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Installation effects of soil exchange drillings on sheet pile driving

Effets de forages d'échange de sol sur le fonçage de palplanches

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ABSTRACT: For the overhaul of a major port construction soil exchange drillings were carried out to aid installation of the new quay wall. The design of the quay wall includes the construction of a combined HZ/AZ sheet pile wall in front of the existing harbor wall at a distance of 5 m. The new wall consists of 30+ m long double beam HZM 1080 king piles as structural support and AZ sheet piles as intermediate infill elements. Due to the predominating very dense sands as well as debris from WW2 bombings, soil exchange drillings using large diameter cased boreholes were carried out along the wall alignment to support the installation process of the subsequent pile driving. The exchange drillings were backfilled using, if suitable, the excavated material as well as sand from a nearby depot. During the pile driving several of the king piles sank up to 9 m into the ground with minimal application of driving energy. An extensive investigation was launched to identify the cause of these failures with particular regard to the soil density within the exchange drillings and the impact on the structural integrity of the wall. This paper will go into further detail about the various construction aspects as well as installation effects and present the findings of the above mentioned investigation.

RÉSUMÉ : Pour la révision d'une importante construction portuaire, des forages d'échange de sol ont été effectués pour faciliter l'installation du nouveau mur de quai. La conception du mur de quai inclut la construction d'un rideau de palplanches combiné HZ/AZ devant le mur du port existant, à une distance de 5 m. Le nouveau mur se compose de pieux King à poutre double HZM 1080, de 30+ m de long, comme support structurel, et de palplanches AZ comme éléments de remplissage intermédiaires. En raison de la prédominance de sables très denses ainsi que de débris provenant des bombardements de la Seconde Guerre mondiale, des forages d'échange de sol utilisant des puits de forage coffrés de grands diamètres ont été réalisés le long de l'alignement des murs pour soutenir le processus d'installation du fonçage de pieux ultérieur. Les forages d'échange ont été remblayés en utilisant, tant que cela était approprié, les matériaux excavés ainsi que du sable provenant d'un dépôt voisin. Dans le contexte du fonçage des pieux, par la suite, plusieurs des pieux King se sont enfoncés jusqu'à 9 m dans le sol avec une application minimale de l'énergie de fonçage. Une étude approfondie a été lancée pour identifier la cause de ces défaillances, en tenant compte notamment de la densité du sol à l'intérieur des forages d'échange et de l'impact sur l'intégrité structurelle du mur. Cet article examine plus en détail les différents aspects de construction ainsi que les effets de cette méthode et présente les résultats de l'étude susmentionnée.

KEYWORDS: soil exchange drillings, soil structure interaction, combined sheet pile wall, installation aid, installation effects

1 INTRODUCTION

The overhaul of a major tidal port construction in Germany entails a new, approximately 2.2 km long and 15 m high, quay wall in front of the existing wall at a distance of 5 m. The new combined sheet pile wall consists of 30+ m long double beam HZM 1080 king piles as structural supports, and AZ sheet piles as intermediate infill elements. The wall is tied back using pressure grouted steel displacement piles (Figures 1 & 2).

Due to the predominating very dense sands, locally occurring soft marine clay as well as debris from WW2 bombings, soil exchange drillings using large diameter cased boreholes were carried out along the wall alignment to support the installation process of the pile driving. The exchange drillings were backfilled using, if suitable, the excavated material as well as sand from a nearby depot.

2 GROUND CONDITIONS & CONSTRUCTION PROCESS

The local geology is composed of superficial quaternary soils, consisting of soft cohesive soils and sand. Onshore, along the quay wall, the upper layer consists of made ground underlain by soft marine clay followed by medium dense to dense sands. The upper layer of the harbor basin consists of mud of up to 5 m thickness (average thickness 3 m) underlain mostly by sand and in parts by marine clay or silty sands (Figure 1).

The first step of construction was to remove the fluid mud layer in front of the existing wall and replace it with a sand berm in order to stabilize the structurally inadequate quay wall and to avoid settlement of the future backfill. This was achieved by dredging the material using water injection while simultaneously backfilling with sand (Matthiesen 2015). Prior to driving of the new combined sheet pile wall, the soil exchange drillings using large diameter cased boreholes were carried out along the wall alignment.

