Experimental studies of the deformation properties of frozen soils under static and dynamic loads

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Abstract. The results of experimental studies of the deformation properties of sand of different water saturation are presented. The studies were conducted for frozen and unfrozen sand in static and dynamic loading conditions. The medium in all cases exhibits nonlinear properties. Dynamic strain diagrams were obtained using the Kolsky method in the split Hopkinson rod system. Static compression tests of sand were carried out in an elastic cage with registration of lateral pressure. The dynamic strain diagrams differ markedly from the static ones for both frozen sand and unfrozen sand. The level of stress in dynamic compression is much higher than in static. The diagrams of static deformation of frozen and unfrozen dry sand practically coincide. With increasing water saturation, the stress level for frozen and unfrozen sand increases.

1. Introduction

The study of the deformation properties of porous media is an important and urgent task. A significant amount of work on this topic is known in the scientific literature [1-5]. Under various temperature conditions, soils change their properties [6,7]. Experiments on the properties of frozen soils and ice under dynamic loading are the subject of [8-10]. In [11, 12], phenomenological models of ice deformation and destruction under dynamic loads were considered. Using these models, numerical results were obtained for solving a number of problems of explosive and shock loading of frozen media and ice [13-15]. In addition to various temperatures, humidity and soil composition, the loading mode and the strain rate have a significant effect on the deformation properties of soils. This paper presents the results of experimental studies of the deformation properties of sand of various water saturations. Frozen and unfrozen sands are tested under static and dynamic loading conditions.

2. Static experiments with various water saturation of sand

Compression of the soil in the static loading mode was carried out on the example of sand with the size of sand grains from 0.1 mm to 1 mm. Static soil compression was carried out on a Zwick/Roell Amsler HA100 servo-hydraulic machine with TestExpert II software. For the experiments, a snap was made. A thick-walled hollow cylinder with a diameter of 40 mm, a height of 40 mm, and a compression cylinder with a diameter of 39.9 mm and a height of 80 mm. Sand fell into a hollow cylinder and squeezed in a hydraulic machine. The initial layer thickness was 30 mm, compression was carried out up to 100 kN. Three types of soil were chosen for testing depending on water saturation: dry sand with a density of 1.75 g/cm^3, water saturated with 10% water with a density of 1.92 g/cm^3, water saturated with 18% water with a density of 2.06 g/cm^3. The percentage of water saturation was determined by the ratio of the mass of water to the mass of dry sand. The mass of dry sand in the equipment was 64 g. The sand was compressed with intermediate unloadings when the compressive forces of 30 kN, 70 kN and 100 kN were reached. According to the results of experiments, deformation curves were obtained for sands with different water saturations – Figure. 1. The unloading module in the tests ranged from 10 to 30 GPa. Deformation curves are nonlinear and irreversible.

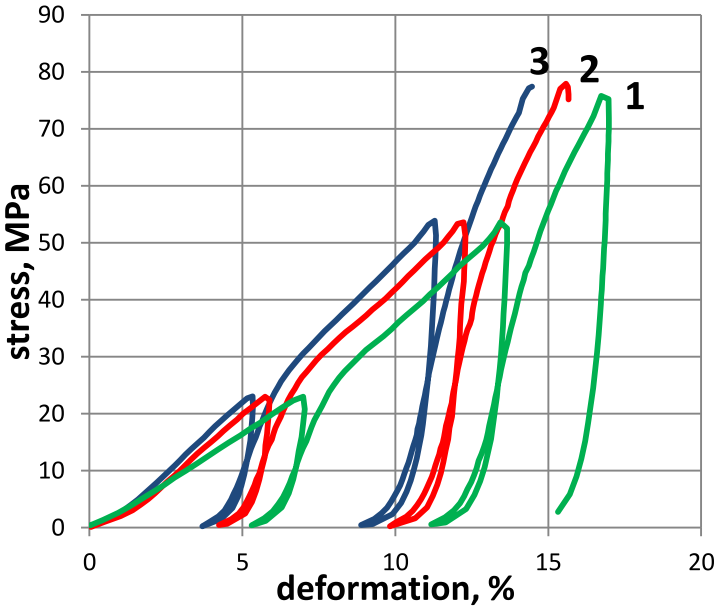

Figure 1. 1 is a curve of the deformation of dry sand, 2 – 10% of water-saturated sand, 3 – 18% of water-saturated sand.

3. Static experiments for various water saturation at a temperature of -18°C

In conditions of negative temperatures, soils change their deformation properties. With an increase in negative temperatures, they become much tougher due to the transformation of the water contained in them into ice. New stronger bonds between particles are formed. On the other hand, due to natural porosity, soils and in the frozen state can retain the difference in deformation properties in static and dynamic loading conditions. The identification of the properties of soil media at low temperatures is of great importance for evaluating their compressibility, fracture, and transfer of loads on structural elements. Of particular importance these studies are for structures interacting with soil in arctic conditions.

