UDC 539.3 DOI: 10.32326/1814-9146-2019-81-4-443-448

DYNAMIC TESTS OF FROZEN SAND SOILS*

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Received by the Editor 02.08.2019

The study of the laws of contact interaction of hard and deformable impactors with frozen soils is of great scientific and applied value. In solving such problems, numerical methods are widely used. For numerically modeling the behavior of frozen soil under dynamic loading, it is necessary to use models of soil media that adequately describe their behavior at various negative temperatures, humidities and strain rates. To identify the parameters of these models, experimental studies are required for determining dynamic properties of soils at low temperatures.

The paper presents the results of experimental studies of dynamic deformation of samples of frozen sand with humidities of 10% and 18%. Compression experiments were conducted using a stand implementing the Kolsky method. Deformation curves of frozen sand at a temperature of −18 °C were obtained under uniaxial stress conditions at various strain rates in the range of 400–2500 s^{-1}. Diagrams of strength of frozen sand under uniaxial compression as a function of strain rate are constructed. The diagrams are linear for samples of different humidity in the studied range of strain rates. Maximum stresses in frozen water-saturated sand are higher than those in frozen sand of 10% humidity. With increasing strain rate, compressive strength of water-saturated sand grows faster than that of sand with a moisture content of 10%: at a strain rate of about 500 s^{-1}, the stresses in frozen water-saturated sand, at which the samples fail, are 1.5 times higher than those in the frozen sand with a moisture content of 10%, and at a strain rate of 2500 s^{-1} they are 3 times as high.

Keywords: frozen sand, uniaxial compression, strain rate, strength, Kolsky method.

Introduction

The behavior of frozen soils under pressures not exceeding 20 MPa and strain rates of up to 10^{-2} s^{-1} are well enough studied in experiments with uniaxial and triaxial compression in [1–6]. Higher strain rates, of about 10^2–10^3 s^{-1}, are implemented in experiments using the split Hopkinson pressure bar (SHPB) system [2, 7–12], where deformation diagrams for frozen soils (sand and clay) at temperatures up to −28 °C were obtained. The experimental data is used for equipping mathematical models of elastoplastic behavior of soils with

* The work was done with financial support from RFBR (grant 19-08-00977 a).

various approximations of yield surface and failure [4–12] as a function of strain rate, test temperature etc. The development of such models is necessary for the numerical solution of problems of impact interaction with frozen soils [2, 13]. However, the wide variety of frozen soil media differing in their granulometric content, density, content of frozen and liquid water and temperatures calls for conducting a large number of experimental investigations to study the effect of those factors on the dynamic properties of frozen soils.

The experimental setup

Soft soils were dynamically tested using an experimental stand implementing the Kolsky method [14–17], that included a 20 mm-caliber gas gun, a complex of measuring and registering tools and a set of 20mm-diameter split Hopkinson pressure bars of 1500-mm long each for compression tests, made of aluminum alloy D16T.

The set was modified for tests at temperatures below 0 °C. A special chamber of foam plastic contained a specimen and the ends of pressure bars adjoining it. The chamber was cooled with vaporized liquid nitrogen for several minutes to bring the temperature of the ends of the pressure bars and of the specimen down to −18 °C (Fig. 1). The temperature at the ends of the pressure bars was registered with a thermocouple.

a)

b)

Fig. 1. General view of the stand for testing frozen soils (*a*) and of a frozen soil specimen (*b*)

To dynamically test frozen soils, specimens in the form of 10mm high and 16mm-diameter cylinders were made of sand with the water content of 10% and 18% of the mass of the sand. The specimens were prepared using drinking water. Sand with the water content of 18% was practically fully saturated with water. The specimens were made of a natural sandy mixture, sifted to remove particles bigger than 1 mm and smaller than 0.1 mm. The granulometric content of the sand was similar to that used in papers [18–20]. The density of the sand was 1750 kg/m^3. The specimens were made by using special cylindrical cartridges. Sand of required humidity was poured into a cartridge and compacted up to a density of about 1920 kg/m^3 for the sand of 10% humidity and 2050 kg/m^3 for the sand of 18% humidity. Then the specimens were frozen in a freezing chamber for 24 hours at a temperature of −18 °C. After that, the specimens were removed from their cartridges and held at a temperature of −18 °C for 24 hours more.

