SETTLEMENT OF A HIGH-RISE BUILDING DUE TO LOADS VARYING WITH TIME

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Introduction

The subsoil of some towns in Hungary is very unfavourable from the aspect of foundations, especially those of high-load, high-rise buildings. The building discussed here was erected in *Szeged*, in a part of the town where the subsoil consists of thick strata in poor condition, the characteristic flooding soil sorts of the *Tisza* river valley. Near the surface fine sand or sandy silt, deeper down silts and clay layers follow each other. Beside the unfavourable soil stratification, also the ground water table is very high.

For this reason spread foundations near the surface are hardly possible, because the large settlements to be expected would impair stability of the building. Therefore rather deep foundations are used and of these the cast in-situ piles are most favoured. Here *Franki* piles were proposed. Unfortunately, design, construction and load capacity determination of *Franki* piles not always takes the quality and the condition of the soil strata into consideration.

Because of construction errors of the foundation planned with *Franki* piles of a 60 m high industrial tower, the stability of the whole building had to be re-examined. It was found that the bearing capacity of the piles had been overrated. Since the number of piles could not be further increased, the strengthening had to be carried out by applying a foundation raft slab and when testing the load capacity, both the piles and the soil under the foundation raft slab had to be taken into account. Thus a principle essentially contradicting that of pile foundations, and inadvisable according to earlier practical experiences had to be applied. The story of the foundation, causes and method of correcting were reported by Kézdi (1976). Settlements were estimated in design by approximate assumptions and controlled in construction by systematic and detailed measurements. For such non-traditional combined foundations, the question arises how the settlement can be determined more accurately.

Analysis of the load transfer

Interaction between a spread foundation and a pile foundation involves load distribution between the foundation raft slab and the piles in a certain proportion determined by the displacements.

Namely the soil surface under the foundation raft slab is only able to take the load if the soil is compressible. The foundation raft slab and the pile are in rigid connection, therefore the system is only able to a combined settlement. It has to be examined what is the load causing the pile and the foundation raft slab to settle.

For this purpose partly the settlement likely to occur for a spread foundation alone and partly, the load capacity of the pile, the tip resistance and the skin friction were separately calculated.

Under full load, the foundation raft slab settled by about 30 cm, the maximum of the pile skin friction was 880 kN, and the tip resistance 1560 kN. Pile displacements and load transfer were determined by KÉZDI's method (1973). Measurements under similar soil conditions showed the skin friction of the pile to be completely exhausted already at a settlement of 30 to 40 mm, when the tip resistance only begins to take more important loads. At the same time the spread foundation can only transmit 10% of the total load. An interesting load distribution pattern is obtained by examining the maximum load supported by the foundation structure as a function of settlement.

Kézdi's formula permits to determine the skin friction and the tip resistance for any settlement.

The force taken up by the foundation raft slab is plotted as a linear function of the settlement. Fig. 1 shows the variation of force taken up by a pile

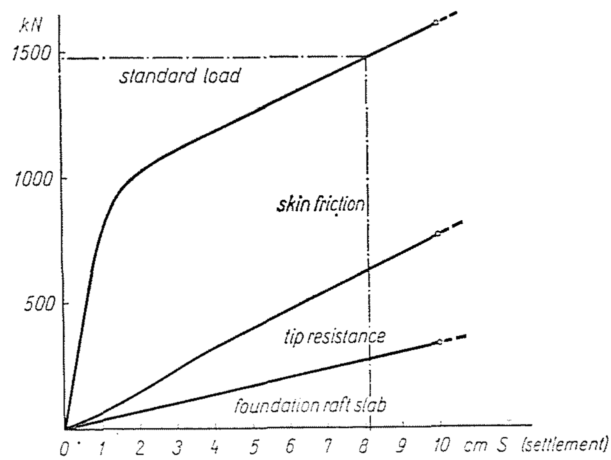

Fig. 1. Load transfer of the combined foundation system

vs. penetration as well as the proportional part of the load carried by the slab and pertaining to one pile. The structure is seen to take up the standard load at about 8 cm settlement.

From the view-point of settlement, the other important question is where the load is transferred. The foundation raft slab and the pile skin are bearing on soil layers above the pile tip, whereas the tip resistance loads the soil under the pile tip. An adequate tip resistance is only possible if the tip bears on a harder, less compressible soil layer.

According to the above, the load is first transferred by the pile skin to the upper soil strata. In proportion to the penetration, the pressure transferred by the foundation raft slab also increases. After the skin friction is exhausted, the remaining load is divided between the foundation raft slab and the tip resistance.

Butterfield and Banerjee (1971) suggested a solution for the load bearing of pile and foundation raft slab, the load distribution and the pattern of settlements, supposing an elastic medium. Though in this case there is a stratified, anisotropic medium, as an initial approximation for the load distribution, also the share of the foundation raft slab load in bearing and thus, the expected settlement, were calculated according to Butterfield—Banerjee. According to the calculation, the foundation raft slab provides a load transfer of about 30% at a rate of 9 to 10 cm of settlement.

