SETTLEMENT OF A MULTI-STOREY BUILDING ON HETEROGENEOUS CLAYEY SOIL

TASSEMENT D'UN HAUT EDIFICE SUR UN SOL ARGILEUX HETEROGENE

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SYNOPSIS A multi-storey building is being constructed on heterogeneous clayey soil. The foundation conditions worsened during an interruption of construction works after excavation. A simple method was applied for the calculation of settlement in a heterogeneous, non-linear medium. The results enabled a spread foundation of reinforced concrete raft to bo used an the calculated values are in faire agreement with deformations measured repeatedly.

INTRODUCTION

Foundation ground on a site selected for a 50 m high building consisted of clayey soils. Before the kind of foundation was decided, several boreholes and shafts had been sunk, which discovered the bedrock of Silurian clayey shales with a dip of 40° N. Their upper part was weathered to stiff clay with a layer of soft clay on the top. It was decided to put the foundation base to a depth of 2 m below the surface of the bedrock i.e. where the clayey shales would be less weathered.

LOADING TESTS

The compressibility of stiff clay and shales was proved by a loading test in a shaft. Stiff clay at the depth of the foundation base (2 m) was tested on the first standpoint. Further, less weathered clayey shales 4.30 m below the bedrock surface were examined. Loading tests with a stiff steel plate 706x706mm ($0.5 m^2$) and a circular plate ø 356mm ($0.1 m^2$) were performed on each standpoint. Stress-strain graphs are drawn in Fig.1. The deformations are of sublinear character especially in stiff clay, where the exponent of parabolic course n equals 1.9, nonlinearity NL is 25 %, and plasticity PL equals 0.58 (elasticity EL is 0.42). These parameters are explained in a previous publication of the author (1961).

From the relations for an elastic semi-infinite body, the moduli of deformation E_o were derived, using the first branch of the stress-strain curve. For stiff clay and a pressure range 0 to 3 kp/cm^2 E_o equals 1340 to 130 kp/cm^2, which proves the non-linearity of deformations. For weathered shale and the same pressure range E_o is 1580 to 1225 kp/cm^2.

After excavation to the level of the foundation base, the construction work was interrupted. To prevent a further weathering of stiff clay, the foundation base was covered by a layer of sand with gravel 1 to 1.5 m thick. The surface of the foundation soil was secured by drains against a further softening by water.

CONDITIONS AT THE (STAGE OF) REOPENING OF WORK

After a 2 year pause construction work started again and the foundation base was uncovered by several shafts. On the surface of stiff clay a layer of soft clay 5 to 20 cm thick was ascertained. This fact can be explained either by an imperfect removal of the original soft layer or by kneading of the stiff clay by vehicles during the transport of sandy fill. A failure of drains could have also contributed to the disturbance.

It has also been ascertained that the stratum of stiff clay encloses interlayers of harder clayey limestone. The compresibility of limestone can be compared to that of weathered shales (loading tests c and d). Interlayers occured prevailingly in the southern part of the site and formed a sandwich-like soil with the clay to limestone ratio approx. 3 : 1

