Surprising Settlement in Soft Soils – Two Case Histories

Tassement étonnant dans les sols mous - Deux études de cas

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Abstract: The paper illustrates two case-histories of structures with shallow foundations on soft clay in south Germany. The acquired experience in estimating the settlement in these regions was considered to be satisfactory for the most practical cases. Long-term settlement observations of an office building and a tank showed 2 to 3 times larger settlement than expected using the conventional methods.

Résumé : Cet article illustre deux études de cas de structures avec fondations superficielles sur argile molle au sud de l'Allemagne. L'expérience acquise en estimant le tassement dans ces régions donne des résultats satisfaisant dans la plupart des cas pratiques. Les observations du tassement à long terme d'un immeuble de bureaux et d'un réservoir ont montré que le tassement mesuré de ces structures est environ 2 à 3 fois plus grand que prévu à l'aide des méthodes coventionnelles.

1. Introduction

This paper demonstrates two case histories of structures with shallow foundations on lacustrine soft clay in southern Germany, especially near the lakes in front of the Alps, where the raft foundation is the most used type by construction of normal buildings. The engineering experience in this area shows that the calculated settlements using the deformation parameters from the standard consolidation test are on average 50 % larger than the settlements actually measured in situ. This observation is recently confirmed by (Kempfert and Soumaya 2004), who analyzed 10 buildings with raft foundations on lacustrine soft clay and indicated that the discrepancy is due to the overestimating of the compressibility parameters in the standard consolidation test.

The acquired experience in estimating the settlement in these regions was considered to be satisfactory for the most practical cases since the calculated settlement is on the safe side. Long-term observations of an office building and a tank showed that the measured settlement of those structures is about 2 to 3 times larger than the expected values in the design phase.

Using numerical analysis by means of the finite element method, two reasons for the unexpected settlement are recognized. In the first project, the safe bearing capacity was slightly exceeded. In the second project the soil was rapidly loaded (quick filling of the tank). Thus, significant settlements were recorded, which could not be predicted using the conventional settlement analysis.

2. Soils and geology

The soils near the lakes in front of the Alps belong to the lacustrine and fluvial young sedimentations from the Holocene and the last ice age. Soil investigations from several towns in this region indicate that the properties of these soils are uniform over a large area.

In geotechnical terms the lacustrine clays in southern Germany are normally consolidated silt clays to sandy silts of low to middle plasticity with soft to very soft consistency. The natural water content varies from 25 to 50 % and averages about 33 %. Drained shear parameters are $\varphi' = 22.5\text{-}25°$ and $c' \approx 0$ kN/m², undrained shear strength is c_u = 10-40 kN/m².

Because of their low strength and high compressibility the lacustrine clays in southern Germany are considered as difficult soils in foundation engineering. Loads of normal buildings on this type of soils are typically carried by raft foundations.

3. Case-histories

3.1. Case 1: office building, Constance city

The first case deals with an office building in Constance town. The 4-story building with an underground floor has a base dimension of 20 x 34.4 m² with a total load of 97 kN/m². It is founded on a 0.5 m thick raft foundation that rests on a 2.5 m thick well-compacted granular fill. Hence, a net load of about 62.6 kN/m² is applied on the soft soil.

The subsoil conditions were explored by borings to a depth of about 40 m. A layer of soft, middle plastic lacustrine clay with a total depth of 28 m was encountered below the ground surface. This layer is followed by soft, low plastic lacustrine clay up to the end drill depth. The subsoil conditions and soil properties are summarized in Fig. 1.

