Development of pressure and deformation at a quai wall in the Hamburg harbour

Développement de la pression et la déformation d'un quai au port de Hambourg

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ABSTRACT: Because of the further deepening of the harbor basins specially in the German seaports the retaining wall construction will gain importance in future. The larger height of the constructions and the application of fundamentally other construction methodologies raise the question whether the current design codes and designing rules still deliver a correct description of the structure loading. Therefore measurements and calculations have been carried out at the O´Swaldkai at the Hamburg harbour since 1992 by the Institute for soil mechanics and foundation engineering of the Technical University of Braunschweig (IGB·TUBS) required by the River and Harbour administration, Hamburg

1 INTRODUCTION

Because of the further deepening of the harbor basins specially in the German seaports the retaining wall construction will gain importance in future. The higher surface jumps and for the driving unfavorable ground conditions in the Hamburg harbor will replace the for decades prevailing sheet pile wall construction method. The larger height of the constructions and the application of fundamentally other construction methodologies raise the question whether the current design codes and designing rules still deliver a correct description of the structure loading.

The most decisive differences at the comparison of retaining wall- and sheet pile wall construction are in the development of the earth pressures. During the driving work of the sheet pile wall in the water no earth pressure occurs. Finally through the sluicing of the back-packing material appear horizontal stresses whose size can not be indicated exactly. Under the assumption of relieving wall displacements one can proceed that after the backfilling or back-packing nearly the active earth pressure has adjusted.

Considering the retaining wall which is constructed on a on-land construction site, there is first of all a primary state of stress, the earth pressure at rest, whose size can only be estimated. The slot is excavated with a gripper and supported through a fluid. Thereby, the primary state of stress is transformed into one the fluid pressure corresponding condition. By concreting in the slot horizontal stresses emerge which correspond to the concreting pressure and lie over the stresses forced by the fluid because of the larger unit weight of the unset concrete. With the following driving of the cast-in-place pile a further increase of the stresses is expected (Rodatz, 1992).

The development of the stresses behind a quay wall construction, however, does not only depend on the construction method, but also on the possible displacements. So the question raises whether a retaining wall presents a similar flexible system as the sheet pile wall to allow the necessary movement for the creation of the active earth pressure.

Basically with these constructions, which differ in geometry, constructivity and methodoligy clearly from the current methods a new way of constructing is followed up. That is why the Institute of Foundation and Soil Mechanics of the Technical University of Braunschweig (IGB·TUBS) conducted this measuring and investigating program in th^ Hamburg harbor.

2 PROJECT DISCRIPTION

To accept further traffic in the Hamburg free port the expansion of the O´Swaldkai was designed for additional berths. The loading and unloading procedure should be conducted with both traditional cranes and container loading bridges. For the conduction a joint venture of the enterprises GKT Spezialtiefbau, H.C. Hagemann and Dyckerhoff and Widmann INC in 1992 was authorised. The main step at the O´Swaldkai west was the building of an approx. 130 m long quay wall as a retaining wall construction (Böttger et al. 1992).

With the different and for the most part of each other independent measuring systems informations about the stress and deformation should be gained. Thereby the measurements were accomplished on both the load side, which means in the soil and also on the resistance side, which means in the reinforced concrete structure. The electric devices were installed in five depth positions in the area of the retaining wall and at three places in the area of the quay plate.

The devices were customary, but adjusted to the special conditions, measuring systems with electric data taker capability. The development of extensive earth pressure cushions and their technical conception is described in Maybaum (1996).

