Subgrade improvement measures for the main rescue roads in the urban redevelopment area HafenCity in Hamburg

Mesures d'amélioration du sol de fondation des principales routes de secours dans la zone du réaménagement urbaine de la HafenCity à Hamburg

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ABSTRACT: The level of many streets in Hamburg's HafenCity is being raised by around 3 m to ensure safety from flooding. The marshy soils in this area– mainly clay (a soft clay) and peat – necessitate the use of different foundation-soil improvement concepts for the limitation of settlement; these have to take account of the surrounding infrastructure (buildings, river-bank structures, services). The Honkongstrasse serves as a good example of such concepts. Stress and deformation measurements were carried out on the site, in which the concept of a "pile-supported, geogrid-reinforced sand sub-base layer" was used; this paper reports on the results.

RÉSUMÉ: Dans le quartier d'HafenCity à Hambourg, la plupart des routes seront surélevées jusqu'à 3 mètres pour atteindre le niveau de protection contre les eaux. Les sols en place, d'origine marécageuse, sont constitués d'argile et de tourbe. Du fait de l'hétérogénéité des sols, et en fonction des ouvrages existants (bâtiments, murs de rive, tuyaux enterrés), différentes approches ont été appliquées pour améliorer les sols et limiter les tassements. Dans cette communication, le cas d'étude de la rue « Hongkong » sera présenté. Dans ce projet, des géogrilles sont utilisées en renforcement d'une couche de forme sableuse pour la répartition des contraintes. Une instrumentation complète a été mise en place. Des mesures de contraintes et de déformation ont été effectuées. Les résultats de cette instrumentation sont présentés dans cette communication.

KEYWORDS: urban redevelopment, soil improvement, geogrid, piled embankment, expanded clay, pre-loading

1. INTRODUCTION

At the HafenCity in Hamburg, previously part of the harbour area, the current inner-city area south of the historic warehouse district is being extended by some 40 % to a total of 157 hectares (Figure 1). 5,500 dwellings for 12,000 residents are to be constructed, along with office space for 40,000 employees.

In the course of these infrastructure projects, the trafficked areas – with the exception of the quay and embankment promenades – are being raised from the current MSL +5 m to MSL +7.5 m to + 8.0 m, to make them safe for flood events.

Figure1: City-planning concept of the HafenCity Hamburg (as of January 2008)

The soil conditions around today's Honkongstrasse (formerly Magdeburger Strasse) are typical for the HafenCity Hamburg. Fill material of low bearing capacity overlies soft organic layers of clay and peat which in turn overly firm sands (Figure 2). Raising the level of the road embankment by approximately 3.0 m would have resulted in long-term settlements of between 300 and 400 mm, and significant differential settlements would have been expected.

The following subgrade-improvement methods are used to limit settlement in the HafenCity:

- pre-emption of settlement with a sand pre-loading layer and vertical drains
- use of lightweight materials (expanded clay)
- construction of a piled, geogrid-reinforced sand layer

The choice of method depends largely on the local boundary conditions. On the Honkongstrasse site, all three methods were used on different sections. Measurements of stresses and deformations were carried out on the section with the piled, geogrid-reinforced sand layer. The paper therefore concentrates in greater detail on this method.

2. METHOD DESCRIPTION AND CONCEPT

2.1 Sand pre-loading layer and vertical drains

If the local boundary conditions e.g. space available, existing and planned services, local structures (buildings, river-bank structures, sewers) and the time constraints permit, the use of a sand pre-loading layer and vertical drains to pre-empt settlements is an economical standard method.

To accelerate consolidation, vertical drains are installed in the area to be loaded. The planned, elevated cross-section is then constructed, and an additional 2.0 to 3.0 m thick sand pre-load is placed.

The consolidation of the weak organic layers is monitored over time using settlement gauges.

After the time required for settlement (usually at least three months), during which no further construction takes place, the sand pre-load is removed to the agreed planned height and the structure passes out of the responsibility of the earthworks contractor.

2.2 *Use of lightweight aggregates (expanded clay)*

In areas where pre-emption of settlement is impractical because of local structures or services, lightweight aggregates are often used. These materials significantly reduce settlements resulting from the raising of ground levels.

For forecast residual settlements of around 50 to 70 mm, the lightweight materials are placed to a depth of around MSL + 2 m.

The expanded-clay layer is wrapped in a nonwoven geotextile to prevent particle displacement and leaching-in of soil.

The use of expanded clay is regulated in the "Merkblatt über die Verwendung von Blähton als Leichtbaustoff im Untergrund von Straßen" of the Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV).