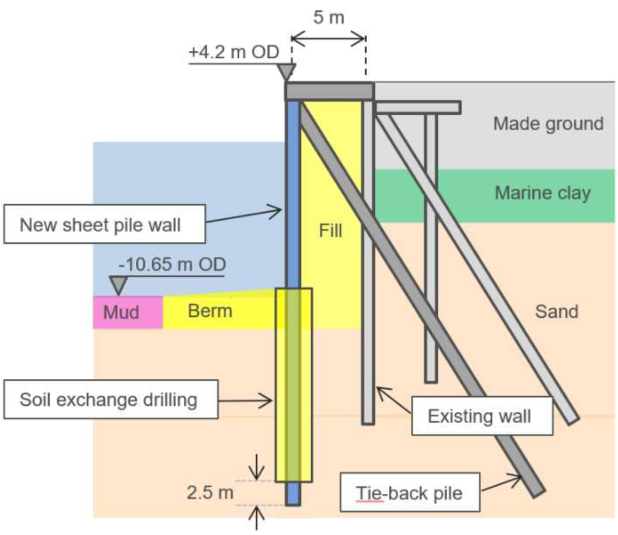

Figure 1. Cross section of the old and new quay wall including ground conditions

Figure 2. Installation of the king piles

3 SOIL EXCHANGE DRILLINGS & ANOMALIES

The soil exchange drillings were carried out from a jack-up barge along the alignment of the new sheet pile wall using large diameter cased boreholes. The soil was extracted using the Kelly drilling method (Figure 3). The boreholes were drilled to a depth of 2.5 m above the bottom of the king piles (Figure 1) to ensure sufficient toe resistance of the piles or 0.5 m above the bottom of the infill elements. After completion of the borehole the excavated material was reinstalled as backfill material. Before its reuse the soil was checked for obstacles and its suitability as filling soil. If necessary it was replaced by sand from a nearby offshore depot.

Figure 3. Execution of the soils exchange drillings

Figure 4 shows an example of the alignment and the sequence of the soil exchange drillings. First 3 to 4 boreholes for the infill elements were completed followed by the intervening boreholes for the king piles.

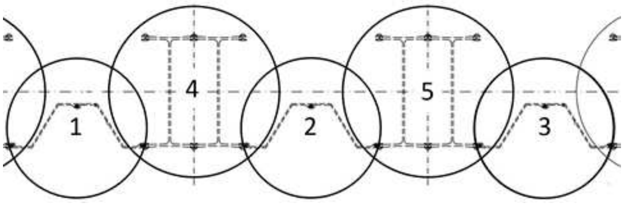

Figure 4. Soil exchange drillings - alignment and construction sequence

The exchange drillings were backfilled through a funnel which was attached to the top of the borehole casing. The casings were pulled successively with the filling progress of the borehole.

In the course of the works, a large number of the soil exchange drillings required a considerable additional amount of backfilling material of up to twice the arithmetic volume of the borehole. During the subsequent pile driving several king piles sank up to 9 m into the ground with minimal application of driving energy.

4 INVESTIGATION

In order to identify the cause of the aforementioned failures different fill materials as well as filling methods of the exchange drillings were investigated. The results of these tests were assessed by CPT testing within the exchange drillings and by comparing these results to CPT tests in the adjacent natural ground at a distance of 3.5 m to the borehole. The CPTs were used to determine the density of the sand as well as for the detection of potential embedded cohesive layers within the fill.

In the following the results of the investigation will be shown using the CPT Data of four representative king pile exchange drillings. The installation details of these drillings are listed in Table 1.

Table 1. Filling details of the investigated soil exchange drillings

Borehole no.	140	150	189	206
Reused soil (m³)	27,0	27,0	-	-
Depot sand (m³)	16,5	16,5	-	-
S-G mix (m³)	-		32,5	31
Additional fill (%)	48,0	48,0	0	0
Filling time (min)	30	33	80	150

The first locations are two randomly picked exchange drillings (nos. 140 & 150) carried out by the 'standard' backfilling method using the excavated material plus additional sand from the depot. The particle size distribution of the excavated material is shown in grey in Figure 5. The particle size distribution of the substitute depot sand lies within this range. The additional fill required to backfill the boreholes amounts to 48 % in both cases. Both boreholes were backfilled in the, at that point, standard construction time of roughly 30 mins.

