Conception of the deep foundation for the new construction of a warehouse and administration building based on CPT, CPTU, pressuremeter and phicometer tests

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ABSTRACT

A large company from northern Hesse planned to build a new warehouse and administration building in Schlüchtern. The rectangular floor plan of the new building measures 107 m by 220 m, divided into two building sections. At a building height of 48 m, the highest settlement requirements apply according to FEM guideline. The foundation is reinforced by a total of 6 staircases and more than 200 single foundations under columns with a load of more than 10 MN. The site has shown intensive fault block geology from the Triassic (Upper Buntsandstein, Röt) to the Tertiary (Miocene) geological periods, with Vogelsberg volcanism. In the northeast, heavily subsided deep blocks of poorly consolidated, cohesive, partly volcanically influenced Miocene strata were found down to depths of 36 m below the ground surface. In the southwest, the Buntsandstein Formation (Röt, Layer 4) extends to just below the ground surface, forming a horst. For subsoil exploration, 18 core drillings up to 72 m, 152 cone penetration tests (CPT) and 41 piezocone penetration tests (CPTU) were carried out. In addition, an extensive laboratory program and for in-situ measurements of the subsoil's deformation characteristics and as a basis for the design of the planned deep foundation, 14 pressure meter tests were conducted at various depths, as well as 19 borehole shear tests in two boreholes. A complex geological subsoil model and a comparison of prebored pressuremeter tests by Ménard procedure, borehole shear tests and cone penetration tests with laboratory test results is presented. The ground stiffnesses will be derived from the results. The developed foundation concept consists of Franki piles with enlarged bases and lengths between 8 m and 36 m. Measurements conducted on the structure, which have been in operation for six years, confirm the successful implementation of the field measurements in the design and construction.

RESUME

Une grande entreprise du nord de la Hesse prévoyait la construction d'un nouvel entrepôt et d'un bâtiment administratif à Schlüchtern. Le nouveau bâtiment, de plan rectangulaire, mesure 107 m sur 220 m et est divisé en deux sections. À une hauteur de 48 m, les exigences de tassement les plus élevées s'appliquent, conformément à la directive FEM. Les fondations sont renforcées par six escaliers et plus de 200 fondations individuelles sous colonnes, soumises à une charge de plus de 10 MN. Le site présente une géologie intensive de blocs de failles datant du Trias (Sandstein supérieur, Röt) au Tertiaire (Miocène), avec un volcanisme du Vogelsberg. Au nord-est, des blocs profonds et fortement affaissés de strates miocènes mal consolidées, cohésives et partiellement influencées par le volcanisme ont été découverts jusqu'à 36 m de profondeur. Au sud-ouest, la formation du Buntsandstein (Röt, couche 4) s'étend jusqu'à la surface du sol, formant un horst. Pour l'exploration du sous-sol, 18 forages carottés jusqu'à 72 m, 152 essais de pénétration au cône (CPT) et 41 essais de pénétration au piézocône (CPTU) ont été réalisés. De plus, un vaste programme de laboratoire et, comme mesures in situ des caractéristiques du déformation du sous-sol et servant également de base à la conception de la fondation prévue, 14 essais pressiométriques ont éte réalisés à différentes profondeurs ainsi que 19 essais de cisaillement dans deux forages. Un modèle géologique complexe du sous-sol et une comparaison des essais pressiométriques réalisés selon la méthode Ménard, des essais de cisaillement en forage et des essais de pénétration au cône avec les résultats des essais en laboratoire sont présentés. Les rigidités du sol seront déduites de ces résultats. Le concept de fondation développé se compose de pieux Franki à bases élargies et de longueurs comprises entre 8 et 36 m. Les mesures effectuées sur l'ouvrage, en exploitation depuis six ans, confirment la mise en œuvre réussie des mesures de terrain dans la conception et la construction.

Keywords: soil investigation; core drillings; cone penetration test (CPT); piezocone penetration test (CPTU); pressure meter test; borehole shear tests; phicometer; deep foundation design.

1. Project overview

Engelbert Strauss GmbH & Co. KG, Biebergemünd (Germany), intends to build a new warehouse and administration building on a site in Schlüchtern. The new building can be divided into three building sections (automatic small parts warehouses + shuttle, logistics + technology and logistics + administration).

Figure 1. Strauss CI-Factory.

2. Location

The project area is located directly northwest of the federal highway A66 – exit "Schlüchtern/Fulda" (Hesse, Germany) on a north-northwest-facing slope.

