$

where S_{1A}, S_{2A}, S_{3A}, and S_{4A} are the settlements at point A due to holes 1, 2 3, and 4 respectively. Similarly, the settlement due to anchor installation, for example at point 3 (Fig. 3), is the sum of the superimposed settlements due each anchor drill hole with in the influence area.

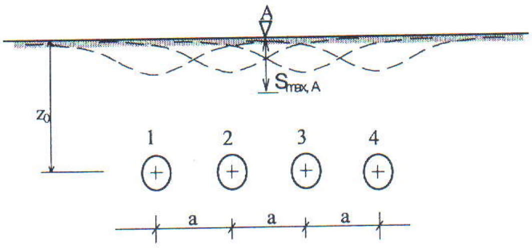

Figure 11. Settlement superimposition.

4.3 *Discussion of the result*

The settlements due to the excavation works at different stages and during the pre-stressing of the anchors in both directions are obtained directly from finite element analysis, where as the settlement due to anchor installation is further derived using analytical approaches as discussed in the above two sections. Figure 12 shows the calculated progress of the settlements for settlement control points 3, 4, 7 and 8 at various construction stages. The initial settlement in Figure 12 is a measured settlement due to pile installation obtained from Figure 5. The percentages of the calculated settlements due to anchor installation at points 3, 4, 7 and 8 are 55%, 52%, 46%, and 23% respectively. This values are less than that of the measured values (Table 1).The difference might come from the vibration effect since this effect is not included in the back analysis. The maximum calculated settlement at points 3 and 8 are less than those measured, whereas at point 4 and 7 they are greater than the measured settlements. However, the general trend of the calculated settlement progress seems to agree with the measured settlement.

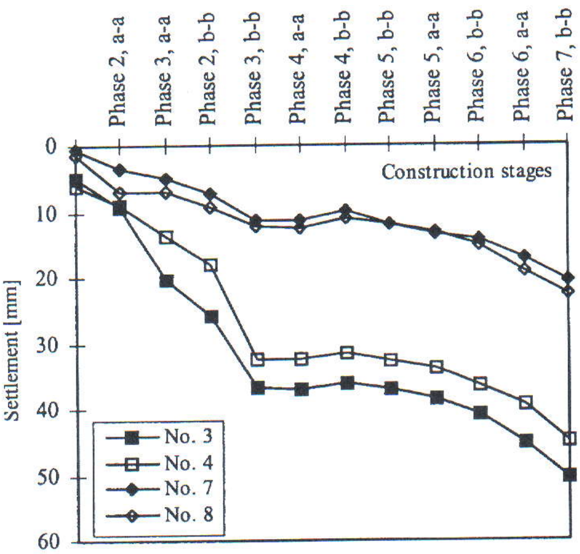

Figure 12. Calculated progress of ground settlement at the surface at different construction stages.

5 CONCLUSION

60 -72% of the total settlement was measured during the anchor installation whereas the back analysis shows 23 to 55 % only. This indicates that both the fresh cement-bentonite slurry in the drill hole and the vibration produced from percussion drilling, driving and pulling of the casing seems to contribute to the ground settlement during the anchor installation. Therefore, leaving the drill hole in soft soils to rely its support on the fresh cement-bentonite slurry is not recommended. Furthermore, percussion drilling may not be recommended for drilling anchor hole in a ground sensitive to vibration.

Though the anchor installation at the external corners is a typical three dimensional problem, it is possible to model the problem using a two dimensional plane strain finite element method and an analytical approach. However, three dimensional analysis is strongly recommended.

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