The Impact of the Groundwater Table Level on the Influence Zone Depth – Experimental Analysis

Miroslav Broucek
Department of Mechanics - Czech Technical University in Prague, Prague, Czech Republic
Pavel Kuklik
Department of Mechanics - Czech Technical University in Prague, Prague, Czech Republic

ABSTRACT
The paper presents experimental results obtained from laboratory large-scale 1g experiment. The governing idea of the experiment is the observation of the soil behaviour under the constant load, while the groundwater level is changing in time. We experience a soil wetting-induced collapse due to matrix suctions cancellation even for soil generally described as gravel. The results of the experiments can be easily compared with in-situ results as the experiment satisfies the standard static plate load test conditions. Finally, the obtained results are incorporated into the elastic solution of the layer in the Westergard manner assumptions.

RÉSUMÉ
Ce papier présent les résultats expérimentaux obtenus dans laboratoire pendant un 1 G expérimente à grande échelle. L'idée principale de cet expérimente est le comportement des sols sous charge permanant alors que le niveau des eaux souterraines change avec du temps. Nous avons éprouvé un effondrement mouillage-induit par sol dû à de la matrice d'aspiration, même pour le sol décrit comme gravier. Le résultat de cet expérimente peut être comparé facilement avec les résultats in-situ, comme il rempli les standards du test plaque de charge statique. Pour conclure, les résultats obtenus sont incorporés à la solution élastique de la couche dans les prétentions de façon de Westergard.

1 INTRODUCTION

The soil's ability to memorize the highest load which it was subjected to in the past is well known. The theory of the influence zone, below which the deformations in the soil are negligible, is a direct consequence of this primary mentioned fact. There are several approaches for estimation of the influence zone depth but not all of them can be used without constants which can hardly be derived from the theoretical base.

Changes in the groundwater table level influence the subsoil. While rising, the groundwater cancels suction and decreases the shear strength of the soil but on the other hand it also increases the pore pressure. The soil structure collapse induced by wetting has been described in the past (Tadepalli et al. 1992) and sometimes it is also described by decrease of the soil overconsolidation ratio. Falling groundwater table level increases the effective stress and causes additional deformation. The influence of the groundwater table variations to the SPT measurement was also observed (Mendes and Loradni, 2008)

During past decade we have experienced several flood events that have reached the magnitude between one to five hundred year floods. Many buildings and engineering constructions were damaged or destructed not as a result of hydrodynamic or hydrostatic force but as a result of soil structure collapse. What is important on this experience is that while the soil structure collapse is generally assumed to be important for fine soils great part of the group of damaged buildings were founded on coarse soils.

Similar issue was lately described for sacred buildings experiencing failure of the drainage system.

2 EXPERIMENT

The governing idea of the experiment is to provide set of laboratory results for different soil types but also allow comparison with the in-situ results. The aim is to measure the soil behaviour under the constant load, which could represent an upper structure, under changing conditions of the groundwater table. When similar values of load and settlement are measured in situ on the appropriate type of the soil we can estimate the influence of the probable groundwater change to the upper structure. This will allow us to improve the standard methodology for structure hazard during floods so it actually will fit to what we observe during and after flood events.

With a general classification of the structures based on the change in subsoil it is easy to present an improved risk analysis of the flood areas which is a useful tool for any cost-effective analysis of suggested protective measures.

When preparing the experiment we have used information gathered from small scale inundation experiments carried out in previous years.

2.1 Description of the Model Stand and Preparation Procedure

The stand for the soil sample is a massive reinforced concrete box without the top covering part. The bottom part contains a system of pipes 12.5mm in diameter that is connected to the water storage tank. The side walls are 20cm thick and the box is constricted by steel beams in two levels. Steel frame is attached to the box to take the reaction force and additional small frame presents an inertial body to which the deformations are measured. The inside size of the box are 1 x 1 x 1m.

Load is applied through a hydraulic jack to the steel plate 2cm thick and 30cm in diameter. The load is measured in the hydraulic system and once more in the pressure cell bellow the reaction frame. Figure 1 shows a scheme of the experiment.

