On the Design of Foundations by the Method of Limit State of the Soil Base

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The method of foundation design according to the limit state of the soil bases is used at present in the USSR and was developed on the strength of the latest data on soil mechanics as well as the practice growing out of many years of observations of settlements and deformations of structures. These data showed that the bearing capacity and the deformations of the base depend not only on the soil properties but on the design features of the structures as well.

The method of foundation design according to limit conditions permits:

(a) Full utilization of the strength and deformation characteristics of the soils of the base and a guarantee of the safety of the structures erected, and

(b) Detailed evaluation of separate factors which affect the performance of the base and the foundations by introducing coefficients: of overloading (greater than unity); of uniformity of the foundation (smaller than unity); and of the conditions of work of the foundations, or to be more precise, of the reliability of design assumptions.

The use of this method of foundation design permits considerable economies. Thus, according to data of the Institute of Foundations (Moscow), the use of this method in areas of permanently frozen soils gives an economy up to 15 per cent of the value of the foundations which, over a period of five years, equals approximately one billion roubles.

The following limit conditions of soil bases are considered: limit stability, i.e., the loss of bearing capacity, and limit deformations, i.e., such deformations which when reached cause a rupture of continuity in structures (i.e., the appearance of cracks) so that the use of the structures is impaired.

The design for the first limit condition, the loss of bearing capacity, is based on the general theory of limit equilibrium for which a number of rigorous solutions have been obtained during the last decades both in the USSR, work of V. Sokolovsky, V. Berezantzev and others, as well as in the West, by Skempton, Meyerhoff and others. This method permits the determination of the maximum possible loads on the soil of the base, by using known physical properties of the soil and given boundary conditions.

Two cases have to be considered during such studies:

1. The beginning of appearance under the edge of foundations of zones of limit stress conditions (i.e., under pressures which reach the end of the phase of consolidation—p_o kg/cm^2) *(Fig. 1)*. A full development of zones of limit equilibrium *(Fig. 2)* whereby under the foundation surfaces of slippage of one part of the soil along the other are formed under full (maximum) utilization of the bearing capacity of the foundation. Under such conditions, the slightest increase of the acting load creates a state of unstable equilibrium in a certain zone of the soil under the structure so that a phase of squeezing out of the soil is reached. Thus a design according to the first limit condition permits the determination of the start of plastic flow and of the maximum limit load on the foundation.

Computations according to the second limit condition (for limit deformations) are of basic importance for the design of foundations of structures. The following two conditions serve as starting point for the computations. They vary depending on the uniformity of the soils of the base:

(a) For relatively uniform bases

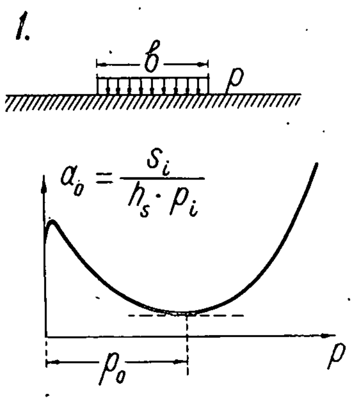
$$S_c < S_u$$

(b) For any types of non-uniform soil bases

$$\Delta S_c < \Delta S_u$$

where S_c is the computed settlement of the foundations determined according to well-known equations of soil mechanics, e.g., according to data given *(Figs. 3, 4)*; and where S_u is the limit settlement of founda-

1.



$$a_0 = \frac{S_i}{h_s \cdot p_i}$$

Fr	h_s
Fr < 3%	$h_s = 1{,}0 \cdot b$
3 – 10%	$1{,}1\, b$
10 – 30%	$1{,}2\, b$
Fr > 30%	$h_s = 1{,}3\, b$

2.

$$p_u \leqslant \frac{\pi(\gamma h) + \frac{c}{tg\varphi}}{ctg\varphi + \varphi - \frac{\pi}{2}} + \gamma h$$

$$p_u = \pi c_e$$

$$[p_u]_s \leqslant \frac{B}{b} \cdot p_0 ;$$

$$[p_u]_{cl} \leqslant 1{,}2\, p_0 ;$$

FIGURE 1

Determination of the limit of the consolidation phase: 1. according to the results of a load test (determination of the value p_0 kg/cm^2); 2. according to theoretical equations (of Pouzirevsky, Froelich and others): determination of the pressure (p_u) below which zones of limit equilibrium are not present in the soil. Where: ψ = angle of internal friction; c = cohesion; B = width of the foundation; b = width of the tested area; a_0 = reduced coefficient of consolidation; c_e = permanent cohesion for cohesive soils; $(p_u)_s$ for sands; $(p_u)_{cl}$ for clays.

tions permissible from the point of view of the strength and of the use of structures—determined according to rules of building codes or on the basis of generalized observations of settlements of structure.