The experimental results

More than sixty experiments were done with sand of different humidities at a temperature of −18 °C. Strain rate in the experiments varied from 400 to 2600 s^{-1}. Characteristic deformation diagrams for sand of different humidities are presented in Fig. 2. It can be seen that the strain rate in the experiment remains practically constant. The initial parts of the stress-strain curves are close to linear. The stresses reach their maximum at a deformation of 3–3.5%, followed by an abrupt drop of stresses with increasing strains, testifying to failure of the soil specimens. Such behaviour is similar to those of rocks and concretes, as well as of ice [17] under uniaxial compression. The maximal stress attained in the experiments was taken as strength. It is noted that for the sand of 10% humidity maximal stresses are considerably lower than that of the water-saturated sand. Thus, it can be concluded that compression strength of frozen sand increases with its humidity. Evidently, it is connected with the increased content of ice that binds sand particles and the decreased free pore space. A similar phenomenon was observed for sand with a different granulometric content and density [9].

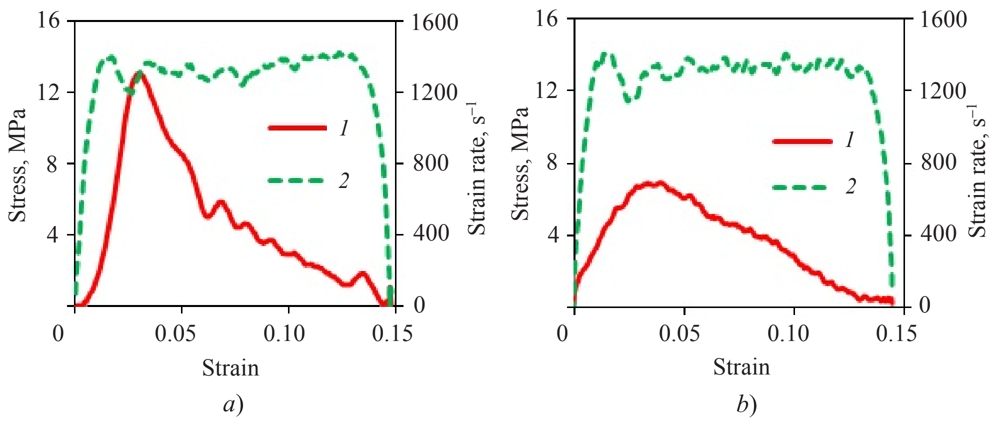

Fig. 2. Characteristic curves of axial stress and strain rate as a function of strain for water-saturated sand (*a*) and sand with 10% humidity (*b*), *1* – stress, *2* – strain rate

Diagrams of strength as a function of strain rate are shown in Fig. 3.

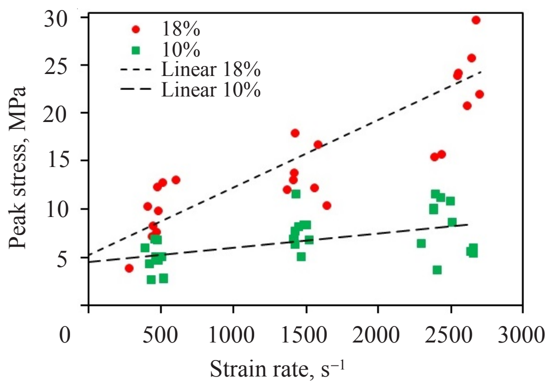

Fig. 3. Strength as a function of strain rate for uniaxial compression of frozen sands of different humidities (18% and 10%)

Noticeable scatter is observed in the experimental data for both types of specimens tested in similar conditions. The character of the deformation diagrams in the experiments with similar conditions does not change, while the maximal stresses can differ up to 2–3 times.

Compression strength grows with strain rate in the specimens of water-saturated sand and the sand of 10% humidity. Similar results were obtained in the strain-rate range of 400–1000 s^{-1} for sand with different granulometric composition and density [9].