Settlement is measured by two settlement sensor installed on the plate with guaranteed accuracy 0.01 mm.

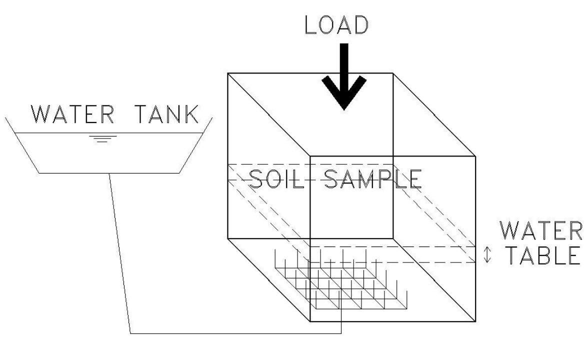

Figure 1. Scheme of the experiment

The soil is inserted into the box by layers 20cm thick. Each layer is compacted by vibrating plate. The time over which is the vibrating plate acting on each layer is estimated by compacting experiment carried out previously. The soil contains natural amount of moisture as it is kept in plastic covers after being removed from the site. The time of storage is as short as possible. The moisture content is also tested on small samples. Figure 2 and 3 show the entire model and detail of the instrumented plate before the first loading cycle.

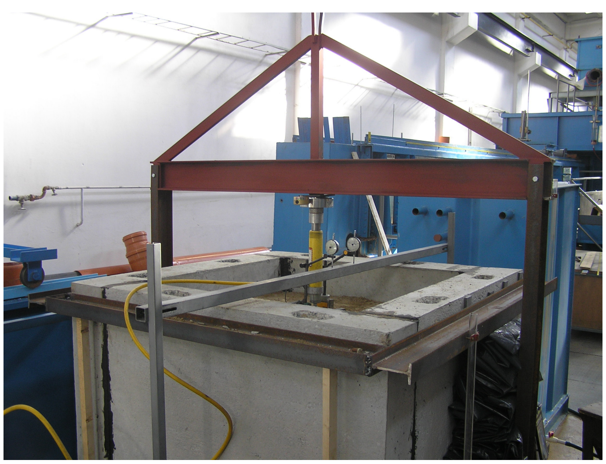

Figure 2. Complete model – ready stage

2.2 Experiment plan

Our current area of interest involves mainly coarse types of soil as the description of the processes involved in wetting induced soil structure collapse were presented for clays and fine soils in the past. The tested soils had high hydraulic conductivity so all the changes in the settlement caused by the water were assumed and proved to be relatively fast. The plan of the experiment involves several loading and unloading cycles on the dry sample. After that full load was applied and kept constant in time and water valve was open. As the water table rise in the sample the settlement is measured.

After the prescribed position of the water table is reached, the soil is slowly drained. Next experiment is performed on the same sample in a short period of time, but for completely drained sample to prove the ability of soil to memorize the load after structure collapse.

Figure 3. Detail of the instrumented plate

3 SOIL DESCRIPTION

The presented results were obtained on soil specimen classified as G2 – GP, i.e. poorly grained gravel. Figure 4 shows the grain distribution of the soil sample. The portion of particles larger than 60mm was 17.3% of the weight. The optimal moisture content and maximal dry soil density was evaluated using standard Proctor test and the compacting experiment prescribed 25 minutes duration of compaction with vibrating plate for each layer.

The soil was obtained from deep excavation in the central area of the Prague city. This soil is typical for one layer of the Prague area, which can be divided into 5 nearly horizontal layers - terraces. In this part of the city the soil is experiencing large groundwater movement especially due to engineering activity linked with lowering water table for foundation work.