Excavations of up to approximately 9 m are planned for the building area along axis 1, and embankments of up to 4 m are planned for axis 37. A terrain drop of up to approximately 9 m is created near the highway A66.

3. Geology

3.1. General overview

Geographically, the project area is located between the Vogelsberg volcanic region to the northeast, the Spessart to the south, and the Southern Rhön to the east. North of the project area, near the towns of Flieden and Neuhof, begins an area where underground potash salts from the Zechstein Formation (Permian) are mined.

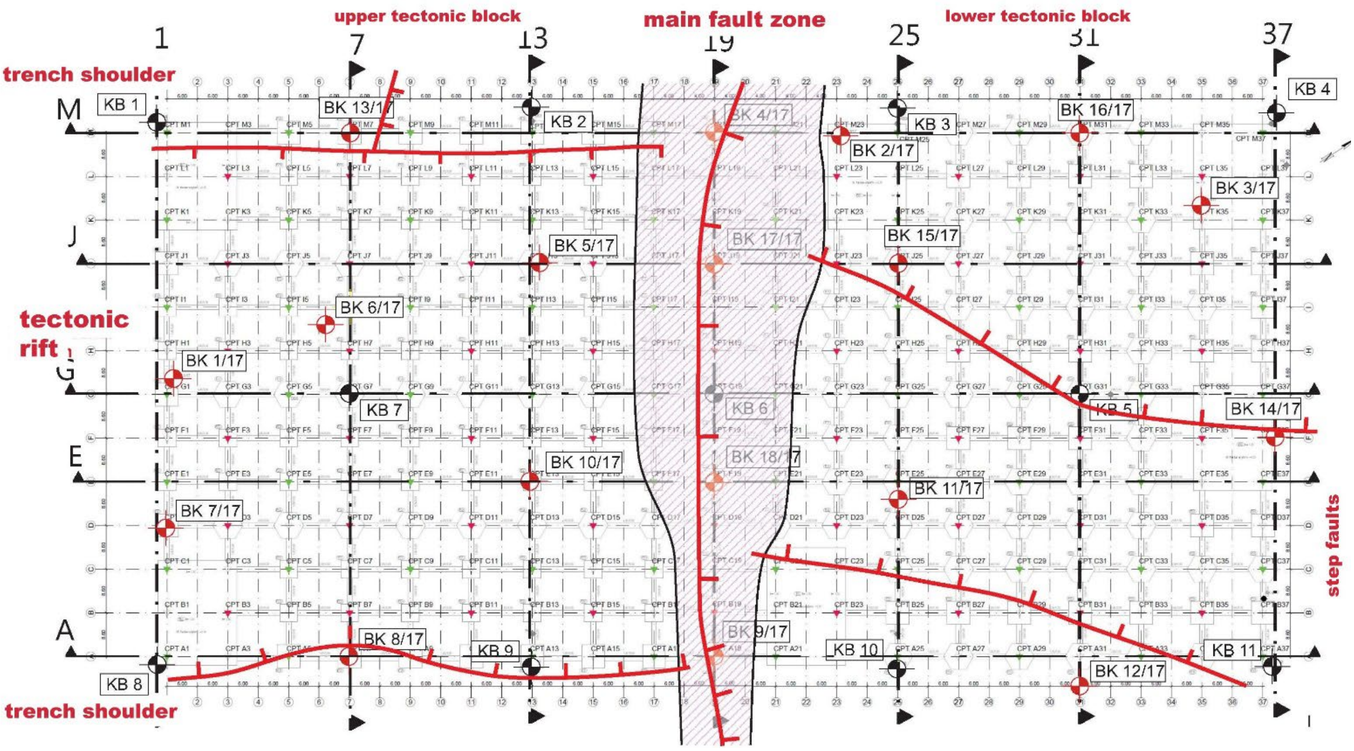

Figure 2. Site exploration and tectonics.

The rectangular floor plan of the new building measures approximately 107 m by 220 m. The building height is approximately 48 m in the southwestern section (automated small parts warehouse; axes 1 to 19) and in the central section (logistics + technology; axes 19 to 23). In the northeastern section with logistics + administration (axes 23 to 37), the building height is approximately 28 m.

