Response observation of a full-scale geosynthetic-reinforced pile-supported system to environmental actions

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Abstract. The collected field data from well-instrumented reinforced embankments in the framework of a real project for the extension of the inner-city area at HafenCity in Hamburg is used to study the effect of environmental changes on the load transfer process over the structure lifetime. A particular focus is put to improve the understanding of the load transfer mechanism from the soil embankment to pile foundations through the reinforced geosynthetic layer and to investigate the corresponding long-term settlements. The time-dependent stress and strain distribution of the reinforced load transfer platform has been focused to investigate the process of soil arching on top of the piles and examine the overall settlement of the embankment. Finally, the most common available prediction models in European design guidelines are applied to estimate the loads on structural components and the results are compared with the measurements.

1 Introduction

So far, several analytical and empirical models have been proposed to predict the complex interaction of pile-soil-geosynthetic reinforcement and accordingly to estimate the resulting loads applied in different structure components. The majority of such models implement a so-called "soil arching" mechanism to spread the loads between different structure elements [e. g. 1-10]. Some of the aforementioned models are widely used in practice and are already implemented in the current design guidelines and standards to analyse geosynthetic-reinforced pile-supported (GRPS) embankments. In practice, the majority of GRPS embankments are currently designed using the design guidelines BS 8006-1 [11], EBGEO [12] and CUR 226 [13].

Despite of considerable advances in design and analysis of GRPS embankments due to the contribution of the aforementioned studies, there is no universal method yet for the design procedure, and the application of the current methods may lead to dissimilar outcomes [e.g. 14, 15]. Moreover, even after a proper design of a GRPS structure, changing of the boundary conditions over the structure life time (e. g. construction in the vicinity of the structure, variation of the water level) may cause unexpectable loads on the structure and, consequently, may endanger the stability or disturb the serviceability of the structure. This shows the necessity of conducting further experiments and especially field measurements to: (i) evaluate the existing design procedures in order to identify the applicability and validity

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range of these approaches and; (ii) to investigate the response of such structures to extreme load events which may induce due to unexpected events.Site plan and setup of instruments

1.1 Description of the site plan

At the HafenCity in Hamburg, which was previously part of the harbour area, the current inner-city area located in the southern part of the historic warehouse district was planned to be extended by 40 % (planned in 2008) to the total area of 157 hectares (Figure 1). In the frame of this project, the trafficked areas with the exception of the quay and embankment promenades were raised from the level of MSL +5 m to the level of MSL +7.5 m to + 8.0 m in order to keep them safe against flood events.

Fill material of low bearing capacity overlies soft organic layers of clay and peat which in turn overlie firm sands. Raising the level of the road embankment by approximately 2.0 m to 3.0 m would have resulted in long-term settlements of 300 and 400 mm, and as a result differential settlement would have been occurred. As an alternative solution, construction of a GRPS structure could have reduced the structure settlements.

Fig. 1. The development plan for HafenCity Hamburg and the location of Hongkongstraße.

1.2 Construction phases

The most highlighted construction phases and events occurred for the GRPS structure in Hongkong street from the beginning of the construction to present are presented follows:
Phase I: The concrete piles were constructed in the soft soil and pile caps were covered with a soil layer with a thickness of 15 cm (2009). The diameter of the vertical piles is 0.42 m and the pile caps are circular with a diameter of 0.6 m.

Phase II: In December 2009, the first layer of geogrid was placed over the piles on the soil cover layer. The transversal reinforcement was instrumented with measuring devices. The inclinometer was set-up and the earth pressure sensors were installed on the pile and in the middle of span (see Figure 2 for instrument set-up).

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Phase III: In February 2010, the reinforced sand layer on the piles was fully constructed with a thickness of 50 cm with one longitudinal (1 x Secugrid® 400/40 R6) and two transversal (2 x Secugrid® 200/40 R6) geogrid layers fabricated by Naue GmbH & Co. KG.

Phase IV: In March 2010, the soil embankment was constructed on the reinforced sand layer. Huge volume of soil was put on the reinforced sand layer over a relatively short time.