Table 1. Characteristics of tested soil

Characteristics	Value
Optimal water content from PS (%)	11
Original water content (%)	4
Maximum dry density PS (kg/m^3)	1950

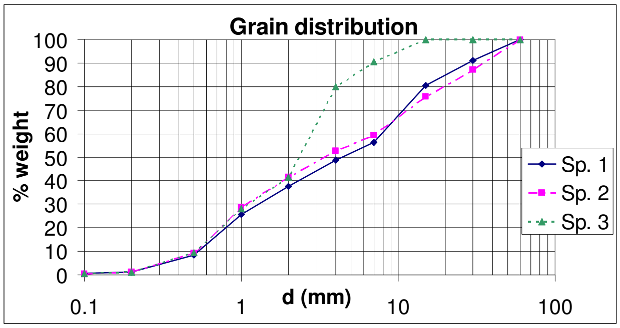

Figure 4. Grain distribution of the tested soil

This soil has also proved its predisposition for internal erosion and collapse when exposed to high hydraulic gradient or flow pressure. Several road and building accidents were reported regarding this matter.

4 SELECTED RESULTS

Results from the experiments are sets of load-displacement curves or time-displacement curves. Figure 5 and 6 show first and second loading tests on dry sample (4% water content). The SM1 and SM2 abbreviations in the charts stand for settlement measurement point 1 and 2. As the plate is instrumented with the joint that allows differential settlement of the plate at least 2 measuring points are necessary.

Three facts can be nicely observed on the Figure 5. First it is the unloading/reloading path that has different slope than primary loading path. This phenomenon of structural strength vs. void ratio was described in the past (Terzaghi et al. 1996).

Second is the characteristic loop in the unloading/reloading path. As the elastic hysteresis is generally load rate dependant it is quite interesting observation when the load steps were no shorter than 5 minutes each.

Third important fact observed is small hardening of the material.

The second test proved creep behaviour of the soil even without the presence of water. Creep was observed in sandy soils in the past (Hsiung, 2008). The important aspects are the magnitude of the creep and the duration. The whole creep behaviour last approximately 1 hour but more than 80% of the creep deformation was reached after first 15 minutes. It is also possible to observe some kind of plastic yielding after exceeding the value of 750kPa.

Following figure shows the results from first loading experiment with water entering the specimen.

