Geotechnical challenges in the design of the new Lueneburg lock next to the existing ship lift

Défis géotechniques à relever dans la conception de la nouvelle écluse de Lunebourg à proximité de l'actuel ascenseur à bateaux

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ABSTRACT: The Federal Waterways and Shipping Administration of Germany is currently planning the construction of a new lock next to the existing Lueneburg twin ship lift on the Elbe Lateral Canal. The ship lift was built between 1969 and 1975 and was at the time the largest ship lift in the world. The vertical lift of both the ship lift and the new lock is 38 m. The new lock will be the biggest of its kind worldwide. Throughout construction and thereafter the adjacent ship lift is to remain in operation. The construction of the lock requires an excavation pit of about 260 m length, 60 m width and 26 m depth. The pit design includes a 2 m diaphragm wall supported by concrete struts and a tremie concrete seal secured by uplift piles. Extensive 2-D and 3-D numerical simulations (FEM) were carried out to determine the exact location of the lock based on predefined allowable deformations of the ship lift. Furthermore, the numerical model was used to derive earth pressure distributions for the wall design. In order to verify the results of the FEM model, a 3-D numerical model using FDM was developed simultaneously. The geotechnical challenges in the design of a large lock next to an existing ship lift along with the results of the numerical analyses, both FEM and FDM, are presented in this paper.

RÉSUMÉ : L'Administration fédérale allemande des voies navigables et de la navigation (Wasserstrassen- und Schifffahrtsverwaltung des Bundes – WSV) planifie actuellement la construction d'une nouvelle écluse à proximité de l'ascenseur à bateaux à deux sas de Lunebourg situé sur le canal latéral à l'Elbe. Construit entre 1969 et 1975, cet ascenseur à bateaux était à l'époque le plus grand du monde. Le dénivelé de l'ascenseur et de la nouvelle écluse est de 38 mètres. La nouvelle écluse sera la plus grande de son type dans le monde. L'ascenseur restera en opération pendant et après la construction de celle-ci. La construction de l'écluse requiert une fouille d'environ 260 mètres de long, 60 mètres de large et 26 mètres de profondeur. La fouille consistera en une paroi moulée de deux mètres, soutenue par des étais en béton et une semelle en béton coulé sous l'eau, stabilisée par des pieux travaillant à l'arrachement. Pour déterminer l'emplacement exact de l'écluse, d'exhaustives simulations numériques FEM en deux et trois dimensions ont été exécutées sur la base des déformations prédéfinies admissibles de l'ascenseur à bateaux. En outre, le modèle numérique a été utilisé pour déterminer les distributions de poussées de terres utilisées pour la conception de la paroi moulée. Dans le même temps, un modèle numérique 3-D par méthode de différences finies (FDM) a été développé afin de vérifier les résultats obtenus par le modèle FEM. Nous présentons dans le présent article les défis géotechniques à relever dans la conception d'une grande écluse située à proximité d'un ascenseur à bateaux d'ores et déjà construit ainsi que les résultats des simulations numériques FEM et FDM.

KEYWORDS: lock, ship lift, numerical modelling, FEM, FDM

1 INTRODUCTION

The Lueneburg twin ship lift (Figure 1) was built between 1969 and 1975 and is situated on the Elbe Lateral Canal (Elbe-Seitenkanal) which connects the port of Hamburg to the entire waterway network of Germany. With a vertical lift of 38 m it was at the time of construction the largest ship lift in the world. The size of the ship lift's troughs is 100 x 12 x 3.4 metres. Due to these trough dimensions the ship lift nowadays represents a bottleneck on this major waterway, since today's larger vessels of 110 m length cannot pass through the ship lift and push tows have to decouple before entering the ship lift.

In order to improve the traffic situation on the Elbe Lateral Canal the Federal Waterways and Shipping Administration of Germany is planning the construction of a new lock next to the existing twin ship lift. The new lock will have a chamber size of 225 m length and 12.5 m width enabling larger vessels and push tows to pass through the lock thereby improving transit.

Figure 1. Aerial photograph, north-east view, of the existing Lueneburg twin ship lift.

The design of the scheduled lock is a reinforced concrete frame structure. Due to the limited space available the water saving basins are situated within the chamber walls making the new lock the biggest of its kind worldwide (Figure 2).

Throughout construction and thereafter the adjacent ship lift is to remain in operation. Due to the small allowable deformations of the ship lift and its lift system, particular focus had to be put on both the exact location of the lock as well as the geotechnical design of the required excavation pit.