Practical measurements on large diameter piles show that there is a higher share of tip resistance only in case of greater settlements; in this case a maximum of 20% has to be taken into account. It follows that the foundation raft slab can take about 20% of the complete load.

Accepting this load distribution proportion (see Fig. 1) the expected compression can be calculated with the effective soil physical characteristics. Since the particular measurement result confirmed the calculated values, our assumptions can be accepted as correct.

Determination of the ultimate settlement

The shape of the diagram of stresses transferred from the foundation raft slab is in accordance with the usual Boussinesq theory. The stress transferred from the pile skin increases linearly with the depth. Stresses acting on the layers above the pile tip can be computed according to Fig. 1 and plotted as shown in Fig. 2.

Soil stratification is given in Fig. 3 with a sketch of the foundation system. The compression moduli were known layer by layer, the design data are given below.

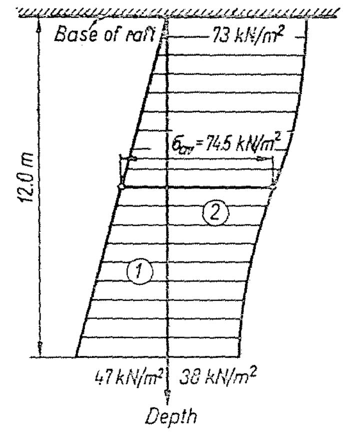

Fig. 2. Stress distribution in the compressed layers along the depth. 1. Vertical stress due to skin friction; 2. vertical stress due to the foundation raft slab

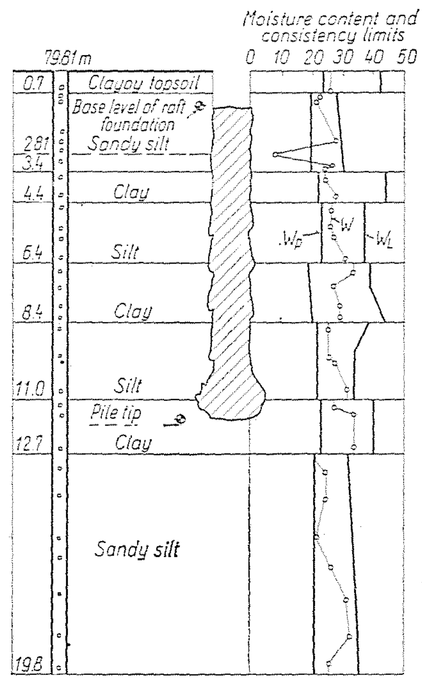

Fig. 3. Soil profile and soil condition

Total load of the building	176 MN + 7.60 MN = 183.60 MN
Number of piles	194
Pile length	12.0 m
Surface of the foundation raft slab	800 m^2
Contact pressure beneath the raft slab	73 kN/m^2
Stress transferred from the pile skin in the plane of the pile tip	47 kN/m^2

Settlement calculated from the above data was $\Delta H = 10.7$ cm, in fair agreement with the value assumed for load distribution. The next step was to determine the change in degree of consolidation as a function of the rate of loading.

Calculation of consolidation

Basic data for the consolidation equation:

k	$= 10^{-7}$ cm/sec	(permeability)
M	$= 8400$ kN/m^2	(average compression modulus)
$2H$	$= 12.0$ m	(thickness of consolidating layer).

Comparing computed consolidation with the results measured during construction, it can be established whether or not the time-settlement diagram determined by measurement and the curve of computed ultimate settlement converge. If settlements larger than expected occur, adequate measures can be taken during the construction phase. On the other hand it is also very important to know the percentage of settlement performed until completion of the structure.

TERZAGHI suggested a method of calculating the one-dimensional consolidation process occurring after sudden loading. The effect of a load increasing with time can only be approximated. In the case considered the load was applied to the soil in a long construction time of 780 days. For time-dependent loads SCHIFFMAN (1958) suggested an exact analytical solution. The other boundary conditions (homogeneity, saturation, etc.) were identical with those assumed by Terzaghi.

Schiffman's differential equation, using symbols in Fig. 4:

$$C \frac{\partial^2 u}{\partial z^2} + R = \frac{\partial u}{\partial t}$$

(where factor R stands for the uniform increase in time of the load) yield the pore water pressure vs. time and place.

