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Force chains in granular media and ultrasound impulse propagation in sand specimen under load

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An analysis of the pattern of stress chains in dense and loose sand and velocity of ultrasound impulse propagation in quartz sand under loading explains the mechanisms by which granular materials, such as loose and dense sand, respond to external loads. Experiments were carried out in pure marine quartz sand under load in a triaxial test camera.

Keywords: Granular media, dilatancy, nonlinear acoustics, ultrasound propagation.

INTRODUCTION

Granular materials are in the centre of attention of various researchers now. Parallel to that, there is research of the pattern formation, densification and fluidization in granular media by vibration [1], of the distribution of static and dynamic load [2, 3, 4, 5, 6] in granular media, studies of nonlinear elastic properties and propagation of elastic waves in granular media [7, 8, 9]. Photo-elastic discs are used to study the force networks within vertically confined loose and dense granular materials under static [2] and dynamic [3] loading. In granular materials [4], force is rarely transmitted uniformly, but rather along network-forming force chains – often next to the areas where there is little or no force. The only origin of quartz sand is the cracked crystal of quartz, fractured into domains, which are approximately similar size, which comprises a whole massif due to cohesion. It is shown that granular packing gives a significant contribution in the understanding of the mechanics of tectonic faults. The similarity of nonlinear properties in the response of fractals and of quartz sand is observed in nonlinear geophysics.

The goal of this research is to analyse the role of dilatancy in chain forming in loose and dense pure fine grained (0.06 – 0.2) mm and medium-grained (0.2 – 0.6) mm marine quartz sand under triaxial load.

DILATANCY OF GRANULAR MATERIALS

The phenomenon known as dilatancy, as consequence of repacking of contacting disks, goes as far back as Reynolds [5]. Dilatancy [6] is the property of granular materials to increase in bulk volume, if the density is higher, and decrease in bulk volume, if the density is lower, when placed under shear load. At the micro level, dilatancy can be explained by repacking of particles from dense condition to a less dense condition, dilatancy coefficient

$\Lambda>0$, and by repacking from loose condition to more dense, $\Lambda<0$. So dilatancy in sandy soils occurs. The sign of dilatancy depends on density of sandy soil. The density at which dilatancy changes its sign is referred to as critical density (ρ_{crit}).

An analysis of the pattern of stress chains in dense and loose sand [4, 5] and velocity of ultrasound impulse propagation in this load-bearing sand will clarify the mechanisms by which granular materials respond to external loads.

Some problems are discussed in triaxial test of sand using ultrasound testing [9].

EXPERIMENTAL CONFIGURATION

Experiments have been carried out using a triaxial testing device with step-by-step loading. Ultrasound research non-destructive testing (NDT) unit DUK-20 served as a source of acoustic impulses and as an indicator of incoming signal (Figure 1a). Its generator generates an impulse of adjustable amplitude up to 1 kV. The diameter of the sand sample was 40 mm, its height – 80 mm, Figure 1b (1). Plane-wave generating and detecting piezoelectric ceramic transducers with 10 mm diameter and resonant frequency 46 kHz were placed on an axis at the top and bottom of a cylindrical container in direct contact with the polished Plexiglas surface. Figure 1c shows the top (load cylinder) and bottom (table) of the triaxial test camera with built-in transducers. The velocity of longitudinal waves is determined using the time of propagation of a signal in view of change in the height of the sample. The method and devices allow defining Vp with an error margin of 2%.

TEST PROCEDURE

Test always starts in loose sand and finishes in dense sand. The test procedure consisted of the following. From the moment of loose sand sample placement in the test chamber, lateral pressure and the axial pressure equal to the weight of the loading piston ($\sigma3=\sigma1$) are applied. The test is drained; filtration takes place in the atmosphere. Then the sample was loaded step-by-step. The loading step was 25 kPa.

As a rule, Vp measurements were done at the moment when deformations stop. It is known that the approach of a limiting condition (destruction of the sample) at step-by-step loading is defined using the loading step with non-attenuated deformation. If measurements of propagation time are made every minute, the Vp1 curve looks like line with points, Figures 2, 3. Deformations are stabilised in 5 minutes after the application of step-by-step load. In loose sand, in the specimen before testing, many contacts between grains are still open. When placed in the testing camera from the moment of putting the sample in the camera, the lateral pressure and the axial pressure equal to the weight of the loading piston act simultaneously. First a Vp measurement is made. Applying the vertical load step 25 kPa, vertical deformations are observed using the values measured by the deformation meter. The measurement of the next V2 is made after the attenuation of deformations – for sand it takes 5 minutes after loading. The line V2 shows the propagation velocity at the moment of the next loading, when the deformations are stabilised. If measurements are made every one minute, the curve of Vp constantly looks like that V1 in Figures 2, 3. If the measurements of the propagation time are made at the moment of stabilisation, before the next loading, the velocity curve smoothly increases to the maximum load – see the V2 curve in Figures 2, 3.

