SOME EXPERIMENTAL OBSERVATIONS RELATIVE TO THE MAGNITUDE AND DISTRIBUTION OF SETTLEMENTS

OBSERVATIONS EXPERIMENTALES EN RAPPORT A LA GRANDEUR ET DISTRIBUTION DE TASSEMENTS

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SYNOPSIS Some experimental observations have indicated that the greatest compression below a spread foundation is not suffered by the immediately underlying but by the layers lying in a depth equal to about the foundation width (fig. 4). Analising these results author concludes that this is due to the relative compressibility of subsequent layers, which however does not affect the final settlement value.

Settlement calculations of spread foundations are based on Hooke's law i.e. the settlement:

$$s = \frac{1}{M_1} \int_{z=0}^{m} \sigma_{zi} \cdot dz$$

with M denoting the compression modulus, σ_{zi} the vertical stress in the compressed layer on the elementary thickness of dz and m the limiting depth of compressed zone.

The formula represents actually that the settlement is proportional to themarea of the vertical stress-diagram. But it must be noted, that not only σ_z but also m and M are variables, these two latter ones being replaced usually by more or less arbitrarily assumed values.

The variation of these factors is taken into account through slicing the compressible strata into stripes with differing M_i values and summarizing the gained elementary compressions.

The summation of elementary strip compression was effected, however, always on the basis that they are underlain by some rigid boundary and compression is restricted to the elementary strip itself. This concept holds, however, only for the compressed body right down to its limiting depth as a whole and not for the single stripes or successive strata, where the relative displacement of the assumed boundary lines is undoubtedly influenced by the yield of the successive underlying strip or layer lying within the stressed zone. Consequently it will be of influence more on the distribution, than on the total settlement value.

This fact was demonstrated by some laboratory experiments executed on various granular test soils with concrete blocks of 12x2o cm contact area. These experiments were started with the scope to get some information upon the deformation and displacement behaviour of double layered soils i. e. on the effect of soil cushions. At the first instance a basalt split being laid on a silty sand (fig.1), respectively on a fine sand (fig.2) layer - at the second instance. The tested mass was divided in $h = 5$ cm stripes by white separation lines. It can be clearly seen that the maximum compression (Δh) was not taking place in the directly underlying but in the next coming strip.

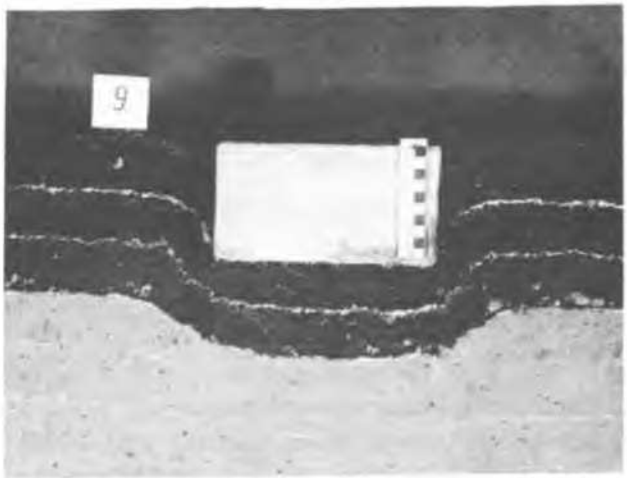


Fig. 1 Compression of layers under the concrete loading block (basalte split over silt)

