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CALCULATION METHOD FOR SETTLEMENT OF HORIZONTALLY REINFORCED SUBSOIL
LA METHODE DE CALCUL DES TASSEMENTS SUR SOL RENFORCE HORIZONTALEMENT
METHODE DER SETZUNGSBERECHNUNG FÜR WAAGRECHT BEWEHRTE ERDE

Reinforced subsoil can be modelled as a multi-layered soil-system in which reinforced layers having a definite thickness of soil surrounding them have to be separated from those having no reinforcement. In the calculation the soil with and without the reinforcement is considered as a material having a linear elastic stress-strain behaviour. Elastic parameters /i.e. modulus of elasticity and Poisson-ratio/ is measured by triaxial tests in which height of the sample is equal to the thickness of the reinforced layer considered in the calculation of the settlement. The initial state of stress is modelled by the confining pressure. Calculation was performed in the case of non-reinforced as well as reinforced soil. The calculated results were compared to those which were measured in a series of model foundation tests. The results correlated closely to the measured ones.

In der Studie versuchen wir die Setzungsberechnung auf Grund der Analogie zu einem mehrschichtigen Bodensystem durchzuführen. Aus den vereinfachenden Ansätzen sind jenen für dem linear elastischem Spannung - Verformung Zusammenhang des Bodens und der bewehrten Erde zu erwähnen. Die physikalische Parameter der bewehrten Erde können ähnlich wie jene der unbewehrten Erde mit der Hilfe von triaxialen Druckversuchen bestimmt werden. Mit Annahme des Seitendrucks wurde der Anfangs-Spannungszustand modelliert, die Messungen wurden dem Elastizitätsmodul bei der Anfangstangente und der Poissonzahl entsprechend ausgewertet. Die Setzungsberechnung wurde für dem bewehrten und dem unbewehrten Boden durchgeführt, die Ergebnisse der Berechnungen wurden miteinander bzw. mit den Ergebnissen. Einige unter den berechneten Ergebnissen stimmen sehr gut mit den Versuchsergebnissen überein.

Soils reinforced with horizontal sheets can be considered as two or multi-layered systems in which the reinforcement together with the narrow band of soil in direct contact with it constitutes one layer and the non-reinforced soil the other. /The idea of reinforced soil layer or medium will be defined later./ When settlements are calculated using the theory of elasticity, the soil is assumed to be homogeneous and isotropic whose behaviour can be characterized with the aid of two parameters: the modulus of elasticity and Poisson ratio.

Reinforced soils are anisotropic because the modulus of elasticity is higher in the horizontal direction than in the vertical one. Instead of searching, however, for the elastic properties in the horizontal direction the vertical modulus of elasticity will be increased as a result of laboratory triaxial compression test. This approximation is within the accuracy of the assumption that the soil is a non-linear and non-elastic material.

Settlement calculations can be made more accurate by taking into account the soil modulus of elasticity E_z increasing with depth. The triaxial compression test, interpreted in accordance with Balla's method (1) is suitable to produce a relationship between the modulus of elasticity and depth. By choosing appropriate values of the all-round pressure, the E_z value of both reinforced and non-reinforced soils can be evaluated.

Strains below an infinitely long strip footing along its axis of simmetry can be expressed by

$$\mathcal{E}_z = \frac{\sigma_z - \mu\ (\sigma_x + \sigma_y)}{E_z} \qquad /1/$$

where σ_z is the vertical principal stress and σ_x and σ_y are horizontal principal stresses, E_z is the modulus of elasticity in the vertical direction. The settlement then is equal to

$$s = \int_0^{z_0} \mathcal{E}_z \ dz \qquad /2/$$

An analitical solution of Eq.2. is practically impossible because E_z is "discontinuous at the bounderies between the reinforced and non-reinforced soil layers.

Graphical integration, however, is possible by dividing the stress distribution diagram into horizontal slices and by the summation of the areas of the slices (2) /Fig.1./.

soil can be determined by triaxial compression tests. In this care the higher E_z value is valid for a layer whose thickness is the same as the height /H/ of the sample.

This method then consists of an application of the theory of compression of multi-layered systems where each reinforced soil layer /of thickness H/ is considered as a separate layer.

