INVESTIGATION OF SOIL DEFORMATION IN FOUNDATION BEDS OF STRUCTURES

ETUDES DES DEFORMATIONS DES SOLS DANS LES FONDATIONS DES OUVRAGES

ИССЛЕДОВАНИЕ ДЕФОРМАЦИЙ ГРУНТА В ОСНОВАНИИ СООРУЖЕНИЙ

B.I. DALMATOV, D.Sc., Department Head
S.N. SOTNIKOV, M.Sc., Assistant-Professor, Leningrad Civil Engineering Institute, Leningrad
N.M. DOROSHKEVICH, M.Sc., Assistant-Professor
V.V. ZNAMENSKY, M. Sc., Senior Researcher, Moscow Civil Engineering Institute, Moscow (USSR)

SUMMARY. The first part of the paper sets forth data of systematic observations of soil deformation in foundation beds of structures erected on a stratum of soft soils. Observations have been carried out on settlement of structures, the deformation of soil in successive layers, and the displacement of the soil surface near the structures. Soft soils under the structures are subject to deformation even at a depth of 25 m. This results in settlement of the soil surface near the structures in a wide zone. Below a certain depth the soil deformations are insignificant, therefore the settlement values can be calculated by the method of the limited compressible soil stratum.

The second part of the paper sets forth formulas for calculating deep foundation settlements on the basis of Mindlin's solution for vertical displacements. Employing the equivalent layer method proposed by Prof. N.A.Tsytovich, these formulas were reduced to a simple form, convenient for designing.

INTRODUCTION.

Settlement values of foundation beds of structures determined in designing by means of calculations often differ from the actual ones. In a number of cases this is explained by the imperfection of the calculation scheme. Investigations in this respect are given in the two parts of this paper.

653

PART I. Written by B.I.Dalmatov and S.N.Sotnikov, deals with the field investigation data of soil deformation in the foundation beds of structures and under settlement plates.

PART II. Written by N.M. Doroshkevich and V.V. Znamensky gives a theoretical solution for determining the settlements of deep foundations.

I. INVESTIGATIONS OF SOFT SOIL DEFORMATIONS IN FOUNDATION BEDS OF STRUCTURES

For making more precise calculation schemes for determining foundation settlements, a number of investigators in the Soviet Union since 1936 (Khakimov, 1938) have been measuring vertical displacements of soil at various depth under settlement plates in laboratory and field conditions. But there is some doubt as to the validity of the results of such settlement plate tests, when the area of the plate is not larger than 10 m^2 to the foundation beds of heavy structures. In the light of the above said special attention is attracted by the observations of soil displacement in successive layers in the foundation beds of buildings and structures (Egorov, 1959, 1971) and by the results of observations of the deformations of the foundation beds formed by a thick stratum of highly compressible soil in Leningrad, which will be considered further on.

The aim of these investigations was:
(1) to determine the depth of the deformation zone;
(2) to determine the deformation characteristics of soils;
(3) to study the dynamics of the development in time of deformation in soils of different composition;
(4) to obtain values of soil deformation near the structure;
(5) to discover the character of the deformation in the frame of the structure during the process of foundation bed settlement.

The territory of the building site, where the above mentioned investigations were carried out, was elevated 2-3 m by means of a sand fill. Under this sand and under the layer of natural sand is a thick stratum of soft soils, the properties of which are given in Table I. The properties of the upper layer of sandy soil greatly depend on the organic content. The thickness of the individual layers varies greatly even under the same building. Several apartment houses were erected: 9-story buildings on strip foundations and 12-story buildings on a continuous slab. The total thickness of the soft soil stratum under these buildings varied from 20 to 30 m.

of the area of locating the foundations of the building. Hence, the statement by Malikova (1972), that the compressible stratum in all cases is less than the width of the foundation plate and not more than 20 m, requires close definition.