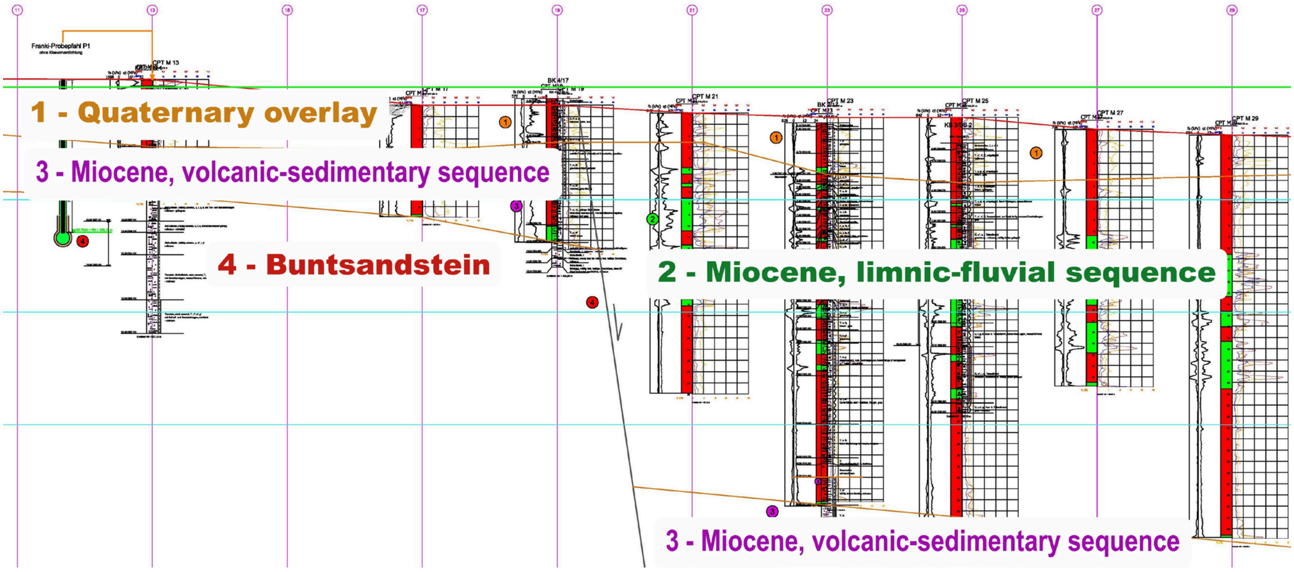

Figure 3. Subsoil section.

At the site for the planned structure, from top to bottom, thin Holocene valley sediment, Pleistocene solifluction debris and soils/rocks of the upper Buntsandstein Formation (Plattensandstein) were to be expected.

3.2. Tectonics

During the ground investigations, fracture-tectonic faults were identified. The total displacement height was estimated at approximately 100 m.

The main tectonic element was a fault that was mapped approximately along the structure axis 19, that means in a NW-SE direction.

Southwest of this main fault there is a high block, which contains a SW-NE trending tectonic graben. The filling of the graben consists essentially of Miocene sedimentary-volcanic alternating sequences.

At the shoulders of the graben, rocks of the Buntsandstein Formation (Upper Buntsandstein, Röt) extend close to the surface, and in some cases, they are exposed at a depth of approximately 24 m below the surface. In the graben itself, they are only below the exploration depths.

Along the NW-SE trending main fault, the layers, which are vertically offset by at least 80 m, are tectonically stressed over a width of about 10 m to 30 m and are mixed at the actual fault.

Within the deep block in the northeastern part of the construction site, a Miocene sequence of layers was explored to depths ranging from approximately 11 m in the southeast to approx. 36 m in the northwest. The layers consists primarily of poorly consolidated clays and silts with intercalations of volcanic ash and tuff layers, as well as brown coal layers and washed-in wood residues. The increase in depth to the northwest is associated with staggered tectonic faults.

3.3. Subsoil model

3.3.1. Stratum 1 - Quaternary overlay

The Quaternary overlay at the site consists of an approximately 20 cm thick topsoil and clayey-silty, usually soft to stiff-consistent, displaced weathering products of the underlying layers.

It is probably glacial (Pleistocene) solifluction debris, which could have formed from flowing soils during freeze-thaw cycles, even on slight slopes.

3.3.2. Stratum 2 - Miocene, limnic-fluvial sequence

The layer begins at its base with approximately 4 m to 9 m thick, dark, stiff to semi-solid clays, which presumably originated partly from heavily weathered tuffs, but also contain organic matter (some wood/coal residues, otherwise finely distributed organic matter). Overall, the base can be described as a tuffite.