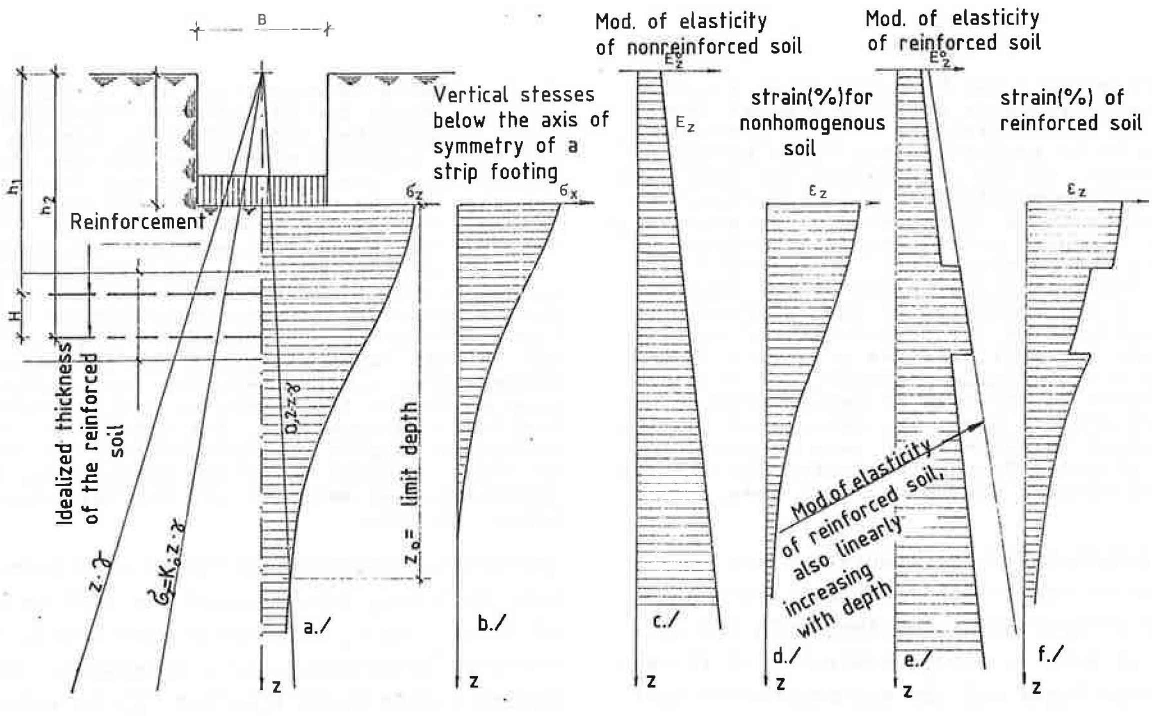

Fig. 1. The beneficial effect of soil reinforcement on the settlement of soils

The limit depth and principal stresses can be determined by the approach used in homogeneous soils and E_z is assumed to increase linearly with depth /see Fig. 1/c./. On the other hand, the E_z values are higher for reinforced soils and quantitatively depend on the spacing /see Fig. 1/e./ of the reinforcement and its depth below ground surface.

The boundaries between horizontal elements /slices/ are chosen depending on the position of the earth reinforcement and the strain of an element is calculated by using Eq.1. The results are then measured along the vertical axis. The elastic modulus of the reinforced

This approximation is simple but within acceptable limits. It has all short comings inherent in those settlement calculations which are based on the assumed elastic behaviour of soils. It is wellknown that soils are neither perfectly elastic nor perfectly plastic. Also in a triaxial compression test, the state of stress is different from that in the real soil where usually plane strain conditions prevail. Further, in the calculations perfect interaction is assumed between the soil and reinforcement in spite of the fact that this is rarely the case. Finally it must be emphasized that more inaccuracies come from neglecting the effect of soil reinforcement on the stress distribution below the footing.

Notwithstanding the above, this method may be more accurate because the properties of the reinforced earth mass are not derived separatelly from the properties of the soil and reinforcement but are obtained from actual measurements on composite samples.

