Experimental Analysis on the Influence of Surcharge Filters on Safety Against Hydraulic Heave

Analyse expérimentale de l'influence d'un filtre de surcharge sur la stabilité contre des soulèvements d'eau d'une fouille de construction

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ABSTRACT: When designing a deep excavation pit, verifying hydraulic heave safety is in many cases crucial for determining the necessary embedment depth of the pit wall. To reduce the required embedment depth, a surcharge filter can be installed on the pit bottom. However, theoretical analyses show that the conventional approaches are not adequate for verifying hydraulic heave safety if the embedment depth of the wall is low and a surcharge filter is installed on the pit bottom. Therefore, a theoretical approach with an extended unstable block was developed by Odenwald and Herten. For further analysis and verification of this extended theoretic approach, big scale laboratory experiments were carried out and the critical hydraulic difference in dependence of the embedment depth and the surcharge filter thickness was determined. In the process it became apparent that the calculated results were qualitatively accord with the experimental results of the test series, yet far more conservative. For a better understanding of the effectiveness of surcharge filters on hydraulic heave safety, one dimensional flow-test with variation of the filter thickness and the relative density of the sand were carried out. This paper presents the results of the experimental series und compares them to theoretical approaches.

RÉSUMÉ : Pour des excavations à proximité immédiate des canaux de navigation en service, la vérification de la stabilité contre des renards est déterminante pour la longueur nécessaire de la cloison de l'excavation. En installant un filtre de surcharge au fond de l'excavation, on peut réduire la profondeur nécessaire de la cloison. Pourtant, analyses conduites sur la base des calculs numériques des courants de l'eau souterraine montrent que les vérifications conventionnelles ne sont pas applicables pour des excavations avec un filtre au fond de l'excavation, parce qu'elles ne prennent pas les courants verticaux au-dessous du pied de la cloison en compte, qui, en ce cas, sont très signifiants. C'est pour cette raison qu'une méthode fiable a été développée sur la base des calculs numériques des courants de l'eau souterraine pour déterminer l'épaisseur nécessaire du filtre de surcharge qui prend les forces des courants en compte. Pour vérifier cette approche et analyser le mécanisme de la défaillance, de nombreux d'essais de laboratoire ont été exécutés et exploités moyennant de différentes méthodes.

KEYWORDS: hydraulic heave, seepage failure, embedment depth, groundwater flow, safety

1 INTRODUCTION

If the water level in an excavation pit is lowered to its base, the difference between the groundwater level outside of the excavation pit and the water level inside of the excavation causes a groundwater flow from the higher to the lower level. This leads to an upward flow from the base of the retaining wall to the pit bottom. In this case, the hydraulic heave safety has to be verified.

If the vertical flow force S in front of the pit wall suspends the buoyant weight of the soil body G' as well as other possible stabilizing forces R (Figure 1), a hydraulic heave will result. This can lead to a rapid flooding of the pit due to regressive erosion around the toe of the wall and eventually to a pit collapse.

Based on the German geotechnical code, the hydraulic heave safety has to be verified according to Terzaghi/Peck (Terzaghi and Peck 1948) or according to Baumgart/Davidenkoff (Baumgart and Davidenkoff 1970). Both approaches simply compare the acting flow forces S with the buoyant weight of the soil G'. Possible friction forces R are neglected. In Terzaghi/Peck's approach a rectangular area is defined as unstable block. The height of the rectangular area corresponds to the embedment depth t of the wall from the bottom of the excavation pit to the toe of the excavation wall. The width of the rectangular area has the half of the embedded depth of the wall t/2. The approach according to Baumgart/Davidenkoff uses an unstable block with negligible width and a height corresponding to the embedment depth t of the wall.

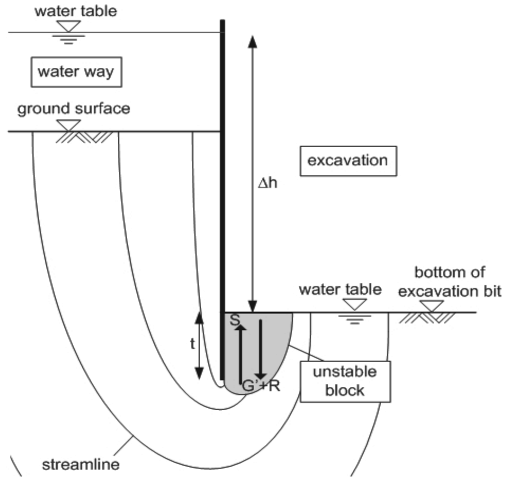

Figure 1. Hydraulic heave at an excavation pit

In both approaches a surcharge filter is considered as an extra load acting at the bottom of the excavation pit and which has no significance for the shape of the unstable block. The magnitude of the extra load corresponds to the weight of the surcharge filter G_F above the unstable block. The surcharge filter only leads to a slight decrease of the water potential.