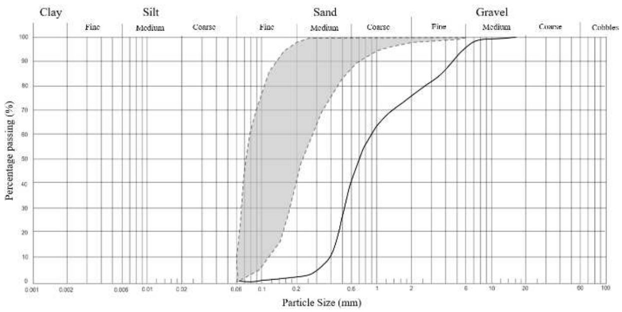

Figure 5. Particle size distribution – excavated material (grey), sand and gravel mix (black line)

In order to investigate the effect of the grain size distribution on the density of the fill material, several boreholes were backfilled using a sand & gravel (S-G) mix with a grain size range of 0 to 8 mm as shown in Figure 5. Boreholes no. 189 and no. 206 are listed as an example in Table 1. Both boreholes did not require additional fill material. While borehole 189 was backfilled slowly within 80 minutes, borehole 206 was also backfilled slowly while additionally using the drilling bucket used for the preceding excavation to regularly compact the backfill material within the borehole.

Figure 6 shows the CPT results of exchange drillings 140 and 150 using the 'standard' backfilling method. The black line (Index A) depicts the cone resistance q_c adjacent to the exchange drilling (before), while the dotted line (Index B) shows the CPT results (q_c) within the exchange drilling (after). The change in cone resistance before and after the execution of the exchange drilling is shown either in red (drop in q_c) or green (increase in q_c). Only the depth from the base of the mud layer to the base of the exchange drilling is analyzed. Table 2 lists a summary of the key data of the CPT results shown in Figure 6.

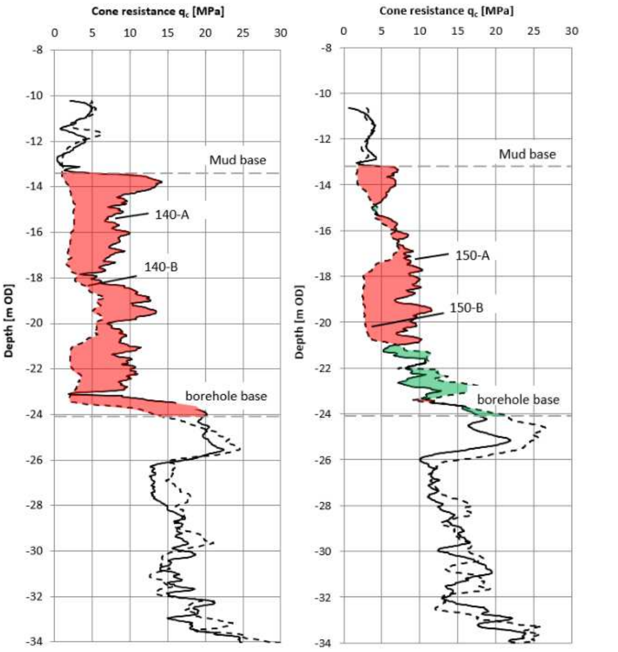

Figure 6. CPT cone resistance q_c of soil exchange drillings nos. 140 & 150 backfilled with reused excavated material and sand – adjacent (A) and within backfilled borehole (B)

The CPTs within the natural ground at both locations (Index A), as expected, show similar results in soil density with a cone resistance q_c ranging between 3,4 MPa and 20,2 (140-A) and 3,7 MPa and 17,9 MPa (150-A). The mean value of q_c lies between 9,8 MPa (140-A) and 8,5 MPa (150-A), indicating predominantly medium dense soil conditions.