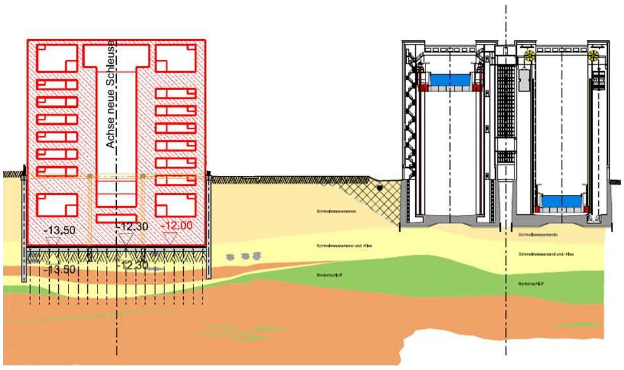

Figure 2. Cross-section of the scheduled new lock (left) and the existing twin ship lift (right).

2 GEOLOGY AND GROUND WATER CONDITIONS

In 2011 an extensive ground investigation was carried out including boreholes and cone penetration tests of up to 70 m depth followed by extensive laboratory testing. Additionally, geophysical crosshole and downhole testing was carried out at different locations to derive the dynamic soil properties required for the intended numerical analyses. Furthermore a groundwater monitoring system was installed in order to establish the design water levels.

The local geology is composed of superficial quaternary soils, consisting mostly of dense to very dense sands and an interbedded cohesive silt layer of varying thickness.

The geo-hydraulic conditions show two aquifers separated by the above mentioned cohesive layer. The ground water conditions of the upper aquifer are strongly influenced by the ship lifts drainage system and the canal itself. The lower aquifer is confined.

3 EXCAVATION PIT DESIGN

The construction of the lock requires an excavation pit of approximately 260 m length, 60 m width and 26 m depth. The principal requirement for the excavation pit was a design that would neither impair the stability of the ship lift nor change the ground water conditions within the area.

The developed pit design includes a 2 m diaphragm wall braced by a framework of longitudinal and transverse reinforced concrete struts. This framework of struts rests on bored piles at the connecting joints to prevent buckling. The bottom of the pit is sealed by a tremie concrete slab which is secured against uplift by more than 3000 tension piles. The tension piles have a length of approx. 35 m.

The location of the excavation pit in relation to the ship lift was determined by numerical modelling, the results of which will be presented in the following section.

4 NUMERICAL MODELLING

Extensive 2-D and 3-D numerical analyses were carried out using two different numerical methods, the finite element method (FEM) and the finite difference method (FDM).

Primarily the numerical analyses were used to determine the exact location of the lock based on predefined allowable deformations of the ship lift. However, during the planning process of the excavation pit, the numerical models were also used as an additional tool to verify as well as to calibrate the geotechnical design of the pit. In order to do so, the numerical models had to reflect both the design and construction stages of the pit as accurately as possible. Hence, close collaboration between the numerical modelling and the geotechnical design was imperative.

4 .1 *Finite Element Analysis*

The finite element analyses were carried out using the software packages Plaxis 2D, Version 2012 and Plaxis 3D, Version 2013.01, 64bit.

The initial analyses were carried out using a 2-D FEM model of a cross section as shown in Figure 2. The spacing between the ship lift and the lock was varied between 40 and 60 metres. During this process the impact of some of the major parameters of the model such as the bracing and the foundation type of the excavation pit as well as the soil parameters were analysed. The model was calibrated using settlement measurements of the ship lift during and after construction. Additionally an independent 2-D FEM model was developed simultaneously by the client's geotechnical advisor (BAW) to verify the results.

In order to capture all of the project's three-dimensional effects a full 3-D FEM model was developed. In addition to the ship lift and the scheduled lock with their surroundings, this model includes the existing approx. 40 m high upstream dam as well as the downstream canal (Figure 3).

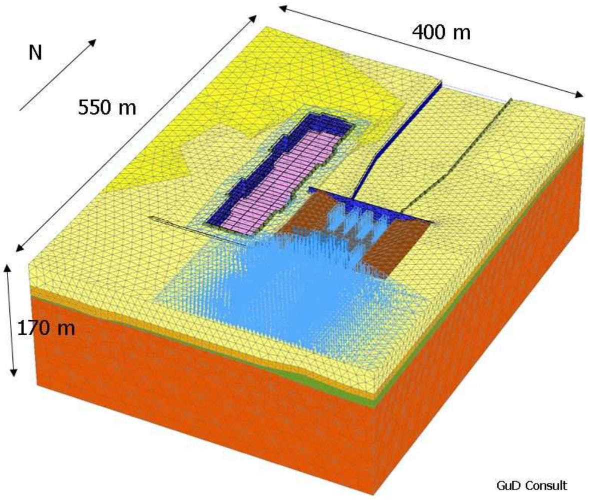

Figure 3. Top view 3-D FEM model (Plaxis 3D) of existing ship lift (right), lock excavation pit (left) and surroundings.