Phase V: In April 2010, the construction of the GRPS structure was completed and the heavy machinery and equipment were removed from the embankment crest. Moreover, some excavations were conducted in the vicinity of the pile embankment to access the water pipes which pass through the soil embankment in order to supply water to the neighbouring buildings.

Phase VI: In April 2011, the construction of the foundation of a so-called 'Green Peace' building was initiated beside the GRPS structure.

Phase VII: In September 2011, a structure beside the pile embankment was demolished. Moreover, the construction of the Green Peace building was proceeded by construction of a slurry wall beside the GRPS structure in order to prevent water to infiltrate the foundation using soil nailing technique to stabilise the soil on the vertical wall beside the pile embankment.

Phase VIII: In January 2013, the construction of the Green Peace building was almost completed.

Phase IX: From 2013 to 2018 several structures were built in the HafenCity area close to the GRPS structure (but not in the vicinity of the structure). The area has developed in a fast pace over the last 5 years.

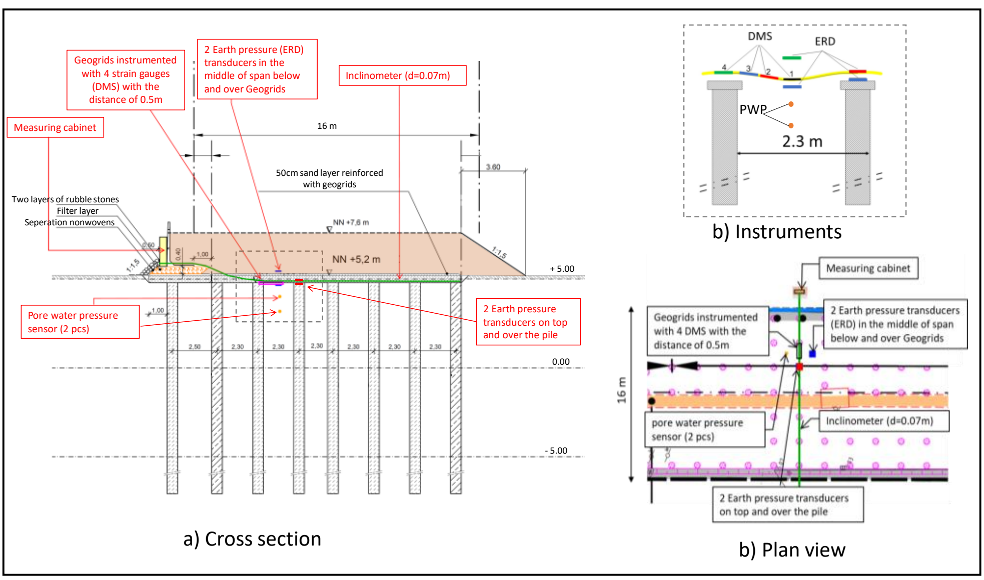

Fig. 2. Set-up of the instruments in the tested geosynthetic-reinforced pile embankment. (DMS = Strain gauges; ERD = Earth pressure transducers; PWP = Pore water pressure sensors)

1.3 Instrumentation and installation technique

In order to observe the short-term and long-term behaviour of the elevated geogrid-reinforced sand layer and pile foundation, several measuring devices are applied in the transversal direction of the embankment. The location of instruments is shown in Figure 2. In general, the GRPS structure is instrumented with four types of devices as follows:

Four strain gauges (DMS) were installed on one longitudinal element of the bottom transversal geogrid with an adjacent order and enable the measurement of the strain over the geogrid from the pile head to the middle of span (Figure 2).

The inclinometer has a clear diameter of 74 mm and is laid over a length of 17.0 m perpendicular to the road axis. In order to avoid any effect of inclinometer on deflection of the geogrid and, consequently, on the strain gauges, this device was installed on an adjacent row of column (Figure 2b).

2 Measurement results and discussion

2.1 Stress development on GR strip and pile foundation

As shown in Figure 3, an efficient transfer of the load to pile foundation due to the arching mechanism can be observed in the measurements. The majority of the load is applied on the piles and the geosynthetic-reinforced strips are subject to much less static loads compared to those transferred to the vertical bearing element (stress on GR strip to stress on pile ≈ 20 %). Moreover, the vertical stress on the pile head (ERD1) is approximately two times higher than the stress over the pile (ERD2).