2.3 *Construction of a piled, geogrid-reinforced sand layer*

2.3.1 *Construction method and system chosen*

The system is characterised by vertical columns (lime-cement treated gravel, unreinforced) and an overlying sand layer horizontally reinforced with geogrids. Use is made of the arching effect of the overburden sandy soil while the foundation soil acts as a bedding layer. In contrast to concrete slabs on (reinforced concrete-) piles, in which the individual elements are very stiff in comparison to the surrounding soils, there is a pronounced interaction between the columns, geogrid and the foundation soil in the system described here.

In contrast to the methods described under 2.1 and 2.2, the foundation soil in this system is only subjected to low additional stresses. The major part of the vertical stresses is transferred in a concentrated manner by the vertical columns into the firm foundation soil. The system settlements remain proportionally very small both during and after the construction phase.

When correctly designed, the system possesses significant reserves of bearing capacity, so that subsequent interventions and changes within limits in the foundation soil have no influence on the serviceability of the structure.

The placement grid of the supporting elements should be designed to transfer the geogrid loads in an orthogonal manner. For Hongkongstrasse, this resulted in a rectangular grid with a spacing of 2.3 m normal to the embankment axis and 2.5 m in the axial direction; the diameter of the elements was 0.6 m (Figure 2). Reinforced-concrete columns with continuous steel reinforcement were used at the edge of the structure to cope with a bending moment (e.g. should any excavation be required at a later date) as a result of lateral pressure.

The geogrid-reinforcement is installed 150 mm above the columns in order to guarantee adequate safety against shear during the construction phase, and in case of large settlements. The reinforcement is placed at right angles to the placement grid, so that the layers are cross-laid in the longitudinal and transverse directions of the embankment.

In the transverse direction, the constructive situation leaves practically no room to anchor the geogrid. The design requirement of a short-term tensile strength of 400 kN/m is therefore assigned to two layers, which are wrapped round at the edges of the structure, and overlapped in the upper layer.

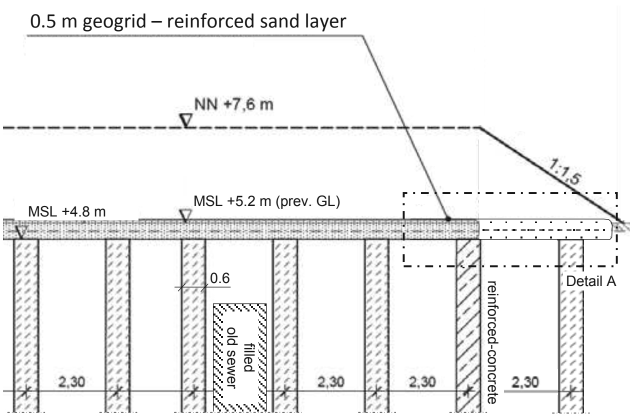

Figure 2: Cross section – piled sand layer

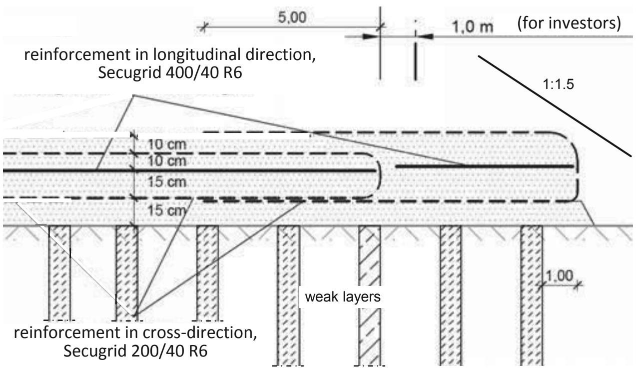

Figure 3: Detail A – sketch of system showing reinforcement placing (vertical scale greater than horizontal)

2.3.2 *Points of constructive relevance near Hongkongstrasse*

To avoid the risk of subsequent construction activity of investors endangering or destroying sections which have already been built, an area of 1.0 m of the traffic section must be able to be removed. Fill which intrudes into investor areas must also be removable.

In order to prevent any damage to the embankment-support system, the geogrid-reinforced fill layer was built with sufficient overlap (Figure 3). The outer section can thus be removed in the course of normal earthworks.

2.3.3 *Design and verifications*

The design of the support system is performed for the columns and the geogrid-reinforced fill layer in co-ordination with one another.

The columns are designed for the total load, and the contribution of the subsoil to load bearing and subgrade reaction between the columns is neglected.