Towards the top, an increasingly limnic-like sedimentation of "ash-laminated" silts and clays (generally with a soft consistency) extends. The soils are irregularly interspersed with organic layers and partly carbonized wood residues. This partially eroded part of Layer 2 was drilled with thicknesses between 10 m and 15 m.

In the higher, preserved part of the partially eroded Layer 2, the volcanic influence continues to diminish. Instead, the limnic sediments (silts, clays, partly sandy) contain frequent fluvial infiltrations and deposits of gravelly components consisting of poorly rounded rock fragments (mainly Buntsandstein, rarely limestone) and quartz pebbles. Except for these deposits, this upper part of the layer has a predominantly soft, sometimes stiff consistency according to in-situ analysis.

The preserved thickness of this layer is approximately 10 m to 15 m

3.3.3. Stratum 3 - Miocene, volcanic-sedimentary sequence

Below layer 2, layer 3 begins with an increasingly volcanic sequence of layers, which transitions towards the base into partly gravelly clays (from relocated, fluvially washed-in Buntsandstein material).

The layer is exposed near the surface in the southwestern part of the construction area (high block), where its base extends in a graben structure below the exploration depth (approx. 30 m). Below this, on the graben shoulders, follows Bunter sandstone in the form of "Röt" (layer 4).

In the northeastern part, the base of the layer is offset due to tectonic faults to below the maximum exploration depth of 72 m.

The upper, volcanic part of the entire layer consists partly of striking blue-gray to green-gray tuffs and tuffites with intercalations of coarser volcanic ejecta (some basalt bombs) as well as locally more or less weathered and decomposed layers of basaltic rock. Darker organic clay horizons with wood and coal residues are also found within the tuffites. The consistency of the upper part is generally semi-solid, with transitions to stiff and solid.

The thickness is approximately 20 m.

In the lower part, Layer 3 shows an increasingly sedimentary character and consists of reddish-brown, partly gray-mottled and gray clays with a semi-solid to solid consistency. The clays contain decreasing volcanic inclusions (tuffs, tuffites in layers) towards the base of the layer and increasingly fluvial, washed-in fragments of Buntsandstein rock and quartz pebbles.

The thickness of the lower part of layer 3, which cannot be explored down to the deep base in the deep block, is at least about 10 m.

3.3.4. Stratum 4 - Buntsandstein, upper Röt sequence

Stratum 4 begins beneath the Miocene sequence, usually beneath a repositioning horizon of stratum 3, with siltstone that has partially weathered to clay/silt, which appears as moderately solid in thin layers just a few meters deeper.A few centimeters thick quartzitic sandstone benches are partially interspersed within this violet-red-brown layer.

4. Subsoil investigation

4.1. First phase subsoil investigations

In a first exploration phase the following subsoil investigations were carried out on site in accordance to DIN 4020:

- 33 Borings (RKS) to depths between 2 m and 10 m below ground surface
- 20 Dynamic Probing Heavy (DPH) to depths between 6 m and 10 m below ground surface
- 11 Core drillings (BK) to depths between 18 m and 30 m below ground surface
- 11 Cone Penetration Tests (CPT) to depths between 7,1 m and 20 m below ground surface

4.2. General subsoil investigations

Deep keyhole core drillings were necessary for correlation with prebored pressuremeters by Ménard and borehole shear tests. So additional subsoil investigations were required based on the first phase surveys. The significant depths of the additional core drillings were necessary due to the deep load influence of the shallow foundation.

Figure 4. Site view.

In the second phase, deepening subsoil investigations were carried out on site in accordance to DIN 4020 (Geotechnical investigations for civil engineering purposes):

4.2.1. Core drillings (BK)

In order to explore the subsoil and to obtain soil samples, a total of 18 core drillings according to DIN EN ISO 22 475-1 were carried out to a maximum depth of 72 m below the existing ground surface.

4.2.2. Cone penetration tests (CPT / CPTU)

For the subsoil investigation a total of 152 cone penetration tests (CPT) were carried out as indirect surveys to determine the bulk density or penetration resistance up to a maximum of 37,45 m below the existing ground surface.

During the cone penetration test the cone resistance qc and sleeve friction fs at the probe tip are continuously measured and recorded, and the ratio of cone resistance / sleeve friction (friction index R_f) is calculated as a function of depth.

