means of vibratory drivers. Shown *(Figs. 14, 15)* is the manufacture of reinforced concrete shells of 5.0 meters (= 16.3 ft) diameter with a wall thickness of 14 centimeters (= 5.5 in.) on a motor road bridge under construction. They are being sunk into sand with fine gravel to a depth of 22 meters (= 72 ft).

FIGURE 15

On the Development of Soil Mechanics in the USSR

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The present communication is devoted to the development of the basic ideas of modern soil mechanics in the work of Russian and Soviet scientists.

The scientists and the engineers of the USSR attach considerable importance to the solution of problems in the field of soil mechanics, since important territories of the Soviet Union are covered by loose deposits of mineral soils of considerable depth. The erection of structures on such soils requires specific knowledge of soil mechanics.

This is all the more important since during the last decades many industrial and housing structures are being erected in the Soviet Union which often structurally are statically indeterminate and which are very sensitive to uneven settlements. A forecast of the magnitude of such settlements can be made only through the use of solutions provided by soil mechanics.

All this compelled Russian scientists a long time ago to devote their studies to the development of problems of the theory of bases of structures (publications of V. I. Kourdyumov, 1889 and others) and to their practical applications to foundation engineering. It is significant that, for instance, a text on "Bases and Foundations" by V. M. Karlovich *(Ref. 1)* was published in the Russian language in 1869 and a systematic text on soil mechanics appeared in 1934 *(Ref. 3)*.

In the following we shall consider:

1. The development of problems of the theory of soil mechanics in the work of Soviet scientists.
2. The development of the fundamentals of the mechanics of separate regional types of soils.
3. The use of solutions provided by soil mechanics for the design of foundations and the performance of earth moving and foundation construction operations.
4. The direction of the latest research in the field of soil mechanics in the USSR.

Problems of the Theory of Soil Mechanics

The following should be considered as basic problems in the field of the theory of soil mechanics to the development of which Soviet scientists have devoted studies during the past 40 years: (a) the application of the theory of elasticity to the design of bases; (b) the study of the interaction between structures and their compressed base; (c) the development of general solutions of rigorous theories on the limit state of stress; (d) the theories of consolidation of water-saturated soils, and (e) the problems of the dynamics of soil bases.

A. The first question which arose in connection with the use of the theory of elasticity for the design of bases was: Is the theory of elasticity applicable to soils of bases? As had already been shown in 1916 by B. A. Minayev *(Ref. 4)*, the use of the basic equations of the theory of elasticity for computations related to granular media is most fruitful. N. M. Gersevanov in his publications of 1930-1933 *(Refs. 7, 8)* has shown that the application of the theory of elasticity to clays and to very fine sands is quite as justified as is its application to steel, whereby was proposed for the non-elastic state of soils the criterion of linear deformability *(Ref. 7)*. In 1936, V. A. Florin *(Ref. 9)* established a relationship between the dimensions of plastic zones in the soil and the dimensions of the structure, which determines the conditions of applicability of the solutions of the theory of elasticity to the design of bases.

At the end of the 1920's and at the start of the '30's, the theory of elasticity began to be widely applied in the USSR to the design of natural bases. Here should be pointed out the remarkable work of N. P. Pouzirevsky *(Refs. 5, 6)*, who proposed an original method for the use of the theory of elasticity which permitted him:

To develop a general theory of the stresses in earthy soils and in particular to give a solution for the problems of the magnitude of pressures in the base of a structure corresponding to the beginning of the appearance of the plastic zones under the edge of the foundation (i.e., he obtained in 1929 an equation for the critical edge load, an identical expression for which was also published in a somewhat different form by O. K. Froehlich in 1934).

To justify an analytical expression for the slip surface in slopes later used for the computations of their stability.

To give equations for lateral earth pressures against retaining structures for various cases of their loading, as well as a number of other solutions.

At about the same time, N. M. Gersevanov *(Ref. 7)* proposed to consider three basic phases of the stressed state of soils under foundations: the phase of consolidation, the phase of displacements (plastic flow) and the phase of squeezing out (progressive flow after N. A. Tsytovich). By a procedure different from the solution of N. P. Pouzirevsky, he obtained for the edge loading the value corresponding to the beginning of the appearance of the displacement phase in soils, which value in practice equals the permissible pressure on the soil.

