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Impact and penetration of cylindrical bodies into dry and water-saturated sand

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ABSTRACT

New results of the experimental-theoretical and numerical analysis of the dynamic behavior of dry and water-saturated sand, impacted and penetrated by cylindrical strikers at the velocities from 50 to 450 m/s, are presented. Forces resisting penetration dependences into soil are determined using the inverse experiment technique, in which a container with sand impacts the end of a measuring bar with flat, hemispheric and conic heads. Based on the experimental-computational analysis of maximal and quasi-stationary values of the force resisting penetration of a flat-ended striker, parameters of dynamic compressibility and resistance to shear of compacted water-saturated sand are found. Using the obtained data the parameters of the Grigoryan's model were determined (identified), with the help of which numerical calculations of the resistance to penetration of impactors into the soil in an axisymmetric formulation of the mechanics of continuous media were carried out. It is shown that the identified mathematical model and the results of the computational experiment are in good agreement with the experimental data. It is found that, when compacted sand is practically fully water-saturated, its shearing properties degrade but remain substantial in the practically important range of impact interaction velocities.

1. Introduction

Determining contact forces and accelerations arising when a striker interacts with a target are the most important tasks of impact dynamics. A special role in solving such problems is played by experimental methods, which can be subdivided into two groups: direct and inverse ones [1]. In direct experiments, an accelerated striker interacts with a stationary target. In inverse one, the striker is stationary (at least at the initial moment) and is impacted with an obstacle made of the material under study, accelerated up to a required velocity.

Studying high-velocity penetration of solids into soil media is a complex task involving a wide variety of their physical-mechanical properties. Sand is one of the most common and well-studied soil media [1]. However, impact interaction of solid bodies with sand obstacles has not been sufficiently well studied experimentally. Allen et al. [2,3] in 1957 pioneered wide-range investigations in this field. They used sand box to study penetration of cylindrical conic-headed strikers into dry sand at the velocities from 700 to 800 m/s and to determine parameters of Poncelet (Resal) equation of motion. A coefficient of resistance to penetration was determined by using x-ray filming in [4,5] where results of direct experiments with cylindrical strikers for the velocities of 80–460 m/s were also presented.

Processes of cavitation were studied in direct tests [6], using brass cylinders and copper spheres striking against a sand target. The motion velocities of sand particles were determined by using the high-speed photography coupled with a particle image velocimetry technique. The piezoelectric sensors located in the target body made it possible to measure the stresses inside the sand in the container.

Stresses arising in the sand target due to the impact and penetration of a steel cylinder with a hemispherical head were also determined in [7]. In [8], the numerical speckle-radiography method was used to register displacements of sand particles, taking place in the target when being struck by a cylinder, an ogive or a semi-sphere at a velocity of around 200 m/s. Based on the results of x-ray filming of the penetration process, a time-history of the penetration depth was also determined.

A considerable number of works tackle the issue of determining final penetration depth [9–12]. Results of measuring final depths of the penetration of steel spheres into dry sand are available in the literature [9] where it is shown that the compaction of dry sandy soil leads to a significant change in penetration depths of strikers. Based on the

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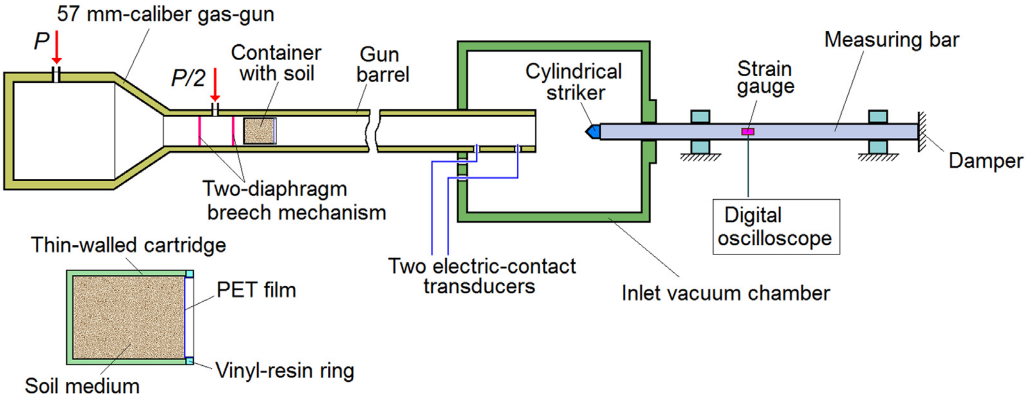

Fig. 1. Schematic representation of the setup for measuring forces resisting penetration in the inverse experiment.

results, characteristic threshold intervals of the variation of penetration depth as a function of impact velocity were found, the presence of which was connected with the sound velocity in sand (~120 m/s). In earlier experiments the existence of a threshold velocity ~ 100 m/s was also found, at which the resistance force shows a discontinuity connected, in the opinion of the authors of [2], with the transfer from quasi-elastic to inelastic deformation of sand particles.