Furthermore a total of 41 piezocone penetration tests (CPTU) measuring the pore water pressure were carried out in accordance with DIN EN ISO 22476-1: 2013-10, up to a maximum depth of 34,49 m beneath the existing ground surface. In addition to the cone resistance qc and the sleeve friction fs, the pore water pressure u is also measured and recorded.

4.2.3. Pressuremetres

For in-situ measurement of the deformation characteristics of the subsoil and as a basis for the design of the planned deep foundation, a total of 14 pressiometer tests (prebored pressuremeter by Ménard procedure) were carried out at various depths in accordance with DIN EN ISO 22476-4: 2013-03.

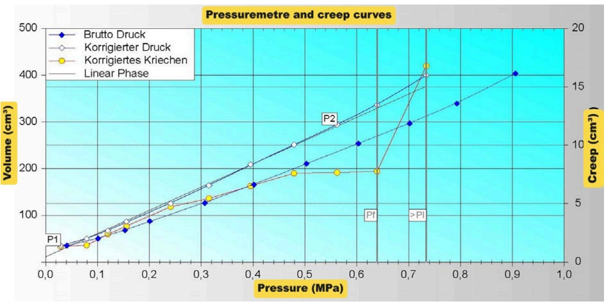

Figure 5. Pressuremetre curve.

The key parameters determined in the test are the pressure modulus (E_m) and the so-called limit pressure (PI). The determined pressuremeter modulus is related to the stiffness modulus (E_s), depending on the soil type, according to the following Eq. (1):

$$E_s = E_m \,/\, \alpha \quad (1)$$

Since the structure has very large floor plan dimensions and the aim was to determine soil parameters of the layers, equation (1) was used.

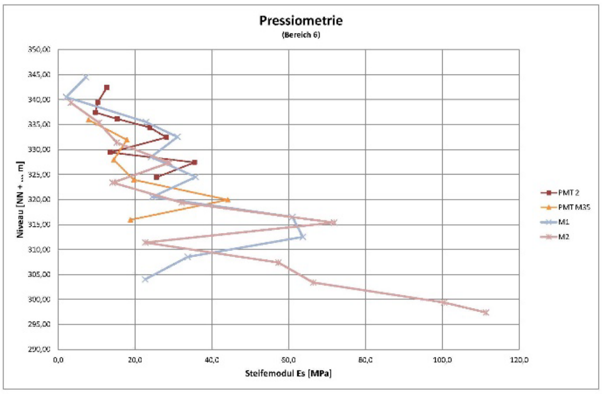

Figure 6. Pressuremetre analysis over depth.

The pressuremetre results show an increase in the pressuremeter modulus in the deeper zones. According to DIN EN 1997-2: 2010-10, Annex E, the ratio of the pressure modulus to the confining pressure (E_m/PI) allows the derivation of normally consolidated (primarily loaded) or fully worked conditions.

The structural coefficient or rheological factor α is essentially 0.5 and 0.67, depending on the soil, subordinate 1. The temporary soil overburden derived from a geological perspective was evidently not overconsolidating everywhere.

As is customary and required in Germany, the pressure meter results were used only to determine the soil parameters of the individual layers. Calculations for bearing capacity and serviceability were then performed using the subsoil model.

4.2.4. Phicometer borehole shear tests

To measure the shear strength (phicometer friction angle, phicometer cohesion) of the in-situ soil, a total of 19 phicometer shear tests were conducted in 2017 in two boreholes at various depths.

The key parameters determined in the test are the phicometer friction angle ϕ_i and the phicometer cohesion c_i. Depending on the soil type, an approximate correlation can be derived between the in-situ determined shear parameters from the phicometer shear test and the shear parameters (friction angle ϕi and cohesion c´) from laboratory tests, which describes the subsoil properties.

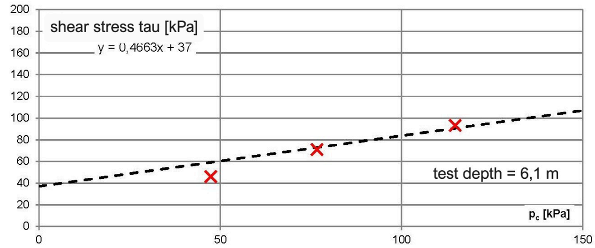

Figure 7. Borehole shear test.

The phicometer shear tests carried out show a tendency for the shear parameters friction angle ϕ´ and cohesion c´ derived from the results to increase with depth.

The determined shear parameters were incorporated into the soil parameters of the layers.