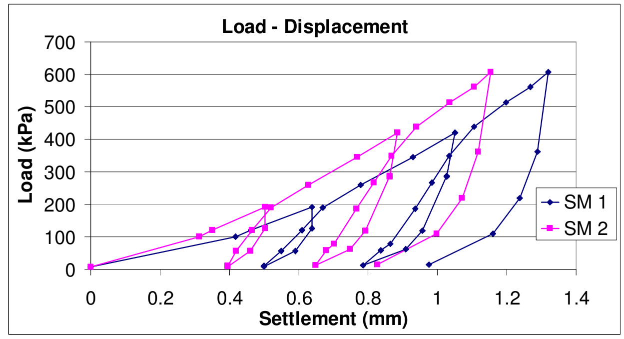

Figure 5. First loading test on dry sample

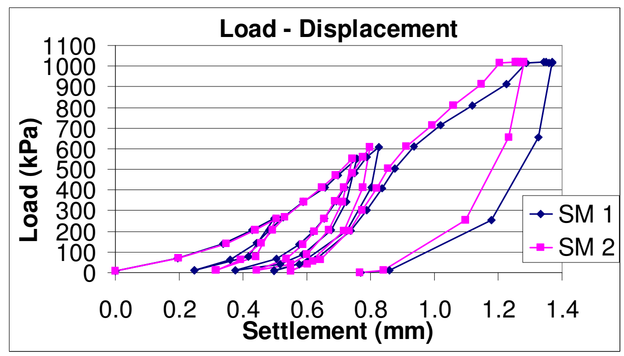

Figure 6. Second loading test on dry sample including creep behaviour

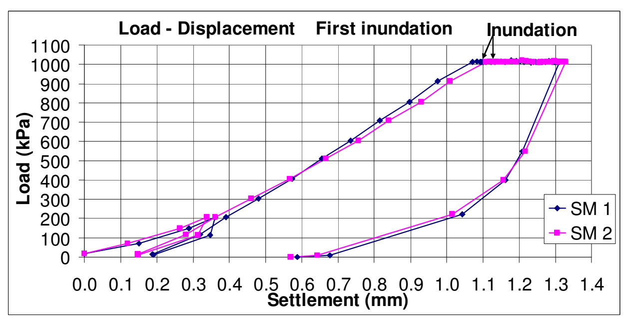

Figure 7. Third loading test on the soil sample – first inundation

Before the inundation takes place the load was kept constant for a time necessary to eliminate the effect of dry creep. On figure 8 we plot the detail of creep behaviour in time and following process of inundation of the specimen on the time-displacement chart. It is important to point out that the highest position of the water table was 40cm below the surface of the specimen. The inundation caused increase in settlement from 1.1mm to 1.32mm in average, i.e. increase by 20%. Although the observed volume change (less than 0.1%) was very low when compared to finer soils, for example 2.5% to 5.8% for sandy silt observed by Jia et al. (2009) or 1.1% for

Mississippi silt observed by Tadepalli et al. (1992), the relative increase in settlement is very high.

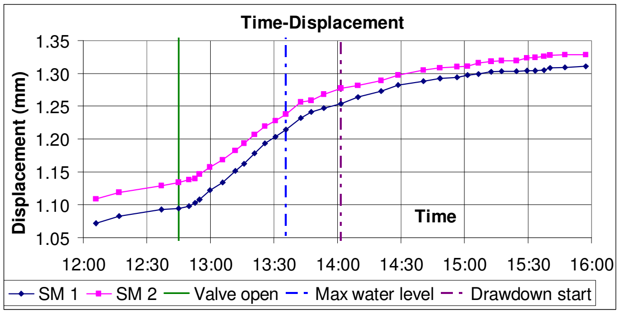

Figure 8. Third loading test - detail of the time-displacement curve during inundation

Figure 9 shows the fifth loading test on the specimen. It can be observed that after the load reaches maximum prescribed for the test the settlement continues to rise for about 0.1mm. Again the increase in the settlement is close to 20%.

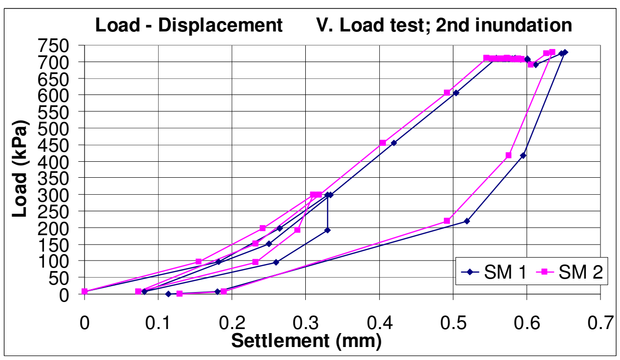

Figure 9. Fifth loading test on the soil sample – second inundation

From the presented figures it is quite clear that the soil sample gives stiffer response every load test. Although this is true it can be shown that by unmounting the plate we allow the specimen to cancel the procedure and for the next loading test it will again follow the primary consolidation line, which can be a little bit stiffer.

Response graph for 6 following load case is presented as Figure 10 and from this is clear that while load test 2 gave much stiffer results than load test 1, the difference between load test 3 and 4 is in the loading part negligible.

The same behaviour is between load test 5 and 6. Also we can see that the level of load where the soil starts to yield varies around 750kPa but after second load test the yielding can be hardly noticed.

When considering the influence zone below the plate we would expect that until the groundwater table reaches the border of the zone no effect on the settlement should be observed. During the first inundation the zone was very close to the bottom and so the change in behaviour took place immediately. The experiment was so far not dried to the starting moisture content so any further attempts made were influenced by the previous load test.