4.1.1 *Constitutive Model*

The mechanical behaviour of the soil was modelled using the Hardening Soil (HS) model with small-stain stiffness (HSsmall). The Hardening Soil model is a well-established advanced shear and volumetric hardening constitutive model for the simulation of plastic soil behaviour (Schanz 1998, Schanz et al. 1999, Plaxis 2012). The additional implementation of the so-called small strain stiffness in Plaxis is an extension of the HS model taking into account the phenomenon of increased soil stiffness at small strain levels (Benz 2007, Plaxis 2012).

The soil parameters were derived from the results of the above mentioned ground investigation with a particular focus on the stress dependent stiffness modules. The parameters needed to describe the small strain stiffness were deduced from the crosshole and downhole seismic. The parameters for the cohesive silt layer were calibrated using the results of the laboratory triaxial and oedometer tests. The full set of soil parameters were agreed upon between the consultant and the client.

4 .2 *Finite Difference Analysis*

The finite difference analysis was carried out using the software package Flac3D 6.0, Itasca Consulting Group, Inc.

Due to the significance of the project and in order to independently verify the result of the 3-D FEM numerical model by the consultant, a full 3-D FDM model was developed simultaneously. The extent of this model is comparable to the discussed 3-D FEM model and includes all major components as mentioned in section 4.1 (Figure 4).

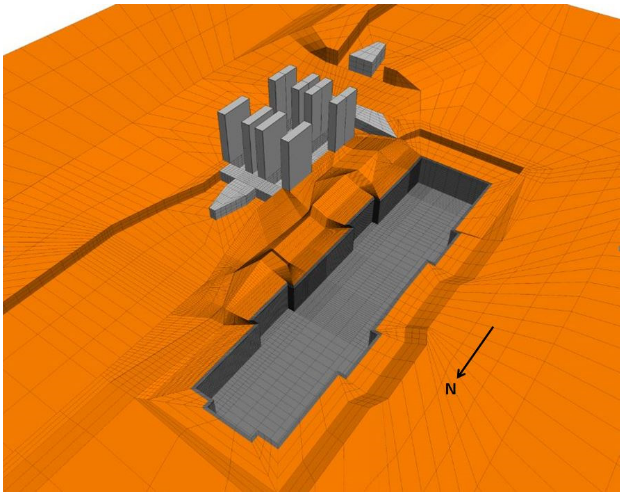

Figure 4. Top view 3-D FDM model (Flac3D) of existing ship lift (left), lock excavation pit (right) and surroundings.

4.2.1 *Constitutive Model*

The mechanical behaviour of the soil was modelled using the newly formulated Plastic Hardening (PH) model (Itasca 2016). The PH model has been developed based on the work by Schanz 1998 and Schanz et al. 1999, thus being comparable to the HS model used in the FEM analyses.

In order to model the effect of the small-strain stiffness, which is not implemented in the PH model, a simplified user defined function was adapted in which the soil stiffness is increased using a bi-linear function once the strain level falls below a pre-defined value. The defined strain and stiffness levels were adapted from the dynamic stiffness parameters of the FEM model.

5 RESULTS

The following section presents a summary of the main results of the different numerical analyses discussed above.

5 .1 *Deformation of the ship lift*

The main objective of the numerical analyses was to determine the location of the lock in relation to the ship lift based on its predefined allowable deformations. Thus the maximum deformations of the ship lift's foundation slab throughout the construction stages were analysed and compared to the allowable tilt of the ship lift towers.

By nature the deformations decrease with increasing spacing between both buildings. As a result of the extensive 2-D FEM analysis, the spacing between the lock and the ship lift was set to 60 m. The maximum heave of the ship lift's foundation occurs at the completion of the excavation pit. The subsequent loading due to the construction of the lock reduces these deformations with the end result of a small overall settlement of the ship lift (Figure 5).

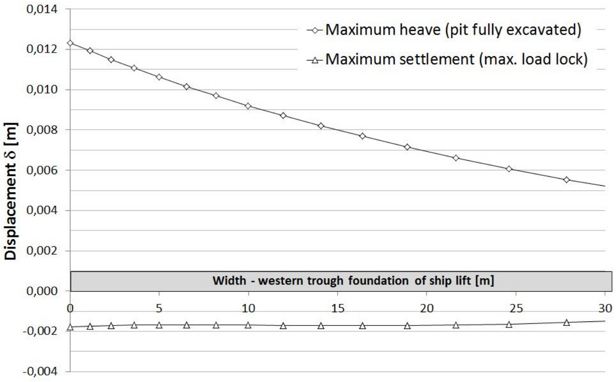

Figure 5. Maximum displacements of ship lift's western trough, 2-D FEM analysis (BAW).