The geogrid-reinforced layer was designed according to a verification concept which has already been used and proven itself several times in HafenCity Hamburg. The limit bearing capacity was first verified in accordance with a suggestion from Kempfert et al. (1997). A conservative value for subgrade reaction was used. This verification procedure does not enable any deformations to be inferred.

However, verification of serviceability and of deformation limitation is compulsory for all construction projects in the HafenCity Hamburg. A complementary design procedure was therefore adopted, using a method developed and extended from EBGEO, which at the time of planning was only available in its 2004 draft stage. This extended design method was verified for similar subsoil and loading conditions (Vollmert et al., 2006). The anticipated further settlements at the level of the reinforcement were estimated at less than 50 mm after termination of construction.

Comparisons with the current EBGEO (2010), available in its final form now that construction is complete, show that the design and verification of the system is sufficiently robust to cater even for the special case "Loss of Subgrade Reaction" in Load Case 3.

It must however be noted, that extreme changes in subgrade-reaction conditions – such as its total loss – will result in load redistribution in the sub-base layer. The long-term influence of these on the serviceability can currently not be finally estimated and is the subject of research. Taking serviceability aspects into account, a conservative, realistic estimate of foundation conditions is therefore critical in the design of such subsoil-improvement projects.

2.3.4 Accompanying measurement

The selection of the subgrade-reaction value at the underside of the reinforced layer is therefore a critical starting parameter for design. Values for this are usually derived from the stiffness modulus of the subgrade and the thickness of the weak soil layers. The actual reaction is, however, a variable whose value depends on, among other things, the soil improvement during the construction phase, consolidation processes, the stiffness of the geogrid-reinforced foundation layer and the sub-base layer.

In order to obtain further information on the subgrade reaction and the actual behaviour of the structure, it is necessary to investigate such structures in-situ. During the development of Hongkongstrasse, boundary conditions for monitoring with a measurement system were ideal, as not only the foundation soil conditions, but also the geometric conditions and the alterations anticipated in the medium term (development of the investor areas and resulting encroachments into the stress distribution in the structure) were seen as exemplary for the particular situation of HafenCity Hamburg.

The objective of the measurement programme is therefore the investigation and measurement of

- the state of stress in the geogrid
- the development of soil arching, taking construction and operational conditions into account
- the proportions of the load allocated to the supports and the weak layer
- the influence of variations in water-table level in the foundation soil, and
- the deformation situation at foundation level.

3. CONSTRUCTION AND MEASUREMENTS RESULTS

3.1 Sand pre-loading layer and vertical drains

After the necessary clearing away of foundations, the removal of old services and the search for unexploded ordinance, in the southern part of Hongkongstrasse, vertical drains were hydraulically driven into the foundation soil. Plastic strip drains with a width b of around 100 mm were used.

In installing the strip drains it was required to ensure that a depth of soft soil of around d = 1.0 m remained under the drains as a natural barrier to the lower groundwater aquifer (lower sands).

After this, the sand layer (including any pre-load) was placed. Sand with a silt content ≤ 5 % by weight, a uniformity coefficient U of approx. 2 and a rating of Z0 in accordance with the LAGA guidelines was to be used. The sands were compacted in layers to at least medium compaction density.

Below the level at which the sand was laid, settlement-measuring rods, each adjustable in length and with a base plate (1 m x 1 m) were installed, and these were continuously monitored while the pre-load was in place. A plot of settlement against time is shown in Figure 4.

3.2 Use of lightweight aggregate (expanded clay)

Lightweight aggregate in the form of expanded clay was used in the northern area of Hongkongstrasse.

Various active services crossed the construction area and it had to be ensured that these were not damaged during the excavation of trenches, around 3.5 m deep. In the area of the services, the expanded clay was installed in so-called big bags as a foundation for the services. In the remaining areas, the expanded clay was placed, spread, and compacted in layers to the design height (base of sand protection layer) (Figure 5).