I. Results of the Triaxial Compression Tests

Measurements were made in the Hungarian Institute for Building Sciences in 1983. During compression of the large samples /H = 17 cm, dia = lo,2 cm/ both the axial and radial strains were measured. Into the middle of the reinforced samples a NETLON geogrid disc /Type Nr. H-11/ was placed. The diameter of the grid was equal to that of the sample. Six unreinforced and six reinforced samples were loaded triaxially. The confining pressures /$\sigma_3 = \sigma_2$/ ranged from lo to loo kPa. The relationship between axial stress, axial strain /σ_1, ε_1/ and radial strain /ε_2/ is illustrated on Fig. 2. On the basis of the stress-strain

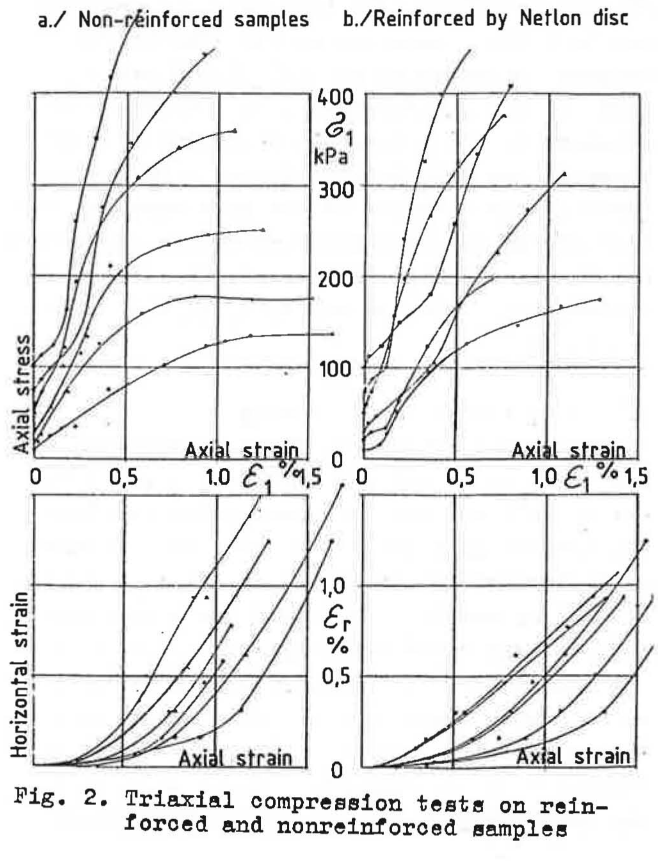

Fig. 2. Triaxial compression tests on reinforced and nonreinforced samples

curves the initial moduli were determined and the ratios σ_3/ε_1, $\sigma_1 - \sigma_3/\varepsilon_1$, Poisson's ratio and the elastic modulus were estimated using Balla's formulae and are plotted as a function of all-round pressures /Fig. 3./. The regression

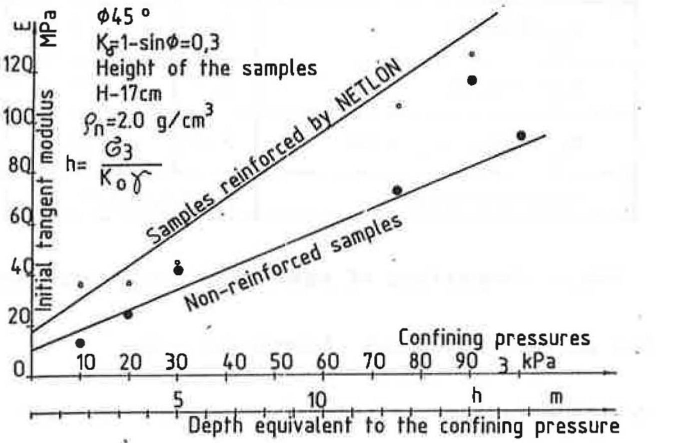

Fig. 3. Initial tangent modulus vs. confining pressure and depth

lines for the five points have the following equations. Non-reinforced samples:

$$E_T = 0,78\ \sigma_3 + 10,8, \qquad /3/$$

reinforced samples:

$$E_N = 1,29\ \sigma_3 + 17,9, \qquad /4/$$

in which E_T and E_N are in MPa, and σ_3 in kPa. The average value of the Poisson-ratio for non-reinforced samples is μ_T = o,28, while for the reinforced samples is μ_N = o,33. Friction angle of both reinforced and non-reinforced sand was found to be $\phi_T = \phi_N = 45^o$. The equivalent depth of the minor principal stress was estimated from the wet density of the soil / ρ_n = 2,o g/cm^3/ and the earth pressure at rest /$K_0 = 1 - \sin\ \phi$ = o,3/.