ΔS_c and ΔS_u are the differential settlements of adjoining foundations, or the slopes of their inclined lower surfaces or the relative deflections of continuous strip foundations.

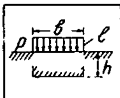
	1. $c = f(t, W, \theta^\circ); \varphi = 0$	2. h/b	$c=0; \varphi = f(t,W,\theta^\circ); p_u = D \cdot \gamma b + \gamma h$ $\varphi = 26^\circ$	30°	36°
$\frac{l}{b} > 10$	$p_u = 5{,}14c + \gamma h$	0	6,8	D = 10,8	26,2
		1	21,3	34,8	79,5
		2	36,3	58,9	138,0
$\frac{l}{b} = 1$	$p_u = 5{,}7c + \gamma h$	0	—	17,3	~56
		0,5	—	33,7	~106
		2	—	122,0	~335
$\frac{l}{b} > 10$	$p_u = c \cdot Ctg\varphi(\zeta - 1) + \gamma h \cdot \zeta ;\ \zeta = e^{\pi tg\varphi} tg^2(45^\circ + \frac{\varphi}{2})$ $\varphi \neq 0 ;\ c \neq 0$				

FIGURE 2

Equations for determination of limit loads on cohesive and granular soils: 1. for cohesive clay soils (after Prandtl and Ishlinski); 2. for dense non-cohesive soils (γ = unit weight of soil above base of foundation; h = depth of foundation base below soil surface.

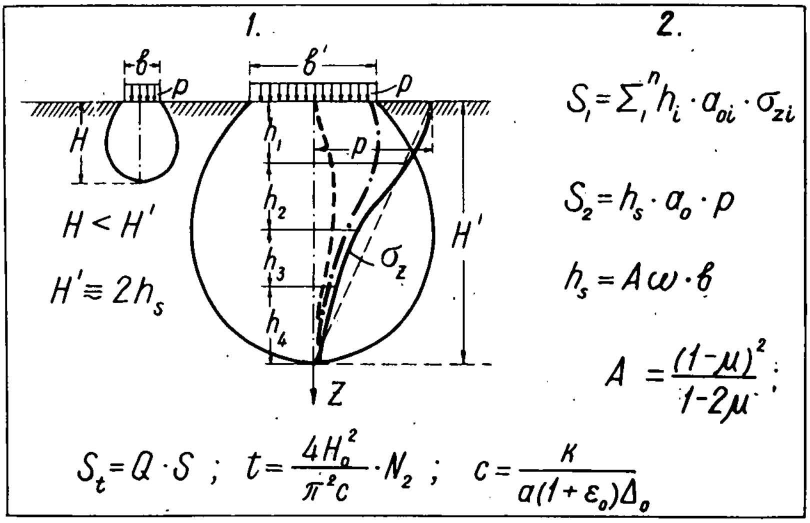


FIGURE 3

Equations for computation of foundation settlements on uniform soils: 1. dependence of zone of consolidation on dimensions of loaded area, the concept of the equivalent soil layer, h_s; 2. equations for computation of foundation settlement on uniform soils: S_1 according to method of elementary summation without consideration of lateral yielding of soil; S_2 according to method of equivalent layer (developed by the author) which takes into consideration lateral expansion of the soil (μ), the dimensions and the shape of the foundation as well as its rigidity (the coefficients w, b); A = coefficient which depends on the lateral yield of the soil (values of Aw given in Fig. 4).

$a = \frac{l}{b}$	Gravel		Sands				Plastic Loams		Plastic Clays	
	Hard Clay and Loams				Sandy Loams					
	$\mu = 0.10$		$\mu = 0.20$		$\mu = 0.25$		$\mu = 0.30$		$\mu = 0.35$	
	Aw_c	Aw_m	Aw_c	Aw_m	Aw_c	Aw_m	Aw_c	Aw_m	Aw_c	Aw_m
1	0.568	0.96	0.598	1.01	0.631	1.07	0.687	1.17	0.790	1.34
1.5	0.687	1.16	0.724	1.23	0.764	1.30	0.832	1.40	0.956	1.62
2	0.775	1.31	0.817	1.39	0.862	1.47	0.938	1.60	1.079	1.83
3	0.903	1.55	0.951	1.63	1.003	1.73	1.092	1.89	1.256	2.15
4	0.994	1.72	1.047	1.81	1.105	1.92	1.203	2.09	1.383	2.39
5	1.065	1.85	1.122	1.95	1.184	2.07	1.289	2.25	1.482	2.57
6	1.124	1.98	1.184	2.09	1.249	2.21	1.360	2.41	1.568	2.76
7	1.173	2.06	1.236	2.18	1.304	2.31	1.420	2.51	1.632	2.87
8	1.216	2.14	1.281	2.26	1.316	2.40	1.472	2.61	1.692	2.98
9	1.254	2.21	1.321	2.34	1.393	2.47	1.517	2.69	1.744	3.08
10 and more	1.288	2.27	1.357	2.40	1.431	2.54	1.558	2.77	1.792	3.17