Table I

AVERAGE VALUES OF THE BUILDING SITE SOIL CHARACTERISTICS

Soil	Particle Content %		Loss from calcination %	Moisture content %	Consistency limit		Unit weight g/cm^3	Void ratio.
	0,05-0.002 mm	<0.002 mm			L.L.	P.L.		
1.Medium-grained sand (slab).	3.2	-	-	-	-	-	1.85	0.657
2.Pulverized sand	6.0	-	-	-	-	-	1.90	-
3.Sandy soil with	74.6	8.5	2.40	27	30.8	24.2	1.94	0.80
4.organic	80.5	12.5	4.50	31	29.2	22.4	1.88	0.88
5.inclusions.	65.0	17.0	13.7	73	68.9	51.2	1.54	1.77
6.Varved flowing loam.	62.8	28.6	-	32	29.0	17.9	1.84	0.943
7.Varved flowing soft clay.	43.4	54.2	-	45	45.8	24.8	1.72	1.347
8.Moraine loam with gravel and pebbles	68.8	23.0	-	25	30.3	20.6	2.02	0.68
9.Moraine sandy soil with gravel and pebbles	28.1	11.5	-	10	15.0	10.2	2.29	0.46

For measuring soil deformation in successive layers through the openings in the foundation plate and between the foundations there were put depth marks. For the sake of control there were put two depth marks at the distance of 40 m from the building. The control marks during the period of observations have not been displaced, the fact which verifies the absence of soil deformation under the action of the weight of the sand hydraulically filled more than 8 years ago.

Figure 1 shows a scheme of the soil stratification, the location of depth marks (a), the epures of their displacement to the date of completing the building (b), to the end of 1971 (c), and according to the prediction, to the moment of stabilizing the settlement (d). Here one can also see the values of volumetric deformation in successive layers to 1971 (e), and to the moment of stabilizing the settlement (f).

Vertical displacements of the depth marks in time are given in Fig. 2. They show that the mark put at the depth of 27.7 m below the foundation footing got the settlement of 2.8 cm. which constitutes some 8% of the average settlement of the building. Thus the compressible stratum under the building constitutes more than 2.1 b, where b - is the width

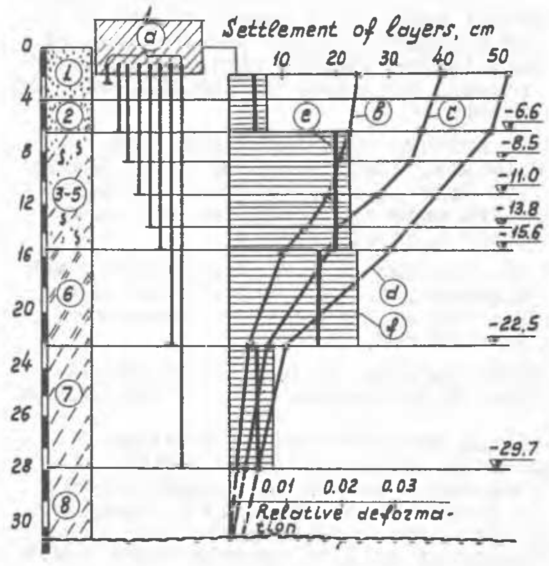

Fig.1.
Soil deformation of successive layers of soil under structure I.

Many investigators (Efremov, et al, 1963) making experiments with settlement plates obtained such results that the main part of the plate settlement was formed on the account of the subsoil deformation in the limits of 0.25 and more seldom of 0.5 b, where b- is the width of the test-plate footing. And in the case under consideration the main part of the settlement of the building is dependent on the deformation of soft soils underlying it at the depth of 4.6 - 20.5 m from the foundation footing, i.e. in the limits from 1.1 to 5.0 the width of the continuous footing, or from 0.35 to 1.5 the width of the strip of loading the whole building. This shows that not always one can make a conclusion as to the size of the active zone from the results of testing the soils by means of settlement plates under static loading.

