Maximum Allowable Non-uniform Settlement of Structures

Tassement Inégal Maximum Admissible pour les Constructions

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Summary

New methods are described for designing foundations, they require that calculated non-uniform foundation settlement should not exceed the maximum allowable value for operation conditions and strength of superstructure.

The following are given on the basis of data of observations for many years of the settlement of many civil and industrial buildings in the U.S.S.R.: quantitative characteristics of accuracy of existing design methods of anticipated foundation settlement, as well as data on the maximum allowable non-uniform settlement of structures. The actual relative deflection of box-section foundation slabs are given, in particular, for multi-storey buildings in Moscow.

At the end of the report the standards of allowable non-uniform settlement of civil and industrial building foundations adopted in the U.S.S.R. in 1955 are given.

Sommaire

Dans ce compte rendu sont exposés de nouveaux principes d'étude pour les assises et fondations, principes qui exigent que l'affaissement inégal des fondations, tel qu'il est défini par les calculs, n'excède pas l'affaissement maximum de la superstructure compatible avec les conditions d'exploitation et les possibilités de deformation.

Sont fournis, sur la base de données recueillies durant de nombreuses années d'observation sur les affaissements de maints bâtiments civils et industriels, une caractéristique quantitative sur l'exactitude des méthodes actuelles de calcul pour les affaissements éventuels à attendre des fondations, de même que des données sur l'affaissement inégal maximum admissible des ouvrages. En ce qui concerne les gratte-ciel de la ville de Moscou le compte-rendu donne les fléchissements relatifs des radiers dalles des fondations.

A la fin du compte rendu, sont exposées les normes utilisées en U.R.S.S. on 1955 sur l'affaissement inégal admissible des fondations des bâtiments civils et industriels.

The modern period of development of design and calculation in the field of foundations is characterized by an endeavour to take into account the deformation of the subsoil and its interaction with the superstructure. The work of K. Terzaghi is well known in this field. In the last few years articles by Meyerhof (1953) and Capper (1953) published in England, and by Meischeider (1954) and Bub (1954) published in Germany, as well as a number of papers read at the Third International Conference on Soil Mechanics and Foundation Engineering have been devoted to this problem.

In the U.S.S.R., the determination of bearing capacity by the limit condition design was put forward in the official Building Code of 1954 as opposed to the determination of bearing capacity based on allowable soil pressures.

The principle of design according to limit condition has been adopted in the U.S.S.R. for all types of engineering structures (steel, reinforced concrete, masonry and timber). By limit condition is meant such a condition of the structure at which it ceases to meet operation requirements, i.e. it loses the capacity to resist external forces or undergoes non-allowable deformation or local damage.

The subsoil of the structure is not generally considered as part of the building. However, the concept of limit condition may also be applied to the subsoil.

The limit condition of the superstructure under certain conditions is reached even without substantial deformation of the subsoil. As to the latter, its condition may be considered as ultimate only in the event that it causes the transition of the superstructure to the limit condition.

On this basis the subsoil of the structure may have two limit conditions: (a) depending on its stability; and (b) depending on its deformation.

Indeed, if the foundation loses its stability (destruction, complete loss of bearing capacity) this determines the transition of the subsoil itself to the limit condition. Structures erected on such foundations always become unsuitable for operation. In that case the limit condition of the structure and of the subsoil thus coincide.

The limit condition of the subsoil depending on deformation is a different matter. The subsoil may deform to such an extent that the superstructure reaches the limit condition although the bearing capacity of the foundation is by no means exceeded.

Building practice shows that the latter case occurs most frequently. Therefore, the design of foundations depending on deformation is of primary importance. Deformation design should be used for the foundations of all buildings and structures; designs checked for stability should be used only in cases when the foundation is in the most unfavourable conditions as in the presence of regularly acting horizontal loads (dams, river embankments, etc.) or the location of the foundation of the building near slopes, etc.

