Unsaturated condition below the ground water table and its effect on pore pressure, soil and structure deformation
Conditions non-saturées sous le niveau de l’eau phréatique et leurs effets sur les pressions interstielles et les déformations des sols et des constructions

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Keywords: excess pore pressure, hydraulic failure, soil and structure deformation, finite elements

ABSTRACT: Deep pit excavations below ground water level often cause large deformation such as ground heaving and bending of excavation linings, not expected during construction work to the extent and direction, in which deformation occurred. Comparing these observations with considerations on the change of water pressure during construction time, it can be shown that the compressibility of the pore fluid should be taken into consideration. The paper presents the physical background and some results of numerical FE-calculations adopting a 3-phase model in order to simulate major loading phases during reconstruction work of an inland navigable lock. It is shown that unsaturated conditions in the porous medium below water level have a significant influence on stability of retaining wall structures. The danger of hydraulic failure caused by transient pore water pressure therefore consequently demands a new design concept.

RÉSUMÉ: Les excavations profondes sous le niveau de l’eau phréatique produisent fréquemment des gros déformations (soulèvement du fond de l’excavation ou déformations des structures de soutènement), qui ne sont pas toujours attendues comme ampleur et direction. Une analyse des ces observations en tenant compte des changements des charges hydrostatiques permet de prouver que la compressibilité de l’eau interstitielle doit être prise en compte. L’article présente les bases physiques d’un modèle triphasique et des résultats de simulations numériques données à l’aide de la méthode des éléments finis pour la reconstruction d’une écluse navigable. On montre que les conditions non saturées dans le milieu poreux ont une influence significative sur la stabilité des ouvrages de soutènement. Le péril de fracturation hydraulique demande en conséquence une nouvelle conception pour le calcul des ouvrages.

1 INTRODUCTION

A more than 40 years old navigable lock designed in sheet pile wall construction and built on over-consolidated clay had to be enlarged in depth and length. Over the whole period of about four years reconstruction work the lock water level was lowered down to more than eight meters below the surrounding free ground water table inside the gravel stratum above clay subsoil which corresponds directly with the water level of the nearby river Main. During construction work questions arose as to what kind of load conditions should be considered in calculating sheet pile wall stability to serve the different construction stages, especially against the prevailing seepage, water and earth pressure loading. The discussion between the building partners involved showed a great amount of uncertainty as to whether an effective stress design concept could have served to forecast realistic structure deformations and possible failure conditions. To prove our own considerations of adopting effective stress conditions, pore water pressure measurements were carried out inside the clay in the...
final construction stage to obtain the pore water pressure response during the refilling of the reconstructed lock. The results of these in-situ measurements clearly showed the expected influence of the changing water head causing transient pore water pressure inside the clay showing typical potential distributions of an unsteady pore water flow state. (Köhler and Haarer, 1995).

Figure 1. Cross section of the lock under reconstruction

Figure 1 describes the soil and lock profile of the site. The left hand side shows the former structure, on the right hand side the reconstructed new lock profile with a permeable open lock ground structure is shown together with the locations of the pressure gauges K1 to K6.

2 PHYSICAL BACKGROUND

In order to calculate the transient pore water pressure distribution in a deformable 3-phase medium of a submerged soil structure (solids, water and air) the following equation may be adopted (Biot, 1941).

\[
k \left( \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} \right) = n \beta' \rho_w g \frac{\partial \varphi}{\partial t} + \frac{\partial \varepsilon_v}{\partial t}
\]

(1)

where, \( \varphi = \) pore pressure potential, \( \beta' = \) water compressibility, \( \varepsilon_v = \) volumetric strain, \( n = \) soil porosity, \( k = \) permeability, \( \rho_w = \) water density, \( g = \) gravity acceleration, \( x, y, z = \) Cartesian coordinates and \( t = \) time.

The water compressibility \( \beta' \) can be described by a relation of the form:

\[
\beta' = \beta + \left( 1 - S \right) \left( \frac{1}{p_a + p} \right)
\]

(2)

where, \( \beta = \) compressibility of de-aired water (about \( 5 \times 10^{-7} \text{ kPa}^{-1} \)), \( S = \) saturation degree, \( p_a = \) atmospheric pressure and \( p = \) pore pressure.

Equation (1) describes in a simplified form the space and time dependent pore pressure distribution of the deforming subsoil, where the volumetric strain \( \varepsilon_v \) measures the displacement caused by total stress changes. Taking the compressibility \( \beta' \) (2) of the pore fluid into consideration, a saturation degree \( S \) of about 90% may be chosen for natural subsoil conditions (normally it may range between 80 and 100%), which means a medium air content of about 10%.
3 UNCOUPLED FINITE ELEMENT SIMULATION

After having measured the expected transient pore pressures during the refilling stage of the reconstructed lock, a finite element simulation should be employed to allow plausible interpretations of such results. In the first step an uncoupled finite element analysis has been performed, applying the PLAXIS FE-code (Brinkgreve & Vermeer, 1998). In order to introduce the influence of the compressibility of the pore fluid on soil and structure deformation, the program-option of applying separate phreatic lines and ground water heads to specially selected soil clusters was used.