The CPT results within the exchange drillings show, for the most part, a drop in cone resistance q_c compared to the natural ground, as shown in red in Figure 6. However, despite a very similar execution process and refill material used, a clear difference between both locations no. 140 and no. 150 can be seen. While CPT 140-B shows a constant and significant drop in cone resistance q_c throughout the entire depth of the borehole compared to the natural ground, CPT 150-B shows less of a decrease in soil density and even a slight increase near the base of the exchange drilling, as indicated in green.

Table 2. CPT results of soil exchange drillings nos. 140 and 150 backfilled with reused excavated material and sand – adjacent (A) and within backfilled borehole (B)

CPT no.	140-A	140-B	150-A	150-B
Min q_c (MPa)	3,4	0,9	3,7	1,7
Max q_c (MPa)	20,2	14,2	17,9	21,6
Mean q_c (MPa)	9,8	3,5	8,5	6,5
Av. drop in q_c (%)	-	63,7	-	24,3

The average drop in cone resistance q_c at the same depth after the execution of the exchange drilling is 63,7 % at location 140, while at location 150 it is only 24,3 %. The average measurement of q_c within the backfill material lies between 3,5 MPa and 6,5 MPa, which, in accordance with the correlations for the relative density of cohesionless soil of the German Recommendations on Excavation (2012), corresponds to very loose to loose soil conditions.

Figure 7 shows the CPT results of exchange drillings no. 189 and 206 using a sand and gravel mix as an alternative backfill material. Table 3 lists a summary of the key data of the CPT tests shown.

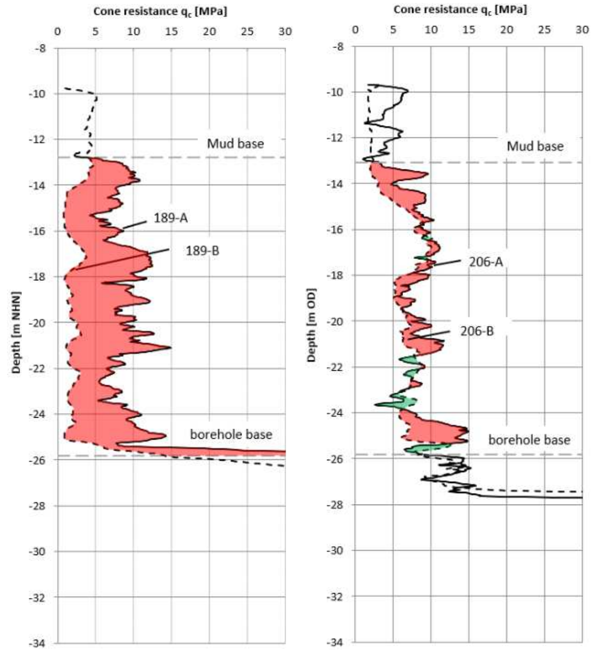

Figure 7. CPT cone resistance q_c of soil exchange drillings nos. 189 & 206 backfilled with a sand and gravel mix – adjacent (A) and within backfilled borehole (B)

Similar to the results discussed above, the CPTs within the natural ground (Index A), show comparable ground conditions at both locations with an average cone resistance q_c of 9,7 MPa and 8,5 MPa throughout the depth of the borehole.

At location 189 the CPT results within the exchange drilling (Index B) show a significant drop in cone resistance q_c compared to the natural ground, as indicated in red. The average decrease in cone resistance q_c is 76,0 %, which is lower than the results of the above discussed drillings nos. 140 and 150 backfilled using finer-grained sand. The average value of q_c within the backfill is 2.3 MPa, indicating very loose soil conditions.

Table 3. CPT results of soil exchange drillings nos. 189 and 206 backfilled with sand and gravel mix - adjacent (A) and within backfilled borehole (B)

CPT no.	189-A	189-B	206-A	206-B
Min q_c (MPa)	4,3	0,8	2,5	1,9
Max q_c (MPa)	52,3	14,0	15,0	12,7
Mean q_c (MPa)	9,7	2,3	8,5	6,8
Av. drop in q_c (%)	-	76,0	-	17,0

The CPT test within the exchange drilling 206 shows the least change in soil density. The average drop in cone resistance q_c is only 17,0 % compared to the natural ground. The average measurement of q_c within the backfill material is 6.8 MPa which is only slightly lower than the surrounding natural ground. However, this was achieved by a time consuming backfilling process (150 mins) where the borehole was backfilled slowly and compacted layer-by-layer.