3 CURRENT DESIGN CONCEPT

Usually the investigation of the loads affecting quay wall are based on an analytical calculation, which leans on the soil parameters, angle of internal friction and cohesion. The sequence of the calculation and the obeied boundary conditions are

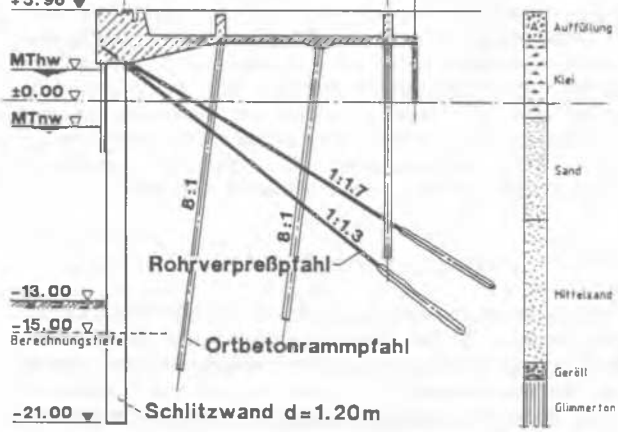

Figure 1. New construction of the O´SwaldkaI

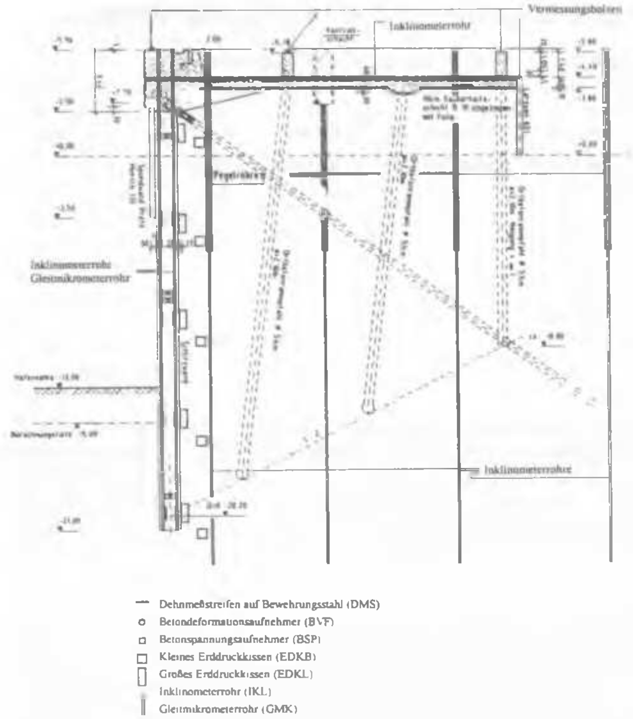

Figure 2 Main measurement segment

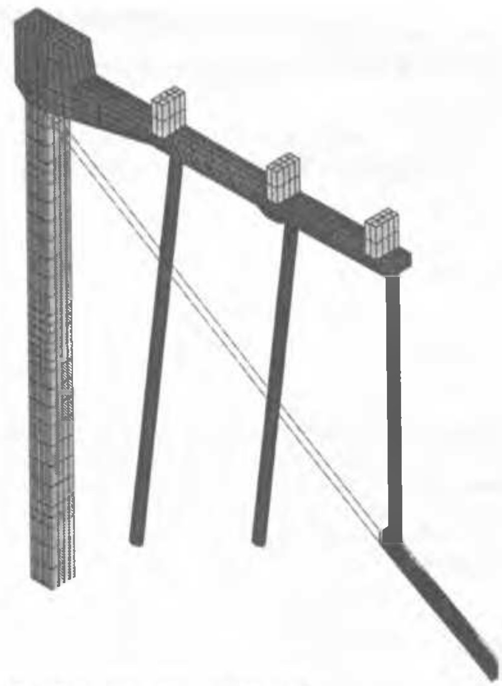

Figure 3 Finite Element Modell

described in the "Recommendations of the Committee for Waterfront Structures, harbors and waterways". In Hamburg the general design codes are completed with the specimen of the River and Harbour administration in details expanded and explained. In the development of the measuring concept and the establishment of the design assumptions for the retaining wall at the O´Swaldkai the experiences and knowhow of the calculation of quay wall in the sheet pile construction method were appropriately considered.

The safety- and measuring concept rests on the introduction of reduced soil parameters which must fulfill the demands of global safety in the stability analysis. The earth static calculation gives only the loads, which are to be considered in the static calculation of the building. Essential shortcoming of the analytical calculation exists in the insufficient consideration of the interaction between soil and building. The stress- and deformation fields adjusting at quay wall constructions can not get the necessary degree of admittance in the judgment of the stability.