II. Laboratory Model Foundation Tests

To find out the optimal depth of NETLON-grid under a foundation some experiments were performed in ÉTI (3). The general setup in the experiments were similar to that in the triaxial compression tests. The model foundation of B = 18 cm width was placed in a 3,2 x 3,2 x x 7,4 m box in which one or two NETLON sheets were embedded at 18, 36, 54 and 18 + 54 cm depth below the surface of the soil. Loads were applied and settlements under a loading of p = loo kPa are shown on the Fig. 4. in

Depth of reinforce layer below the foundation level cm	Measured settlement mm			Calculated settlement mm	Diff. between calculated and measured settlement %
	H 12	H 08	Average		
h_1=/ B=/18	2,3	2,6	2,45	2,5	2
h_2=/2B=/36	1,6	1,6; 2,2	1,8	2,6	31
h_3=/3B=/54	1,7	1,7	1,7	2,7	37
h_1 = 18; h_2 = 54	2,3	2,6	2,45	2,3	- 6
Nonreinforced	2,9;3,3;3,5		3,23	2,8	- 15

Fig.4. Comparison of results of foundation model test with the calculated values /p=1oo kPa/

the second, third and fourth columns.

Settlements were calculated as showed on Fig.5.

Modulus E_N on Fig.5/c. was measured in a triaxial compression test on a sample of 17 cm height, which was reinforced with a single H-11 NETLON--disc across its centre. The E_N vs. h relationship applies to the sample reinforced at 17 cm spacing of depth only. This is the reason why $_z$ is calculated for a soil thickness of 17 cm height, too; i.e. the height of the sample predetermines the thickness of the layer in the numerical evaluation of Eqs. 1. and 2.

The results are also shown on Fig.4., in column 4. In the case of nonreinforced soil 2,8 mm settlement was calculated and 3.23 mm was measured in the laboratory, which shows the reality and accuracy of the computation (15 % difference). Very good agreement was obtained with the NETLON grid at the depth of h_1 = B = 17 cm; it can be seen that the difference between the calculated and measured settlement is negligible.

The discrepancy between measured and calculated settlements with reinforcement at depths of $h_2 \cong 2B \cong 36$ cm and $h_3 \cong 3B \cong 54$ cm was not only larger by varying the bedding level within the range of B to 3B depth caused an altogether different behaviour: according to the experiments, increasing the bedding depth would yield a decrease in settlement, while the calculations show the opposite effect. In other words the optimum bedding depth according to the calculations based on elastic theory, differs significantly from that obtained in the experiments.

In the case of double-layer reinforcement the calculated and measured settlement were in very good agreements with one another. (The calculated settlement was less than the measured one by 6 %). A comparision can also be made between the measured and calculated "efficiency" of the reinforcement: 24 % decrease was obtained in the laboratory tests and 11 % decrease in the calculations for h_1 = 18 cm /=B/. Assuming the decrease of the settlement in the case of the double-reinforced system was better (18 %) than that of the two single reinforced systems (h_2 = 2B = 36 cm; 3o %, h_3 = 3B = 54 cm; 4o %).

III. A Full-size Strip Footing

The width and embedment of the footing are B = t = 1,oo m, and the load is p = 1oo kN/m^2. The subsoil and reinforcement below the footing are the same as in the triaxial compression tests. Reinforcement levels are h_1 = 17 cm, h_2 = 35 cm and h_3 = 52 cm and the theoretical width of the reinforced layer is 5o cm with its upper and lower limits being at 1o cm and 6o cm depth, respectively. Distance between the reinforcing levels is 17-17 cm, thus the "density" of reinforcement is the same as in the laboratory tests, so relationship there-