5 ANALYSIS

According to the Recommendations of the Committee for Waterfront Structures Harbours and Waterways (2012) the in-situ density of dumped non-cohesive soils depends primarily on the following factors: a) A non-uniform granulometric composition results in a higher in situ density than a uniform one. b) Segregation increases with the depth of the water. This changes the particle size distribution, with the coarse-grained fractions reaching a higher in-situ density than the fine-grained ones. This results in a body of soil with an inhomogeneous in situ density. c) The greater the flow, the greater the segregation and the more irregular the settlement of the soil.

Contrary to the above first statement, the analysis of the CPT data has shown that using a coarse-grained, non-uniform sand and gravel mix does not result in a higher density of the backfill within the exchange drillings. In fact, higher soil densities were achieved in our trials using a uniform fine-grained sand.

All 4 examples show a characteristic, strongly undulating course of the cone resistance with depth within the backfill material. This confirms and is a result of the above-mentioned segregation of the material during the sinking process resulting in a different deposition of the filling material within the exchange borehole and an inhomogeneous in situ density. This effect appears to be more pronounced in the boreholes using the uniform sand as backfill material. These boreholes were backfilled much quicker, creating a stronger upward flow within the borehole casing and therefore a greater segregation of the material (see point c) above). Additionally, due to the fast backfilling and stronger upward flow, a considerable amount of fine-grained soil particles were segregated and washed out with the water spilling over the top of the borehole casing explaining the additional amount of backfilling material needed.

The settling velocity of sand (d = 0,5 mm) within a water-filled borehole can be assumed according to Tholen (1997) as 2.5 m/min. For a borehole of 30 m depth, as in this case, this would result in a total time of 12 minutes for each fill charge to reach the base of the borehole. However, due to the aforementioned flow within the casing caused by a quick backfilling process a further reduction in settling velocity should be assumed (Joseph et al 1987).

A clear correlation between the backfill material of the exchange drillings and the sinking of the king piles during driving could not be established by the above investigation. An analysis of the construction logs as shown in Figure 8, however, indicates the impact of the filling time on the quality, i.e. sufficient soil density of the fill material.

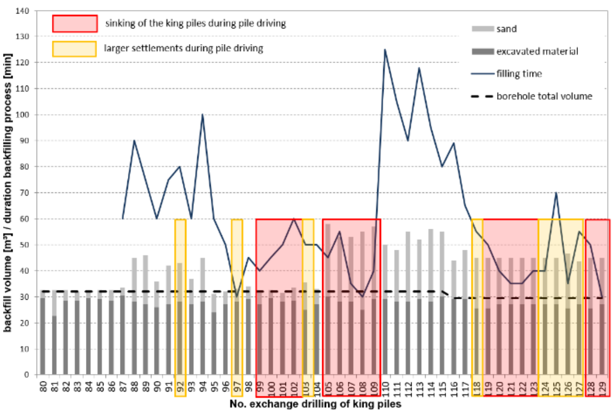

Figure 8. Assessment of the construction logs of the exchange drillings for the king piles

Figure 8 shows that the exchange drillings at which the king piles sank into the ground for several meters (red) or showed large settlements during driving (yellow) show considerably shorter backfill times compared to the locations where the piles were driven without issues. This supports the above assumption of the impact of filling time and therefore of flow within the casing on the segregation and settlement of the filling material.

6 CONCLUSIONS & OUTLOOK

The method of backfilling exchange drillings under water must be adapted to the settling velocity of the material used for backfilling in order to achieve a sufficient and uniform soil density. A fast backfilling process of the borehole leads to a strong segregation and stratification of the fill material due to the generated upward flow within the casing. At the same time, the fine material is discharged by spilling over the top of the casing resulting in a loss of fill material.

Regardless of the grain size of the fill material, a higher density within the backfill could not be achieved without additional compaction in this case. Therefore, only a loose in situ density should be assumed in exchange drillings using non-cohesive material without additional compaction.

A comprehensive numerical analysis simulating the physical behavior of particles in water (Cook et al 2004) could give more insight into the governing factors of the backfilling process and the construction process could thereupon be optimized.

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