Investigations of the bearing capacity of foundations, earth pressure on walls, slope stability and others carried out on conventional models with real soil have an essential shortcoming: the stresses from the structure dead load are many times less than in nature. At the same time, as investigations show, the physical and mechanical properties of many soils (deformability, dilatancy, strength, etc.) change depending both on the magnitude and character of stresses and on the history of stresses. Therefore, model investigations with small loads produce only a qualitative picture of the phenomenon in most cases.

Broader opportunities are offered by the use of the method of centrifugal modeling which permits obtaining not only qualitative but also in many cases quantitative evaluations of the working conditions of a structure. The main virtue of the centrifugal modeling method is that stresses close to natural can be created in the model. This is of great importance in cases when the dead weight factor is determining for the operation of a structure (earth dams, retaining walls, soil slopes, etc.). Such investigations are being carried out in the research department of the S. Ya. Zhuk State Planning, Surveying, and Research Institute (Gidroproekt) on a large centrifugal stand which, technically is among the most modern machines. The maximum acceleration which can be created on this machine at a speed of rotation of 340 rpm is 322 g. The hydraulic system of the centrifuge allows filling the model with water and draining it during the experiment and transmitting an additional horizontal shearing force of up to 10 tons to the model by means of jacks.

The design of the centrifuge machine is shown in Fig. 1, its main elements being a rotating arm with two detachable carriages in which the investigated models are placed, a vertical shaft, lower support, reducing gear changing the direction of rotation, and a drive.

The carriages of the centrifuge weigh 800 kg each. Their inside dimensions, which determine the dimensions of the investigated model, are: length 900 mm, width 400 mm, and height 400 mm. The side walls of the carriages have glass planes for observing deformations of the model by means of television or motion-picture apparatus. Two hydraulic jacks producing horizontal shear in the model are installed in the end walls of the carriages.

Measurement System. The problem of transmitting information is most complex in investigations on the centrifuge. First, the measuring instrument located on the model is subjected to the same accelerations as the model and, second, the signal from the transmitter to the recorder passes through the rotating system of the current collector, creating additional varying errors in the circuit. Therefore, special measuring apparatus was developed in the research department for investigations in a centrifugal force field.

A special set of instruments was created for measuring deformations of the models. This set includes 12 two-component deformation sensors, amplification unit, switchboard, frequency meter, and digital printer. The deformation sensors, designed to operate at accelerations to 322 g, measure deformations of the model in two coordinates. The measurement range is 35 mm vertically and 20 mm horizontally, and the resolution is 0.01 mm. Paired converters of linear displacements and angles of rotation are the measuring elements of the sensors. The information is recorded on tape by a digital printer continuously or at specified time intervals.

The contact stresses along the foundation and on the back faces of the models were measured also in the experiments. Two types of sensors were used for this. The first type are aerostatic pressure sensors proposed by Prof. G. I. Pokrovskii [1]. Their distinguishing feature is their new, more reliable design. A shortcoming of sensors of this type is that they record only the maximum pressure values. The second type - a distance-type soil dynamometer - represents an improved pressure sensor from the set of the standard VI-6 vibratory measuring devices. These

METHOD OF CENTRIFUGAL MODELING IN INVESTIGATIONS OF HYDRAULIC STRUCTURES

Fig. 1. Centrifugal modeling machine. 1) Carriage; 2) arm; 3) reducing gear; 4) vertical shaft; 5) current collector; 6) electric motor.

Fig. 2. Failure of model of slope ($\alpha = 60^\circ$) of cohesionless soil. A coordinate grid is plotted on the model.

Fig. 3. Failure of a model of a slope ($\alpha = 90^\circ$) of a sand-clay mixture (90% sand, 10% clay). A coordinate grid is plotted on the model.

dynamometers permit determining the earth pressure on the model during the experiment. The diameter of the measuring part of the membrane of both types is 20 mm. In addition to this principal measuring device, in the experiments we also used water-level sensors, soil crack locators, and other special instruments and devices. A description and brief results of some investigations performed on the centrifugal modeling machine are presented below.

Investigation of Slope Stability. At present there exists a considerable number of theoretical methods of calculating slope stability. However, their experimental check by means of model investigations is difficult to accomplish. The experiments of D. Harroun in 1940 and of K. Terzaghi in 1941 on the stability of models of vertical slopes made of gelatin are well known. These experiments showed quite graphically the mechanism of disturbance of the stability of unsupported vertical cuts in cohesive soils.

Similar investigations, but with models of natural soils and at stresses in the slope close to the actual, were carried out on the centrifugal modeling machine. Models of homogeneous slopes located on a foundation of the same soil were investigated. The materials of the models were sand and clay mixtures with different values of $\varphi$ and $C$. The density and water content of the soil during placement and after the experiment were checked by taking soil samples.

The models were tested in a gradually increasing acceleration field. The stresses in the slope increased accordingly. Immediately after failure of the slope or appearance of an incipient crack the experiment was stopped. From the magnitude of acceleration reached by the time of failure we determined the critical height of a stable slope, and the form of failure and deformations of the coordinate grid were sketched.

The investigations showed that the character of failure of slopes of cohesive and cohesionless soils is different. In cohesionless soils failure occurs along plane surfaces, whereas in cohesive soils the surfaces of failure are curvilinear. Figures 2-4 show the most characteristic failures of the models.

Horizontal deformations are not observed in the slope of cohesionless soil before failure. Instantaneous failure of a part of the slope occurs upon reaching stresses corresponding to the critical height (Fig. 2). The relation of the critical height of a stable slope to the initial soil density is traced very clearly in the experiments.

Since the models were prepared from moist soil, the angles of the newly formed slopes after failure were rather steep (about 50°). This confirms the presence of "apparent" (in G. P. Tschebotarioff's terminology) cohesion in moist sand.