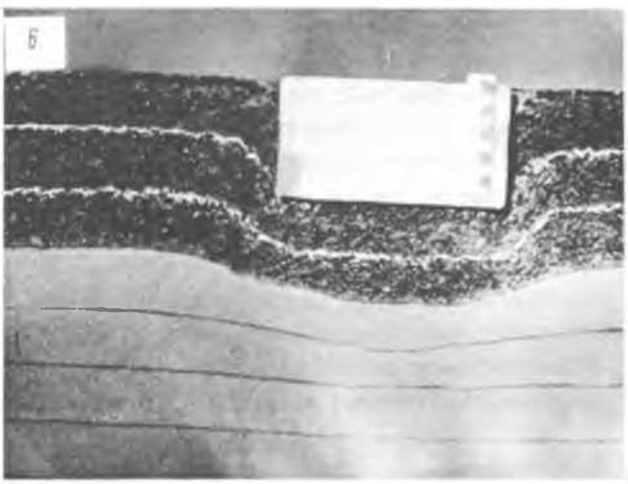


Fig. 2 Compression of layers under the concrete test-loading block (basalte-split over fine-sand)

Fig. 3a and 3b are numerical pictures of the deformed separation lines in loaded soil masses consisting of fine sand overlain by sandy-gravel. As a following step we have carried out some additional tests and observed the deformations under 13,5x16,5 cm, 19,5x23 cm, 26x29,5 cm and 32,4x36 cm steel loading plates. Similar results were obtained in a sand, - and in an artificially produced alundum material. When all results were plotted in a diagram in which the specific

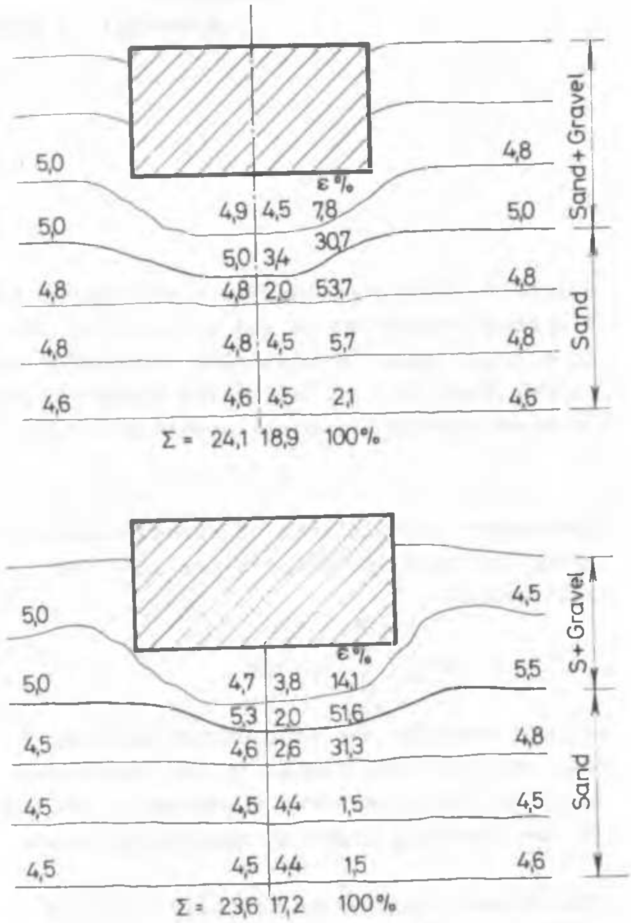


Fig. 3 Compression of layers under the concrete test-loading block (numerical values)

compression values $\varepsilon = \Delta h/h$ are plotted along the horizontal axis, against the relative depths m/B plotted along the vertical axis, similarly shaped curves were obtained for all cases (fig.4); characterized by a maximum of relative compressions ε appearing in about a depth equal to the width B of the loading plate.