The compression strength increases constantly with linear rising strain rates in the studied strain rate range 400–2600 s^{-1} for the sands with different humidity. A similar type of relations is also characteristic for freshwater ice [17]. For all the experimentally realized strain rates, maximal stresses in frozen water-saturated sand are higher than those in frozen sand of 10% humidity. In water-saturated sand, compression strength grows with strain rate faster than in the sand of 10% humidity: at a strain rate of about 500 s^{-1}, stresses in the frozen water-saturated sand, at which specimens fail, are 1.5 times higher than those in the frozen sand of 10% humidity, and at a strain rate of 2500 s^{-1} they are 3 times as high.

Conclusion

As a result of dynamic tests of specimens of frozen sand with different humidity (10% and 18%) it is found that uniaxial compression strength increases with the strain rate and humidity of the specimens.

References

1. Tsytovich N.A. *The Mechanics of Frozen Ground*. Washington, D.C. Scripta Book Company. 1975. 426 p.

2. Lee M.Y., Fossum A., Costin L.S., Bronowski D. Frozen soil material testing and constitutive modeling. Sandia Report Sand 2002-0524. *Sandia National Laboratories*. Albuquerque. New Mexico. March. 2002. 67 p.

3. Zhang S., Lai Y., Sun Z., Gao Z. Volumetric strain and strength behavior of frozen soils under confinement. *Cold Regions Science and Technology*. 2007. Vol. 47. P. 263–270.

4. Yuanming L., Long J., Xiaoxiao C. Yield criterion and elasto-plastic damage constitutive model for frozen sandy soil. *International Journal of Plasticity*. 2009. Vol. 25. P. 1177–1205.

5. Yang Y., Lai Y., Li J. Laboratory investigation on the strength characteristic of frozen sand considering effect of confining pressure. *Cold Regions Science and Technology.* 2010. Vol. 60. P. 245–250.

6. Du H., Ma W., Zhang S., Zhou Z., Liu E. Strength properties of ice-rich frozen silty sands under uniaxial compression for a wide range of strain rates and moisture contents. *Cold Regions Science and Technology*. 2016. Vol. 123. P. 107–113.

7. Ma Q.-Y. Experimental analysis of dynamic mechanical properties for artificially frozen clay by the split Hopkinson pressure bar. *Journal of Applied Mechanics and Technical Physics*. 2010. Vol. 51. No 3. P. 448–452.

8. Xie Q., Zhu Z., Kang G. Dynamic stress-strain behavior of frozen soil: Experiments and modeling. *Cold Regions Science and Technology*. 2014. Vol. 106-107. P. 153–160.

9. Zhu Z., Kang G., Ma Y., Xie Q., Zhang D., Ning J. Temperature damage and constitutive model of frozen soil under dynamic loading. *Mechanics of Materials*. 2016. Vol. 102. P. 108–116.

10. Zhang F., Zhu Z., Fu T., Jia J. Damage mechanism and dynamic constitutive model of frozen soil under uniaxial impact loading. *Mechanics of Materials.* 2019. Vol. 140. P. 103217.

11. Fu T., Zhu Z., Zhang D., Liu Z., Xie Q. Research on damage viscoelastic dynamic constitutive model of frozen soil. *Cold Regions Science and Technology*. 2019. Vol. 160. P. 209–221.

12. Yang R., Lemarchand E., Fen-Chong T. , Azouni A. A micromechanics model for partial freezing in porous media. *International Journal of Solids and Structures*. 2015. Vol. 75-76. P. 109–121.

13. Bragov A.M., Balandin V.V., Kotov V.L., Balandin Vl.Vl., Linnik E.Yu. Experimental study of the impact and penetration of a cone in frozen sand. *Journal of Applied Mechanics and Technical Physics*. 2018. Vol. 59. Iss. 3. P. 482–490. https://doi.org/10.1134/S0021894418030124.

14. Bragov A.M., Grushevsky G.M., Lomunov A.K., Sergeichev I.V., Proud W. Studying the dynamic compressibility of dry sand in the range of loading amplitudes of up to several GPa. *Problemys of Strength and Plasticity*. 2006. Iss. 68. P. 221–228 (In Russian).