In soil mechanics it is usually proceeded on the assumption that in the active limit state the determining earth pressures concerning the theory of Coulomb adjust as the smallest possible loads. The comparison of wall deformation and earth pressure shows a move direction from the soil continuously decreasing earth pressures.

Investigations of Breymann (1983) have shown, however, that smaller horizontal stresses are measured. All accomplished attempts showed that first of all in dependence on the strain a so-called point of failure is reached, at which the pertinent coefficient of active earth pressure remains clearly below the k_{ah} -value. First with increasing values the curve approaches asymptotically from below the Coulomb's borderline.

4 FINITE ELEMENT MODELL

The calculations were accomplished with the Finite element program ANSYS. The Structural model divides into the three parts material modelisation, geometric modelisation and order of the construction events.

For the soil the constitutive equation of Drucker- Prager with expansions for the registration of the stiffness loss and the isotropic change of the yielding cross section was used. The parameters angle of shearing friction φ' and cohesion c' are to be taken from the design profile.

In shear tests on cohesive and non-cohesive soil the appearing shearing stress rises first at increase of the deformation and then falls after reaching a maximum value again. For non-cohesive soil this behavior can be described with the help of the so-called rest of the angle of internal friction. Because of construction management and hydraulic demand of the soil underneath the basin of the habor the structural changes besides the loss of cohesion and resistence to friction (final strength) are to be considered, too. They have been recorded as reductions of the stiffness in the calculation. The four decisive influences are:

- wash-out through berth- and cast off of ships
- Loosening of the soil during the excavation period
- Disturbance of the equilibrium through the current circulation of the wall
- Liquefaction of the soil due to wave propagation

While the loosening of soil infront of the retaining wall through a multi bucket dredger, as it was used here, large dynamic loads appear in the basin of the habor. Constant burdens also effect the soils underneath the basin of the habor which have their reason in the vertical current circulation of the wall during the changes of the tides. In addition to that pore water pressure gradient from natural or due to a vessel wave propagation exists which can provoke a liquefaction of the soil in the area of the surface (Magda, 1993).

However, the extent of the four named effects in the soil mechanical sense provoked parameter changes can, if at all, be estimated only rough for each single case. As part of the check of the calculation it is tried to quantify the influences of final strength and stiffness loss through parameter variations and final value comparison in their entirety.

5 STRESSES IN THE SOIL

The development of the water pressure distribution resulted on the basis of the determination of the free groundwater level in open levels under acceptance of a linear hydrostatic increase. Additinionaly 13 earth pressure cushions were installed to record the total stresses. For the judgment of the primary stage of stress in the soil five earth pressure cushions were inserted in drillings approx. 50 cm from the retaining wall already before the beginning of the construction. The constant tidal ranges led to a quick stabilization of the measured values, so that already after a short time statements could be made for the earth pressure at rest

During the manufacture of the retaining wall the state of stress in the soil are subject to an enduring change. First of all the slot is excavated with a gripper and kept open through the support liquid The primary horizontal stresses which emerged from the product of vertical stresses and k_0 -value, are now in equilibrium with the liquid pressure which rises with the depth linearly and totals at the wallbase to approx. 250 kN/m² Already during the inserting of the reinforcement in the slot filled with the support liquid all gages were activated. The measuring results showed that the horizontal stresses of the concrete brought in with the tremie method reach only about 60% the hydrostatic pressure.

The in-situ pile formed by driving were constructed after completion the retaining wall. With the inserting of the concrete volume in the impending soil an increase of the horizontal stresses has been expected. On the basis of the measured results no considerable increase, however, derives from the stress niveau. In fact the total stresses rise quickly, but they depend to the greatest part on a temporary increase in the pore water pressure. All in all it can be said that the disturbance of the horizontal state of stress was far smaller than assumed through the construction of retaining wall and piles.