Calculations according to deformation are reduced to satisfying the condition:

$$S < S_{\text{lim}}$$

where S = subsoil deformation determined by calculation; and S_{lim} = allowable ultimate subsoil deformation depending on conditions of strength and operation of the designed structure.

Calculation according to deformation comprises an integrated and complicated problem including numerous problems which are naturally divided into two groups corresponding to both terms in the above condition.

The first group includes methods of settlement calculation, consideration of the combined effect of the structure and the subsoil, determination and choice of design properties of the soil, quantitative estimation of accuracy of calculation, of subsoil deformation and other factors obtained by calculation. The second group includes problems relating to determination of allowable ultimate subsoil deformation for various structures.

The least work has been done on the quantitative estimation of accuracy of subsoil deformation obtained by calculation and the problems of the second group.

Estimation of Accuracy of Calculation of Subsoil Deformation

The actual settlement of any foundation depends on a large number of factors which are taken into account by the given method of calculation only with some degree of approximation. The most important of these factors are the following: the load on the foundation, thickness of compressed soil layer in the subsoil, and compressibility of the soil. Moreover, the accuracy of calculation depends upon the theoretical scheme used as the basis of the given calculation method. The theoretical estimation of the influence of the latter is impossible. Only by comparing the design settlement with the results of direct observations can the degree of accuracy of the various methods of subsoil deformation calculations be determined.

The degree of accuracy of the subsoil deformation determined by calculation is measured by the ratio of actual subsoil deformation to the value determined by calculation (coefficient of accuracy).

Data obtained by the Scientific Research Institute of Foundation-beds and Foundations (NIIOF) at the site of a large plant erected on diverse highly compressible soils were used to determine the coefficients of accuracy.

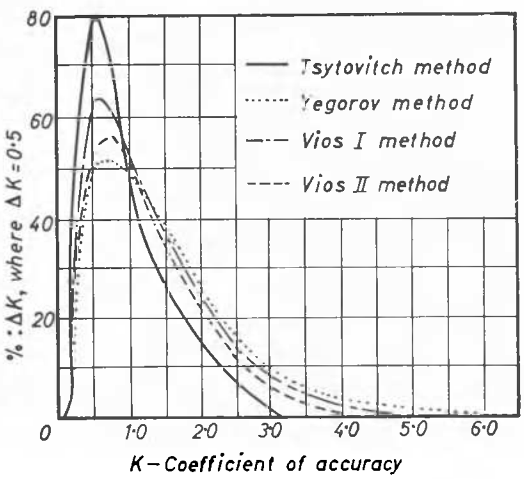

Fig. 1 Coefficiency of accuracy; division of $S = 0{\cdot}5$
Coefficient d'exactitude; division de $S = 0{\cdot}5$

The engineering-geological conditions at the site, including physical properties of the soil, were thoroughly investigated by a scientific survey by the Institute in 1937. From the very beginning of construction observations were carried out of the settlement of many of the shops, as a result of which a record of the rate of settlement of the buildings at this plant has been kept for over 13 years.

Settlement was calculated by the methods of Tsytovich, Egorov (1949) and Vios. The results obtained (93 coefficients of accuracy for each design method) show equal probability of deviation of design settlement values from actual values in the direction of increase and decrease. Distribution curves and integral curves of the coefficient of accuracy for various design methods are given in Figs. 1 and 2, where it may be seen that when the coefficient of accuracy is from 1·3 to 1·8 (for various design methods) the calculated settlement will not be less than the actual value in eight cases out of ten.

Thus, the settlement obtained by the given method of calculation must be increased approximately one and a half times, after which the revised value of S should be compared with the allowable limit value of S_{lim} according to the inequality 1.

Allowable Ultimate Subsoil Deformations

These values may be chosen by the designer on the basis of analyses of the design of the structure and its operation conditions. However, for the most used constructions, allowable subsoil deformation values may be recommended on the basis of building practice.