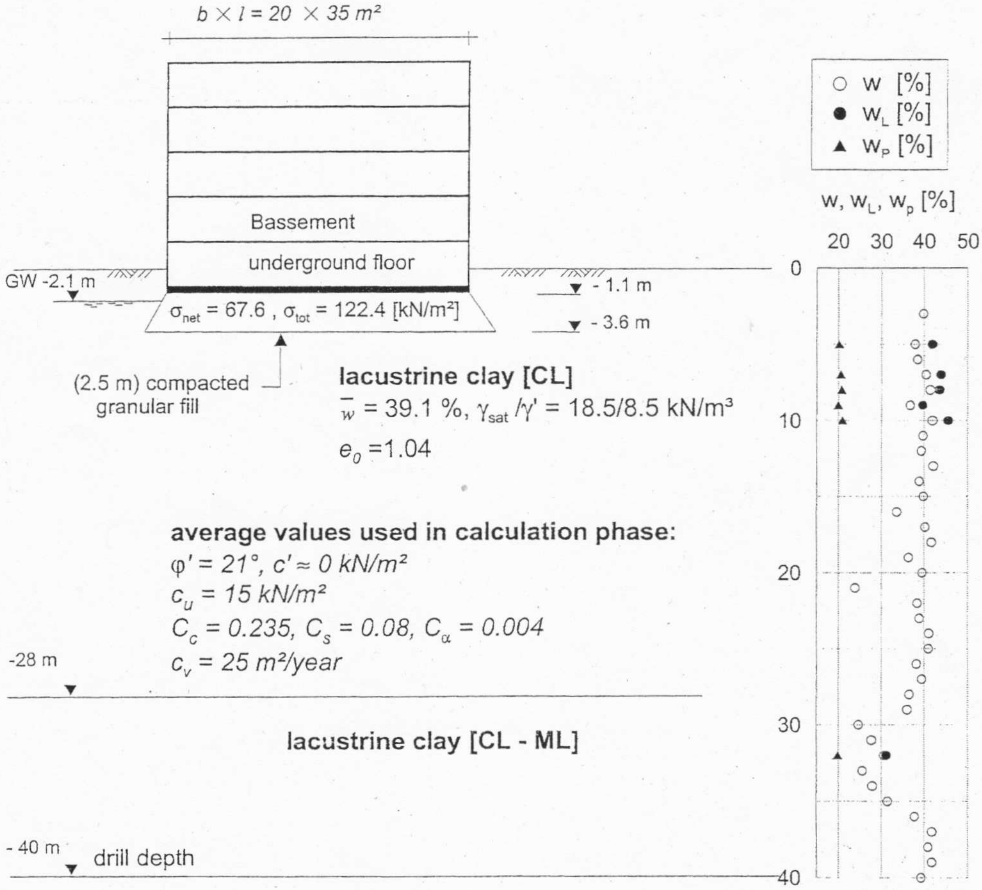


Figure 1. Profile, soil conditions and cross section, case 1

After the raft foundation was in place, settlements had been measured at nine points from September 1986 until May 1999. Fig. 2 shows the observed time-settlement curves. The field observations were analyzed using the method developed by (Asaoka 1978). This method enables to determine the final settlement s_∞ and the coefficient of consolidation c_v for a settlement-time observation.

Using Asaoka' s method the settlement at all measurement points was determined, so that an average final settlement of about 69 cm at the center of the raft close to the measurement point 5 could be interpolated (see Fig. 2). This value is 2.5 times greater than the calculated settlement ($s_{cal.}$ = 27.5 cm).

Thus, it was evident that the soil in the vicinity of the foundation had changed from an elastic equilibrium state to a plastic equilibrium state probably due to a local pre-failure phase. Furthermore, a value of 25 m²/year for the coefficient of consolidation c_v was obtained assuming one way drainage and a thickness of about 7.5 m for the compressible layer. The extrapolated c_v-value after Asaoka' s method using the measured settlements is about 5 times larger than the laboratory value.

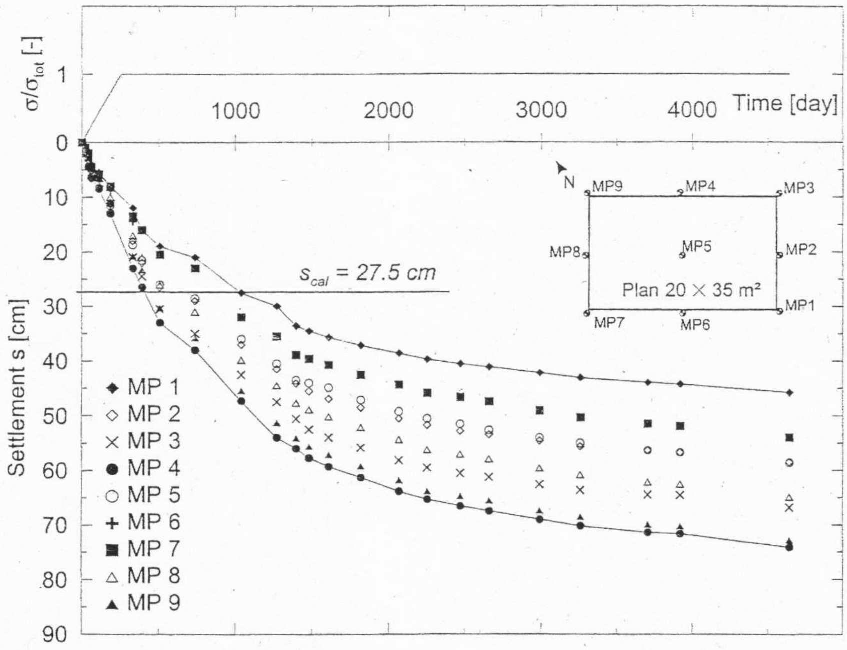


Figure 2. Settlement record, case 1

The ultimate bearing capacity can be conventionally calculated using the well known equation

$$q_{ult} = c \cdot N_c \cdot \upsilon_c + \gamma_D \cdot D \cdot N_q \cdot \upsilon_q + 0.5 \cdot B \cdot \gamma \cdot N_\gamma \cdot \upsilon_\gamma \qquad (1)$$