An experimental study of the properties of frozen soil was also carried out on the example of sand from 0.1 mm to 1 mm (size of grains of sand) and with the same water saturation values. Quasistatic soil compression was carried out on a Zwick/Roell Z100 servo-hydraulic machine, which is additionally equipped with a heating cabinet with a variable temperature from -150 to 600°C. Soil compression was carried out in an elastic cage with a measurement of lateral deformation. The lateral displacements of the cage during compression were measured with a LaserXtens laser extensometer with an accuracy of 1 micrometer. For the experiment, a snap was made. A hollow cylinder with an outer diameter of 30 mm, an inner diameter of 20 mm and a height of 50 mm, and a compression cylinder with a diameter of 19.9 mm and a height of 50 mm. The initial layer thickness was 30 mm, compression was carried out up to 100 kN. The manufactured samples were placed for 24 hours in a freezer with a temperature of -18°C. Based on the results of studies of frozen soils of various water saturation, strain diagrams were constructed. Dependences of lateral pressure on longitudinal pressure were constructed. Lateral pressure was determined using the relations for the displacements of the cylindrical elastic cage under the influence of internal pressure [16]. In Figure 2 shows the longitudinal compression deformation curves for three types of frozen soils (dry sand, 10% water-saturated sand, 18% water-saturated sand).

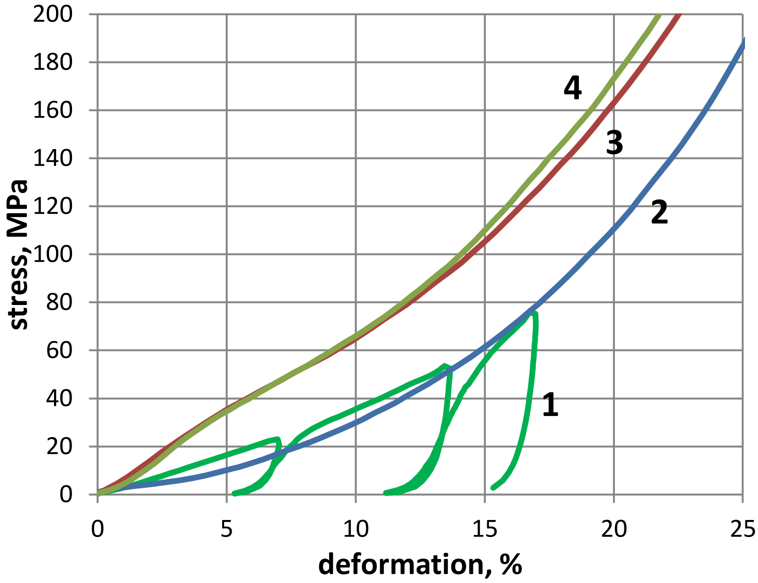

Figure 2. The curves of longitudinal soil compression: 1 – dry sand at a temperature of +20°C, 2 – dry sand at a temperature of -18°C, 3 – 10% water-saturated sand at a temperature of -18°C, 4 - 18% water-saturated sand at a temperature of -18°C.

In Figure 3 shows the dependence of the lateral pressure in the cage on the compression pressure. The deformation diagrams for frozen soils, as well as for non-frozen soils, are nonlinear and irreversible. For dry soils, the deformation diagrams in the frozen and unfrozen state practically coincide without exceeding the experimental errors. Lateral pressure measurements show significant non-physical oscillations at the stage of small displacements of the elastic cage. Further, shelves are formed that reflect the actual behavior of the lateral pressure Figure 3. The range of changes in its relationship to longitudinal stress for all types of soils from 0.6 to 0.7.

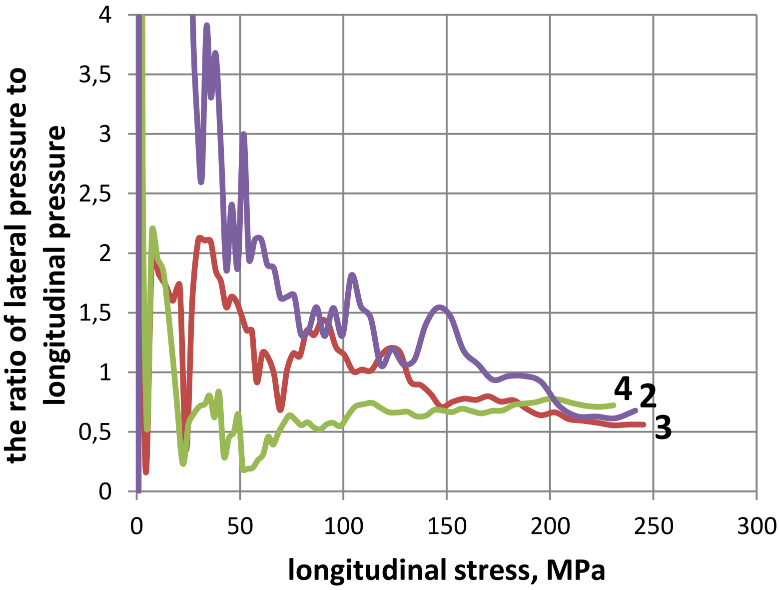

Figure 3. The ratio of lateral pressure in the cage to the compression pressure depending on the longitudinal compression stress

4. Dynamics of frozen and unfrozen soils

To compare static experiments with dynamic ones in Figure 4 compares these curves for 10% water-saturated sand (the upper curve is dynamic, the lower curve is static). A dynamic strain diagram was obtained by the authors of [17] using the Kolsky method [18, 19]. Soil samples for dynamic tests were made in the same way as for static ones. The results of static and dynamic compression are different. The level of deformation during dynamic compression is somewhat lower.