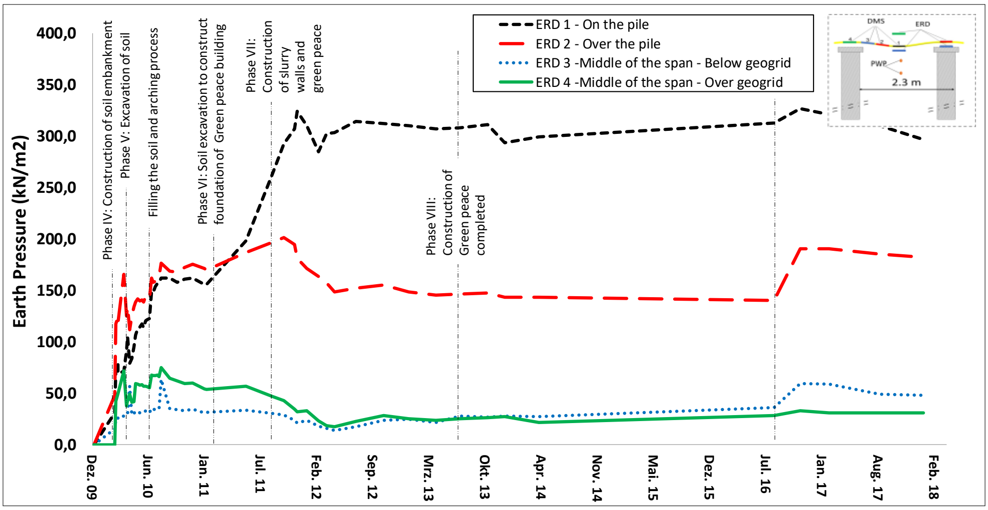

Fig. 3. Continuous measurement of earth pressure in soil from Dec. 2009 to Feb. 2018.

A distinct peak can be observed in March 2009, which is due to the construction of soil embankment on the reinforced sand layer, in which a large vertical force was applied on the GR strips and pile foundation over a relatively short time. After the completion of the embankment construction in April 2010, the stress in the soil is dropped suddenly due to the excavations executed in the vicinity of the GRPS structure to approach the water pipes which pass through the embankment (Phase V). By filling the digs with soil, however, the stress has reached its maximum value again. Dramatic changes of stress in soil and strain in the reinforcement were observed with beginning of the construction of 'Green Peace' building in the vicinity of the GRPS structure in April 2011 (Phase VI & VII). Due to the soil excavations for construction of Green Peace foundation, stress on the pile head is dramatically increased (Phase VI) reaching to its maximum value. By construction of the slurry wall (reinforced concrete wall) in September 2011 to balance the inward hydraulic forces and also retard the water flow into the soil embankment, the vertical stress on the pile

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head is first increased and then dropped. For the earth pressure in the middle of span, the analysis of the data showed a reduction of stress due to the constructions in Phases VI & VII. After the construction of Green Peace until August 2016, constant earth pressures were observed both on/over piles and in the middle of span. After a period of steady behaviour of the stresses in the structure which lasted for more than two years, the stress in soil is raised according to the measured data in July 2016 by all 4 earth pressures (ERD1-4). Since this time, the stress is being decreased gradually. The factors that caused such changes in earth pressure since August 2016 stayed unrevealed for the authors of this paper. However, this variation might be caused by the neighbouring construction sites as the area of HafenCity in Hamburg has been developed rapidly during the recent years.

2.2 Settlement of GR strip and pile foundation

The angle, settlement, deflection and depression of the geosynthetic-reinforced sand layer over the time are recorded by application of an inclinometer in the transversal direction of the embankment. The measurement is done for each 50 cm along the 16 m width of the embankment. The influence of the slurry wall and the construction of the Green Peace building on the behaviour of the GRPS structure may be seen clearly in the collected data by the inclinometer as illustrated in Figure 4.