Foundation deformations are characterized by the following:

(1) Slope, measured as the difference of settlement of two adjacent supports relative to the distance between them;

(2) Relative deflection, comprising the ratio of deflection to the length of the deflected part;

(3) Average settlement under the building.

The results of observations of settlement measurement of various structures on different soils, carried out over a period of 25 years by the Soil Mechanics Laboratory of NIIOF, have been used for finding the allowable ultimate subsoil deformations. Besides this, information from the Leningrad Civil Engineering Institute, partially published in the work of Vasilyev (1952), as well as actual data included in the works of Abelyev (1948), Egorov (1952), Ribakov (1937), Ushkalov (1955), Tsytovich (1951) and others have also been used. In all, the data of over 100 sites were analysed.

The method of generalizing the material obtained will be explained with brick dwelling as an example.

The relationship between ultimate relative deflection of walls f and their dimensions (l = length of wall between settlement

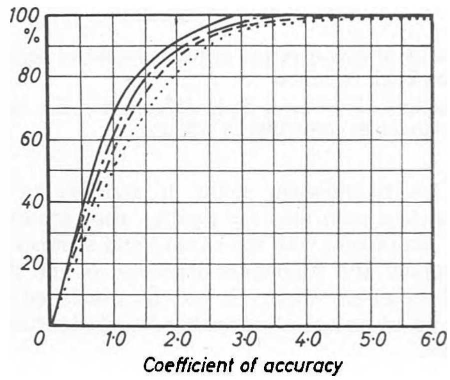

Fig. 2 Coefficient of accuracy
Coefficient d'exactitude

joints, h = height of wall from footing) may be shown theoretically and approximately by the line *abc* in Fig. 3. This line is plotted for cases when the relative elongation of brick masonry before cracking is equal to 0·0005.

The results of measurement of foundation-bed deformation of ten brick buildings are shown in Fig. 3 by dots for walls without cracks and by crosses for walls with cracks.

On the basis of this, it may be concluded that the allowable ultimate subsoil settlement of brick dwellings may be taken as follows:

$$\text{when } L/H \leqslant 2 \qquad f = 0{\cdot}0003$$
$$\text{when } L/H = 8 \qquad f = 0{\cdot}0010$$

Of great importance for industrial buildings is the preservation of the horizontality of the crane ways and the support of the brick cladding.

Investigation of a large number of crane ways has shown that a slope of crane ways as well as tracks for the bridge crane truck up to 0·0030 does not hamper operation. Therefore, a corresponding non-uniform settlement of columns supporting the crane way is allowable.

Generalizations of tests by Polyakov (1952) on the obliquity of brick cladding leads to the conclusion that the difference of settlement of columns of brick-clad structures must not exceed 0·001 of the distance between columns.

A group of multi-storey buildings in Moscow (25 storeys and over) are built on subsoils consisting of sand and clay. The total thickness of the compressible zone of the subsoil is equal to several dozens of metres. The area of the buildings is also large. To decrease non-uniform settlement of supports of such buildings their foundations were made of a box-section reinforced concrete slab underneath the entire building. The rigidity of the foundation slab was designated in the project on the basis of allowable ultimate deformation of the brick-clad skeleton superstructures. It was found that distortions would not cause cracks in the brick-cladding when the slope between the foundations of two adjacent supports did not exceed 0·0005. This requirement made it possible to build the foundation slabs with medium rigidity, thus ensuring in conditions of interaction with the subsoil and superstructure that the longitudinal and transverse deflection of the slabs would not exceed a definite value. It may be concluded that this is the economic advantage of designing foundations according to deformation.