FIGURE 4

Values of coefficient of equivalent layer of soil Aw for computation of foundation settlement on compressible soils: Aw_c—for the corner points of rectangular flexible foundations; Aw_m—for average settlement of rigid foundations.

Ultimate values of settlements

K_r 1	$\frac{dh}{dt}$ m/year 2	S cm 3	$\frac{dS}{dt}$ cm/year 4	Slope $i \cdot 10^3$ 5	Deflection $f \cdot 10^3$ 6
30÷300	0,3-0,9	10-20	3-8	1,5-4,5	1-3
<30	0,9-1,8	20-40	8-15	4,5-8	3-6
≥300	to 2	to 50	to 20	to 10	—

$$K_r \cong 1{,}7(1-\mu_0^2)\left(\frac{A_0}{p}+a_0\right)\cdot\Omega\cdot E_B \frac{H^3}{L^3}$$

FIGURE 5

Values of ultimate settlements (after Oushkalov) when erecting structures under conditions of permanently frozen ground. 1. Coefficient of rigidity; 2. rate of thawing of soils under structure, meters per year; 3. values of settlements, in centimeters; 4. limit rate of settlement, centimeters per year; 5. limit inclination (slope) of foundations; 6. limit deflection of foundations. (According to USSR building codes permissible settlement values are approximately one-half the above.)

The last two conditions require consideration of the interaction of the soils of the base and of the structures erected on them as well as the determination of the coefficient of accuracy of settlement forecast. Given *(Fig. 6)* are the results of observations and of computed settlements of one of the buildings and given *(Fig. 7)* is the statistical evaluation of a series of similar observations.

In order to satisfy the above conditions, the designer may change the left side of the inequalities given above (i.e., by decreasing or increasing the load on the base); or he may change their right part (e.g., by using more rigid structures or statically determinate systems); or he may simultaneously change both parts of the inequalities in order to bring their values closer together.

The author recommends the following procedure of foundation design according to limit states of soil bases:

1. A preliminary selection of the dimensions of foundations using data of soil bearing capacities recommended by building codes for designs (as determined by the equations given in Figure 1).

2. Determination of the computed deformations (S_c) and their comparison with the limit values (S_u).

Re-evaluations of the loads selected (usually their increase under consideration of the two conditions: $S_c < S_u$ and $\Delta S_c < \Delta S_u$); and the design of the foundations.

Check computations of the pressures along the base of the foundations and of the deformations of the base.

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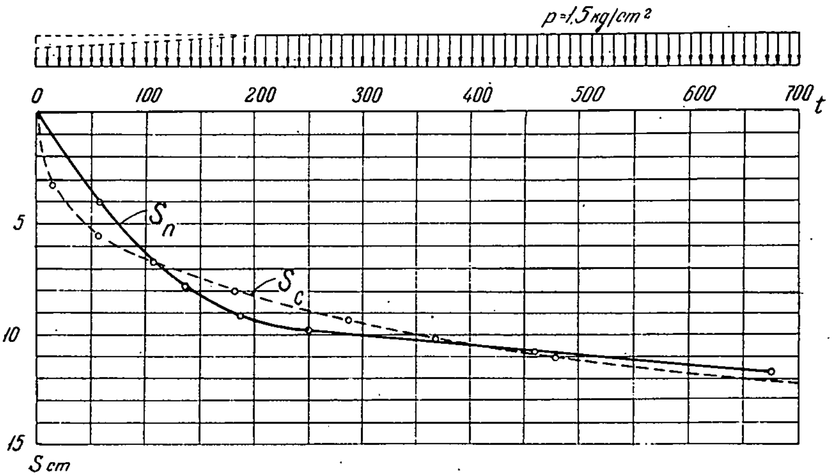

FIGURE 6

Comparison of settlements (S_c) computed according to the method of the equivalent layer with measured settlements (S_n) for a school building erected on a complex (7 layers) soil base.