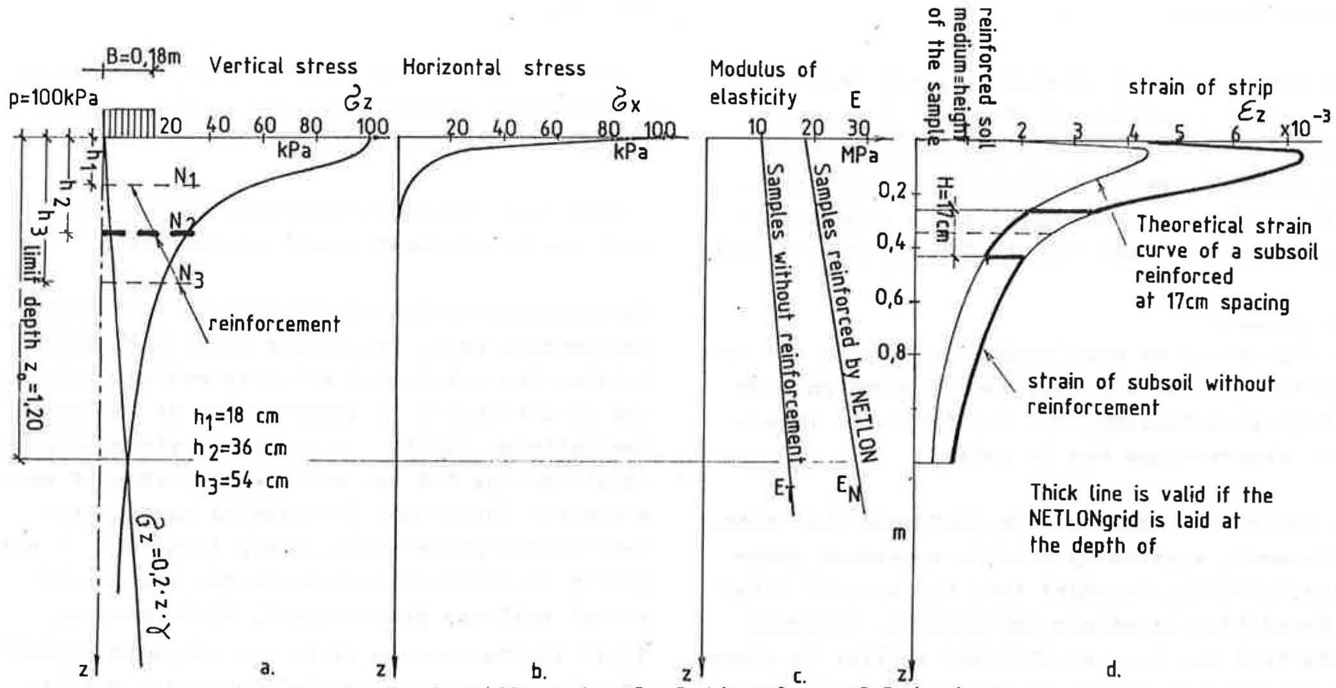

Fig. 5. Steps of settlement calculation for model test

fore, between the initional tangent modulus and depth can be accepted as valid.

Vertical and horizontal stresses along the axis of the foundation are shown on Fig.6. The initial tangent modulus ranges within this zone from E_T = 1o ... to E_T = 18 ... 45 MN/m^2 for the subsoil reinforced by NETLON. In Fig.6/d. the strains (compression for unit thickness of soil layer) are illustrated. It can be seen that the three reinforcement-levels are at the optimum depth according to the stress distri-