In [10], penetration of a steel disk into sand in the velocity range of 150–1200 m/s was studied, and time histories of penetration depth were obtained, as well as final penetration depths and pressure over the container walls. In [11], a series of experiments on the penetration of strikers of various geometries (spherical, cylindrical, ogive) into dry sand at the impact velocities of 850–3000 m/s was conducted. In the experiments, a critical impact velocity, after which the final penetration depth decreases as a result of plastic deformation of the striker, was determined. Final depths of penetration into sand of cylindrical flat-ended and hemispheric-headed strikers were monitored [12].

In [13] ballistic limit in the penetration of a dry sand layer with various compaction range by strikers with different heads were determined experimentally. A weak dependence of the ballistic limit on the initial density of sand, varying in the range of 1530–1673 kg/m^3 was obtained.

In order to understand the fundamental problem of penetration of strikers into partially water-saturated sand at a mesoscale level, x-ray and neutron CAT methods have been used [14], which allow to accurately visualize the penetration process, the formation of cavities and water distribution in the head of a striker.

In direct experiments, displacements of the striker are registered using the frame-target method [2,3] and its modifications [4,5,10], rapid camera and x-ray filming [4–6,8,10,14]. Integral loads acting on strikers of various geometries at the quasi-stationary penetration stage are determined using time histories of penetration depth and Poncelet or Resal type equations of motion [2,5,15]. However, these methods do not make it possible to reliably determine force characteristics at the initial non-stationary stage and, as shown in [10], do not account for the effect of the soil container walls on integral loads and final penetration depths.

To measure the velocity of the striker in the process of penetration, interferometric methods in direct [16] and inverse experiments [17] are used. These methods are rather complex, though highly accurate in measuring displacement velocity. However, to determine integral loading, differentiation of the obtained time histories of penetration velocity is necessary, which can lead to considerably growing inaccuracies.

To measure forces acting on a solid body at an initial stage of penetration in both direct and inversed experiments, accelerometers located on moving strikers are conventionally used [15,17]. It is noteworthy that in direct experiments at impact velocities of more than 100 m/s it is difficult to provide reliable registration of signals from transducers.

The technique of measuring accelerations in inverse experiments is free from this drawback: in this setup the striker with the accelerometer is stationary at least at the initial moment. A disadvantage of the inverse techniques [16,18] is the necessity to accelerate soil containers of considerable mass and small geometric dimensions, allowing reliable registration of the nonstationary phase of the indentation and a relatively short time interval of the quasi-stationary phase.

It can be noted that in the experimental studies of impact processes of solids with soil targets, the final penetration depth [9–12], depending on impact velocity, the current penetration depth [2–5,8] and time history of penetration velocity [12,16,17] are registered most often. The direct measurement of the resistance forces (acceleration) of the striker [15,17] in soft soil is less studied. The results of researches of resistance forces to penetration in water saturated soils are practically absent.

This paper presents new experimental data on the resistance forces to penetration of strikers into dry and water-saturated sand, the results of mathematical modeling and computer simulation of the penetration of rigid cylindrical strikers into sandy soil with different moisture contents.

2. Dynamic tests of soils in an inverse experiment

2.1. The inverse experiment technique using the measuring bars

The methodology of measuring the force resisting penetration of a striker into sand using a measuring bar [18,19] is schematically shown in Fig. 1.

A container filled with soil (sand) is accelerated up to required velocities and impacted against a stationary striker fixed on a measuring bar. The impact velocity and the material properties are to be such that no plastic strains should occur in the bar. An elastic strain pulse $\varepsilon(t)$ is formed in the bar. Registering this pulse on the surface of the bar makes it possible to determine force F, acting on the striker upon its interaction with the medium, according to the known relation $F(t) = E\varepsilon(t)S_0$, where E is elastic modulus of the bar, S_0 is its cross-section area. Thus, in this method, the task of measuring the forces is considerably simplified and reduced to registering an elastic strain pulse in the bar, using strain gages. The setup implementing this method is schematically depicted in Fig. 1. In the present version of the inverse experiment, a soil container is accelerated using a 57 mm-caliber gas-gun with a two-diaphragm breech mechanism, which makes it possible to provide stable and readily controlled impact velocities in the range of 50–500 m/s, using air compressed up to 15 MPa, and up to ~1000 m/s, when using compressed helium.

The container is a thin-walled cartridge, filled with soil medium. To prevent the soil from spilling in the process of preparation of the experiment and during acceleration of the container, the front end of the