Cohesive Soil Resistance and Hydraulic Heave at Excavations

Résistance des sols cohésifs et boulance dans la fouille

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ABSTRACT
The valid design approach of hydraulic heave doesn't consider cohesive soil resistances. The basis for a correct implementation of available soil resistances is a realistic description of the load capacity and the deformation behaviour. The limit state of hydraulic heave at the bottom of an excavation in cohesive soil can be described as a shear failure or as a combination of the development of initial cracks leading to a shear or uplift failure. A liquefaction or erosion of the soil continuum, as dominant in non cohesive soil, cannot appear. Already a small cohesion requires extremely high hydraulic gradients to mobilize single particles or aggregates. In cohesive soil the limit state is not gained loosing the effective stress. Further resisting forces are activated. The failure types describing the limit state fundamentally depend on the stress state, the soil type, the stratification and the thickness of the soil layer, the water content of the soil and finally on the hydraulic impact. A consideration of the different influences and constrains leads to a detailed comparison of possible approaches to analyse the limit state adequately.

RÉSUMÉ
Les critères de boulance qui s'établient au pratique ne tient pas compte des sols cohésifs. La déformabilité du sol et une description réelle de la limite de chargement est la base pour une approximation plus réaliste de la résistance. La condition aux limites de boulance pour les sols cohésifs en fond de la fouille est ou une résistance au cisaillement ou une résistance au sous pression respectivement au cisaillement après le développement des micros fissure. La liquéfaction ou érosion interne du sol élément comme en sol non cohésive n'est pas valable. Déjà une résistance cohésive minimal causer des énorme gradients hydraulique nécessaire pou mobiliser des particules ou des agrégats. En sols cohésifs la décroissance des contraintes effectives ne représenter pas la condition aux limites. Des résistances supplémentaires peuvent activer. Le mode de rupture est dépendant de l'état des contraintes, du type de sol, de la teneur en eau, de la stratification, de l'épaisseur du sol et finalement de l'influence hydraulique. Avec la considération de l'impact différent et les conditions aux limites il est possible de faire une comparaison agréable de différente approximation d'analyse de la résistance limite.

Keywords : hydraulic heave, cohesive soil, soil resistance

1 INTRODUCTION

A bottom failure at a braced excavation in non cohesive soil occurs as a certain kind of piping if the upward directed hydraulic gradient is large enough to create liquefaction and heave of the soil. The bottom of the excavation gets liquefied and finally eroded if seepage resulting from the pressure head Δh is equal to the weight of the soil. During the process the effective stress disappears. Even in non cohesive soil this consideration is conservative since shear and wall adhesion are neglected (see Figure 1a). Hence, when the excavation is located in a cohesive soil stratum, as shown in Figure 1b, a soft soil loose its load capacity and flows beneath the wall corresponding with the stream lines of the valid flow net. In contrast to this stiff cohesive soil will mobilize shear resistance against deformation and base instability. The resistances are consisted on both, shear in a failure plane that may be in direction of a stream line and wall adhesion. Main objects during designing excavation are to provide a sufficient depth l of the piling, to lower the hydraulic gradient and to prevent failure of hydraulic heave.

The focus of the present article are the usable resistances against such a hydraulic impact on cohesive soils. The objective is the investigation of the phenomenon of a sudden collapse at the bottom of an excavation in cohesive soil caused by hydraulic heave. In particular, the boundary conditions of a variable stress state caused by pit excavation and modification of the outer or inner groundwater level and at the same time the saturated soil conditions are essential.