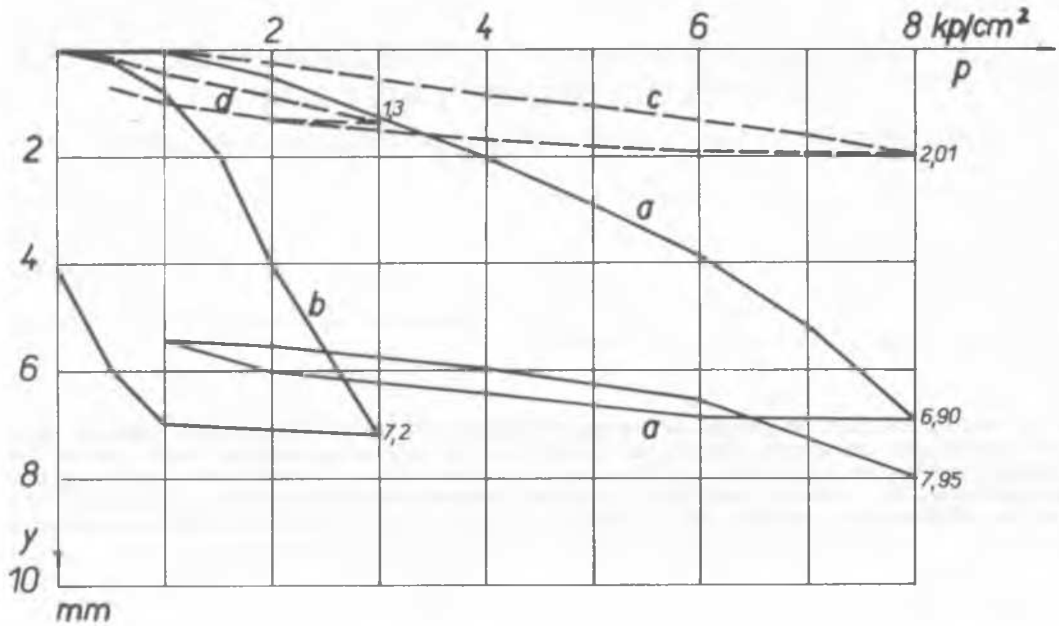

Fig.1
Stress-strain graphs of loading tests. Stiff clay : a - circular plate 0.1 m^2, b - rectangular plate 0.5 m^2. Weathered shales : c - plate 0.1 m^2, d - plate 0.5 m^2.

As the deformation properties of stiff clay were known it was only necessary to examine the layer of soft clay between sand and stiff clay. The oedometric coefficient of its compressibility C is 40 for a pressure range 1 to 2 kp/cm^2. A geological section is given in Fig.2.

The heterogeneity of foundation soil raised the question of differential settlement and inclination of the building. It was decided to construct a reinforced concrete raft-foundation and to leave below its base a sand layer 1 m thick to accelerate the consolidation. The porosity of sand was 30 % and a series of loading tests had linear course of deformations but the differences in deformation modulus E_0 from 345 to 530 kp/cm^2 for a pressure range 0 to 4 kp/cm^2 suggested a non-conformity of compaction.

PRELIMINARY CALCULATION OF SETTLEMENT

Two cases were distinguished in calculating the settlement which enabled to estimate its maximum and minimum value. The layers of sand and soft clay were considered as homogeneous and linear. For the layer of stiff clay the coefficient of compressibility s was applied. This coefficient introduced by the author (1961) gives the settlement of the standard circular plate 0.1 m^2 for a contact-pressure of 1 kp/cm^2 and is given in cm^3/kp.

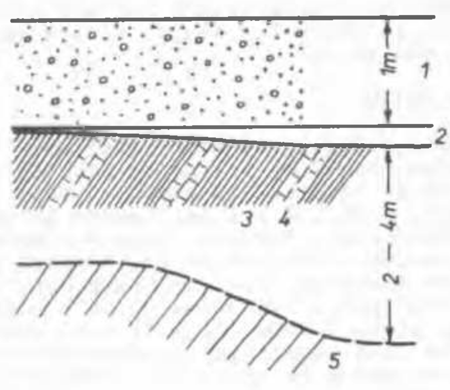

Fig.2
Geological conditions after reopening of works. 1 - fill of sand with gravel, 2 - soft clay, 3 - stiff clay, 4 - interlayers of limestone, 5 - weathered shales.

The relation for the settlement y on a limited layer $y = \omega p\, b\, (1 - \nu^2) / E_o$.
Here ω - depends on the shape and size of the contact area and the thickness of the layer.
Further is p - the average contact pressure
b - the width of the plate
ν - Poisson's number.
At the standard plate y_o = s.p and further $s = \omega_o\, b_o\, (1 - \nu^2)/ E_o$, where $\omega_o = \pi/4 = 0{,}79$. At a foundation with another ω $y = (\omega b/ \omega_o b_o) \cdot p.s$.

Let us also take into account the non-linearity of deformations. Introducing the compressibility coefficients s instead of deformation modulus we obtain the displacement of the loading plate y_o in this form :

$$y_o = p_1 s_1 + p_2 s_2 + p_3 s_3 + \dots p_i s_i$$

where p_i is the pressure range for the respective coefficient s_i. For our case the compressibility coefficients are :

Pressure range kp/cm^2 :	0 - 0.5	0.5 - 1	1 - 1.5
Stiff clay s_1 :	0.018	0.054	0.102
Weathered shale s_2 :	0.016	0.021	0.021
Stiff clay with limestone s_3 :	0.018	0.046	0.082

The coefficients for the sandwich layer was approximately determined from the clay-limestone ratio $s_3 = (3s_1 + s_2)/4$. The thickness of the sandwich layer was estimated at 4 m as a maximum and 2 m as a minimum. A coefficient of non-uniformity 1.5 was introduced with regard to the limited number of loading tests. The maximum settlement was calculated at 34.5 mm, minimum at 18.9 mm. These values and the differential settlement 15.6 mm are allowable.