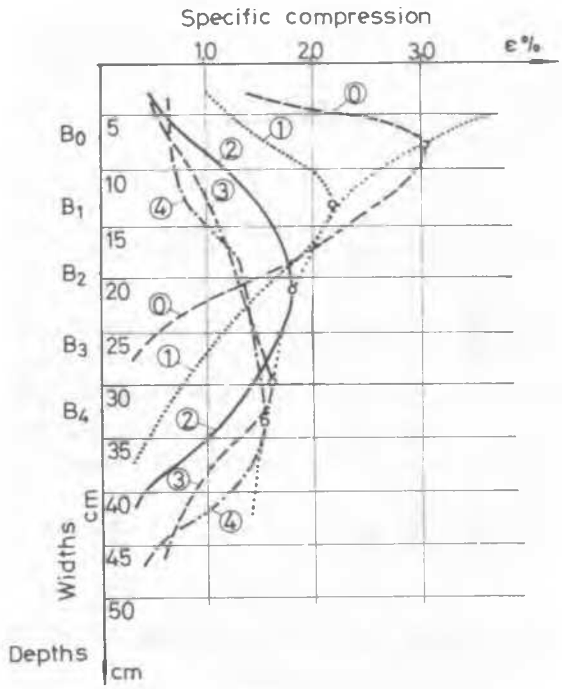


Fig.4 Specific compression of underlying layers in function of foundation width

The other conclusion which could be drawn from all experiments was, that practically no deformations appeared beyond the depth exceeding the double width of the loading plates, corresponding to Jáky's limit depth value-proving its justified applicability and admitting its use as a fairly good approximation.

Looking now for the theoretical explanation of this result it may arise from two reasons.

1. The one is that the friction between the surface of the loading block and loaded soil is acting against lateral deformation,establishing a certain kind of confined stress condition bringing about in turn a certain decrease of effective vertical strains due to the opposite effect of normally acting stresses. This reduction is a clear consequence of Hooke's law expressing that the specific deformation in vertical direction is

$$\varepsilon_z = \frac{\sigma_z}{E} - \frac{\nu \cdot \sigma_x}{E} = \frac{1}{E}(\sigma_z - \nu \cdot \sigma_x) \qquad (1)$$

indicating that the reduction is varying with σ_x i.e. that it is decreasing with the distance from the contact surface.

Similar results may be deduced from stress distribution theory when computing vertical stresses produced from horizontal friction which may be computed from the formula (fig.5)

$$\sigma_z = -\frac{2f}{\pi}(\cos\beta_2 - \cos\beta_1) = -\frac{2p\cdot\tan y}{\pi}(\cos\beta_2 - \cos\beta_1) \qquad (2)$$

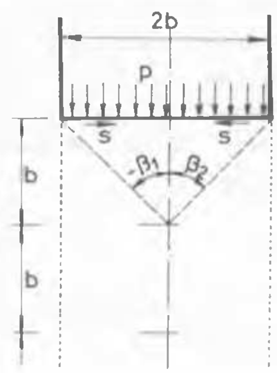


Fig.5 Computation-scheme of vertical stress due to contact-friction

From this equation the following average values of vertical stresses may be obtained for ,various depths:
for

$$\left.\begin{array}{ll} m_a = b/2; & \sigma_{za} = -0{,}30p \\ m_b = b; & \sigma_{zb} = -0{,}18p \\ m_c = 2b; & \sigma_{zc} = -0{,}10p \end{array}\right] \qquad (3)$$

According to this, friction will also reduce compression at a rate diminishing with the distance from the contacting plane (cf. fig.5).

2. <u>The other theoretical reasons</u> may be derived from the distribution of suffered compression between overlaying and underlying compressible strips resp. layers. E.g. at the boundary of strip ① and strip ② the total compression of strip ① must have a magnitude corresponding to the average vertical pressure. It will be equal to

$$\delta_1 = \frac{\sigma_{za1}}{M} \cdot h_1$$

but the boundary line 1-1 will not remain in its position-owing to the compressibility of its subgrade. Thus the deformation will be shared with the underlying layer (2). The rate of distribution may follow the ratio of deformation moduli M_1/M_2 and in a homogeneous mass, where $M_1 = M_2$ it must be distributed equally i.e.

$$\Delta_1 = \Delta_2' = \delta_1/2 \qquad \text{(fig.6)}$$

(should $M_2 \to \infty$ that would mean that $\Delta_1 = \delta_1$ and $\Delta_2' = 0$).