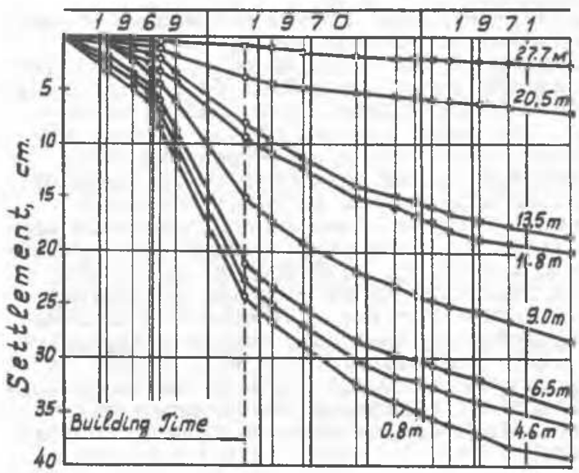

Fig.2.
Settlements of depth marks under the Structure I.

Making the linear extrapolation of the displacement below the deepest mark one can suppose that the thickness of the compressible stratum in the foundation bed of the building I is 30 - 35 m, i.e. about 2.5 the width of the loaded area.

The measurement of the displacement in successive layers made it possible by way of calculating to determine the moduli of soil deformation of individual layers.

Table II. gives the following designations:
h - thickness of layers in the place of locating depth marks;
P_z - the average compacting stress in each soil layer caused by the external load; E_k - the average value of the deformation modulus according to the compression tests; S_p - the settlement of the soil layer according to the calculations by the method of summation;
S_∞ - the settlement according to the extrapolation of the investigation data;
E_s - the modulus of deformation obtained proceeding from S_∞.

Table II
THE RESULTS OF DETERMINING THE SETTLEMENT AND THE MODULUS OF SOIL DEFORMATION IN SUCCESSIVE LAYERS.

Soil No in Table I	h, m	P_z, kg/cm^2	E_k kg/cm^2	Settlement, cm S_p	S_∞	E_s, kg/cm^2
1	2.0	1.05	100	1.5	1.5	134
2	2.6	1.05	200	1.0	1.5	170
3-5	8.9	0.85	23	26.3	20.3	38
6	7.0	0.58	40	8.1	17.0	24
7	7.2	0.46	63	4.2	5.3	62
8	6.6	0.30	200	0.8	5.8	-

Values S_∞ for each layer were determined on the basis of extrapolation the curve of the settlement in time, proceeding from the theory by Terzaghi and Gersevanov.

In considering Table II one can notice that the values of the modulus of soil deformation according to the data of the compression tests give approximately correct characteristics of the settlement of individual layers. The differences probably are caused by the fact that soils in successive layers are non-homogeneous, and the average values of E_k are obtained from the samples taken from the same layer in the boundaries of the whole area of the foundation bed of the building.

The choice of the scheme for calculating the settlement in great extent is dependent on the influence of the adjoining areas. With great depth of soft soils this influence causes the bending of long buildings, as is evident from Table III.

Table III.
DATA ON THE NON-UNIFORMITIES OF THE SETTLEMENTS OF BUILDINGS.

Building No.	Type of foundation	Settlement, cm max.	min.	Bending	Skew at ends.
1.	Strip	41.6	28.6	0.0007	0.0050
2.	Slab	52.2	30.3	0.0015	0.0070
3.	Slab	38.3	31.1	0.0003	0.0060

It is worth while noting that the greatest non-uniformity of settlements (skew of 0.006) was observed near the ends of the buildings. Therefore, it is expedient to allow the minimum stretching of foundations under side walls, and in any case it is not recommended to stretch the foundation plate beyond the limits of the end outside wall.

The influence of loading the adjacent areas is most clearly seen in the displacement of the marks put at the depth of placing the foundation plate footing on the cross axis of the building at different distances from it.