After the construction of a formation on the bottom edge of the quay plate at NN +3,5m and the exposing of the pile heads first a concrete underneath has been brought in place. Since the concrete of the quai plate is first in the harden-out condition, it has been introduced in the FEM - computation in this calculation step almost stiffnessless to guarantee an introduction of the forces resulting from concrete dead weight in the soil.

The changes due to the further construction steps, particularly the excavating, are related to the point in time after completion of all concrete parts and the soil backfill. The calculated and measured deformation present the difference of the displacements compared to this state.

The mathematical emerging horizontal stresses after excavating are depicted in picture 4.

First considering the land side it has obviously occurred a reduction of the active earth pressures particularly in the field area. The absolute stresses total to 65 kN/m² in the primary case and 30 kN/m² for the completed excavation. The earth pressure reduction is limited in the area of the pile foot because of the here existing load introduction. Furthermore a stress concentration is recognized on the passive side in the area of the harbor basin surface.

If the calculated and measured deformation curves for the

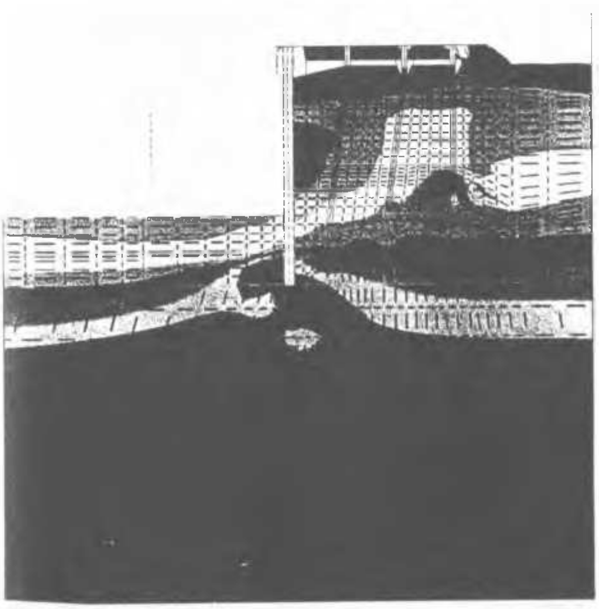

Figure 4. Horizontal stresses after excavating

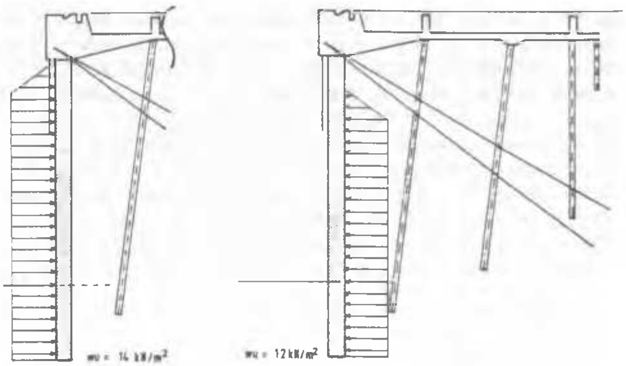

Figure 5. Earth- and water pressure due to the tide

construction end phase are compared with eachother the influence of the fixed support is clearly overestimated. The considered final stiffness events due to excessive shearing demand do not enough to receive a realistic picture of the stress - deformation behavior of the retaining wall and soil in the fixing area. Therefore in the following calculation steps a progressing stiffness loss of the middle sand to 25% and of the retaining wall stiffness to 55% has been assumed.

Due to the tides a reciprocal load of the wall adjusts. At high tide the excess water pressure emerge on the river side, at low tide the excess water pressure on the land side. In the earth static calculation only the change of the unit weight of the soil impending behind the wall front is considered. Because of the linear connection between unit weight and effective stresses larger earth pressures emerge mathematically from low tide than from high tide. In contrast to that the measured values of the effective stresses showed a clear reduction at low tide To be able to describe the consequences of the wall load, simultaneously the excess water pressures must be considered Get the effective stresses of a depth position plotted along with the excess water pressures, one can see that the increase of the land side excess water pressures leads to reductions of the earth pressures in equal order.