2 MOTIVATION FOR EXPERIMENTAL ANALYSIS

Motivated by a case of damage at an excavation pit next to a waterway, Odenwald and Herten (Odenwald und Herten 2008) started numerical flow computations respective (?) to the hydraulic heave safety with surcharge filters. Preliminary they did their calculations according to Terzaghi/Peck's and Baumgart/Davidenkoff's approach and developed a functional relation between t/Δh and d_F/Δh (t: embedment depth of the pit wall; d_F: thickness of the surcharge filter; Δh: potential difference). A ratio of $\gamma_F/\gamma_W = 1.0$ (γ_F: unit weight of the surcharge filter material; γ_W: unit weight of water) and $\gamma_S'/\gamma_W = 1.0$ (γ_S': buoyant unit weight of the soil) was assumed. The functional relation is illustrated in Figure 2 (dashed line) for the conventional unstable block according to Baumgart/Davidenkoff's approach.

As expected, the required filter thickness initially rises with constant potential difference Δh and decreasing embedment depth t. However, after reaching a maximum the necessary filter thickness d_F decreases with constant potential difference Δh and continuously decreasing embedment depth t down to zero. Hence, an unstable block that only reaches to the wall toe is inadequate to verify the hydraulic heave safety if a surcharge filter is installed and the embedment depth of the pit wall is small (Odenwald and Herten 2008).

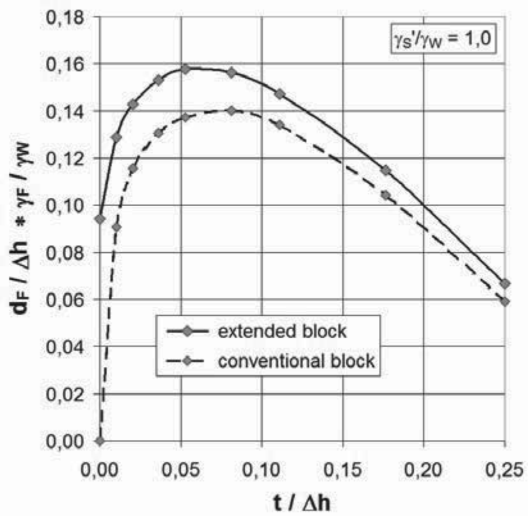

Figure 2. Required thickness of the surcharge filter d_F (Odenwald and Herten 2008)

Therefore, Odenwald and Herten developed an unstable block which additionally considers the vertical flow forces below the wall toe. Hence, the unstable block according to Davidenkoff was extended to the depth where the specific hydraulic gradient i_z (vertical hydraulic gradient) and the limiting gradient i_{gr} (hydraulic gradient corresponding to the ratio γ_S'/γ_W) have the same value ($i_z = i_{gr}$).

Figure 2 (solid line) also shows the results of the computation with the extended unstable block ~~also~~ as a functional relation between t/Δh and d_F/Δh. However, a maximum is also reached here, which means that with constant potential difference Δh, a further reduction of the embedment depth t requires a smaller thickness of the surcharge filter d_F.

To verify the results of the numerical approach with the extended unstable block, numerous large scaled laboratory experiments were performed.

3 SIMULATION OF HYDRAULIC HEAVE

In order to verify and improve these theories, several large-scale experiments to simulate hydraulic heave with a low embedment depth t and installed surcharge filter were carried out at the Institute of Soil Mechanics and Foundation Engineering of the Bundeswehr Universität München. In these experiments, the embedment depth as well as the thickness of the surcharge filter was varied. The aim of the experiments was to appoint the critical potential difference Δh_{crit} as a function of the embedment depth t and the surcharge filter thickness d_F.

The test rig (Figure 3) consists of two parts: the water supply, which is used to increase the potential difference continuously, and the test box. The rectangular test box has the following dimensions: length x with x height= 1.70 m x 0.40 m x 1.50 m. It mainly consists of 4 acrylic glass walls, a base plate and a vertically moveable partition acryl panel in the middle of the box. The partition wall simulates the retaining wall in the laboratory test. An inlet connects the box with the water supply. On the feed stream side of the test box, three, 3 cm in diameter, pipes allow free drainage.