4.2.5. Soil mechanical laboratory testing

From the taken soil samples some were selected for soil mechanics laboratory testing:

- Water content acc. to DIN 18 121-1
- Consistency limits – Determination of liquid limit and plastic limit acc. to DIN 18 122-1
- Determination of grain-size distribution acc. to DIN 18 123
- Determination of density of soil acc. to DIN 18 125
- Oedometer consolidation test acc. to DIN 18 135
- Unconfined compression test acc. to DIN 18 136

5. Test piles

Based on pile load tests on five individual piles FRANKI Grundbau GmbH & Co.KG tested a foundation concept using "Franki piles" as a first step.

The test piles were carried out with a shaft diameter of 61 cm and lengths between 8,50 m and 14,50 m. The maximum test loads ranged between 5.000 kN and 6.000 kN. With the five test loads, the required settlement of ≤ 5 mm at a service load of 2.500 kN was verified. The required ultimate load of R_k = 4.000 kN was also verified.

Further soil investigations consisting of core drilling, prebored Ménard pressuremeter tests by and phicometer tests, were planned, supervised, and evaluated by our office for and with FRANKI with regard to the foundation concept for the warehouse building.

Based on this, the additional investigations were carried out.

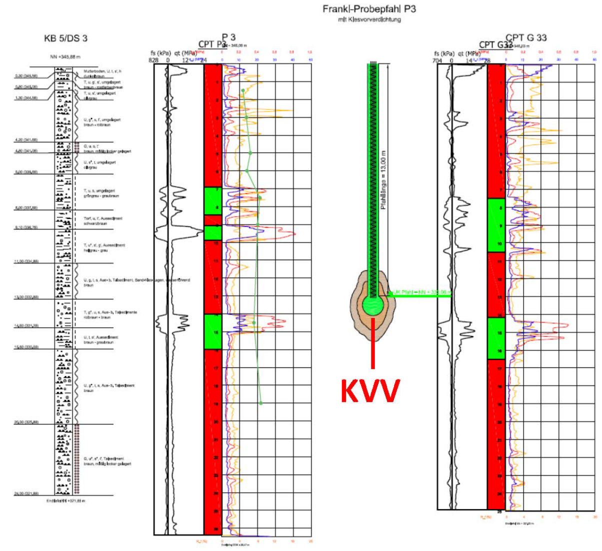

Figure 8. FRANKI test piles.

6. Foundation

6.1. Requirements

The settlement requirements apply according to FEM guideline 9.832 (Basis of calculations for S/R machines, tolerances, deformations and clearances in automatic small parts warehouses) to a maximum of 1.9 mm at 12.0 m and a maximum of 1.5 mm at 8.6 m center distance as maximum rotation allowed.

6.2. Loads

As mentioned above the structure was founded bay a total of 6 staircases and more than 200 single foundations. Depending on the loads 4 different types of single foundations were designed as shown by Fig. 10.

For the single foundations the permanent loads (G_k) varied between 4.509 kN and 11.616 kN with live loads (Qk) between 1.232 kN and 6.712 kN. For the staircases the permanent loads (G_k) varied between 47.515 kN and 73.336 kN with live loads (Qk) between 9.994 kN and 16.629 kN. The total loads sum up to 1.884.102 kN (G_k) and 1.056.475 kN (Q_k).

6.3. Foundation design / layout

The structure was founded on 200 individual footings, each resting on four to seven Franki cast-in-place concrete piles, depending on the load, usually with enlarged bases, sometimes with gravel pre-compaction. Within the structure 6 staircases are included as shown in Fig. 9.

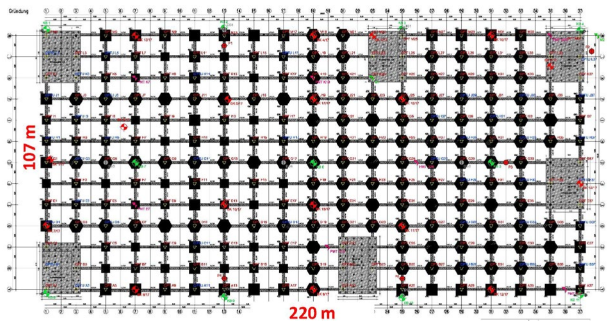

Figure 9. Foundation layout.

