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An experimental study of high strain-rate properties of clay under high consolidation stress

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ABSTRACT

A split Hopkinson pressure bar (SHPB) combined with high pressure consolidation apparatus and high speed camera was used to obtain dynamic compressive stress-strain curves of clay whose over consolidation stress state in the process of formation was properly considered. The stress-strain relationship at various high strain rates from 60 s^{-1} to 600 s^{-1} was obtained. The strain rate and degree of consolidation effects on the compressive response of the consolidated clay were determined. The results show that the dynamic mechanical properties of clay in high pressure consolidation is sensitive to strain rate, and parameters like dynamic strength, failure strain and so on are significantly improved compared with unconsolidated clay which indicate that the initial stress history of the soil materials is also one of the most important factors that affect the dynamic mechanical response.

1. Introduction

It is necessary to master the dynamic properties of materials to solve underground engineering problems, such as the missile penetration, mine blasting, shield excavation, etc. We know that there always exist elastic deformation and plastic deformation in the dynamic response of materials. As for the dynamic response of rock materials, most scholars focus more on its dynamic properties, material physical state and the relationship with the impact load. However, as for the soil, a kind of granular medium, whose compressive and tensile strength are smaller than rock and concrete, especially the perennial underground deep soil, in its long years formation, has gone through the effect of overburden pressure and other external loads, being a fully compressed stable state. This unique forming environment makes its resistance to high-speed deformation greatly improved compared with the surface soil. So the dynamic response of the soil under the impact load after high consolidation stress is also a relatively interesting research topic.

Split Hopkinson press bar is the most widely used test equipment in the study of the dynamic properties of materials. According to Felice et al. [5], the size of initial porosity is one of the factors that affect the soil stress-strain response. Song et al. [9] studied that non-uniform deformation and asymmetric strain lead to the error of the dynamic response of soil materials; Zhu et al. [12] improved the nonlinear viscoelastic constitutive model proposed by Wang et al. [11] according to the experimental curve; Liu et al. [7] analyzed the impact of the compaction degree and moisture content on the dynamic properties of cohesive soil; Chen et al. [3] studied the mechanical properties of deep clay under the condition of long-term high-stress k_0 consolidation. It found out that for the deep remolded clay the consolidation time and stress have great influence on its triaxial compressive strength. Other scholars [1,2,8] have carried out similar studies on dry or saturated sand, and most of them are done within the SHPB system which is similar to the conventional three axis test. These experimental results showed that the dynamic mechanical response of sand soil was less relevant to strain rate when the strain rate was 500 s^{-1} to 1000 s^{-1}. Further research [10] showed that the stress and strain relationship of sand had a significant effect on the size of the stress, and in unconfined conditions, the dynamic response of sand material was very sensitive to density, but the strain rate had minimal impact on dynamic response of sand material.

Compared with other materials, research findings on the dynamic response of sand and clay are less. Based on Φ 75 mm SHPB system, the impact compression test of different strain rates is carried out on the clay specimen of Beijing subway tunnel with long time and high consolidation stress in this paper. The uniaxial compression dynamic properties of the clay specimen are also studied by high speed photography.

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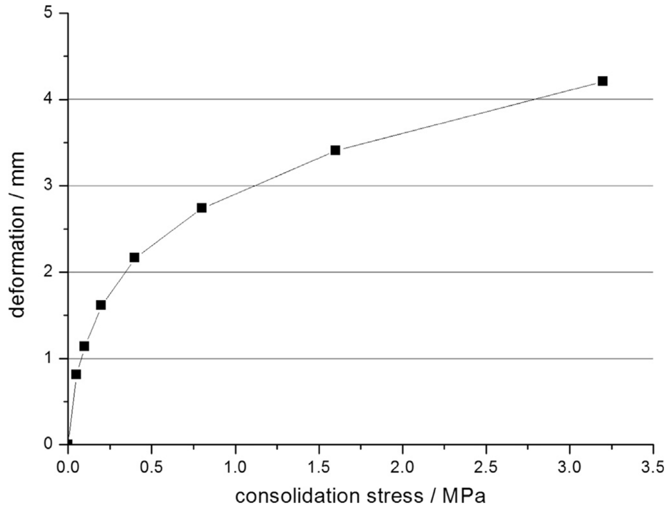

Fig. 1. Consolidation curves of clay specimen under high consolidation stress.