These input values of the unsteady pore pressure state according to the different construction phases result out of a finite difference simulation, solving Biot’s equation (1), here carried out for simplification one dimensionaly. As a general solution of this numerical model a design chart has been provided and may be employed, to calculate the unsteady pore pressure distribution over the soil depth z due to water level head changes as a function of soil permeability k and draw down time $t_A$ (Schulze & Köhler, 1999).

Figure 2 describes the profile of the structure and the soil parameters at lock site. (fig.2, left). The right hand side of Figure 2 shows the selected individual soil clusters of the generated finite element mesh, forming a field of clusters analog to a typical steady state seepage ground water flow field. Small deviations of this flow field introducing thin and tiny layers of soil clusters should be noticed, where the unsteady pore pressure potentials near the lock ground level were to be expected due to water level head changes inside the lock. The applied simplified ground water flow field has been reduced to only two flow tubes to minimize the amount of calculation and input parameters to be used in modeling the unsteady pore pressure distribution at different construction stages. In all soil clusters the same constant soil parameters have been used, but variations of pore pressures at different individual soil clusters have been adopted as input parameter following the solution of the above mentioned design chart (Schulze & Köhler, 1999).

In computing the induced structure deformations, three main construction phases have been simulated, phase 2 – excavation, phase 3 - water level lowering and phase 4 – raising of the lock water level.

In Figure 3 the input pore pressure distributions (left hand side) and the computed displacement fields (right hand side) of the three construction phases at different construction time stages are shown. The upper part stands for the results out of the soil excavation under water, the lock water level has been kept constant at the mean water level elevation of 1.5 m below ground water level. The middle part shows the results at the time step 7 days after lock water level lowering and the lower part describes the time step 4 years later, just after refilling the completely reconstructed
lock. In order to visualize the different pore pressure distributions in a more easy way, the permeability of the clay had been chosen to $k = 10^{-8} \text{[m/s]}$, which exceeds the realistic in situ permeability of the clay by more than 5 orders of magnitudes. Therefore the amount of computed displacements will not coincide exactly with the in situ displacements, but give a valid schematic impression of the induced displacement fields during the construction phases. It should be mentioned that in phase 3 (lowering of the lock water level) a 1 m thick layer of a permeable porous structure, temporarily acting as a top load in order to avoid subsoil failure, had to be employed to guarantee numerical stability in the finite element simulation.

Figure 3 Total displacements resulting out of uncoupled FE-simulation in three different construction phases (left: input pore pressure, right: displacement fields)
4 COUPLED FINITE ELEMENT SIMULATION

A second possibility of simulating the behavior of the soil-water-air system is to perform a coupled solid-pore pressure analysis, and to model the water as a compressible medium. ABAQUS FE-code (Hibbit, Karlson & Sorensen 1997) was used for the analysis, with a modification in order to consider the variation (2) of the water compressibility with the pore pressure (a quasi-explicit update of the water compressibility value in a new time step based on the pore pressure values calculated in the previous step - Kohler, Feddersen, Schwab 1999). In contrast with Jeng & Lin 1997 a nonlinear elastic- perfect plastic soil behavior was assumed here.

Figure 4  Pore pressure history

Figure 5  Evolution of the vertical excess pore pressure

Figure 6  Distribution of the excess pore pressure in phase 4 (normalized in respect to the water load)
The simulated construction history and the pore pressure evolution of a point in the symmetry axis of the lock are shown in Figure 4 (note that the construction phases 2 and 3 are in opposite sequence as in the uncoupled simulation). The pore pressure evolution follows the load history with a considerable time delay due to the water compressibility and the low permeability of the clay.

The vertical distribution of the excess pore pressure in the symmetry axis of the lock (Figure 5) shows the delayed depth propagation of the pressure changes on the pit bottom and the superposition of the influences of construction steps. The evolution of the pore pressure during the raising of the water level is represented in Figure 6 showing a clearly different behavior than was to be expected in the case of an incompressible fluid.

5 HYDRAULIC FAILURE AND CONCLUSIONS

During the construction phase 3 (lock water level lowering) a permeable gravel top layer of 1 m thickness had to be applied to obtain numerical stability and to prevent limit state conditions ($\eta < 1$). In Figure 7 the total incremental displacement field at a safety factor of $\eta = 1.1$ clearly indicates the onset of failure (left side). By using a shear parameter reduction, the failure condition (Mohr-Coulomb-model) is shown on the right hand side of Fig.7 together with the active and passive sliding surfaces, where the effective stress is greatly reduced by the acting transient pore water pressures. The arrows indicate the direction, in which the time dependent excess pore pressure decreases. The results of these finite element simulations clearly indicate hydraulic failure of the soil, caused by rapid water head changes inside the lock pit.

Summarizing the experience gained out of the results of measurings and FE-simulations it should be concluded for practical design purposes that the submerged subsoil should be taken into consideration as a deformable 3-phase-medium (solids, water and air), causing time dependent excess pore pressures and hydraulic failure conditions, which in future should no longer be neglected.

REFERENCES