Figure 3. gives the epures of the settlements of such marks, testifying to the process of forming the large-size craters of soil surface settlement near the buildings erected on the thick stratum of soft soils. At the distance of 8 m from the end of the foundation plate to the moment of completing building works the surface settlement was 6.5 cm, and in April 1972 it was already 13.2 cm. And besides, the process of increasing the settlement is still far from completion. Even the point, which was at the distance of 18 m. from the building, got the settlement of 35 mm. And only at the distance of 32 m the surface settlement turned to be actually equal to zero. In this case the soil surface had suffered settlements in the boundaries of the strip the width of which was approximately equal to the value of the compressible stratum. The first of the mentioned marks was located at the distance of 1 m from the side of the foundation plate. If one makes the linear extrapolation up to the side of the plate, then one will obtain the soil settlement near the plate which is practically equal to the plate settlement. The difference of some 2.3 cm. constitutes only 6% of the value of the settlement of the building This difference in fact is still less, for the nearer to the foundation the more intensively the settlements increase; and this is not taken into account by the linear extrapolation.

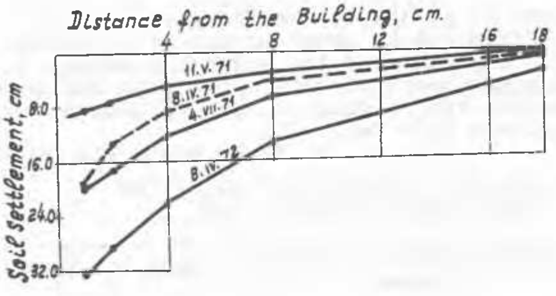

Fig.3.
Diagram of soil surface settlements near Structure 3.

If one calculates the soil surface settlement by the method of summation and takes for all calculated points the same value of the compressible stratum, obtained for the middle point of the foundation plate, then by April 1972 one will obtain the curve shown in Fig.3. by dotted lines. This curve rises more abruptly upwards, which verifies the great understating of the influence of loading the adjacent areas in calculating the settlements by the method of summation. Perhaps, the more correct consideration of the influence of the adjacent areas may be taken by the method of the limited compressible stratum (Dalmatov, 1968).

II. DEVELOPMENT OF THE EQUIVALENT LAYER METHOD PROPOSED BY N.A.TSYTOVICH FOR A CASE WHEN THE LOAD ACTS INSIDE A LINEARLY-DEFORMING HALF-SPACE.

The equivalent layer method, suggested and developed by Tsytovich, which permits to determine total foundation settlements and to predict their development in time with sufficient accuracy for practical purposes, is widely known in design practice (Tsytovich, 1969).

In calculating the foundation bed settlements according to this method the space problem in the theory of compacting a linearly-deforming bodies is reduced to an equivalent one-dimensional problem. The condition of the equality of the soil layer settlement under the action of a continuous uniformly-distributed load and the settlement from local loading of the surface of a linearly-deforming half-space is fully complied with. Owing to this, the depth of the load application is not taken into account. For very deep foundations this may result in a discrepancy between the predicted and the actual settlements. Therefore, it is important to develop the equivalent layer method for the case when the uniformly-distributed load acts inside a linearly-deforming half-space. This will permit to take into account the depth of load application and will increase the accuracy of determining the settlement of deep foundations.

For this purpose, by double integration of the Mindlin equation for determining the vertical displacements of the points of the linearly-deformed half-space under the action of the concentrated force inside it, there were obtained the values of the settlement of the central S_o and angular S_c points of the rectangular area loaded by the uniformly-distributed load:

$$S_o = \frac{pb}{E_o} K_o \quad (1) \qquad S_c = \frac{pb}{E_o} K_c \quad (2)$$

where p = intensity of the uniformly-distributed load;
b = width of the rectangular loaded area;
E_o = modulus of total soil deformation;
K_o, K_c = dimensionless coefficients determined from equations:

$$K_o = 2A + 2B\left(\ln\frac{\sqrt{m^2n^2+m^2+16}+mn}{\sqrt{m^2n^2+m^2+16}-mn} + n\ln\frac{\sqrt{m^2n^2+m^2+16}+m}{\sqrt{m^2n^2+m^2+16}-m}\right) +$$
$$+\frac{8c}{\sqrt{m^2n^2+m^2+16}}\left(\frac{1}{m^2+16}+\frac{1}{m^2n^2+16}\right) +$$

$$+4D\left(2\arcsin\frac{4n}{\sqrt{m^2+16}\sqrt{n^2+1}}+2\arcsin\frac{2}{\sqrt{m^2n^2+16}\sqrt{n^2+1}}-\pi\right)$$

$$K_c = A+B\left(\ln\frac{\sqrt{m^2n^2+m^2+4}+mn}{\sqrt{m^2n^2+m^2+4}-mn}+n\ln\frac{\sqrt{m^2n^2+m^2+4}+m}{\sqrt{m^2n^2+m^2+4}-m}\right)+$$

$$+\frac{C}{\sqrt{m^2n^2+m^2+4}}\left(\frac{1}{m^2+4}+\frac{1}{m^2n^2+4}\right)+$$

$$+D\left(2\arcsin\frac{2n}{\sqrt{n^2+1}\sqrt{m^2+4}}+2\arcsin\frac{2}{\sqrt{n^2+1}\sqrt{m^2n^2+4}}-\pi\right)$$

Here

$$A=\frac{(1+\mu_o)(3-4\mu_o)}{8\pi(1-\mu_o)}\left[\ln\left(\sqrt{n^2+1}+n\right)+n\ln\left(\frac{\sqrt{n^2+1}+1}{n}\right)\right]$$

$$B=\frac{(1+\mu_o)(8\mu_o^2-12\mu_o+5)}{16\pi(1-\mu_o)} \qquad C=\frac{mn(1+\mu_o)}{4\pi(1-\mu_o)}$$

$$D=\frac{(1+\mu_o)(2\mu_o-1)^2}{4\pi m(1-\mu_o)} \qquad m=\frac{b}{h}; \quad n=\frac{a}{b};$$

h = depth of the applied load;
a = length of the rectangular loaded area;
μ_o = Poisson's ratio

Values of coefficients K_o and K_c were calculated by a computer and can be determined from tables and graphs in dependence of the relationships between m, n and the coefficient μ_o. Graphs of coefficients K_o and K_c at $\mu_o = 0.3$ are given in Fig.4.

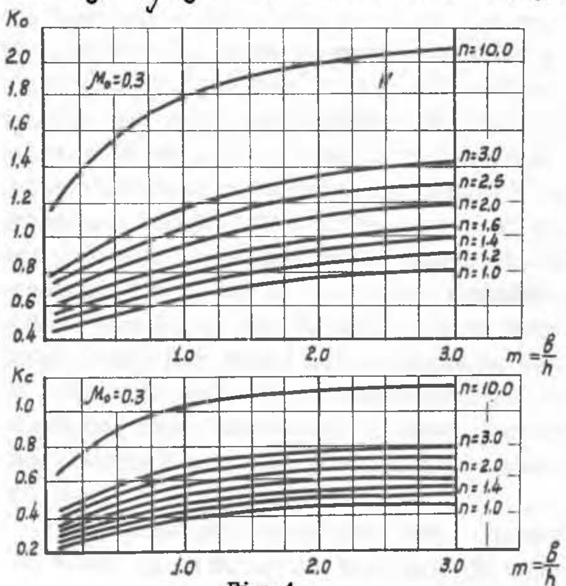

Fig.4.
Curves of coefficients K_o and K_c.

Following a well-known method (Tsytovich, et al, 1969), the height of the equivalent layer h_s can be determined by equating the soil layer settlement subject to a continuous uniformly distributed load to the settlement of a deep foundation, where 1 denotes that the depth of load application is taken into account. In so doing, the settlement of the central point of the loaded area S_o is taken as the settlement of a deep foundation.

$$h_s^1 = \frac{K_o b}{\beta} \qquad (5)$$

where $\beta = \dfrac{1-\mu_o-2\mu_o^2}{1-\mu_o}$

Then the foundation settlement on a homogeneous base will be determined by equation:

$$S = h_s^1 \; m_v P \qquad (6)$$

where m_v = the coefficient of volume change.