ACTUALY MEASURED SETTLEMENTS

The settlements were measured on 40 control-points using a precise levelling. The course of displacements is drawn in Fig.3. A considerable settlement up to 7 mm was observed at an average stress 0.3 kp/cm^2 (Fig.3-a) which roused suspicion that the real deformations could be twice as large as calculated. The author, however, concluded that these initial displacements had originated owing to the loosening of the sand surface caused by construction works. This opinion was confirmed by further measurements at which the deformations were nearly stabilized (Fig.3-b,c). A larger increase of settlement appeared again when the stress on the surface of stiff clay exceeded 0.5 kp/cm^2 (compare graphs 1-b and 3-d). The average stress nowadays has reached approx. 1.5 kp/cm^2. The settlement is max.24 mm, min. 11 mm.

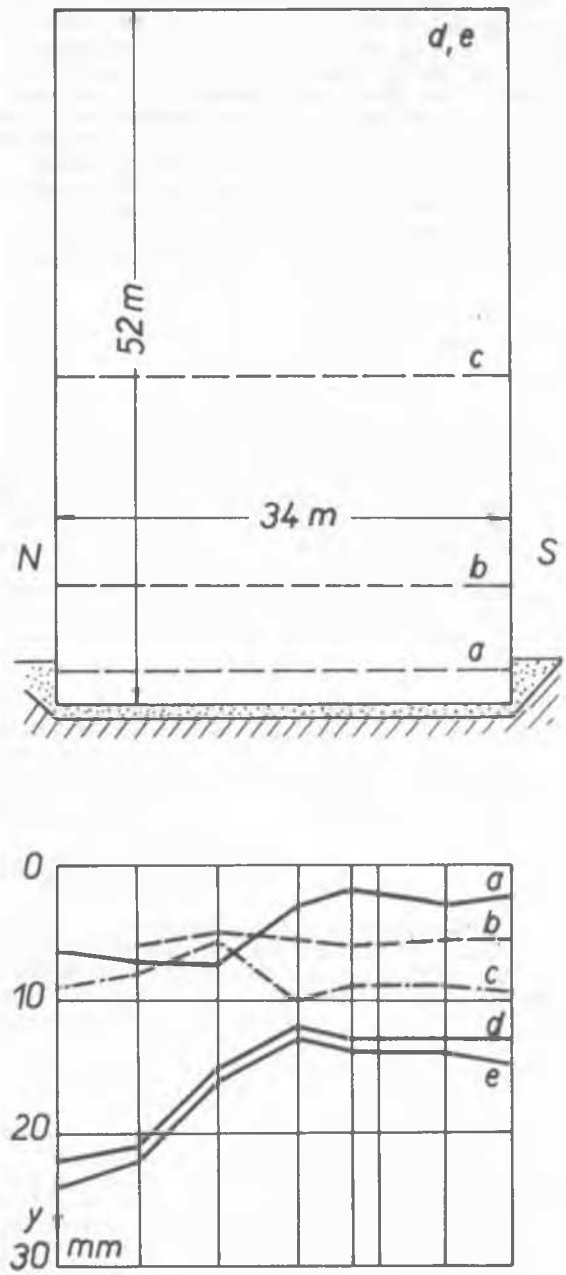

Fig.3
Settlement of the building. Upper part : Longitudinal section with levels of successive contact stresses in foundation base (kp/cm^2) : a - 0.30, b - 0.45, c - 0.80, d - 1.20, e - 1.50. Lower part : Corresponding settlement for the most unfavorable line of observed points.

A small inclination to the north, i.e. in the direction of the dip of strata is caused by the anisotropy of the sandwich layer as shown previously by the author (1966). The final settlement for a stress of 2.0 kp/cm^2 derived from present settlement is 32 mm max. and 15 mm min. which is in agreement with the preliminary calculation. It is evident that the settlement can be determined with a satisfactory accuracy even by simple methods if the initial parameters are correctly chosen.

REFERENCES

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