2. High pressure consolidation test of soil

Experimental clay specimens were taken from a subway tunnel in Beijing. With standard consolidation experiment method, the clay which was through 2.0 mm round hole sieve was prepared as specimen with a diameter of 61.8 mm and a height of 40 mm, its initial density is 1.87 g/cm^3, and the moisture content is 17.3%. The soil consolidation compression tests are carried out by using incremental step loading method [4]. The maximum consolidation pressure is 3.2 MPa, and the total consolidation time is 108 h.

Under the condition of complete restriction and drainage, the compressive deformation of clay specimens under various loads were recorded, and the compression deformation of the specimen were obtained. The typical compression curve is shown in Fig. 1:.

After the completion of consolidation test, by measuring the quality and height of clay specimens, the consolidation clay density and moisture content was calculated. For each specimen having different heights after consolidation, the density and moisture content that have been calculated are discrete in a certain range, so the average value–the density ρ=1.98 g/cm^3 and moisture content ω=15% is adopted in this experiment.

3. Kolsky bar experiments

3.1. Experimental set-up

The experiment would adopt SHPB dynamic test device (Fig. 2) with the diameter of =75 mm aluminum bar in State Key Laboratory of Geomechanics and Deep Underground Engineering. A gas gun was used to launch the striker bar whose length is 0.3 m. The velocity of the striker bar, which is controlled by gas pressure, is measured by two parallel light gates and an electronic time counter. The length of incident and transmission bar is 2.0 m..

Fig. 2. The test device of SHPB.

The strain gauges in the middle of the waveguide bars were used as measuring sensors to record the incident wave, reflected wave on the incident bar and the transmission wave on the transmission bar. Based on the assumption of one-dimensional stress wave and homogeneity, the front and back stress of the specimen is given by the following equations:

$$\sigma_1 = \frac{A}{A_s} E(\varepsilon_i + \varepsilon_r) \tag{1}$$

$$\sigma_2 = \frac{A}{A_s} E(\varepsilon_t) \tag{2}$$

If a state of dynamic stress equilibrium exists, where the stresses on both sides of the specimen are equal $\sigma_1=\sigma_2$. The specimen stress, strain-rate and strain can then be derived using the strain pulses measured from the bar surface. Equations are as following:

$$\dot{\varepsilon}(t) = -\frac{2C_0}{l_s}\varepsilon_r \tag{3}$$

$$\varepsilon(t) = -\frac{2C}{l_s}\int_0^t \varepsilon_t dt \tag{4}$$

$$\sigma(t) = \frac{AE}{A_s}\varepsilon_t \tag{5}$$

Based on the previous experiments of sand material and considering the clay specimens prepared were compressed under high consolidation stress, the specimen used with a diameter of 61.8 mm (80% of the waveguide bar diameter), and a height of about 35 mm to ensure the aspect ratio will be within the range of 0.5–0.6. The system has been calibrated before the experiment. The typical waveforms in this experiment are shown in Fig. 3 below:.

3.2. SHPB compression test results

3.2.1. Dynamic properties of clay under high consolidation stress

After 108 h of consolidation, the clay specimens were tested on the SHPB with the average strain rate from 60 s^{-1} to 600 s^{-1}. Taking the analysis of specimens with the strain rate of 170 s^{-1}, 328 s^{-1}, 514 s^{-1} as examples, we have the following results shown in Fig. 4:.

According to the results obtained, the dynamic properties of clay specimens under different impact loads could had some regularity:

During the impact process, the clay specimens had three stages in turn: elastic compression–plastic flow–extreme failure.

In the elastic compression stage, the stress-strain relationship was linear correlation, and with the increase of the strain rate, the slope increased, also the peak stress was greater. It is worth noting that due to the high consolidation stress, the clay specimen itself was already dense, and cracks and holes inside were bare, most of them were closed soon under the impact. So the clay specimens reached the peak value at a tiny strain.

Then plastic deformation occurred quickly. At lower impact loading (ie, low strain rate), the stress slowly pushed up, reaching the maximum limit before the extreme failure. Under the high impact load, the stress of the specimen reached the peak value soon, the strain increased over time and the stress had a certain degree of fluctuation. As to the cause of the fluctuation of the stress value in plastic flow, the analysis is as follows: Because of the relationship between the cohesive force and the inertia force of the clay itself, the specimens had passive deformation under unconfined conditions after elastic compression of clay samples. Under one dimensional impact load, the soil particles moved along with the incident bar. As a result of the failure of the particles, the soil pressure decreased the same with cohesive force and