Under undrained conditions ($\varphi = 0,\ c = c_u$) the following equation can be used in a short time analysis

$$q_{ult} = 5.14 \cdot \upsilon_c \cdot q_u + \gamma_D \cdot D \qquad (2)$$

Using the effective shear parameter and substituting the appropriate factors into equation (1) a value of $q_{ult} \approx 455$ kN/m² can be estimated. On the other hand a value of $q_{ult} \approx 140$ kN/m² is estimated using the undrained shear strength in equation (2). Hence, the calculated safety factor (SF) ranges between 1.14 and 3.7.

Allowance for the applied load has been accepted. This decision has been made because the designer assumed that the soil will be partially consolidated and additionally, that the shear strength will be improved and the settlement will be decreased regarding to the compacted granular backfill. Due to this considerations the required safe factor (SF = 2) in the German practice could be achieved.

According to the measured settlement it is quite evident that the allowed load is very questionable and a partial shear failure can not be excluded. However, these assumptions could not be verified in the design using the conventional analytical solutions. Hence, a numerical analysis methods is unavoidable to consider the soil behavior in a more realistic way.

3.2. Case 2: Storage tanks, Radolfzell city

The second case deals with storage tanks. The structure consists of three juice containers with a total storage capacity of 3 x 225 = 675 m^3.

The subsoil conditions were explored by borings and penetration tests to a depth of about 10.5 m. A lacustrine sediments layer with a thickness of 2.5 m below the top ground surface was found. This layer is followed by sand layer to a depth of 5 m where the lacustrine normally consolidated clay layer begins. Some soil characteristics are shown in Fig. 3. According to the geotechnical data a settlement of 9 cm has been calculated.

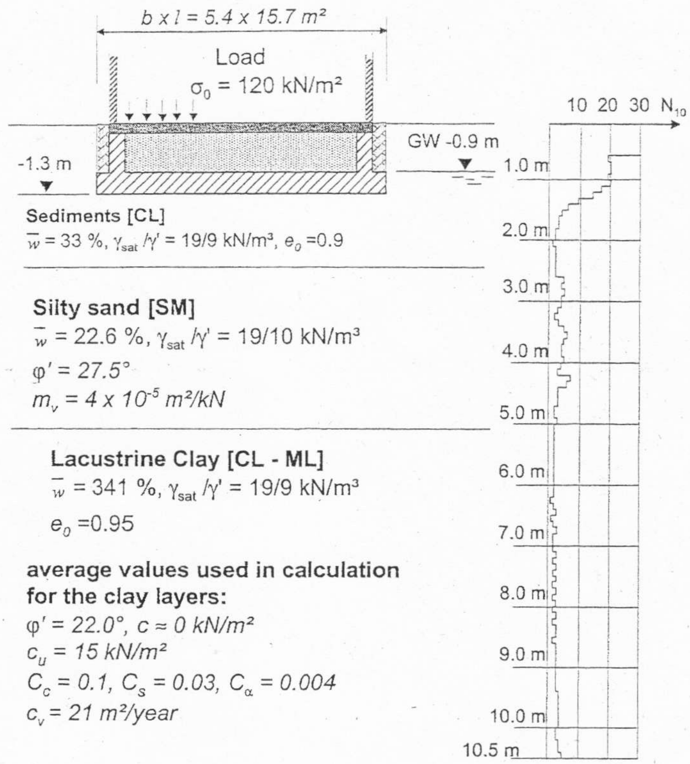


Figure 3. Profile, soil conditions and cross section, case 2

The settlement has been recorded in 4 measurement points for a period of 7 years after completing the raft foundation (Fig. 4).

Using Asaoka' s method settlements of 22 cm at the southern side and 13 cm at the northern side with an average value of 17.5 the measurements a settlement of about 17.5 cm. Thus, the observed value is approximately twice larger than predicted.