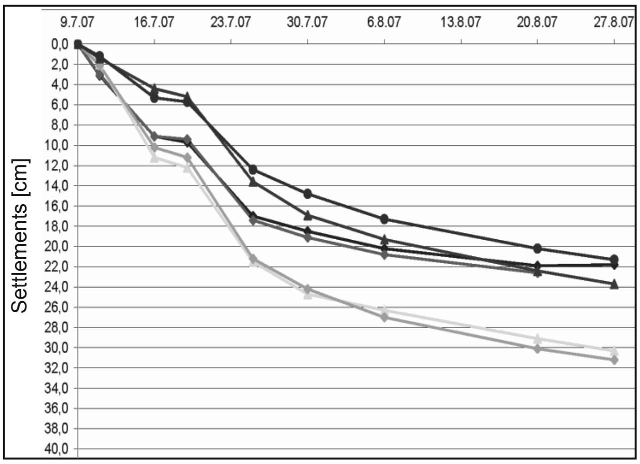

Figure 4: Development of settlement during loading phase

3.*3 Piled, geogrid-reinforced sand base layer*

3.2.1 Construction

For the required design working load of 500 kN, partial-displacement bored columns with a diameter of 420 mm and an unreinforced, fresh-in-fresh tapered cast cap C25/30 with a cap diameter of 600 mm were installed by GKT Spezialtiefbau GmbH working for Eggers Umwelttechnik GmbH.

High-strength, high-modulus geogrids Secugrid 200/40 R6 and Secugrid 400/40 R6 were used to reinforce the sand base-layer. The construction of the geogrid-reinforced sand layer had to be carried out with overlap. A length of grid from the lower layer, which was laid across the width of the base layer, was rolled and stored at the edge of the fill. After the lengthwise reinforcement and the fill had been placed, the stored roll was pulled up, wrapped round the fill, and overlapped by the length required in the design calculations (Figure 6). For a workmanlike placing it is therefore necessary to ensure that the roll overlaps are arranged in a staggered pattern in order to avoid distortion and twisting of the geogrids.

The results of the measurements have been published by Weihrauch et al. (2010) indicating the expected performance as well as meeting the deformation requirements as given by the design.

Figure 5: Placing of expanded clay

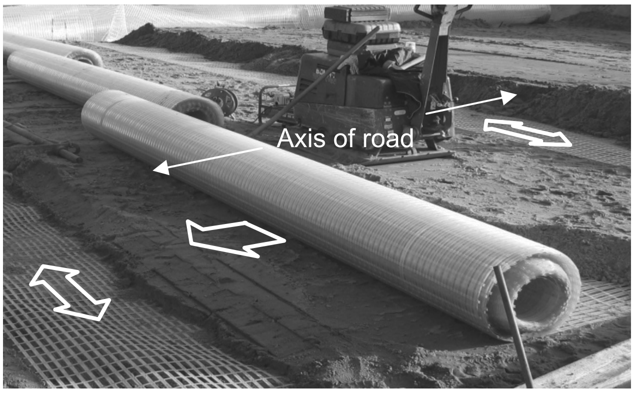

Figure 6: Laying of the geogrid

4. CONCLUDING REMARKS

Three quite different methods of soil improvement techniques were used in the area of Hongkongstrasse. The prime objective of the soil improvement is, in all cases, the reduction of subsequent settlements in order to guarantee the serviceability of the trafficked areas under operating conditions.

The decisive factors in the choice of construction method are the local conditions, the time constraints, and the economic conditions applicable to the section being planned or built.

Settlement pre-emption with vertical drains and a sand pre-load requires a relatively long lead time. Significant associated settlements must be expected in the immediate vicinity; in the case of existing buildings or services these will usually have to be classified as unacceptable. On the other hand, the foundation soil remains more or less undisturbed in its stratification and composition, and is free of construction elements.

In contrast to this, soil improvement using expanded clay, i.e. a lightweight aggregate, involves only very small additional settlements. This method is therefore advantageous mainly at the interface with existing structures, and with existing roads. Because of the cohesionless nature and the low compressive strength of expanded clay, difficulties can be experienced later if services and anchorage layers are installed, or reconstruction work carried out.

With its columns and the geogrid layers, the pile-supported base-course method contains the most construction components. Depending on the construction process of the columns, this method can be used even close to existing structures. Particularly in cases of large fill depths – and these are typical of the HafenCity – services can be constructed at a later date without problems. And the structure can be continued without a break in the adjoining construction section; building over existing elements such as pipes is not a problem. Perforation of the geogrid-reinforced base, e.g. by anchor layers, is possible in principle.

The sandfill material can be assumed to incur the lowest cost as regards the pure construction costs of the structure. Under the conditions applying at the HafenCity, the pile-supported, geogrid-reinforced method is usually somewhat cheaper to construct than an expanded-clay fill layer. Absolute costs must be ascertained taking into account project-specific reconstruction, protection and follow-on measures. In addition to the cost aspect, the time flexibility for individual measures, and their technical feasibility under local conditions, are decisive criteria.

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