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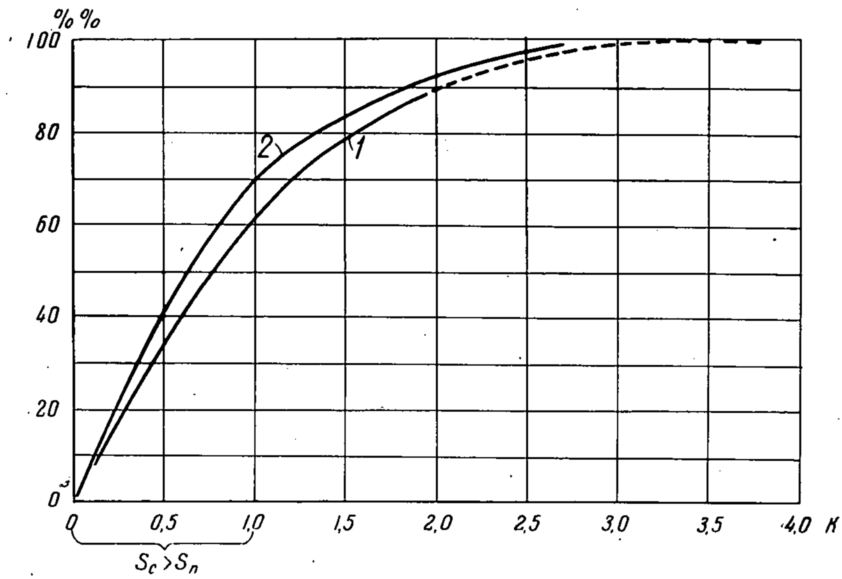

FIGURE 7

Curves of statistical distribution of probability coefficients (K) for various methods of foundation design: 1. when computed by the method of elementary summations; 2. when computed by the method of the equivalent layer of the soil (when 80 per cent of cases of computed settlements are no smaller than the real ones, a probability coefficient varying between 1.3 and 1.5 is obtained).

on the occasion of its 250th anniversary. Prague, 1958.

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The Value of the American-Russian Exchange Visits

I. M. Litvinov, *Chairman,*
The Soviet Delegation
(National Academy of Sciences, Washington, D. C., June 18, 1959)

Permit me in the name of the Soviet Delegation of Scientists and Construction Specialists, to express our cordial gratitude for your amiable invitation to visit your country and to familiarize ourselves with your achievements in the field of theory and practice of soil mechanics and foundation engineering.

We express our gratitude to the National Academy of Sciences, to the American Society of Civil Engineers and to all those gentlemen who with sincere good feeling helped us to utilize our stay in the USA as rationally and usefully as possible with the aim of organizing scientific and business contacts between specialists of our countries.

We particularly thank the deeply esteemed chairman, Dr. Connolly, Mr. Burggraf and Profs. Kersten, Tschebotarioff, Winterkorn, Schmid, Jumikis, Lambe, Peck, Leonards and Seed—who did extensive practical work for the organization of the exchange of our delegations and for the creation of particularly favorable conditions in the USA for our delegation.

Our brief visit to the United States of America is coming to an end. However, although we stayed here a short while, we nevertheless saw and learned must which is interesting and useful. We received much satisfaction from our study of the interesting construction and especially road building sites and test roads in a number of American cities. We were particularly interested by the remarkable organization of test road research. We received much that was interesting and valuable as a result of our participation in seminars concerned with various problems in the field of soil mechanics and foundation engineering.

At these seminars, as well as in laboratories, on construction sites and in other places, we had the agreeable opportunity, not only to present reports concerning a number of our Soviet scientific studies, but also to make personal contacts with many outstanding scientists and specialists of America.

The Soviet scientists and specialists follow with great attention the interesting, and in a number of cases, outstanding achievements of American scientists. In spite of complications in the matter of direct exchanges between the specialists of our two great countries, we in the USSR study with great respect and interest the work of the specialists and scientists who are known the world over in that field: Terzaghi, Casagrande, Tschebotarioff, Peck, Burggarf, Lambe, Osterberg, Kersten, Hanson, Thornburn and many others. In the USSR books of American specialists have been published in large printings.

The considerable achievements of American specialists in the field of road construction are generally acknowledged. In this respect, the American roads designed and built in complicated geological conditions are presentations in nature equivalent to beautiful books and scientific studies.

Much that is useful is being done by Soviet scientists, too. We also have a number of achievements which help the technical advance of construction work, and because of geographical and climatic conditions of our country, we have to develop