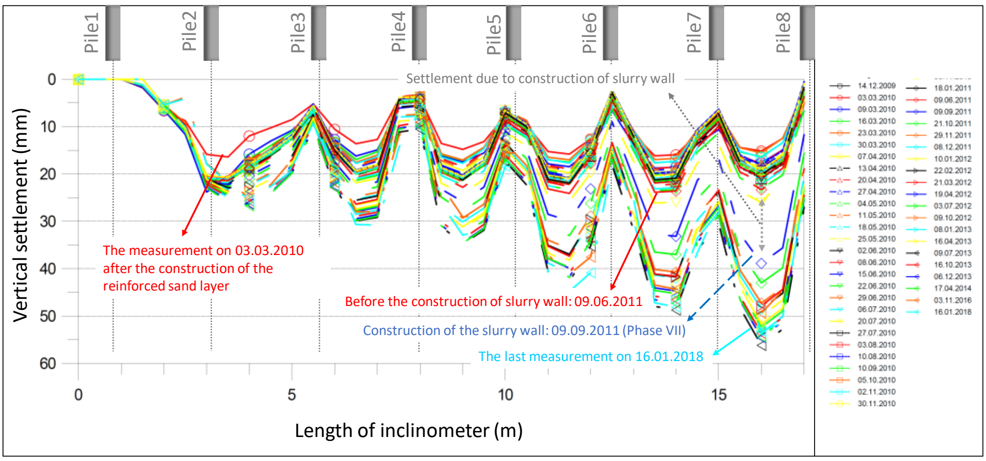

Fig. 4. Measurement of geosynthetic-reinforced strips and piles from Dec. 2009 to Jan. 2018.

The preliminary analysis of the data showed that the settlement due to the neighbouring construction in September 2011 has not only caused a deflection on the GR strips, but also caused settlement of the piles close to the slurry wall. However, the settlement of the GR strip is larger than the pile due to the higher rigidity of the pile foundation. In general, the pile foundation was designed to tolerate all types of static, cyclic and transient loads over the structure life time using a total resistance which is supplied by the pile skin friction and tip bearing capacity. This gives a high rigidity to the piles and, as a result, the maximum recorded settlement of the pile foundation due to the construction is only 20 mm.

3 Application of available design guidelines

In this section, the plausibility of the models proposed for analysis of GRPS embankments in design codes EBGEO [12], CUR 226 [13] and BS 8006-1 [11] is examined. The models in the mentioned design codes are applied to predict the vertical stress on GR strip and pile foundation and to estimate the associated deflection of GR strip considering the boundary conditions for the GRPS structure in Hongkong street in Hamburg. The results are compared against the data from the field measurements and are graphically illustrated in Figure 5.