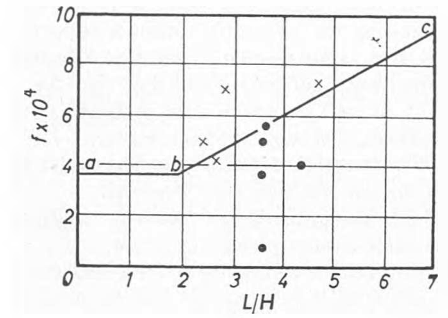

Fig. 3 Results of measurement of foundation-bed deformation for ten brick buildings

Résultats des mesures de la déformation des assises de dix immeubles construits en briques

Careful observations of the settlement of the buildings for a period of five years from the beginning of their construction were carried out by scientific workers of the Soil Mechanics Laboratory of NIIOF (Bright, Egorov, Komnatny, Pereponova and Rudnitsky); they show the relative deflection of foundation slabs given in Table 1.

Table 1

Building	*Foundation slab dimensions,* m	*Relative deflection*	
		Longitudinal	*Transverse*
Building on Smolenskaya Ploshchad	97 × 37	0·00022	0·00022
Hotel on Dorogomilov Embankment	60 × 24	0·00040	0·00058
Building on Vosstanye Ploshchad	114 × 85	0·00038	0·00058
Moscow University on the Lenin Hills	86 × 53	0·00030	0·00030
Building at Krasnye Vorota	44 × 26	0·00027	0·00012

These values of foundation slab deflection, as operation of the buildings has shown, do not exceed the allowable ultimate values for such structures.

Foundation Deformation Standards

Ultimate values of settlements of foundations of buildings and industrial structures adopted in 1955 in the U.S.S.R. are shown in Table 2.

Table 2

Item No.	*Description of standard value*	*Subsoil*	
		Sand and clay in hard condition	*Clay in plastic condition*
1	Slope of crane way, as well as tracks for bridge crane truck	0·003	0·003
2	Difference in settlement of civil and industrial building column foundations:		
	(a) for steel and reinforced concrete frame structures	0·002 *L*	0·002 *L*
	(b) for end rows of columns with brick cladding	0·007 *L*	0·001 *L*
	(c) for structures where auxiliary strain does not arise during non-uniform settlement of foundations (*L*—distance between foundation centres)	0·005 *L*	0·005 *L*
3	Relative deflection of plain brick walls:		
	(a) for multi-storey dwellings and civil buildings		
	at $L/H \leqslant 3$	0·0003	0·0004
	at $L/H \geqslant 5$	0·0005	0·0007
	(*L*—length of deflected part of wall; *H*—height of wall from foundation footing)		
	(b) for one-storey mills	0·0010	0·0010
4	Pitch of solid or ring-shaped foundations of high rigid structures (smoke stacks, water towers, silos, etc.) at the most unfavourable combination of loads	0·004	0·004

The use of this data for designing foundations may in a number of cases offer some difficulty due to the complexity of determining probable subsoil deformations, taking into account the combined effect of the building and the subsoil.

Soil mechanics shows that the value of average settlement of a perfectly flexible foundation does not differ greatly from the settlement value of a perfectly rigid foundation; the difference not being more than 7 per cent. The difference is even smaller between the average settlement of a perfectly rigid foundation and a foundation of intermediate rigidity. It is, therefore, possible after finding the average settlement of a brick building, assuming perfect flexibility (this may be done very simply using existing soil mechanics methods), to find with sufficient accuracy its actual average settlement. An estimate of the probable relative deflection may be made from the average settlement using an empirical equation taking into account the combined effect of the building and the subsoil.

This equation was evolved on the basis of the abovementioned data during observation of settlement of buildings and structures.

Table 3 contains the ultimate values of average settlement included in the Building Code of the U.S.S.R. of 1955.

Table 3

Item No.	*Kind of building and type of foundation*	*Average settlement* cm
1	Buildings with plain brick walls on continuous and separate foundations with the wall length *L* to the wall height *H* (*H* counted from the foundation footing): $L/H \geqslant 2 \cdot 5$ $L/H \leqslant 1 \cdot 5$	 8 10
2	Buildings with brick walls, reinforced with reinforced concrete or reinforced brick belts (not depending on the ratio of *L*/*H*)	15
3	Framed buildings	10
4	Solid reinforced concrete foundations of blast furnaces, smoke stacks, silos, water towers, etc.	30

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