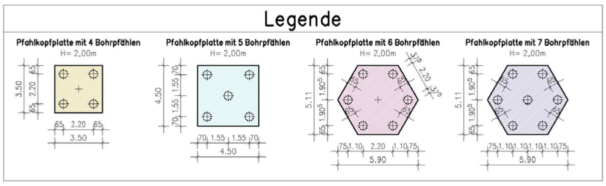

Figure 10. Pile layout.

The individual footings are connected by beams to form a cross-shaped girder grid. According to the load data provided by the structural engineer, the load applied to the individual footings is composed of an average of 60% permanent loads (G) and 40% live loads (Q).

6.4. Deep shallow footing

Special calculations were necessary to take into account the group effect of the piles.

The foundation was calculated for a deep shallow footing. Therefore a replacement level at the level of the pile base is assumed. According to the EA-Pile Guidelines, a replacement area is first calculated. Using the position-specific characteristic loads of the individual foundations and stairwells, the average characteristic area load, divided into the permanent load (G_k) and live load (Q_k), is then determined for the respective replacement area.

6.5. Deep foundation

The Franki tube is bottom driven to the required founding depth using an internal drop hammer. Once the desired toe level is reached, the enlarged base is constructed. Depending on the subsoil strength and the pile load, a defined base volume is driven/created. At the end of pile construction, the pipe is driven back into the base. Reinforcement is placed in the dry and concrete is introduced into the Franki tube. Once the required concrete is placed, the tubes is removed and pile is complete.

The pile base is designed based on the locally determined subsoil resistance, based on the driving energy applied during the last two meters of driving of the jacking pipe. The required base volume is then dimensioned using base design nomograms.

Figure 11. Deep foundation rigs.

Based on the load tests carried out on 5 Franki piles, the field tests carried out (particularly pressuremetres) and the evaluation of the cone penetration tests, layer 3 (volcano-sedimentary sequence) and layer 4 (red clays and siltstones) were suitable from a geotechnical point of view as the foundation level and for setting the Franki piles.

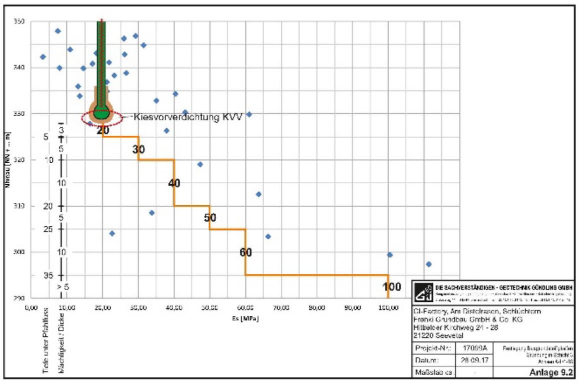

Figure 12. Determination subsoil stiffness and piling depth.

Fig. 12 shows the depth gradation of the stiffness modulus used in the calculations from the lower edge of the gravel pre-compaction (KVV).

The load-bearing capacity of the Franki pile can be increased by creating a larger base. Additionally, prior to actual pile construction, the existing soil can be improved with gravel pre-compaction (KVV). For this purpose, the pipe is driven into the ground below the planned setting depth of the piles. While simultaneously pulling the pipe, gravel is expelled and the existing soil is improved. After the KVV is completed, the pipe is driven back into the planned setting depth and the actual base is created. When KVV is implemented, the base volume is dimensioned by the driving work performed when re-driving the pre-driven pipe.

7. Settlement monitoring

The AKL + Shuttle area (axes 1 to 19) is subject to the FEM 9.832 guideline of the Fédération Européenne de la Manutention in Brussels, referred to here as FEM, which contains information on permissible tolerances and deformations of automatic small parts warehouses.

The settlement monitoring / measuring systems consists of:

- 4 Extensometers acc. to DIN EN ISO 18674-2: 2017-03
- 1 Inclinometer acc. to DIN EN ISO 18674-3: 2020-06
- 114 Measuring points

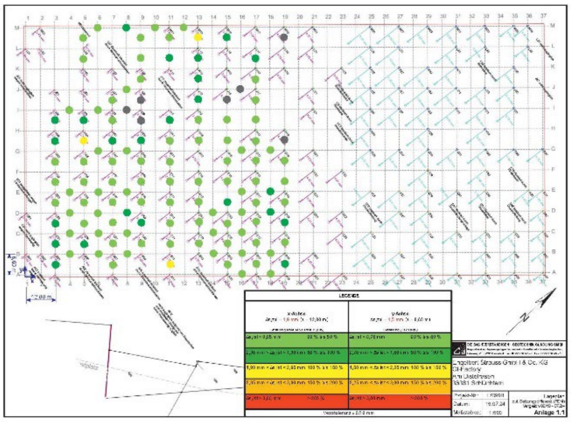

Figure 13. Settlement monitoring.