Because the analysis of this project has been carried out in terms of total stresses, possible effect of local shear or progressive failure was excluded. In trying to explain the discrepancy between measured and calculated settlement, the authors suppose at first that the soil was rapidly loaded due to a quick filling of the tank. To verify this assumption the use of numerical methods is inevitable to consider the influence of loading rate on the deformation because the conventional methods are limited in this respect. From the project documents it followed that the tanks were approximately filled within 7 months after beginning of the construction. This piece of information was used to derive the average rate of loading that was used later in the numerical analysis.

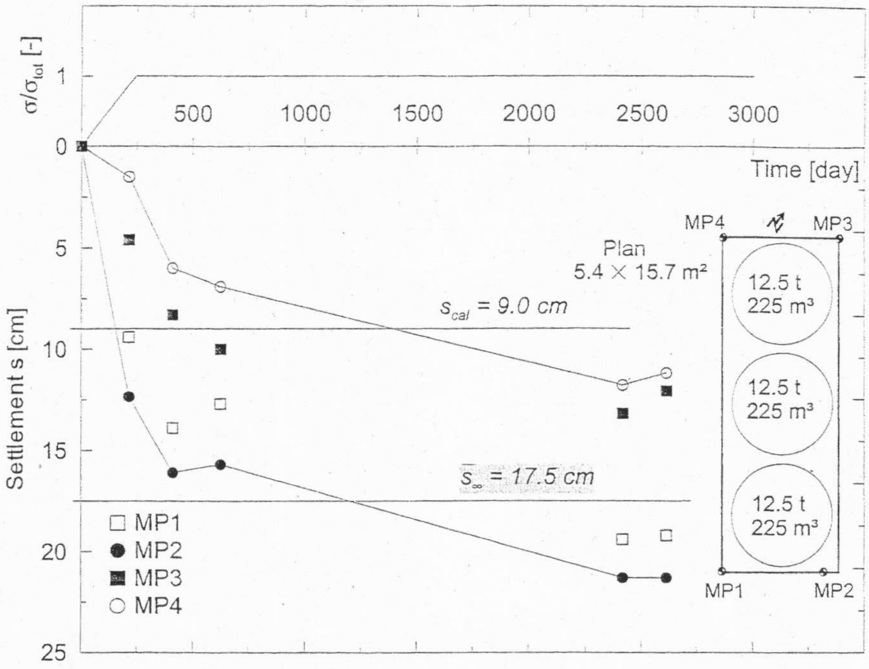


Figure 4. Settlement record, case 2

4. Numerical analysis

Because the settlement and the bearing capacity are estimated in different steps using the classical analysis, a large settlement may be interpreted as a failure (Chapuis et al. 1988). In some cases, a determination of load-settlement relationship is required by the designer, especially when unusual conditions are to be expected. This relationship, as it is well-known, is neither nonlinear nor elastic and can only be simulated using the numerical methods. The finite element method is a useful procedure to simulate the soil behavior in more realistic way and become popular in the modern soil mechanics.

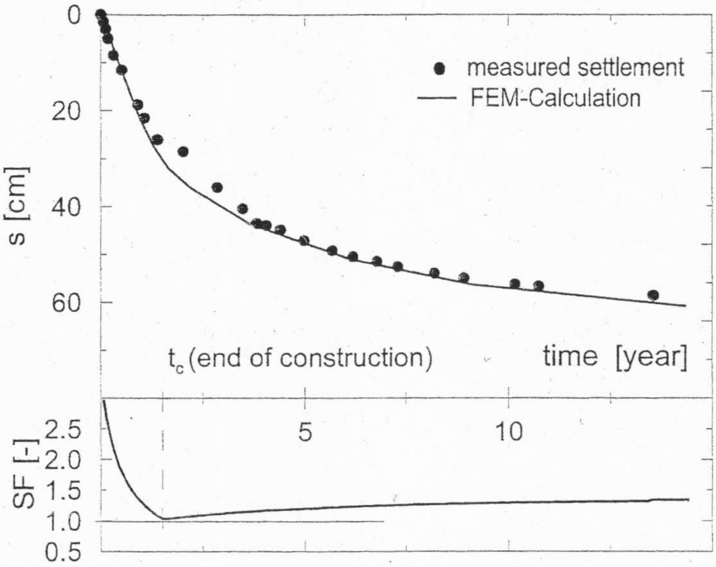
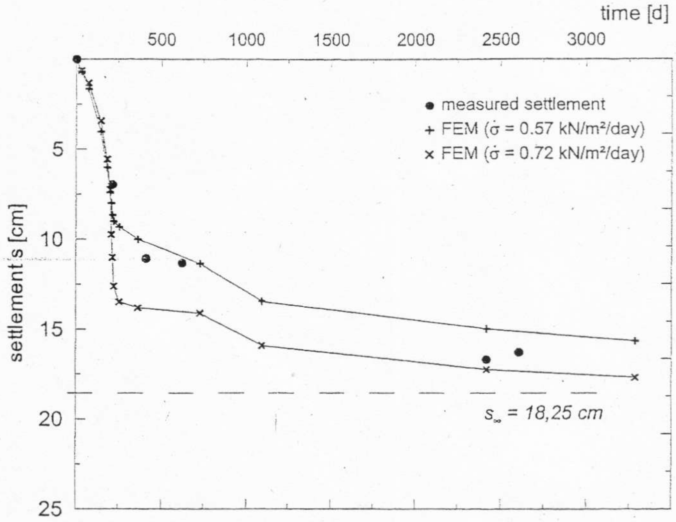