B. Studies of the interaction between structures and their compressed bases have received much attention from Soviet scientists. Efforts were directed mainly towards the development of general theoretical solutions. Here, first of all, should be noted the work of Pouzirevsky *(Refs. 5, 11)* and of Academician A. N. Krylov *(Ref. 10)* who by developing a method of initial parameters reduced the complex fourth order differential equation for the design of beams on a local (Winklerian) base to a solution of two equations with two unknowns.

This permitted the development of a very effective method for the determination of all design values. As was shown by later investigations (N. A. Tsytovich and others), the method of the design of beams and of slabs on a local elastic base (developed on the assumption of direct proportionality between the pressure and the elastic settlement only at the place of the application of the load),* can be successfully used only in the case of highly compressible soils and of a small thickness of the deposits underlain by incompressible layers such as rock.

During the further development of the work of USSR scientists, the model of a locally compressed base was improved: First, in the direction of a more precise evaluation of the elasticity of the base (the method of M. M. Filonenko-Borodich according to which the elastic base may be represented by a localized Winklerian base superposed on a membrane stretched in all directions); and second, in the direction of the introduction of two coefficients to characterize the compressed base (i.e., of coefficients of elastic compression and of elastic shear or slide, after P. L. Pasternak) *(Refs. 12, 13)*.

However, the model of a locally elastic base in many respects did not satisfy Soviet scientists in spite of its improvements, since it did not permit the determination of soil deformations at some distance away from the place of load application, but mainly because its characteristic coefficients were not constant. Therefore, they started a long time ago the direct use in its pure form of the theory of elasticity for the design of foundations on a so-called elastic half space.

Here one should note apparently the first publication in that field, the work of G. E. Proctor *(Ref. 14)*; and then the publications of N. M. Gersevanov and I. A. Macheret *(Ref. 15)*; V. A. Florin *(Refs. 16, 17)*, as well as B. N. Zhemochkin, S. S. Davidov, V. Z. Vlassov, B. I. Kloubin and others *(see, e.g., Ref. 18)* and a generalized summary publication by M. I. Gorbounov-Possadov *(Ref. 19)*. In this latter publication were given the results of the research of Gorbounov-Possadov as well as of other Soviet authors with numerous tables for the rapid and precise design of beams and slabs on an elastic or linearly-deformable half space.

As was shown by special discussion of the methods of design of beams and of slabs on a compressible base *(Ref. 18)*, the method of an elastic half space, i.e., the method of general elastic deformations, is more applicable to compact and hard soils which can be assumed uniform to a sufficient depth below the lower surface of the foundations.

It is also interesting to note that a general method for the solution of the so-called contact problem of distribution of pressures along the lower surface of a foundation under conditions of a two-dimensional problem for foundations of any rigidity and for any load on the foundation as well as beyond its periphery was published in 1936 by Prof. Florin *(Ref. 16)*. This paper also considered the effect of tangential stresses along the lower surface of the foundation. A number of partial problem solutions were published in 1949 by I. I. Steuerman *(Ref. 20)*.

The further development of this type of problems of the theory of soil mechanics is taking place along the lines of improvement of the design models of the soil and the development of solutions of mixed problems of the theory of elasticity and of the theory of plasticity *(see, e.g., Ref. 21)*.

C. The development of a general theory for the limit stressed condition of soils both in the formulation of the problem itself as well as in the development of mathematically rigorous solutions belongs mainly to Soviet scientists. Thus in 1939-1942 were published the remarkable works of V. V. Sokolovsky *(Refs. 22, 23)*, in which were given the general analytical solution of a two-dimensional problem of the theory of limit equilibrium for uniform and for layered, isotropic and anisotropic granular media and, specifically, a precise determination of the value of lateral pressures of soils against retaining structures, of the stability of soils in the bases of structures, of the critical height of slopes and of their equivalent stable form, etc.

* The hypothesis concerning direct proportionality of pressures and local settlement of the soil was advanced as early as 1801 by the Russian Academician N. I. Fouss.

A grapho-analytical solution of the two-dimensional problem of limit equilibrium for granular media was studied by S. S. Gouloushkevich *(Ref. 24)*. The three-dimensional problem of the theory of the limit stressed state of soils has been elucidated in the publications of V. G. Berezantzev *(see, e.g., Ref. 25)*.

The latest studies of Soviet scientists concerning the theory of the limit stressed state of soils are devoted to the consideration of various boundary conditions, to the greater precision of the basic equations for the limit equilibrium of soils, to the study of the strength of bases under deep foundations and to other problems resulting from the practice of the design of structures.