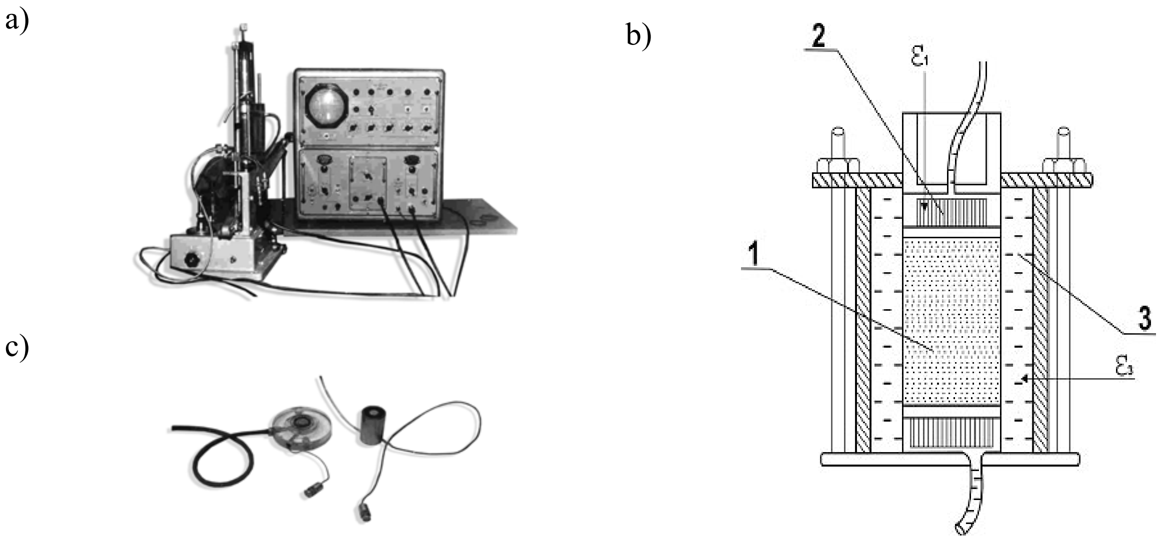

Figure 1. Triaxial testing device and ultrasound NDT unit DUK-20 were used in experiments (a), (b) – stress camera. Plane-wave generating and detecting transducers (c), (diameter 10 mm) were placed on the axis at the top and bottom of the cylindrical container in direct contact 2, with the polished Plexiglas surface, with sand specimen 1 placed in rubber. 3 – water in camera around the specimen for lateral pressure creation, ε_1 – vertical deformation and ε_3 – radial deformation. The transducer diameter was equal to ¼ of the specimen diameter (c). It provided the emission of an ultrasonic signal in the soil specimen only. Filtration from end faces of the sample around the transducers is open

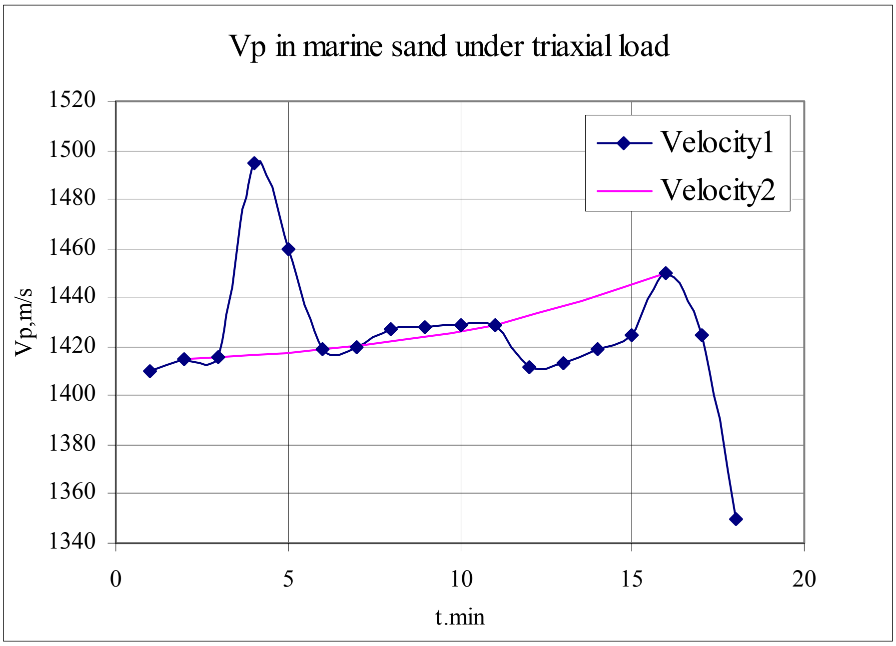

Figure 2. Ultrasound impulse propagation velocity Vp in fine grained (0.06 – 0.2) mm marine quartz sand under triaxial load. The moments of deformation stabilisation and application of the next loading step 25 kPa are the 1-st, 6-th, 11-th and 16-th min. If the measurements of the propagation time and vertical deformations of sample are made after stabilisation, before the next loading step, the curve of V2 smoothly increases. By the 11-th minute, the sand reaches the critical density, by the 16th minute the destruction of the sample took place