The next step was to verify the above results using the 3-D FEM model which allowed a more accurate insight into the different mechanisms of the undertaking.

The settlements of the above 2-D analysis could be confirmed using the full 3-D FEM model. The deformations obtained are within close range of the values of the 2-D analysis. The ship lift tilts towards or away from the pit depending on either excavation or loading, i.e. construction of the lock. Additionally the 3-D model shows a tilt of the ship lift in longitudinal direction, an effect which could not have been captured by the 2-D model. The maximum deformation, either heave or final settlement occurs in the North West corner of the ship lift near the middle of the adjacent excavation pit (Figure 6).

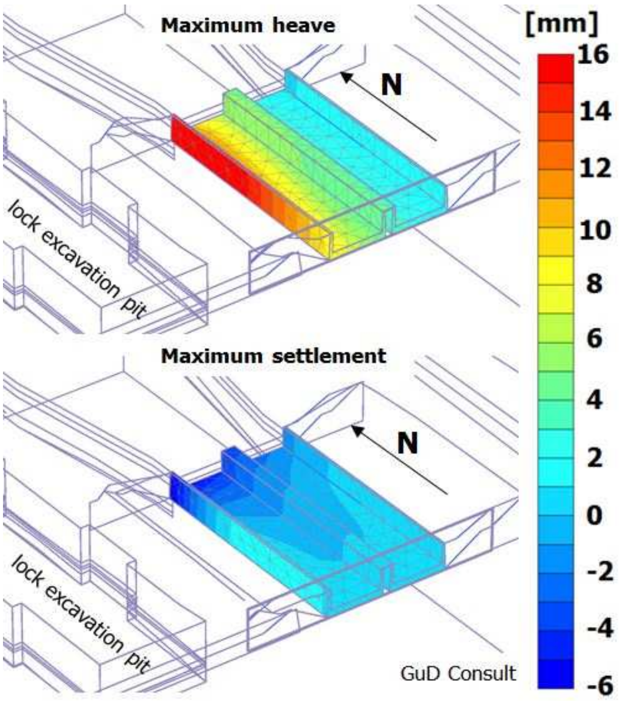

Figure 6. Ship lift foundation, max. heave (top) at full excavation stage of adjacent pit and max. settlement (below) after lock construction, 3-D FEM analysis.

The deformations obtained from the 3-D FDM model were yet again similar to the above 2-D and 3-D FEM computations providing additional confidence in the results obtained (Figure 7).

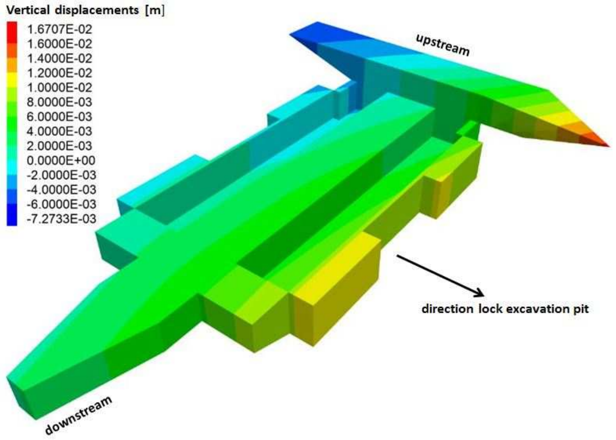

Figure 7. Ship lift foundation, max. displacements (heave) at full excavation stage of adjacent pit, 3-D FDM analysis.

Apart from the deformations of the ship lift the 3-D model was used to analyse the settlements of the existing upstream dam and the foundation of the canal bridge connecting the dam with the ship lift. The computed deformations were within the allowable tolerances.

5.2 *Excavation pit design*

The numerical models, particularly the 3-D FEM model, were used as an additional tool during the design phase of the pit to verify the geotechnical design. The main use was to derive earth pressure distributions as well as the modulus of subgrade reaction for the wall design. During this process, comparisons between the results of FEM and the geotechnical design were made - such as wall bending moments, shear forces and strut forces - to ensure design assumptions were on the safe side.

6 CONCLUSION

The scheduled construction of a new lock next to the existing Lueneburg twin ship lift has brought with it a number of geotechnical challenges. Due to the significance of the project and the requirement that the adjacent ship lift remains in operation, multiple extensive numerical analyses have been carried out using 2-D and 3-D models. Different numerical methods, FEM and FDM, have been used to independently cross-check the numerical result.

The results obtained from these different analyses regarding the predicted deformations of the ship lift were within very close range of each other. This provides confidence in the decision of the chosen location for the new lock.

The numerical models also proved to be very useful tools in verifying and thus supporting the analytical geotechnical design of the excavation pit providing additional insight into a complex 3-D problem.

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