D. The theory of consolidation of water-saturated soils has received wide development after publication of the works of K. Terzaghi (1925, and others). The studies of Soviet scientists in this branch of soil mechanics were directed towards obtaining more rigorous solutions for the linear problem of consolidation, to the formulation of the two- and three-dimensional problem of consolidation and to the development of effective methods of solutions for different boundary conditions and for varying values of the coefficients characterizing the consolidation.

Thus, one should specially mention here the work (1931-1948) of N. M. Gersevanov *(Refs. 26, 27)*, in which the problem of consolidation of a layer of water-saturated soil under a continuous load was studied in detail, equations were formulated of consolidation of a uniform and isotropic soil mass for the cases of a two-dimensional and of a three-dimensional problem, and a solution of the problem of initial stresses when loading a soil mass by an instantaneous strip load was obtained. A solution of the problem of swelling of a layer of clay soil was published by S. A. Rosa in 1937 *(Ref. 28)*; methods of consideration of the initial gradient of hydraulic head were published by him in 1950 *(Ref. 29)*.

A complete formulation of the two-dimensional and of the three-dimensional problem of the theory of consolidation of an earth mass was published by V. A. Florin in 1938 *(Ref. 30)*. In 1948 *(Ref. 31)* he published numerical methods for the solution of these problems under any special conditions as well as methods for the determination of the initial effective and neutral stresses at any moment in time for the case of uniform and non-uniform anisotropic media under consideration of changes in the coefficient of permeability.

The theory of consolidation of soils received further development in the work of D. E. Polshin *(Ref. 15)* who formulated in a general form the three-dimensional problem of the filtration theory for rectilinear and non-rectilinear consolidation of clay soils; also in the latest publications of V. A. Florin *(Refs. 32, 33)*, who studied the consolidation of clay soils in the presence of an initial hydraulic gradient and of entrapped air, as well as under consideration of the creep of the mineral skeleton of the soil and of a gradual increase of the consolidating zone as the structure was being erected.

E. The problems of dynamics of soil bases were developed by Soviet scientists in two directions. They studied the vibrations of foundations and the conditions of liquefaction of water-saturated loose sands under dynamic action.

In the USSR the work of N. P. Pavliuk, "On the Oscillations of a Solid Body Resting on an Elastic Base," which was published in 1933 *(Ref. 34)*, is rightly considered a fundamental publication concerned with the vibrations of foundations.

An important contribution to the dynamics of bases was made by D. D. Barkan who published the results of many years of studies on the vibrations of foundations and on dynamic properties of soils *(Ref. 35)*, and by O. A. Savinov who developed methods for the determination of elastic characteristics of soils (the coefficients of elastic uniform and nonuniform compression and of elastic horizontal displacement), necessary for the computation of vibrations of foundations. He also published a summarizing study on the design of foundations for machinery *(Ref. 36)*. S. S. Davidov developed the theory of oscillations of soils under the action of a load of short duration.

There are also important studies in the field of the dynamics of soil bases as regards the conditions of liquefaction of loose water-saturated sands. Here should be noted the theoretical and experimental studies stretching over many years of three groups of USSR scientific workers directed by V. A. Florin *(Ref. 37)*, M. N. Goldstein *(Ref. 38)*, and by N. N. Maslov *(Ref. 39)*.

In the work of Profs. Florin, P. L. Ivanov and others, it has been shown that the condition for the liquefaction of water-saturated sands is determined by the relationship between the intensity of the dynamic action, the porosity of the sand and its stress condition, and not just by the value "of the critical porosity during shear," i.e., as a basis the theory of dynamic dislocation of the structure of water-saturated sands. This theory already had been advanced by N. M. Gersevanov (1948).

Maslov and his collaborators based their studies on the so-called "filtration theory of dynamic stability of water-saturated sands" which is based on the study of the hydraulic heads which develop in water-saturated sands under dynamic action.

Extensive studies for the precision of the concept of "critical porosity" and of the methods for its determination, as well as for the study of the conditions of liquefaction of sands, have been carried out by Goldstein and his collaborators *(Ref. 38)*.

Development of Fundamentals of the Mechanics of Separate Regional Types of Soils

In separate regions of the USSR occur extensive deposits of special types of soils, mainly of structural types, the properties of which differ appreciably from the properties of ordinary soils. The erection of structures on such soils without consideration of their special features leads to inadmissible deformations which frequently cause complete collapse.