6 DEFORMATIONS

In the main measuring section of the retaining wall two inclinometer tubes have been installed. The both tubes have been led continuously in the interior reinforcement cage parallel to the longitudinal reinforcement. One was facing the water side the other the land side. The distance of the measuring axes were approximately 1,0 m. Both tubes served simultaneously for the import of a sliding micrometer. With the exploitation of the differential equation of the beam the measurements of inclinometer and sliding micrometer can be transfered in one another. Using the example of this measuring - and investigation program it can be demonstrated that the above described processes guarantee reliable measurements with an overall good compatibility and correlation. The comparison of the measured and calculated deformations shows the continuously increasing agreements of the maximum deflection and the curvature in the field and foot area.

7 ANCHOR FORCES

The horizontal loads from earth and water pressure at the O'Swaldkai should be transfered mainly over inclined tube injected piles. After the quay plate and the quay head have been concreted and hardened out, the anchors are examined first and then stressed. The construction step with the sequence of superstructure completion and prestressing of the anchors corresponded with the usual habits.

The goal of each anchor prestressing is the reduction of the deformation and a load redistribution from the field area to the supports. The reduction of the horizontal stresses in the soil impending in front of the wall proceeds with an increase of the earth pressures behind the wall. In the numerical analysis it became obvious, however, that a large part of the anchor forces had been introduced in the quay plate. The compressive strain in the reinforced concrete structure are to be understood like the prestressing of an elastic spring. They contribute neither to the redirection of the stresses in the soil nor to the reduction the general deformation. In FE parameter studies it could be shown that the increase of the anchor forces due to the excavation remained almost constant and unaffected by the chosen prestressing.

8 CONCLUSIONS

The determination of the earth pressure on the basis of the Coulomb's theory with the expanded estimates was to some extent correct for all construction phases, as far as excess water pressures were not considered. The reduction of the earth pressure at rest to the active earth pressure could be proved measured - and calculated wise. On the design of the retaining wall for increased active earth pressure, as recommended in the EAU, E 144, can be dispensed accordingly.

In the design relevant case the excess water pressures on the land side lead to a reduction of the earth pressure loads in almost the same order. The missing registration of this interaction of buildings and construction sites in the current codes leads to a considerable overestimation of the loads affecting on the retaining wall. The stresses determined by this measuring and investigation program do not even have half of the desinged values. It is suggested for future calculations according to the EAU, R19-1 to reduce the assuming excess water pressures for the load case 2 and 3 in their maximum values. Since in this existing case a reduction of approx. 50% the results of the measurement and calculation reflects, a reduction factor of e.g. 0.9 (LC 2) or 0,8 (LC 3) is put up for discussion.

As the check and particularly the parameter studies show the determination of the forces acting on a section according to the theory I. order and the formulation of ideal bending stiffness for the condition II was appropriate. However, the moments, especially in the field area, were farely overestimated because of the in general too high applied loads. It is proposed, that the demand of the EAU, E 77, the moment reduction of thick retaining walls not to take into account, to modify accordingly.

The retaining wall at the O'Swaldkai has been assumed as a free supported construction in the static calculation. The measured deformations show that this formulation was right because the creation of a fixation in the soil has almost not occurred. For analytical calculations becomes the determination of the effective (part-) earth resistence is proposed according to the EAU, E 174 due to conservative estimation of the expected displacements.

The creation of a bending resticted frame corner at the passage from the retaining wall to the quay plate is statically only limited effective. Is considered that beside the reduction of the field moments also a reduction of the quay head displacement is caused, however this type of construction can be recommended at monolithic buildings made out of reinforced concrete where it is not too great additional expense.

The prestressing forces and especially the prestressing time of the horizontally stiffening anchors of the construction should be subjected to a critical test.

The accomplished studies showed that there has to be expected also with clearly smaller prestressing forces no change of the load carrying behavior of the general system. In contrast to the current recommended estimates one should consider the introduction of pile forces particularly from the first pile row lying directly behind the quay wall construction.

For the quay wall at the O'Swaldkai no indication of individual overloaded construction parts emerge from all the investigations. The quay wall is more than sufficient designed and classified as stable.

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