The settlement monitoring of the measuring points installed on the precast concrete columns above the individual foundations founded on pile groups is carried out every six months by means of fine levelling (settlement measurements).

According to the evaluation of the time-settlement curves, immediate settlement and primary settlement for the load state "structural load (P) and the traffic load applied (Q)" have now been completed, and the secondary settlement phase has been reached.

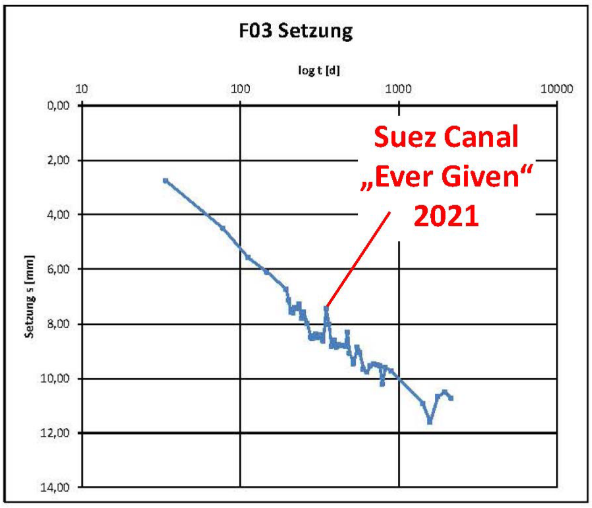

Figure 14. Time-setting diagram – measuring point F03.

In the storage area (axes 1 to 19), a slight decrease in the overall settlement on average has been observed since the last settlement assessment. This may be due to a lower storage level, e.g. in 2021 when the container ship Ever Given blocked the Suez Canal as shown by Fig. 14 and Fig. 15.

The observed long-term settlement behavior therefore shows no deviations from expectations, so that long-term, decreasing consolidation can be expected. Future load increases must always be considered and assessed separately.

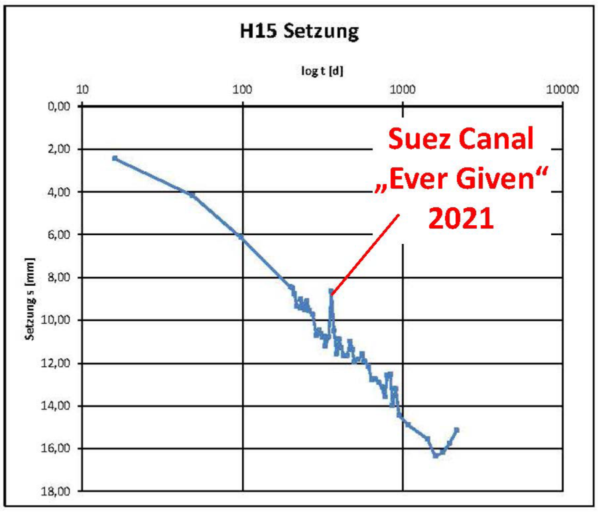

Figure 15. Time-setting diagram – measuring point H15.

8. Conclusion

In order to realize the foundation of a highly loaded high-bay warehouse with very high demands on settlement differences, the results of field tests using prebored pressuremeters by Ménard and phicometers had to be applied in addition to the usual exploration methods using core drilling, dynamic and pressure probing.

As is common practice in Germany, the results from the pressuremetres and the phicometer could be used exclusively to determine the soil parameters of the individual layers of the subsoil model. The field tests made a significant contribution to determining the layer-specific parameters, particularly the subsoil stiffness.

The German testing engineer did not allow calculations of the load-bearing capacities of foundations or piles from individual test results, so that the use of the results from the pressuremetres and phicometer for the determination of the layer-by-layer parameters was presented here.

This meant that the project could be completed economically and technically safely in a short construction period.

The measurement observations that have been ongoing for 5 years confirm the success.

Acknowledgements

The authors are grateful for the support provided by Engelbert Strauss GmbH & Co. KG, FRANKI Grundbau GmbH & Co. KG, StatiKo Bauingenieur-Gesellschaft mbH, Ingenieurbüro H. Dietz and Ingenieurbüro Becker & Partner GmbH.

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