A number of Soviet scientists devoted their work to the study of regional types of structural soils, developing the fundamentals of the mechanics of these types of soils.

As regional types of soil we consider:

(a) Mud and peaty deposits (organic-mineral deposits).

(b) Loesses and loessial soils (macroporous deposits).

(c) Frozen and permanently frozen soils (cryogenic deposits).

During recent decades as a result of the efforts of Soviet scientists the fundamentals of the mechanics of separate regional types of soils have been formulated and methods for the successful erection thereon of major structures have been developed.

A. Problems of mechanics of mud-silts have been treated in a series of publications of the Institute of Foundations in Moscow (the work of D. E. Polshin and others) and of the Hydro-Energo-Project in Leningrad (the work of S. A. Rosa and others). In these publications it was shown that organic silts under low pressures not exceeding their stuctural strength have one set of properties (neither their compressibility nor their resistance to shear in practice depend on their natural water content), whereas under pressures which produce a destruction of their structural strength they become excessively compressible and unstable soil formations *(e.g., Ref. 40)*.

A series of investigations by Leningrad scientists *(see, e.g., Ref. 41)* has been devoted to the study of peaty soils and of peats as bases for structures and much attention has been given to this problem by the scientists of Byelo-Russia *(see, e.g., Ref. 42)*. As a result of the study of the laws of deformation of peaty soils the values of limit deformations of civil and industrial structures during their erection on peaty soils have been outlined and methods of erection and necessary structural measures have been developed.

B. The special features of loess and loessial soils, such as settlements due to their collapse when wetted under load, came to the attention of Soviet scientists in the 1930's when it became necessary to erect a number of industrial buildings on loessial soils.

Here should be noted the studies of U. M. Abelev *(Refs. 43, 44)*, who developed the fundamentals of the mechanics of loessial macroporous soils; the studies of N. I. Denissov *(Ref. 45)*, who studied the nature of the sudden settlements of this type of soil; and the newest work of M. N. Goldstein *(Ref. 46)* and of G. M. Lomize *(Ref. 47)*, which showed the dependence of such settlements on the stressed state of soils and the simultaneous occurrence with vertical settlements of macroporous soils; also of lateral squeezing out of masses of soil with remolded structure when such soils were wetted under load.

C. The problem of the study of frozen and of eternally frozen soils and of the conditions of construction thereon is of particular importance for peaceful construction in the USSR, since approximately 47 per cent of its territory is located within the zones of permanently frozen soils. The erection of structures on these soils is extremely complicated without appropriate measures. Thus, the mass occurrence of deformations of structures erected on permanently frozen soils is well-known, both as a result of the thawing of frozen soils under heated structures and as a result of frost-heaving foundations.

Soviet scientists began the study of research problems of permanently frozen soils a long time ago. One should note the well-known publication of M. I. Soumgin, "Eternal Freezing of Soils Within the Limits of the USSR." *(Ref. 48)*, and the studies of N. A. Tsytovich *(Refs. 49, 50, 51, 52)*, who, on the basis of a synthesis of numerous experimental studies, formulated the fundamental principles of the mechanics of frozen soils on which was based the development of methods of stable erection of structures on permanently frozen soils.

Then there are the studies related to transport construction on permanently frozen soils of M. N. Goldstein *(Ref. 53)*; the studies of S. S. Vialov on the rheology of frozen soils *(Refs. 54, 55)*; the studies of the Institute of Foundations, and others.

Present studies on the mechanics of frozen soils are directed towards the creation of structural mechanics of frozen soils and the development of problems of rheology of ice and of frozen soils.

Utilization of Soil Mechanics for Design of Foundations and Performance of Earth and Foundation Work

On the basis of the development of the theory of soil mechanics and of the development of a series of concrete solutions of its problems and of the verification of the results in nature, it proved possible to elaborate a very progressive method for the design of foundations according to the limit states of the soil bases. This method produces appreciable economies *(Refs. 56, 57)*, and according to Soviet building codes *(Ref. 58)* has been compulsory for all design organizations since 1955.

This method is based on the rule that the design (i.e., the forecast) settlement or the differential settlement of separate parts of the structure must be smaller than limit values established on the basis of direct observations of foundation settlements and of the deformations of structures.

The development of soil mechanics and of the dynamics of bases in particular permitted Soviet scientists, D. D. Barkan and others, to develop and to use with success the vibratory method of driving piles, sheet piles and sampling tubes into granular and into plastic cohesive soils *(see, e.g., Ref. 60)*.