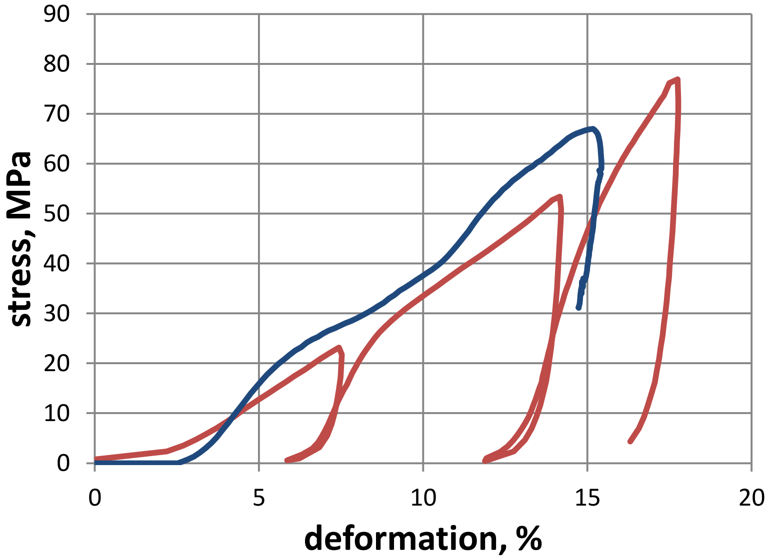

Figure 4. Comparison of static and dynamic strain curves

A consolidated graph of the tests of frozen and unfrozen soils under dynamic loading is shown in Figure 5. In dynamic tests, the presence of a liquid increases the pressure level at the same deformations. In the frozen state, water-saturated soils also significantly increase the resistance of the medium to compression. A large difference in the deformation curves during loading and unloading is preserved.

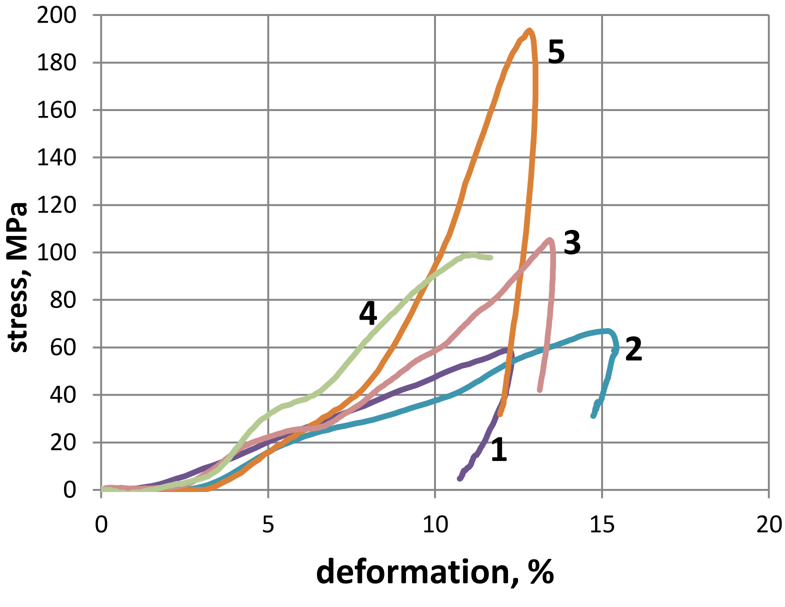

Figure 5. The curves of deformation of frozen and unfrozen soils at different water saturations: 1 – dry sand; 2, 3 – non-frozen soils with water saturation of 10% and 18%; 4,5 – frozen soils with a water saturation of 10% and 18%.

5. Conclusion

The experimental studies of the deformation properties of sand of various water saturations in frozen and non-frozen state showed:

- Non-linear dynamic diagrams of deformation significantly differ from static ones both for frozen sand with various water saturations and for non-frozen.
- Stress level during dynamic compression is much higher than under static (with identical deformations).
- Diagrams of static deformation of frozen and unfrozen dry sand coincide.
- With increasing water saturation, the stress level for frozen and unfrozen sand increases with the same deformations.

The performed studies can be used to equip elastoplastic models of soil deformation as porous media under static and dynamic loading conditions [20].

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Notification
Amsler HA100 – is a Zwick/Roell Test Machine Model
TestExpert II – is Zwick/Roell software from which the test machine is controlled and experimental data is recorded

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