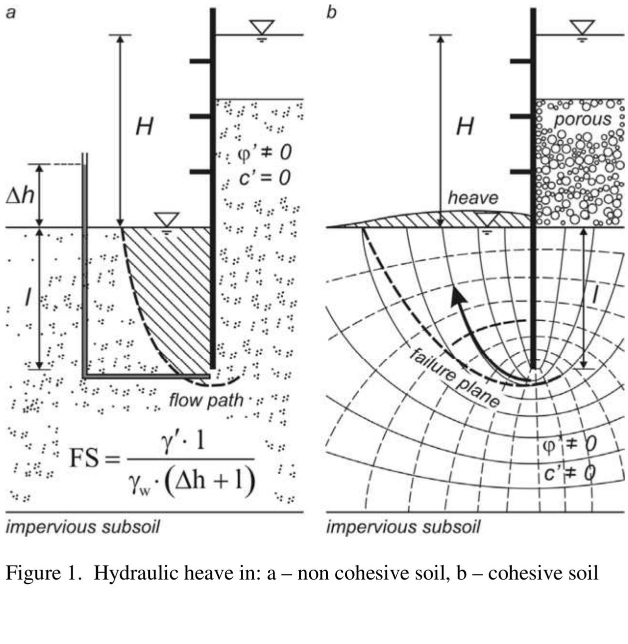

Figure 1. Hydraulic heave in: a – non cohesive soil, b – cohesive soil

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2528

The valid regime of the current standard (Eurocode 7) [1] specifies the analysis of a stability problem of a discrete control volume by determining the stress state or by comparison of effective forces acting on the control volume. Considering the valid partial safety factors, the limit state is defined by a weightless soil body in the control volume. If a differentiation of the activated soil resistance as a function of soil type is not provided, the load capacity of a cohesive soil loaded hydraulically is underestimated. Moreover, a complex variable stress state existing at the foot of a pit wall, is not taken into account.

Objective of this paper is the exposition of boundary conditions specifically valid for hydraulic heave in cohesive soil on the basis of the hydraulically induced structure loss typical for cohesive soils. The identification of activatable and existing soil resistances and conclusions regarding their compatibility to existing calculation methods will be presented.

2 COHESIVE SOIL PROPERTIES INFLUENCED BY WATER

The stability of structures from a geotechnical background is referred to, either the direct contact area between the building and the adjoining soil or to the processes in the soil continuum. For both approaches, the mechanical properties of the existing soil are of central importance. The dimension of the area relevant for the load capacity analysis is essential for the classification of proof as global or local. From a geotechnical point of view the stability is primarily determined through the strength and deformation properties of the soil.

The mechanical properties of the soil are directly influenced by interactions of the three basic soil elements solid, liquid and gas. Moreover, the influence of chemical processes have to be considered, that cause in connection with liquids various types of water storage and water bonds and with the gas phase available in partial saturated soil a change of the material properties.

In case of hydraulic heave in cohesive soil the effective stress state is in focus of the stability analysis. In particular, a change of the flow conditions leads to variable pore water pressures and therefore is essential for the assessment of the limit state. Basically, without considering the soil, an increasing pore water pressure and at the same time a constant total stress state cause a reduction of the bearing capacity. In other words, the increasing pore water pressure gets particularly compensated by the total activated resistances. Considering the soil fabric, which is mainly determined by the particle size composition of the soil, mobilized resistances are defined for particle contact areas.

The types and mechanisms of stress transfer in soils are a function of pore size distribution within the grain structure. The pore sizes of the soil are determined by the composition of the soil and therefore can be represented by the equivalent pore diameter. For non-cohesive soils a load transmission can be found on the grain contacts of the particles. Resistances are activated due to friction within the soil matrix. Deformations are needed to initially mobilize the necessary resistances.

The transfer of forces in cohesive soil is not limited by grain-to-grain contacts. Further influences on the transmission are the attractive and repulsive stresses between the clay minerals, often explained with the theory of diffuse double layers [2]. The effect of the presented principles of load transmission in cohesive soil can be explained by the formation of a secondary structure within the material due to the formation of aggregates. The aggregates consist of clay minerals and vary depending on the nature of the mineral and the chemical composition of pore water. For cohesive soil, a differentiation between intra aggregate pores and inter aggregate pores is useful (see Figure 2). The effect of the tendency of clay minerals with midget pore sizes (< 600 Å) to group together, explains that for such materials the mechanical behaviour of clay minerals as the smallest element in the soil is dominant. An increase of the soil internal pore sizes leads to a decrease of the influence of the mentioned stresses. Above a certain pore size their influence does not matter anymore. The then-expiring transactions between soil and water can be displayed by simple capillary models. Shear resistances are activated in the physical contact areas of the aggregates.