Брагов А.М., Грушевский Г.М., Ломунов А.К., Сергеичев И.В., Прауд У. Исследование динамической сжимаемости сухого песка в диапазоне амплитуд нагрузок до нескольких гигапаскалей. *Проблемы прочности и пластичности*. 2006. Вып. 68. С. 221–228.

15. Bragov A.M., Konstantinov A.Yu., Lomunov A.K. Determining dynamic friction using a modified Kolsky method. *Technical Physics Letters*. 2008. Vol. 34. No 5. P. 439–440.

16. Bragov A., Lomunov A. Methodological aspects of studying dynamic material properties using the Kolsky method. *International Journal of Impact Engineering*. 1995. Vol. 16. No 2. P. 321–330.

17. Bragov A., Igumnov L., Konstantinov A., Lomunov A., Filippov A., Shmotin Yu., Didenko R., Krundaeva A. Investigation of strength properties of freshwater ice. *EPJ Web of Conferences*. 2015. Vol. 94. P. 01070. https://doi.org/10.1051/epjconf/20159401070.

18. Balandin V.V., Balandin Vl.Vl., Bragov A.M., Kotov V.L. Experimental study of the dynamics of penetration of a solid body into a soil medium. *Technical Physics.* 2016. Vol. 61. Iss. 6. P. 860–868. https://doi.org/10.1134/S1063784216060037.

19. Kotov V.L., Balandin V.V., Bragov A.M. Balandin Vl.Vl. Quasi-steady motion of a solid in a loose soil with developed cavitation. *Doklady Physics.* 2013. Vol. 58. Iss. 7. P. 309–313. https://doi.org/10.1134/S1028335813070094.

20. Bragov A.M., Balandin V.V., Igumnov L.A., Kotov V.L., Kruszka L., Lomunov A.K. Impact and penetration of cylindrical bodies into dry and water-saturated sand. *International Journal of Impact Engineering*. 2018. Vol. 122. P. 197–208. DOI: 10.1016/j.ijimpeng.2018.08.012.

ДИНАМИЧЕСКИЕ ИСПЫТАНИЯ ЗАМОРОЖЕННОГО ПЕСЧАНОГО ГРУНТА*

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Исследование закономерностей контактного взаимодействия жестких и деформируемых ударников с мерзлыми грунтами имеет важное научное и прикладное значение. При решении подобных задач широкое применение находят численные методы. Для численного моделирования поведения замороженного грунта под действием динамических нагрузок необходимо использование моделей грунтовых сред, адекватно описывающих их поведение при различных отрицательных температурах, влажностях и скоростях деформации. Для идентификации параметров моделей необходимо проведение экспериментальных исследований для определения динамических свойств грунтов при отрицательных температурах.

Приведены результаты экспериментальных исследований динамического деформирования образцов из замороженного песка влажностью 10 и 18%. Эксперименты на сжатие проводились на установке, реализующей метод Кольского. Получены кривые деформирования мерзлого песка при температуре -18 °С в условиях одноосного напряжения при различных скоростях деформации в диапазоне 400–2500 $с^{-1}$. Построены зависимости предела проч-

* Выполнено при финансовой поддержке РФФИ (грант №08-00977 а).

ности мерзлого песка при одноосном сжатии от скорости деформации. Эти зависимости в исследованном диапазоне скоростей деформации линейны для образцов различной влажности. Максимальные напряжения в мерзлом водонасыщенном песке превышают максимальные напряжения в замороженном песке 10%-ной влажности. С ростом скорости деформации предел прочности на сжатие для водонасыщенного песка растет сильнее, чем для песка влажностью 10%: при скорости деформации около 500 $с^{-1}$ напряжения в мерзлом водонасыщенном песке, при которых происходит разрушение образцов, превышают аналогичные напряжения в замороженном песке с влажностью 10% в 1,5 раза, а при скорости деформации 2500 $с^{-1}$ – в 3 раза.

Ключевые слова: мерзлый песок, одноосное сжатие, скорость деформации, прочность, метод Кольского.