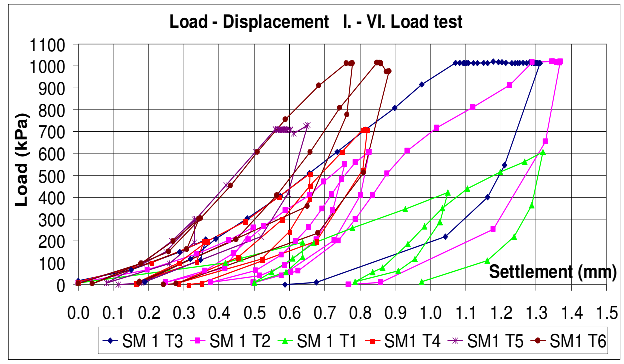

Figure 10. Loading tests I.-VI. – load/displacement curves

5 INFLUENCE ZONE THEORY

The influence zone presents an area below the acting load. It is the area where the deformations due to the applied load take place. Below the influence zone all the deformations from the particular load are negligible. It is easy to see that the depth of influence zone surely depends on the size of the load, its magnitude and the characteristics of the soil.

The governing idea for estimating the depth of influence zone is the overconsolidation of the soil which is generally caused by the excavation. When the additional load is applied the vertical stress from the load is added to new (after excavation) geostatic stress and where the sum is equal to the original geostatic stress (before excavation) that is the depth of influence zone. It can be easily written as eq. 1.

$$\sigma_{zz}(0,H)=\gamma h \quad [1]$$

Where H is the depth of influence zone, h represents the depth of excavation, γ stands for the specific weight of the soil and zero coordinate is placed at the surface of the excavated ground, i.e. where the load is applied.

The influence zone theory has wide area of use but the best example is the back analysis of mechanical parameters of the soil from in-situ static load tests. It was experimentally confirmed that using plate with different diameter and employing generally used Bousinesq formula (Equation 2) we obtain very different results (Kuklik et al. 2008).

$$E_0=\frac{\pi}{2}\left(1-\nu^2\right)\left(\frac{f_z r}{s_{tot}}\right) \quad [2]$$

Where r is the radius of the plate, s_{tot} represents final settlement, f_z is the load magnitude and ν is the Poisson's ratio.

The only problem we have in estimating the influence zone depth is how to calculate the vertical stress for complex geotechnical problems when it is dependent on the soil parameters and we can not obtain them before we estimate the influence zone.

Instead of time consuming FEM analysis we suggest the use of elastic layer solution in Westergard manner. For the back analysis of the static plate load test all the assumptions made are quite reasonable and the errors are usually much smaller than the spatial differences at the construction site.

Using this method we can obtain the estimation of the influence zone very fast as analytical solution is derived for different shapes of the footing. For example for infinite strip footing the depth of the influence zone can be calculated as eq. 3.

$$H = \frac{\pi a}{2}\sqrt{\frac{2-2\nu}{1-2\nu}}\frac{1}{\sinh^{-1}\left(\tan\frac{\pi\gamma h}{2f_z}\right)} \quad [3]$$

Where a is a half of the strip width, f_z is the load magnitude, h represents the depth of excavation, γ stands for the specific weight of the soil and ν is the Poisson's ratio.

For the circular load it is necessary to introduce the $F_r(\beta)$ function:

$$F_r(\beta) = 1 - \beta\int_1^{+\infty}\frac{t}{\sqrt{t^2-1}\cosh\left(t\frac{\pi}{2}\beta\right)}dt \quad [4]$$

As we calculate the $F_r(\beta)$ function we can obtain the depth of the influence zone by solving easily equation 5.

$$\beta = \frac{2\alpha r}{\pi} = \frac{r}{H}\sqrt{\frac{2-2\nu}{1-2\nu}} \quad [5]$$

Fortunately it is possible to follow the basic idea of the influence zone and plot the "excavated" geostatic stress against β as shown in figure 11. From this chart we get β and then we calculate H with the use of Poisson's ratio and radius of the applied load.