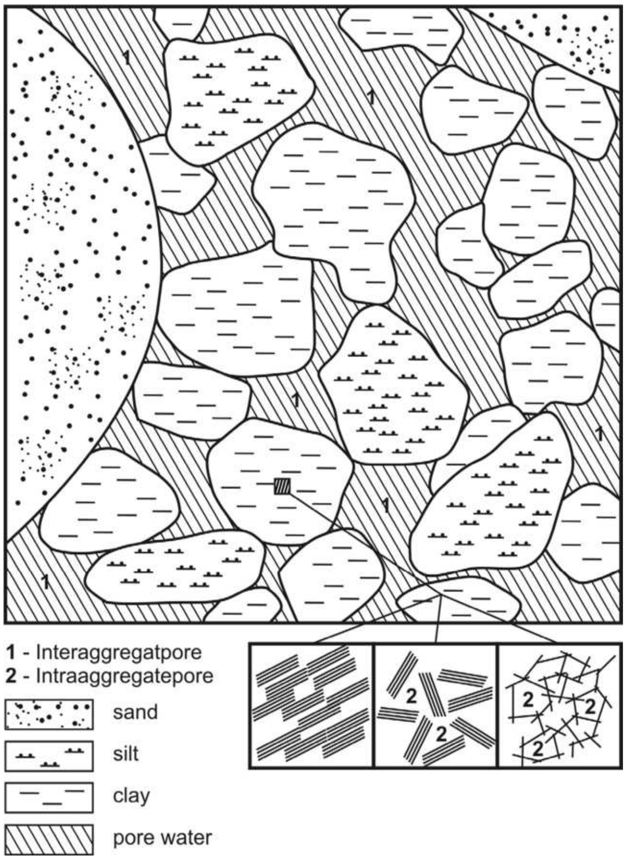

Figure 2. Soil fabric of soil with high clay content, according to [2]

To obtain a qualitative statement about the destruction behaviour of cohesive soil facing a hydraulic influence, tests were carried out at the Bauhaus-University Weimar. The experiments described a flow around an excavation wall in cohesive soil. As a result of the tests, it was possible, to classify the failure course of hydraulic heave in cohesive soil as a sequence of pore expansion, initial crack, formation of a discrete fracture body during the gradual destruction of the soil continuum followed by the final formation of a flow channel [3]. The test results clearly classify the failure process in the cohesive soil. The results are especially visually evaluable, because the influence of stress state at foot of a retaining wall could not be expressed realistically. In addition, changes of the soil structure in the form of dissolution phenomena that are typical for unloaded surfaces of water saturated cohesive soils could not be avoided in the model [4].

Comparing the course of the flow caused failure in non cohesive and cohesive soils shows that primarily because of the above-described different soil structures, a various destruction behaviour of the soils is present. For both soil types the limit state is gained by a local volume expansion, accompanied by a rise of the water content of the soil. The deformations caused, however, differ in the way the soil compensate them. The activated resistances vary due to constraints like grain size distribution, particle shape as well as pore size, orientation and type. Concerning the limit state of hydraulic heave the latter has essential influence on the contact area between the solid and the liquid (soil - water).

3 SOIL RESISTANCES IN SATURATED COHESIVE SOIL

In particular, the structure and composition of soils have influence on the available soil resistances. The interactions between soil particles and water are crucial for the strength and deformation properties of soils.

The deformation behaviour of soils is determined by the grain composition and the pore volume fraction filled with water or air. Loading of a soil continuum induce a deformation and is represented by a stress change that leads to a reduction of the pore volume. During the process, water and air gets displaced from the soil, if possible. The solid particles are not be assumed to be compressible. The influence of capillary stress is particularly relevant for fine-grained soils, but can be excluded outside of the closed capillary zone, that is for saturated and dry soil.

For saturated cohesive soil a squeezing out of pore water is mostly prevented due to its low water permeability. A time-dependent load-deformation behaviour valid. Considering a defined moment undrained conditions can be assumed. Assuming incompressibility of the pore water a load increase will be compensated by the pore water first and as a result of a delayed water flow from the pores a gradually progress will induce an increasing pressure to the grain structure while the pore water pressure decreases. Therefore the bearing capacity of the soil, represented by the soil resistances, is also time-activated.