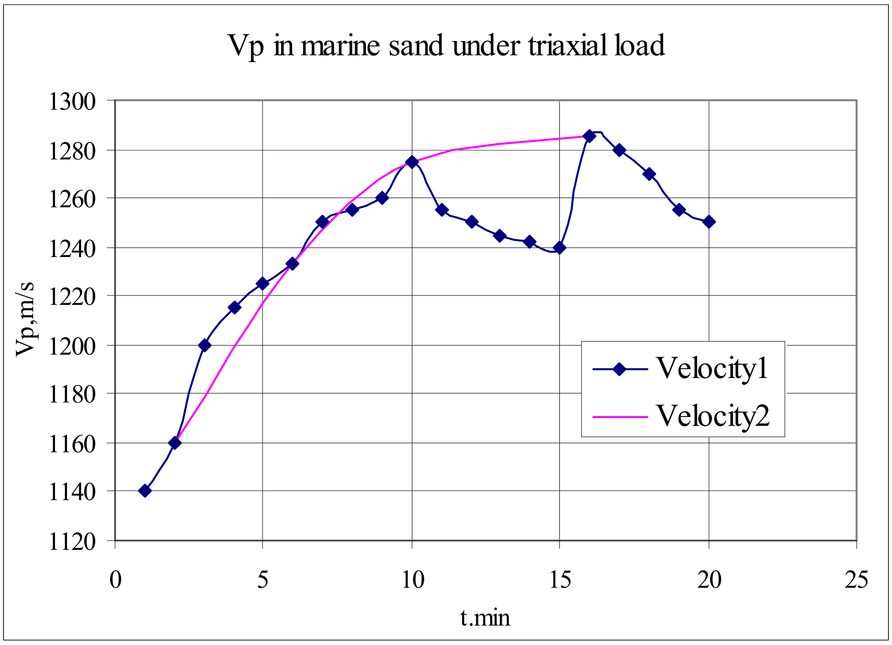

Figure 3. Ultrasound impulse propagation velocity Vp in medium-grained (0.2 – 0.6) mm marine quartz sand under triaxial load. If the measurements are made every minute, the curve looks like the V1 curve for water-saturated sand. The 1-st, 6-th, 10-th and 16-th min are the moments of loading using the step 25 kPa. If the measurements of the propagation time are made at the moment of stabilisation, the V2 curve smoothly goes up. By the 8-th minute of testing the specimen reaches the critical density, and the bend of V1 changes the sign

CONCLUSIONS

1. Elastic wave propagation velocity in pure marine quartz sand during triaxial tests with step-by-step loading has demonstrated that the response of the material appear primarily in the force chains than in the entire volume. Loading and sounding directions coincide.
2. Do of dilatance, the loaded force chains in dense sand collapse at deformations with less density, the loaded force chains in friable sand collapse at deformations with heightened density.
3. Force chains in loose sand under a certain loading step display heightened density until $\rho < \rho_{crit}$ is reached that is higher than the bulk density at the stabilisation moment.
4. Force chains in dense sand under a certain loading step, from $\rho > \rho_{crit}$ are formed by deformations with the density that is lower than the bulk density at the stabilisation moment. From the moment of reaching the critical density, force chains in the transient process of load stabilisation become less dense compared to the volumetric density. By the moment of stabilization of deformations from increasing load, the

average density has increased that is reflected in the value of Vp measured in the stable state.

5. The well-known in geophysics phenomena of Vp lowering in places of earth crust some time before an earthquake is well modeled in sands: under the load step immediately before destruction in dense sand the decrease in Vp is observed, see Fig. 2, 3.
6. Dilatancy of loose sand under loading occurs, resulting in the compaction during shear deformation and formation of the dense chains of loading.
7. Dilatancy of dense sand occurs in the same loaded chains, but density in chains goes down by deformation. Vp in the load stabilisation process of dense sands goes down.
8. This phenomenon is observed only in the transient process of load stabilization by testing loose sand in the triaxial testing camera. If Vp measurements are made only after load stabilisation, odder sounding direction is perpendicular to loading, phenomenon is not observed.

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