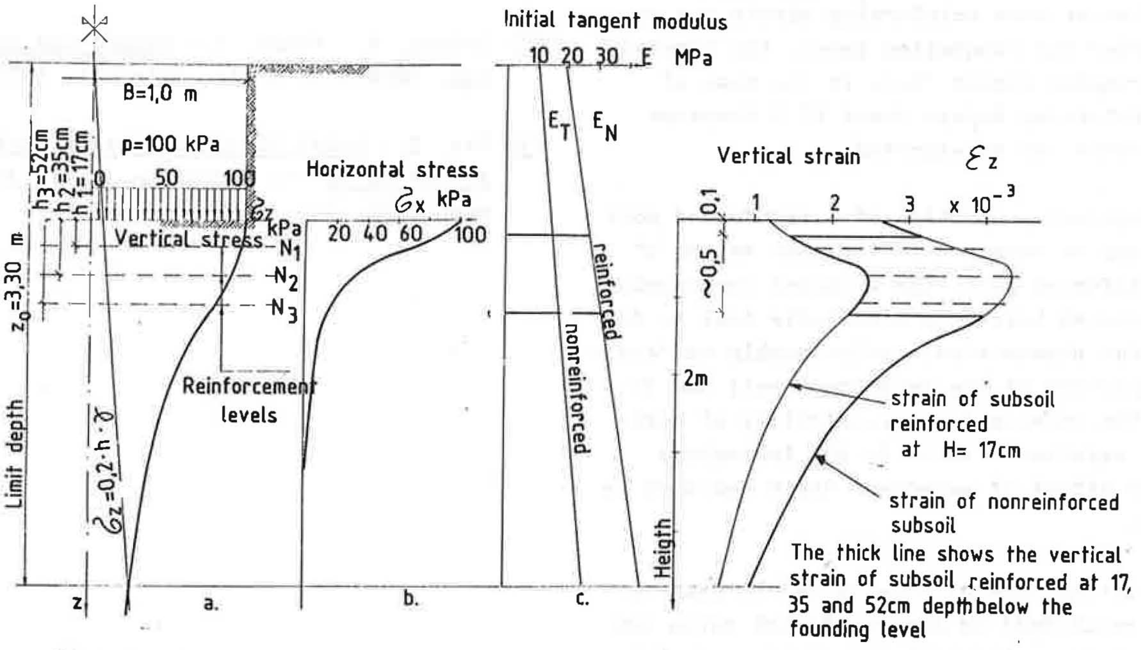

Fig. 6. Steps of settlement calculation for a full-size foundation example

bution diagram.

The results of the calculations are very encouraging: a settlement of S_s = 5,8 mm and S_R= 4,5 mm was obtained for a non-reinforced and reinforced subsoil, respectively, which means a 15 % (Δs = o,9 mm) improvement relative to the result obtained for the non-reinforced soil.

IV. Summary

In this study we were unable to compare the calculated settlements with the measured ones on a full-size footing, but the following important observations can be made:

1. Laboratory measurements confirmed that reinforcement, especially elastic non-woven geogrids (NETLON), embedded into the subsoil below a foundation decreases settlements. Although this fact has been established earlier by other researchers it cannot be overemphasized, because there are very few cases when reinforcement has been installed below footing for the purpose of settlement control.

2. Assuming a similar foundation arrangement (dimensions, properties of soil and reinforcement detailes) for a single reinforcing layer, about 5 % decrease of settlement can be expected. If two or more reinforcing sheets are embedded below the foundation level, the improvement is roughly linear /i.e. in the case of three reinforcing layers about 15 % decrease of settlement can be expected.

3. The physical properties of a reinforced soil element can be measured in the same way as of a non-reinforced soil. The triaxial compression test presented before is a suitable tool to determine the stress-strain relationship or "elastic" properties of the reinforced soil and to measure the decreased compressibility of horizontally reinforced soil. By the laboratory tests the effect of embedment depth can also be measured.

4. The initial tangent modulus and Poisson-ratio for reinforced or non-reinforced soils can be used in any settlement calculation. In this study a very simple example was presented proving that

- the settlement calculation is as accurate as in any other method based on the assumption of the theory of elasticity,

- with this method the decrease of the settlement can be reasonably well approximated.

The proposed method is suitable to calculate settlements using laboratory data. Differences between the calculated and measured settlements can be attributed to inaccuracies of the basic assumptions: partly - e.g. linear stress-strain relationships for the soil, application of axisimmetric laboratory (triaxialy) compression test to the plane-strain strip load etc., - and partly to differences between the tested and actual soil and plastic grid. While keeping there limitations in mind, the proposed method of calculation is suitable to predict settlements of foundations resting on reinforced subsoil.

References

(1) Balla, Á.: Determination of Young's modulus of the Soils. /In Hungarian./ ÉKME Tudományos Közleményei, Vol. 13, 1967, p.5

(2) Széchy, K., Varga, L.: Foundation Engineering, Akadémiai Kiadó, Budapest, 1978

(3) Vas, I.: Model Foundation Tests with Reinforced Soil. /In Hungarian./ ÉTI, Internal report Nr. 3oo, 1981