Sand (as basic material) and a mixture of coarse sand and fine gravel (as filter material) were used as test materials for the simulations of hydraulic heave with filter layers at the excavation side of the wall.

The behavior of the soil during the experiment was monitored via displacement transducers, water pressure sensors, water quantity measurement and the Particle Velocimetry Method (PIV).

A more detailed description of the employed measurement techniques, the test materials and the construction of the experimental rig is given in (Schober, Boley and Odenwald 2011).

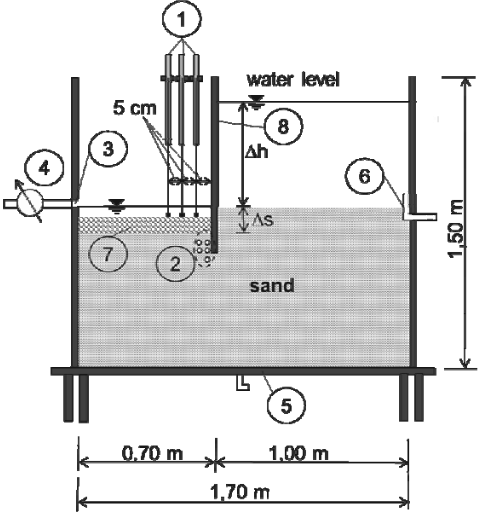

Figure 3. Schematic of experimental rig: (1) displacement transducer, (2) water pressure sensors, (3) outlet, (4) water meter, (5) base plate, (6) inlet, (7) surcharge filter, (8) partition panel

Overall, 24 tests were carried out. The embedment depth was varied between t = 0 cm and t = 5 cm in 0.5 cm and 1.0 cm steps. Moreover, the surcharge filter was installed in different sizes, with a thickness of d_F = 2, 4 and 6 cm.

3.1 *Test results*

Due to different boundary conditions of the numerical model (Odenwald and Herten 2008) and the experimental rig (Figure 3), it was not possible to compare the results directly to each other. Therefore, it was necessary to adapt the theoretical approach to the boundary conditions of the experiments series. This was done by numerical calculations with the same boundary conditions as the experimental model (Schober and Odenwald 2012).

Figure 4 shows the results of the test series the adapted numerical calculation as a function relation of t/Δs and Δh_{crit}/Δs (Δs: level difference between up and down stream side of the wall, Figure 3).

From Figure 4 it can be seen that the experimental results agree qualitatively well with the results of the numerical calculation. Both the experimentally determined and the numerically calculated curves reach a minimum at a certain ratio t/Δs where the lowest critical potential differences Δh_{crit} arise for a constant thickness of the surcharge filter d_F. Starting from this minimum, further reduction of the embedment depth t enables higher critical potential differences Δh_{crit}. The laboratory experiments confirm the findings of the extended theoretical approach of Odenwald and Herten.

However, the critical potential differences Δh_{crit} achieved during laboratory tests are significantly higher than the critical potential differences Δh_{crit}, calculated by Odenwald & Herten, which lie on the safe side. Moreover, the difference between the results of the experimental series and the theoretical approach increases inversely proportionately with increasing thickness of the surcharge filter (Figure 4).

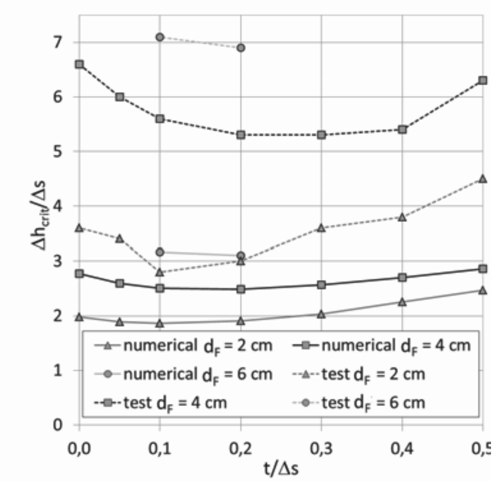

Figure 4. Comparison of test results with the results of the extended theoretical approach

Basically the difference between the numerical calculations and the experimental test results is due to the highly simplified unstable block, which is applied in Odenwald and Herten's calculation approach. Secondly, in the numerical calculations only the weight of the sand and the surcharge filter was recognized as retaining force, frictional forces were neglected.