Figure 5. Time-dependent settlement and safety factor of the 1. case using the FE-method

Thus, the projects represented above are recalculated using the finite element method with the program PLAXIS using the so-called soft-soil-creep as material model. Real field condition and real deformations parameters are used in the calculation in order to achieve representative results that may be compared with measured values. The required soil parameters are taken from Fig. 1 and Fig. 3.

In Fig. 5 the results of the recalculation of the first project are represented in form of time-settlement-line and compared to the measured settlement at the measurement point 5. Additionally, the time-dependant safety factor is determined and plotted in the same Figure.

The finite element analysis shows a good agreement with the measurements, because the input parameters are estimated from the settlement back analysis. The resulting safety factor SF-values are of great importance. At the end of construction a safe factor of 1.1 was achieved and the building was near to failure after 1.5 years which may explain the large measured settlement.



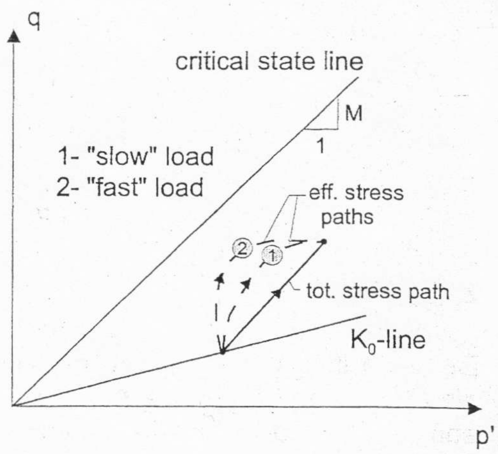


Figure 6: a) Comparison of the measured and computed settlements of the tank foundation

b) Dependency of the stress paths on the rate of loading

Fig. 6a shows the computed and measured results of the tank in the form of time-settlement-lines. The upper and lower lines correspond to a loading rates of 0.57 kN/m²/day and 0.72 kN/m²/day respectively. The choice of these rates has been made taking into account a probable filling period of 165 to 215 days.

From the measured values the settlement has been interpolated at the center of the mat foundation and compared with the calculated settlement. It is obvious that the response of soft soil depends on the rate of loading. The behavior can be interpreted schematically with the help of the actual effective stress path for each loading rate as shown in Fig. 6b. The faster the load is applied, the nearer the effective stress path is to the critical state line due to the developed excess pore pressure. Consequently, the deformations are larger for a "fast" loading. This fact helps to explain the significant settlements of the tanks that could not be expected using the conventional method.

5. Conclusions

- Oversized backfill layers under foundations are needless because the pressure of the backfill could be larger than the overburden pressure in this case. Staged construction is necessary when the backfill layer is to be oversized to improve the strength of soft soils via consolidation.
- A safety factor of SF = 2 in a total stress analysis may lead to unexpected settlements in the soft soils because the settlement and the bearing capacity are estimated in

different steps using the classical analysis. A minimum value of SF = 3 is recommended.

- The response of soft soil depends on the rate of loading. Faster loading causes larger deformations due to undrained conditions.
- The results of the analysis show that attention must be paid in the design and construction of shallow foundations on soft clay. A load-settlement relationship is required in the design phase , especially when unusual conditions are to be expected.

6. References

Asaoka A (1978) « Observational Procedure of Settlement Prediction » Soil and Foundations, Vol. 18(4), 87-101.

Chapuis R. P., Silvestri V., Soulié M. (1988) « Theoretical bearing capacity of clay under shallow footings: verifying whether it realistic » Canadian Geotechnical Journal 25, 62-75.

Kempfert H. G., Soumaya B. (2004) « Settlement Back-Analysis of Buildings on Soft Soil in Southern Germany » Proc. of 5th International Conference on Case Histories in Geotechnical Engineering, New York, to be published.