During foundation excavations the problems of water-level lowering and of the use of artificial waterproofing barriers of frozen soils acquire considerable importance. These questions also received attention in the studies of specialists of the Soviet Union, notably those of G. M. Marioupolsky in the Institute of Foundations concerning water-level lowering on construction sites *(Ref. 61)*; N. G. Troupak *(Ref. 62)*, and H. R. Hakimov *(Ref. 63)* concerning the theory and the practice of artificial freezing of soils for construction purposes.

As methods of improvement of properties of weak soils, the following should be mentioned: The original method of artificial compression of clay soils by lowering the head of ground water in underlying sands (method of M. E. Knorre) *(Ref. 64)*, and the methods of chemical and of electro-chemical stabilization of soils developed by B. A. Rzhanitzin *(Ref. 65)*, as well as the method of electro-osmotic drainage and water-level lowering in soils clarified in publications of G. M. Lomize *(see, e.g., Ref. 66)* and the method of thermic stabilization of soils with sand used (I. M. Litvinov and others) for the prevention of sudden settlements of loessial soils *(Ref. 67)*.

As main directions of new studies the following can be considered:

Further development of general solutions of the theory of soil mechanics, both on the basis of a more precise formulation of the fundamental physical assumptions using for that purpose refined methods of physical experiments, and on the basis of results of direct observations in nature and on special experimental structures;

The development of the fundamentals of the statistical mechanics of soils, a successful start on which has been provided by the studies of G. I. Pokrovsky *(see, e.g., Ref. 68)*, and the development of the fundamental laws of structural mechanics of soils which is used with success for the solution of specific problems concerned with the erection of structures on structural types of soils such as organic muds and silts, peaty, loessial, permanently frozen and other similar soils *(see, e.g., Ref. 69)*;

The development of methods for a more complete utilization of properties of soils (e.g., during the design of foundations according to the limit states of soil bases) and of methods of alteration of their properties in the desired directions.

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NOTE: All of the above references unless otherwise noted are in the Russian language.

Basic Principles of Flexible Pavement Design and Construction in the USSR

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In the USSR, which comprises a vast territory between 35° to 78° North latitude and from 169° West longitude to 19° East longitude, there are widely varying physical conditions. There are regions now being economically developed, for which rational types of road pavements and bases have not as yet been worked out practically. Therefore, the elaboration of methods for estimating the quality of bases for the design and construction of road pavements is of very great importance in the USSR.

To take into account the climatic factors while projecting roads, the territory of the USSR is divided into road climatic zones coinciding approximately with typical landscape and soil zones; namely, the tundra and forest zones, the wet zones, the forest-steppe, transitional zones, the steppe zones, insufficiently wet zones, the semi-desert, dry steppe arid zone, except for mountain regions.

Moreover, within the limits of each road climatic zone there are various types of terrain distinguished by the influence of local moisture sources, character of surface drainage, and peculiarities of the hydrological conditions.

About 15 years ago the method worked out in the Central Highway Scientific-Research Institute (SOJUZDORNII) under the guidance of Prof. N. N. Ivanov began to be used in the Soviet Union for designing roads. This method for determining the thickness of flexible road pavements was based on the following thesis:

1. The stress conditions in the road structure at the beginning of failure are characterized by a definite ultimate value of accumulated vertical displacement, deflection, of the pavement. This increases in the wet period of the year under the repeated action of automobile wheel loads. For roads with high-duty and high-type pavements with high-speed traffic, the ultimate value of accumulated vertical displacement is limited by the allowable degree of smoothness of the riding surface.

It is necessary, however, to consider the possibility of failure of the road pavement before the accumulated deflections allowable for the given pavement are exceeded, with less strict requirements as regards permitted surfacing irregularity and the ease with which it can be restored. In such cases the allowable deflection is limited by the need to insure the required strength of the road structure.

2. The modulus of deformation of the structure (E) depending on the ratio between the unit load (p) acting on the surface of the structure and the total relative deflection (λ) caused by it, is the criterion for determining the resistance to deformation of flexible road pavements in the USSR.

$$E = f\left(\frac{D}{\lambda}\right) \quad (1)$$

Relative deflection (λ) is a non-dimensional value equal to the ratio between the absolute deflection (ρ) and the diameter of a circle (B) equivalent to the contact area of dual-tire wheels of the design automobile with the road surface and for the subgrade, with the area of load transfer $\left(\lambda = \frac{\rho}{B}\right)$.