It has to be kept in mind, that when installing a surcharge filter on the pit bottom frictional forces are acting in the shear zone of the surcharge filter and in the base material in critical condition, too.

In addition, it was found out, that the size of the unstable block increases with increasing surcharge filter thickness. Since, in conventional procedures for verifying the safety against hydraulic heave, the thickness of the surcharge filter is only considered as additional weight in calculations, but with no impact on the shape and size of the unstable block. These methods do not offer any realistic result if a surcharge filter is installed (Figure 5).

To achieve more realistic and therefore, more economic calculation results, an approach that brings the unstable block closer to the realistic failure body and also takes into account the frictional forces in the surcharge filter and in the base material has to be developed.

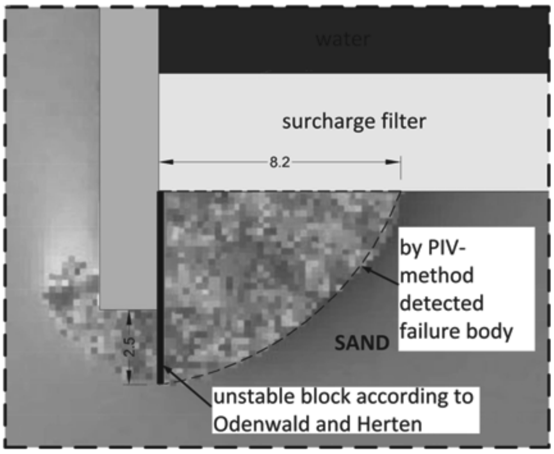

Figure 5. Comparison of test results with the results of the extended theoretical approach

The observation of the experiments and the evaluation of the results also showed that the thickness of the surcharge filter has significant influence on the failure mechanism and shape of the unstable block. In order to analyze the hydraulic heave with surcharge filter more detailed, multiple uniaxial flow-tests were carried out.

4 UNIAXIAL FLOWED SAND COLUMN

To analyze the influence of the surcharge filter thickness on the hydraulic heave more detailed, numerous uniaxial flow-tests were performed. For this purpose a specific apparatus was designed to simulate uniaxial flow through a sand column (Figure 6). A more detailed description of the test materials, the construction of the test rig and the used measurement technique is given in (Schober and Boley 2012).

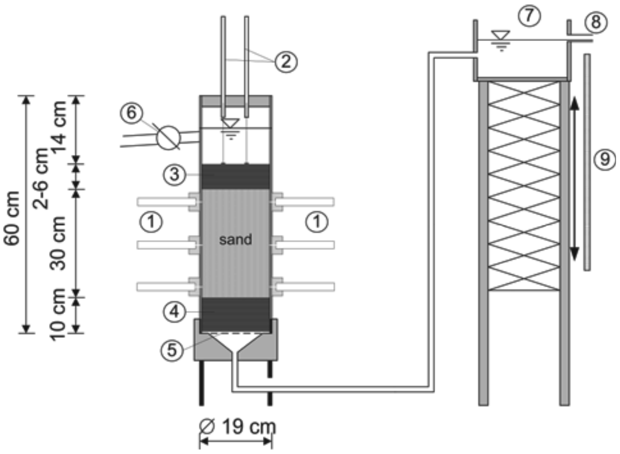

Figure 6. Schematic of flowed cylinder: (1) water pressure sensors, (2) displacement transducers, (3) surcharge filter, (4) filter, (5) perforated plate, (6) water meter, (7) water supply, (8) over fall, (9) staff gauge

The aim of the test series was, among other things, to determine investigate the influence of the surcharge filter thickness d_F and the relative density D of the test material on the critical hydraulic gradient i_{crit}. The results of the uniaxial flow-tests are used for a better understanding of the results of the hydraulic heave experiments.

Altogether, 25 tests were carried out. The relative density was varied between D = 0.1, 0.5 and 0.8. Moreover, the surcharge filter was installed in different sizes, with a thickness of d_F = 1, 2, 3, 4, 5 and 6 cm. Tests without a surcharge filter were carried out too. In the test series, different relative densities of the sand were combined with different sizes of the surcharge filter d_F.

5 TEST RESULTS

The critical hydraulic gradient i_{crit} was determined in each test, so that the dependence of the critical hydraulic gradient i_{crit} on the relative density D and the thickness of the surcharge filter d_F. could be shown.