Applying now this simple rule and successively proceeding with the depth we may arrive at the following results:

When assuming that the decrease of vertical stresses beneath a rigid loading strip takes place in direct proportion to the depth and extends just to a limit-depth $m=4b$, the vertical stress can be expressed at any depth z (fig.6)

as
$$\sigma_z = p\,\frac{m-z}{m} \qquad (4)$$

and the compression of the overlying layer of thickness z just to this depth

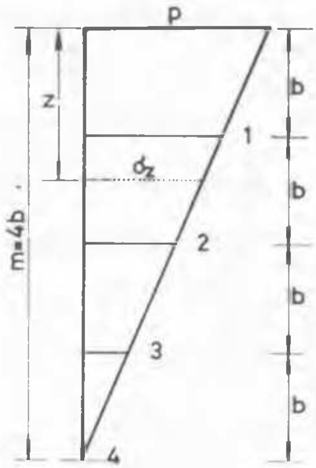


Fig. 6a Scheme of vertical stress distribution (Jáky)

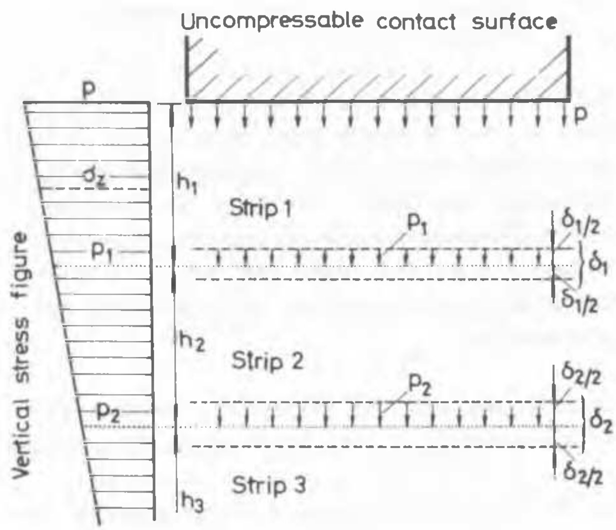


Fig. 6b Distribution of compression between contacting layers

$$\delta_z = \frac{p+\sigma_z}{2} \cdot \frac{z}{M} = \frac{p + p\cdot\frac{m-z}{m}}{2} \cdot \frac{z}{M} =$$
$$= \frac{zp}{2M}\left(2 - \frac{z}{m}\right) \qquad (5)$$

Thus the total compression down to the plane 4-4 equal to the settlement of foundation strip

$$s = \frac{pm}{2M} \qquad (6)$$

and with

$$\alpha = \frac{pm}{M}\ ; \qquad s = 0{,}5\ \alpha$$

Computing now the elementary compressions to the planes 1-1, 2-2 and 3-3 and distributing them between the the overlying compressed and underlying bedding layers;
at plane 1-1 with $z = m/4$

$$\delta_1 = \frac{zp}{2M}\left(2 - \frac{z}{m}\right) = \frac{mp}{4 \cdot 2M}\left(2 - \frac{m}{4m}\right) =$$
$$= \frac{pm}{8M}\left(2 - 0{,}25\right) = 0{,}21875\ \alpha$$

Relative displacement of plane 1-1:

$$\Delta_1 = \frac{\delta_1}{2} = 0{,}109375\ \alpha$$

Compression of soil mass above plane 2-2 with $z = m/2$

$$\delta_2 = \frac{mp}{2 \cdot 2M}\left(2 - \frac{m}{2m}\right) =$$
$$= \frac{pm}{4M}\left(2 - 0{,}5\right) = 0{,}375\ \alpha$$

and relative displacement of plane 2-2:

$$\Delta_2 = \delta_1/2 + \delta_2/2 =$$
$$= 0{,}109375\ \alpha + 0{,}1875\ \alpha = 0{,}296875\ \alpha$$