In the case of a laminated soil the mean value of the coefficient of volume change m_{va} is introduced into formula (6),

here $$m_{va} = \frac{1}{0.5(H_a^1)^2}\sum_{i=1}^{i=n} h_i m_{vi} z_i \qquad (7)$$

where h_i = thickness of i^{th} soil layer;
m_{vi} = coefficient of volume change of i^{th} soil layer;
z_i = distance from the center of the layer under consideration to the depth of the active compressive zone, whose height is equal to

$$H_a^1 = \left(\frac{P-P_{str}}{P}\right)2h_s^1 ,$$

here P_{str} = structural strength of the soil.

In determining the settlement of the angular point strength of the soil coefficient K_o in formula (5) should be substituted by K_c.

The equivalent layer method developed for the case of the action of a load inside a linearly-deforming half-space, was applied for calculating the settlements of pile foundations according to a procedure developed in the Moscow Civil Engineering Institute (Tsytovich, et al, 1972).

Pile foundation settlements, obtained by calculations, and those obtained from prolonged observation data is given in Table IV.

Table IV.

COMPARISON OF PILE FOUNDATION SETTLEMENTS.

Type of foundation	Soil under piles	Settlement, cm. Obtained by summation method	According formula (6)	Actual
group of 4 piles	clay at 0.25 B 0.50	1.87	0.9	0.9
group of 5 piles	loam at 0.50 B 0.75	10.3	6.1	5.0
Strip pile foundation	clay at 0.25 B 0.50	13.2	9.0	7.7

The application of the equivalent layer method taking tinto consideration the depth of load application for calculating the settlements of pile foundations permitted to determine them with greater accuracy as compared with the summation method (See Table IV.). The disagreement between the calculated and actual data is explained mainly by the fact that in deriving formula (5) the settlement of a foundation with given dimensions was taken as the settlement of a central point of a loaded area, i.e. - the maximum settlement. The obtained relationships can be used for calculating the settlement of deep foundations. However, these calculations are somewhat approximate, due to the use of Mindlin's equation.

REFERENCES

DALMATOV,B.I. (1968) "Designing the foundation beds of buildings and structures by ultimate conditions". Stroyizdat. Leningrad.

EGOROV, K.E. (1959) "Studying the deformation in successive layers at the base of the funnel. "Foundation Engineering and Soil Mechanics". No.4.

EGOROV, K.E., POPOVA, O.V. (1971) "Foundation settlements of the tower structures". "Foundation Engineering and Soil Mechanics". Proceedings of the 3d All-Union Conference. Ed. "Budevilnik". Kiev.

EFREMOV, M.G., KONOVALOV, G.A., MIKHEEV, V.V. (1963) "On distributing the soil deformations in successive layers in the compressible stratum of clayey and sandy foundation beds." "Foundation Engineering and Soil Mechanics" No.6.

KHAKIMOV, Kh.R. (1938) "Experimental study of the thickness of the bearing soil stratum in the foundation bed". "Hydroengineering" No.1.

MALIKOVA T.A. (1972) "The analysis of field settlements of plate and box foundations of multi-storied buildings". "Foundation Engineering and Soil mechanics", No.2.

TSYTOVICH, N.A., DALMATOV, B.I. (1969) "On the engineering method of predicting foundation settlement and its application." Proceedings of the Seven International Conference on Soil Mechanics and Foundation Engineering.

TSYTOVICH, N.A., DOROSHKEVICH, N.M., ZNAMENSKY, V.V. (1971) "Design of Pile Foundation Stabilized Settlement", Collected Papers, Issue II, Central Office of Scientific-Technical Information, Pub. House, Moscow.