Figure 7 shows the critical hydraulic gradient i_{crit} as function of the surcharge filter thickness d_F for the different relative densities D. Moreover, the figure shows the theoretical critical hydraulic gradient $i_{crit,theoretical}$ calculated according Formula (1) (l: length of the sand column). The figures also display the difference between the test results and the theoretical approach.

$$i_{crit,theoretical} = \frac{d_F \cdot \gamma'_F}{l \cdot \gamma_W} + \frac{\gamma'_S}{\gamma_W} \tag{1}$$

The results of the test series show that the critical hydraulic gradient i_{crit} strongly depends on the thickness of the surcharge filter d_F. With increasing thickness of the surcharge filter d_F, the critical hydraulic gradient i_{crit} increases inverse proportionately.

The relative density D of the sand has a significant influence on the critical hydraulic gradient i_{crit} too. For a sand with a low relative density (D = 0.1), the critical hydraulic gradient i_{crit} is smaller than theoretically calculated (Figure 7). The results of the test series with a relative density of D = 0.5 and 0.8 show, that the critical hydraulic difference Δh_{crit} and the critical hydraulic gradient i_{crit} respectively is always higher than the gradient theoretically predicted (Figure 7).

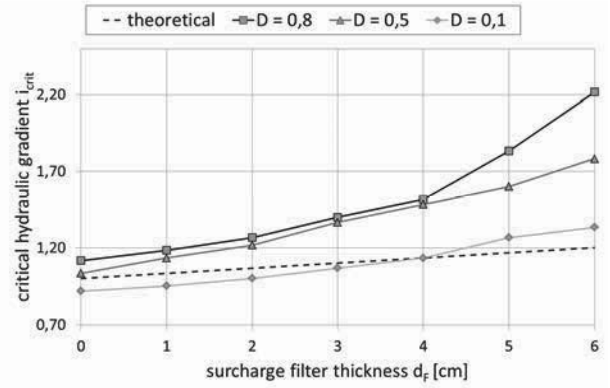

Figure 7. Critical hydraulic gradients of uniaxial flow-test

The disproportional increase of the critical potential difference Δh_{crit} with increasing thickness of the surcharge filter d_F which was detected by the big-scale experiments could be confirmed by the uniaxial flow-tests. The reasons for this behavior will be analyzed in more detail by the Discrete Element Method (DEM) by the Institute of Soil Mechanics and Foundation Engineering of the Bundeswehr Universität München.

The influence of the relative density D on hydraulic heave safety, if a surcharge filter is installed on the pit bottom, needs further investigation by experimental tests. Nevertheless, by the analysis of the uniaxial flow-tests it becomes apparent, that the relative density D of the basic material has a significant influence on the hydraulic heave safety even if a surcharge filter is installed on the pit bottom.

6 CONCLUSIONS

The experiments carried out at the Institute of Soil Mechanics and Foundation Engineering of the Bundeswehr Universität München strives for the verification of the approach with an extended unstable block (Odenwald and Herten 2008). The results of the big scale experiments fit quantitatively to the results of the theoretical analysis. Thus, it could be observed that there is an unfavorable embedment depth for a pit wall with a surcharge filter on bottom of the construction pit floor. The safety towards hydraulic heave increases when the embedment depth is reduced or enhanced. According to that, the safety towards hydraulic heave can rise due to reducing the embedment depth. The numeric results are however more conservative than the experimental results. This could be due to the simplified failure shape as well as the neglected friction forces in the sand and surcharge filter. Moreover, the difference between the results of the experimental series and the theoretical approach increases proportionally with increasing thickness of the surcharge filter

Furthermore, one dimensional flow-tests were carried out to determine the influence of filter thickness and relative density of the test sand on the critical hydraulic gradient. The experiments showed an inverse proportional correlation between the critical hydraulic gradient and the thickness of the surcharge filter. This was confirmed by the uniaxial flow-tests.

The object of further studies will be to verify and improve the theoretical approach by means of the experimental results towards the hydraulic surcharge and one dimensional flow-tests. The improved approach has to consider friction forces and a more realistic unstable block so that results get closer to reality and the disproportional increase of critical potential difference Δh_{crit} with increasing filter thickness will be considered.

7 ACKNOWLEDGEMENTS

The project is supported by the Federal Waterways Engineering and Research Institute Karlsruhe, Germany.

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