Compression of soil mass above plane 3-3, with $z = 3m/4$

$$\delta_3 = \frac{pm\,3}{4 \cdot 2M}\left(2 - \frac{3m}{4m}\right) = 0{,}46875\ \alpha$$

and the relative displacement of plane 3-3

$$\Delta_3 = \frac{\delta_3}{2} + \frac{\delta_2}{2} =$$
$$= 0{,}234375\ \alpha + 0{,}1875\ \alpha = 0{,}421875\ \alpha$$

and at last the compression of the total soil mass above plane 4-4 with

$$\delta_4 = \frac{pm}{2M}\left(2 - \frac{m}{m}\right) = 0{,}50\ \alpha$$

Whereas displacement of plane 4-4 is equal to 0.

Now the relative compression of the single strips may be gained as the difference of their relative displacements as follows:

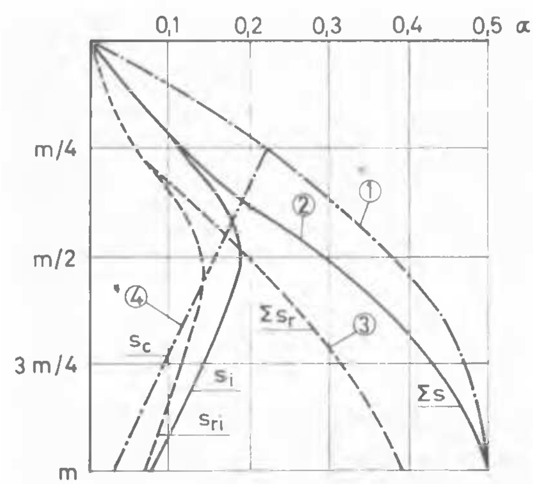
$$s_1 = \Delta_1 = 0{,}109375\ \alpha$$

$$s_2 = \Delta_2 - \Delta_1 = 0{,}296875\ \alpha - 0{,}109375\ \alpha = 0{,}1875\ \alpha$$

$$s_3 = \Delta_3 - \Delta_2 = 0{,}421875\ \alpha - 0{,}296875\ \alpha = 0{,}125\ \alpha$$

$$s_4 = \Delta_4 - \Delta_3 = 0{,}500\ \alpha - 0{,}421875\ \alpha = 0{,}078125\ \alpha$$

Should we distribute now the settlements of tthe strips in the conventional way i.e. according to the diagram (fig.7), of vertical stresses we should get



1 = Total settlements (conventional)
2 = Sum of distributed settlements
3 = Sum of reduced settlements
4 = Compression of single layers

Fig. 7 Comparison of compression distribution between contacting layers for

$$\left.\begin{aligned} s'_1 &= \delta_1 = 0{,}21875\ \alpha \\ s'_2 &= \frac{0{,}75+0{,}50}{M}\cdot p\cdot\frac{m}{4} = 0{,}15625\ \alpha \\ s'_3 &= \frac{0{,}50+0{,}25}{2M}\cdot p\cdot\frac{m}{4} = 0{,}09375\ \alpha \\ &\text{and} \\ s'_4 &= \frac{0{,}25+0}{2M}\cdot p\cdot\frac{m}{4} = 0{,}03125\ \alpha \end{aligned}\right] \quad (8)$$

The compression of the single strips separately and also their sum as φ picture for settlement distributions is plotted in fig. 7. Comparing now the the picture with fig.4 it is apparent that when the relative displacement of strips is considered, the theoretically computed figure has got a similar shape to those gained from the experiments.

From this it may be concluded that the settlement will be reduced with the progressive increase of the strength of underlying layers at a somewhat higher rate, than it was considered by conventional methods. This will be the case however in homogeneous granular materials too, where also a linear increase of compression modulus may be assumed.

The effect of friction is decreasing primarily the compression of the upper layers. Assuming that this reduction will take place in proportion to the decrease of vertical stresses as indicated by the formulae (3), a corrected figure of s_{red} may be plotted resulting at last about a 15% reduction of the conventional values.