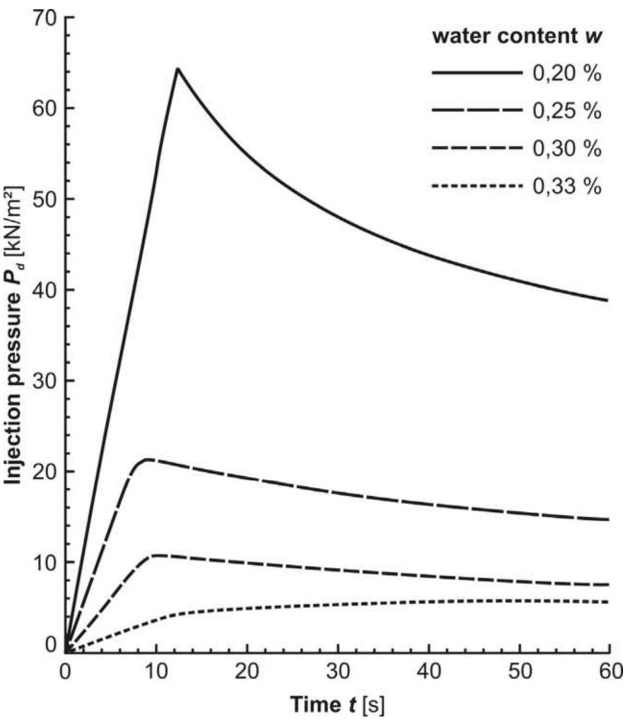

Figure 3. Pressure records of samples with different water content [5]

Especially in context with hydraulic heave on a pit wall in cohesive soil, the described phenomena have an important influence. The soil is loaded during pit excavation carried out during the construction phase and by a simultaneously executed water drawdown in the excavation. Considering the above mentioned bordering conditions and influences the soil may be assumed as water saturated and at least temporary undrained. In order to assess the sustainability of soil especially the dependency of the soil properties on the water content and the stress state as well as the additional consideration of all favourable influences acting is necessary and useful.

Another influence on the structural integrity of the soil at a pit wall, and hence on the load capacity is given through the effect of the pit wall on the soil abutment. Result of the bracing and abutment effect of the soil is a relatively increased effective soil stress, which again has to be compensated by an increased pore water pressure. Although this effect has an impact on the limit state, the effect on the soil continuum is not included in the normative valid definition of safety factor and limit state.

Basically it can be noted that with an increasing clay fraction the plasticity of the soil and the tendency of the soil increases to shrink or to swell during transient water contents. Furthermore a decrease of the water permeability causes an increasing compressibility / deformability and cohesion while at the same time the value of the internal friction angle decreases. With a raising fine-grain-content the fraction of the particle surface forces on the overall resistance increases. Therefore an essential reason for the variability of shear resistances is given by this constraint. To consider the complex relations in a cohesive soil at the limit state of hydraulic heave a state in which the equilibrium is gained through, a hydraulic impact is in focus of the analysis. With constant stress conditions an increased hydraulic influence leads not only to a locally higher hydraulic gradient, but also at least to a local increase of the water content.

The dependence of both phenomena is distinct shown in Figure 3 after [5]. With increasing water content the maximum injection pressure decreases dramatically. A pore water pressure generated in short term will be faster compensated through the soil continuum. At low water content, the failure occurs by a sudden tearing (peak in Figure 3, w = 20%). After failure, the injection pressure aspires an equilibrium condition. For this test scenario the bearing capacity can not be presented by the parameters cohesion and friction angle. The sudden tearing / cracking of the soil represent rather the activation of a tensile strength and therefore this parameter should be taken into account in the evidence.

4 APPROACHES DESCRIBING FAILURE IN COHESIVE SOIL

In order to establish the limit state of hydraulic heave in cohesive soil, the processes which lead to failure and the type of failure have to be analysed. The failure occurs in cohesive soil almost always as a combination of different hydraulically-induced failure mechanisms. Therefore, a differentiated analysis of possible failure modes in terms of their validity as limit state is useful. A hydraulic damage of the soil can occur by loosing the effective stress ($\sigma' = 0$), during an erosion of particles, by shear failure and/or by a crack initiation.

