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Resistance of the Ground.

Tragfähigkeit des Baugrundes.

Résistance des terrains.

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The study of ground resistance is one which has made great advances in recent years, enabling the design and realisation of works, in perfect safety, which formerly could not have been carried out without many misgivings and by the adoption of slow and costly measures.

We are now able, for instance, to make very deep foundations rapidly, and at no great cost to hold up great slips of geological strata such as are apt to follow the execution of earthwork: all that is necessary is to reproduce faithfully the mechanical conditions disclosed by calculations. In each case, starting from the experimental characteristics of the ground, a very careful analysis is made of the stresses in all directions at every point in the mass of earth on the equilibrium of which the work as a whole depends. It is not enough merely to study the equilibrium of some slip plane decided upon *a priori*, but the existence of a general system of stresses compatible with stability must be everywhere confirmed.

For the purpose of determining the conditions of equilibrium there are available, in the first place, the physical experimental laws which govern sliding in the interior of the ground. These elementary laws were formulated in the 18th century by the physicist Coulomb, and have again been verified quite recently by many experimenters in all countries. We now know, for all kinds of ground, the values of the two variables entering into Coulomb's laws; namely the buoyancy and the cohesion. These two values are not fixed for any given kind of soil but depend essentially on the magnitude and duration of the stresses imposed thereon.

It is to *Terzaghi* and his followers that we owe the development of experimental methods from which the first sufficiently accurate information for use in calculating the limits of equilibrium has been obtained. We now regard all soils of low strength as being compounded of two elements: solid grains on the one hand, and interstitial water on the other. By virtue of the law of large numbers this complex of ground conditions acts practically as if it were an isotropic body, but one which shows very different properties according to the incidence of the loads and therefore according to the rate of development of the system of stresses, governed by variations in the mass of interstitial water within a unit volume of soil.

The laws of similarity are approximately accurate, the time variable being practically proportional to the inverse of the cube of the linear dimensions of the grain when other factors remain unaltered. In fact, the law of *Poiseulle-Darcy* applies to the flow of the interstitial water, and the similarity again obtains with sufficient accuracy as regards the time variables under temperature variations if viscosity is introduced into *Poiseulle-Darcy*'s law.

Since the size of the grains varies, as between clay and sand, in at least the proportion of one to a thousand, and since the time varies by at least a milliard to one, it follows that the phenomena may sometimes be compared by taking the unit of time for clay as a century and for certain sands as a second.

In actual fact the shape and arrangement of the grains plays an essential part in the matter and this compels the engineer to be very prudent in making comparisons; the order of magnitude of these numbers must, however, be borne in mind when it is desired to understand the phenomena, for the size of grain in the different soils varies at least in the proportion indicated above.

The interstitial water may perform very slow movements, and the phenomena which take place obey the laws of static equilibrium; it may, on the other hand, possess a velocity which is not negligible and may react upon the grain by reduction, in and consequence of viscosity. This is particularly the case when the currents of water between the grains are governed by external conditions of hydraulic pressure — whether, in any particular case, such conditions are continuous, periodic or irregularly variable. Foundation soils exposed to these accidental effects may remain stable during many years and then suddenly become subject to sliding movements which ruin the structures built on them.

Recently many accidents have come to light which are attributable partly to earthwork on land having been carried out in a particularly damp season and partly, in the case of maritime work, to waves of long period and amplitude.

Even where equilibrium in the slow seepage of the interstitial water may be regarded as due to nothing but the system of stresses operating, the ground will behave very differently in accordance with the duration of the load imposed upon it.

A permanent load, considered as being applied with zero velocity, will scarcely call into play any other forces than those of friction between the grains. In fact, most frequently the experimental data show that even clay ground acts as if it were a simple powdery material. On the other hand in this same ground a second load may bring only cohesive forces due to the interstitial water into operation, and the ground will then act as if it were a medium in which friction is nil and the shear resistance is fixed — a medium to which the author has applied the designation "semi-liquid", and of which the prototypes are to be found in chemically pure metals such as iron, copper, aluminium.

This is why, in a retaining wall, bridge abutment, or many other types of structure, the fields of stress due to permanent loads and super-loads act so differently from the point of view of the general stability. All these circumstances are now amenable to calculation by virtue of the experimental data on which they are based, and these must be faithfully followed if it is desired to construct an economical and durable work, no matter how complicated they may be.

Progress in this field depends essentially on the close understanding of a material which is undergoing physical and chemical development, and secondly it depends on experimental laws which are defined by accurate mathematical determinations of the equilibria that are mechanically possible in such media.

The remarkable practical results which have been obtained by directly applying the results of physical and mathematical study of these questions justifies the anticipation, very soon, of still greater progress. All that is necessary is to start from accurate experimental data, all defined in all their full complication, and not to simplify artificially the natural laws in an attempt to force them into a simple frame which shall be easy to express mathematically but which cannot reproduce the facts with sufficient faithfulness.

That is why the study of foundations depends to so great an extent on the laboratories, which alone can define all the experimental functions that relate together the numerous variables affecting the equilibrium of foundation soils. That is why, also, such study depends upon methods of boring so devised that true samples of geological strata in the physical condition actually encountered can be transmitted to the laboratories.