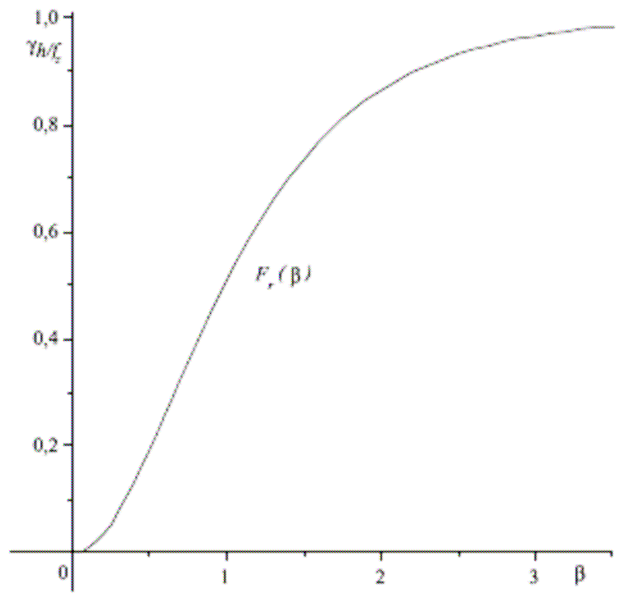

Figure 11. $F_r(\beta)$ function for circular load area

We can see from presented formulas that the depth of the influence zone is not E dependent. The inundation procedure is usually associated with suction cancellation and also overconsolidation ratio cancellation. That means we have do decrease the γh value. As we decrease overconsolidation ratio from the Figure 11 is clear that we also decrease the value of β and consequently increase the value H, i.e. the depth of influence zone. For thicker layers and identical properties of the soil and loading we obtain higher settlement.

6 CONCLUSIONS

The presented experimental results show that coarse soils such as gravel suffers the soil structure collapse due to wetting process and although the volumetric deformation is not as high as in case of finer soils it still presents a great increase in settlement with respect to the applied load and deformation without ground water

The drop in the pore pressure due to drawdown of the water table did not show any significant deformations. This may due to the fact that the increase in an effective pressure due to the drawdown is not high enough when compared with the other involved stresses.

The tested sample also proved creep behaviour in the dry state but the magnitude of the settlement is significantly smaller compared to one caused by the inundation.

The behaviour of the sample also shows better agreement with the critical state constitutive models rather than plasticity models. Unfortunately the use of critical state models is still a problem due to the number of parameters.

We have presented the idea of the influence zone and showed the formulas for practical evaluation of the depth of the zone. They have been used for evaluating the load of the plate in order to avoid influence of the bottom slab.

It has been also used for evaluating the mechanical properties of the soil sample for simple FEM analysis using elastic, modified elastic, Mohr- Coulomb and Drucker-Prager constitutive models.

The influence of the rise of the groundwater table to the increase of the influence zone depth was described and it also can be found in experimental results.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by research projects GA103/07/0246 and GA103/08/1119.

REFERENCES

Hsiung, B-CH.B. 2008. A case study on the behaviour of a deep excavation in sand. *Computers and Geotechnics 36:* 665–675.

Jia, G.W., Zhan, L.T., Chen, Y.M. and Fredlund, D.G. 2009. Performance of a large-scale slope model subjected to rising and lowering water levels, *Engineering Geology* 106: 92-103.

Kuklik, P., Kopackova, M., Broucek, M. 2008. Fast Estimation of the Influence Zone Depth inside the Subsoil in Relation to the Various Shapes of Footing. *12th IACMAG conference*, IACMAG, Goa, India: 281-288.

Mendes, M.R., Lorandi, R. 2008. Analysis of spatial variability of SPT penetration resistance in collapsible soils considering water table depth. *Engineering Geology* 101: 218-225.

Tadepalli, R., Rahardjo, H., Fredlund, D.G. 1992. Measurements of matric suction and volume changes during inundation of collapsible soils. *Geotechnical Testing Journal*, ASTM, 15(2): 115–122.

Terzaghi, K., Peck, R.B., Mesri, G.: *Soil Mechanics in Engineering Practice*, Wiley-Interscience, 1996.