The description of the limit state by the loss of effective stress in a discrete control volume represents an interpretation conforms to the current valid standard (Eurocode 7 [1]). The design against hydraulic heave does not differentiate the soil type and therefore does not take the typical material resistance of cohesive soil into account. Resistances are only activated by the beneficial influence of the soil weight. According to the German national document the safety factor depends on the erodibility of the soil. Therefore fine sand and low cohesive silt demand the highest level of safety.

A damage of the soil continuum through erosion considers the release of individual particles or aggregates from a cohesive soil structure. According to various approaches to analysis the phenomenon [4; 6-8], the cohesive soil resistance takes at least the effective or undrained cohesion into account. Due to the large hydraulic gradient necessary for particle erosion the limit state is not decisive (compare [9-11]).

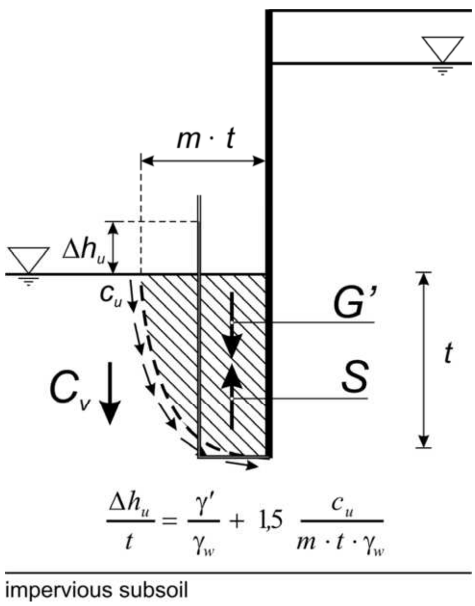

Figure 4. Hydraulic heave as wedge failure according to [3; 9]

On the basis of the documented test results [3; 11], the interpretation of the limit state as a shear failure is possible. For this the gradual destruction of the soil in the control volume is neglected. In [9; 10] a calculation method is presented interpreting the failure on a discrete failure body. In this first approach a simple static analysis was established, resulting in a limit state condition that considers the undrained shear strength or the tensile strength alternatively (Figure 4). This approach can be characterized as conservative, if there are homogeneous and isotropic conditions and neither stratification nor preferred flow path existent. However the process of soil deformation in a pre failure state of a cohesive soil is more complex and failure might be initiated by hydraulic fracturing and will end as hydraulic uplift after a certain degree of crack development.

The identification of the limit state based on fracture criteria interprets the failure during the development of an initial crack in the soil. Although the theory originally was developed for solids (compare [12]), there are now several applications for soil in which i. g. for embankment dams [13] total stresses were assumed. By applying the procedure it is possible to consider the deformation behaviour for varying impacts, such as pit excavation and water level drawdown. During crack development and extension dissipated energy can be used as an additional part of the total soil resistance available [14].

5 CONCLUSIONS

With the objective to develop an optimal design of hydraulic loaded structures, such as inland waterways and flood control facilities, in particular through the consideration of cohesive soil resistances a significant improve of the effectiveness can be achieved.

The soil resistance activated in cohesive soil is mainly determined by the surface forces of clay aggregates. In order to display the limit state effects realistic changes in effective stress and pore water pressure have to be taken into account. A hydraulic heave in cohesive soil can either be considered as a shear or tension failure of a single wedge or as a combination of an initial crack followed by shear failure or uplift. Starting with the initial damage and ending with the final collapse soil resistances getting activated. They can be explained by the theory of linear elastic fracture mechanics as an application for soil and by a combined shear / uplift mechanism. The analysis considers load capacity and deformation parameters which depend on the stress state and water content of the soil or their relative change.

ACKNOWLEDGEMENT

The presented results are based on conclusions of an actual research project "Hydraulic Heave in Cohesive Soil", sponsored by the Federal Waterways Engineering and Research Institute in Germany. The funding assistance provided by the Bauhaus-University-Weimar in support of this project is gratefully acknowledged.

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