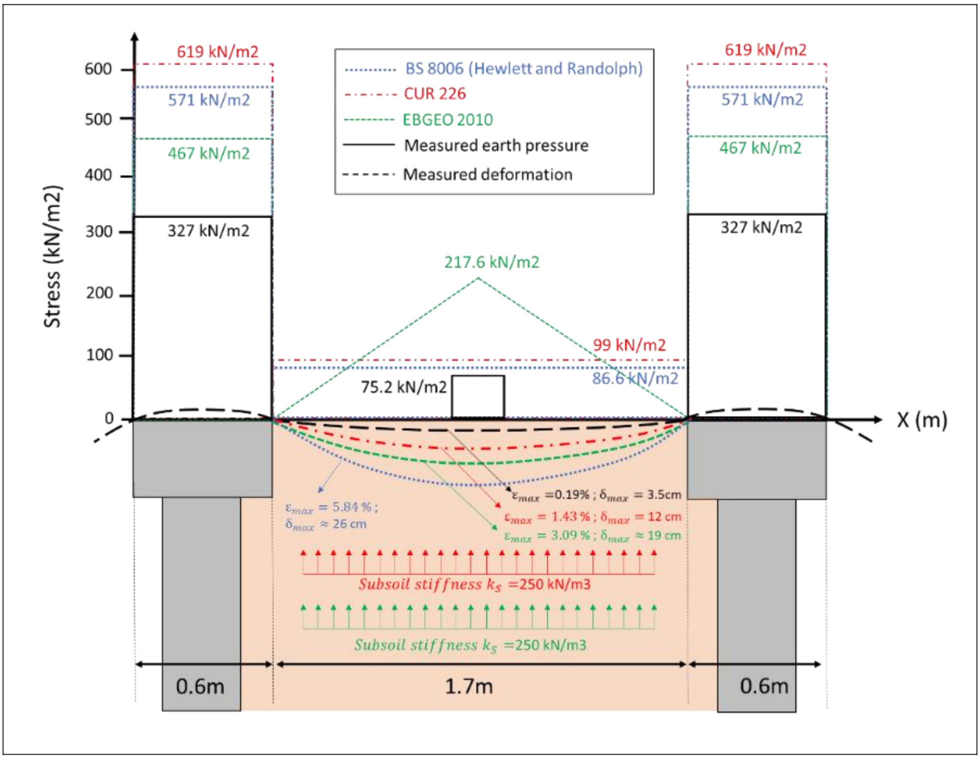

Fig. 5. Graphical comparison of measurements with results by application of models in available standards [11-13] for GRPS structure in Hamburg.

The models proposed in the standards assume that the embankment load is transferred to the piles by the well-known soil arching mechanism. According to this mechanism, a large part of the stress in soil is transferred to the adjacent rigid zones such as piles. Although all models in EBGEO [12], CUR [13] and BS 8006-1 [11] have been developed based on such a unified concept initially proposed by [16], the application of these models may result in non-identical loading of pile foundation, GR strip and subsoil. In general, the soil weight and surcharge load on a GRPS structure may be transferred to the underground soil as follows: (i) a large part of the soil weight is tolerated directly by the supporting members such as the piles (A); (ii) another part is carried through the membrane effect of the geosynthetic grid indirectly into the piles (B) and; (iii) the rest is transferred via the soft subsoil between piles (C).

Overall, among the models used in this study to predict the loads on the GR strips and to estimate the strain and settlement of the reinforcement, the model recommended in CUR 226 led to more logical results. However, even considering a very stiff subsoil ($k_s = 250$ kN/m^3), CUR 226 overestimates significantly the strain and deflection of GR. Moreover, CUR 226 predicts larger force on the pile cap (approx. 2 times higher) and earth pressure in the middle of span (approx. 20 %) compared to the measurement.

4 Key results and discussion

In this study, the collected data from several years of measurements related to a GRPS embankment constructed in Germany is used to: (i) study the behaviour of GRPS structures against the load events that may apply due to the changes in the environment of the structure over its life time and; (ii) evaluate the design models proposed in the most common standards and guidelines [11-13] by comparing their results against measurements. The key conclusions of this study may be summarised as follows:

- Due to the construction of slurry walls and buildings in the vicinity of the GRPS structure, considerable changes were observed in the behaviour of the structure. The knowledge gained from the analysis of data collected over more than 8 yeas revealed that the design of GRPS structures should not only be performed for boundary conditions in the beginning of construction, but also for the probable scenarios that may occur over the structure life time. This requires the preparation of a comprehensive development plan of the site and might only be possible with the cooperation of governmental decision makers (e. g. municipality) with consultants (project designers) and contractors.
- The application of available formulae recommended in the design codes EBGEO, CUR and BS 8006-1 for prediction of stress and strain in the GRPS structure in Hongkong street in Hamburg resulted in significant and moderate overestimation of vertical force on the mid-span GR strip (189%, 15% and 31% by EBGEO, BS 8006-1 and CUR 226 respectively) and a large overestimation of forces on the pile foundation (43%, 75% and 89% by EBGEO, BS 8006-1 and CUR 226, respectively) as compared to the measurements.
- BS 8006-1 has adopted the conventional models developed by [17] and [2] which determine a constant distributed load on the GR strips and ignore the effect of subsoil stiffness in prediction of strain and stress in reinforcement. Based on the knowledge achieved from this study and considering a high stiffness of the subsoil in GRPS embankment in Hamburg, a design by BS 8006-1 provided very conservative results.

Considering dissimilar outcomes resulting by the application of current design formulae, further experiments and field measurements are needed through which the applicability range of available models in terms of load and subsoil variations are identified.

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