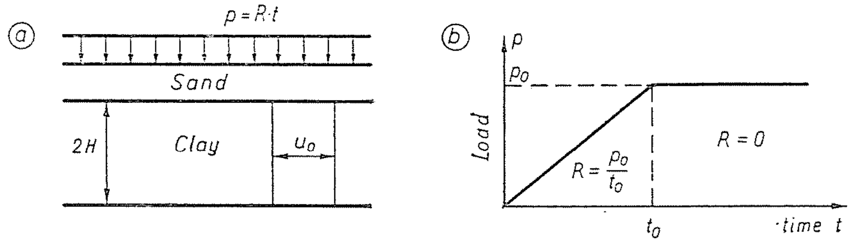

Fig. 4. Compressed layer and scheme of change of load for computing the consolidation

Solution of the differential equation for the construction period t_0 ($t < t_0$) of linear load increase:

$$u_a(T) = \frac{32u_{ao}}{T_o\pi^4} \sum_{n=1,3,5}^{n=\infty} \frac{1}{n^4}\left[1 - \exp\left(\frac{n^2\pi^2}{4}T\right)\right]$$

and after application of the full load ($t < t_0$), when the load becomes constant:

$$u_a(T) = \frac{32u_{ao}}{T_o\pi^4} \sum_{n=1,3,5}^{n=\infty} \frac{1}{n^4}\left\{\left[1 - \exp\left(\frac{-n^2\pi^2}{4}T_o\right)\right]\exp\left[-\frac{n^2\pi^2}{4}(T - T_o)\right]\right\}$$

Fig. 5 shows the quotient $\frac{u_a(t)}{u_{a0}}$ factored out of the equation as a function of time. As long as $t < t_0$, the degree of consolidation is given by $\varkappa_1 = \left(\frac{t}{t_0} - \frac{u_a(t)}{u_{ao}}\right)$.

After time t_0, the degree of consolidation is:

$$\varkappa_2 = 1 - \frac{u_a(t)}{u_{ao}}.$$

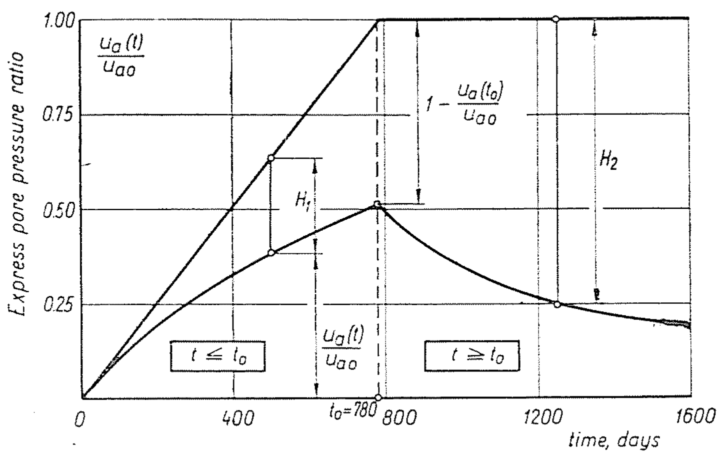

Fig. 5. Computed neutral stresses vs. time

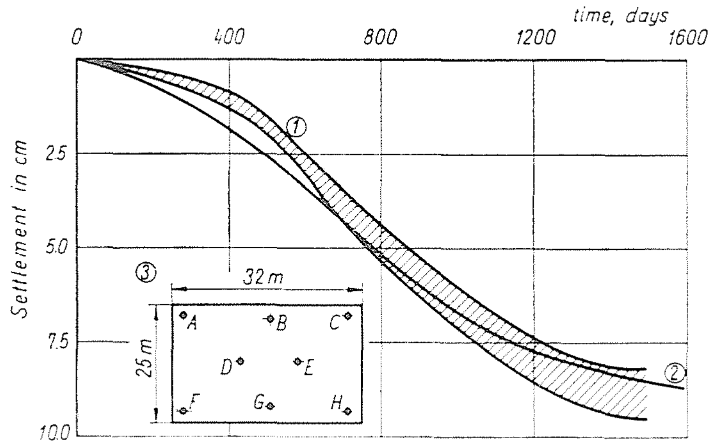

Fig. 6. Computed and measured settlement. 1. Measured values; 2. computed values; 3. ground plan of the building with the measurement points

The change of settlement in time is given by:

$$\varkappa \Delta H_{\infty} = H_t$$

involving $\varkappa_1$ or $\varkappa_2$ depending on the design period.

Numerical calculation of formulae described above is made simple by a digital computer. In present case a *Hewlett—Packard* computer type 9830 A was used. Fig. 5 shows the computed numerical values for the ratio $\frac{u_a(t)}{u_{ao}}$ whereas Fig. 6 gives the time-settlement curve.

It is seen that by the end of the 780-day construction time, the settlements are half-way complete. Comparison of computed and measured settlements in Fig. 6 shows a good agreement.

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Summary

A method of theoretical approximation of the settlement of an unusual foundation system composed of spread and pile foundations, based on load distribution analysis, is presented. The rate of load increment is very important in determining the consolidation. The method applied is suitable for computing soil consolidation under any large foundation raft slab, permitting at the stage of design to determine the permissible rate of loading. Good agreement between the measurement results and the computed values justifies the applicability of this theory.

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