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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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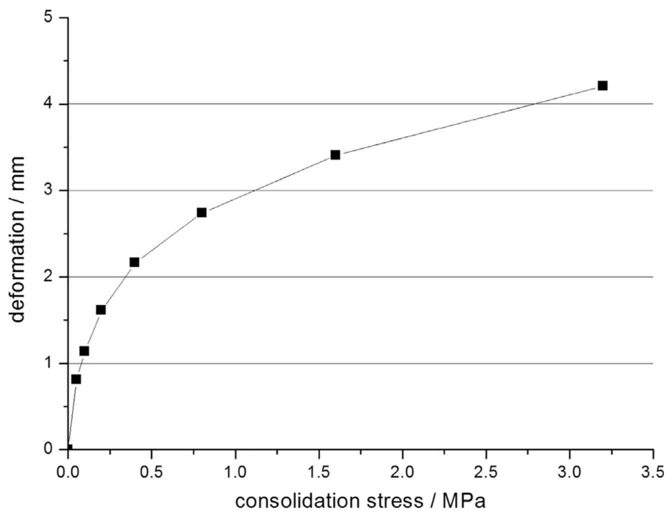


Fig. 1. Consolidation curves of clay specimen under high consolidation stress.

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 σ_1=σ_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

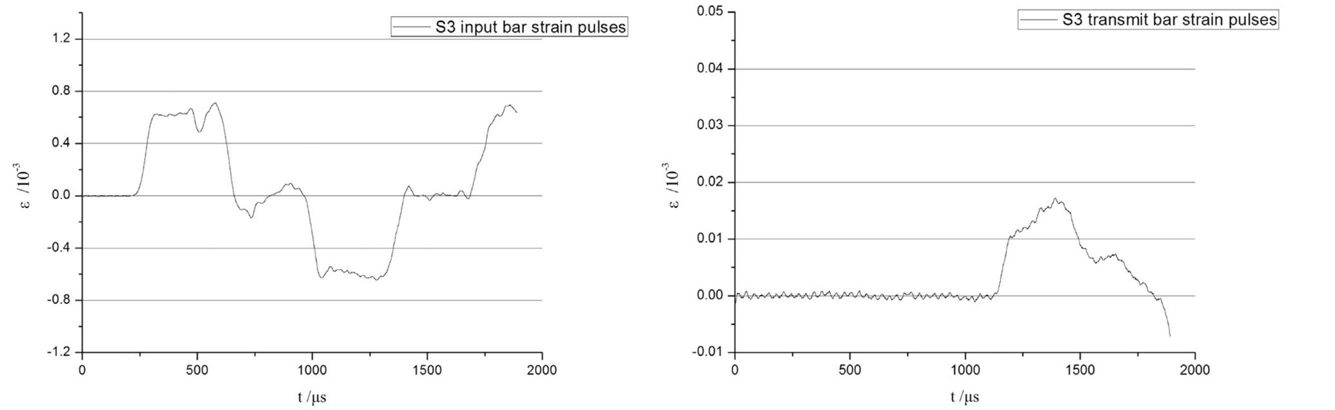
After 108 h of consolidation, the clay specimens were tested on the SHPB with the average strain rate from 60 s^{-1} to 600 s^{-1}. Taking the analysis of specimens with the strain rate of 170 s^{-1}, 328 s^{-1}, 514 s^{-1} as examples, we have the following results shown in Fig. 4:.

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

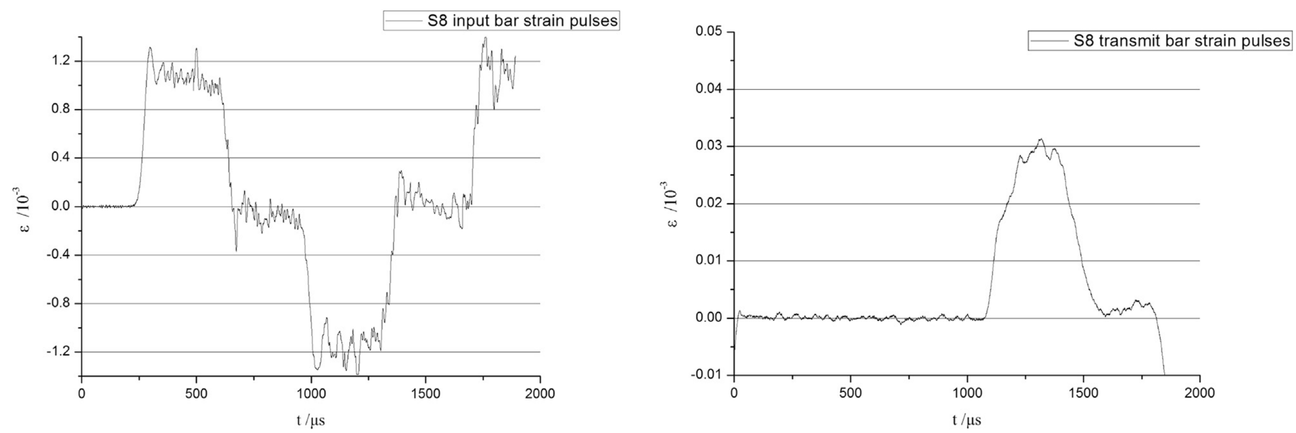
During the impact process, the clay specimens had three stages in turn: elastic compression–plastic flow–extreme failure.

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.

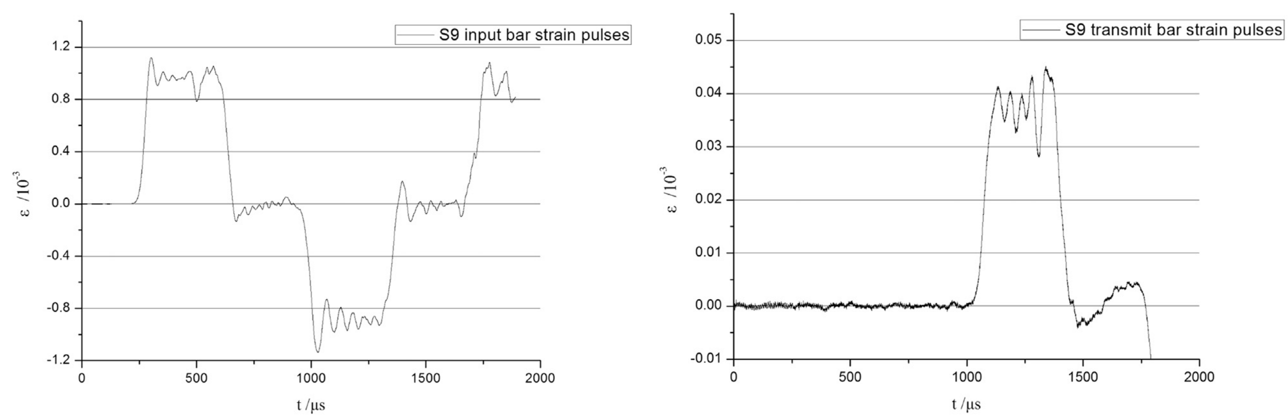
Then plastic deformation occurred quickly. At lower impact loading (ie, low strain rate), the stress slowly pushed up, reaching the maximum limit before the extreme failure. Under the high impact load, the stress of the specimen reached the peak value soon, the strain increased over time and the stress 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



(a) S3 incident and transmission bar strain pulses



(b) S8 incident and transmission bar strain pulses



(c) S9 incident and transmission bar strain pulses

Fig. 3. Typical measured strain pulses in Hopkinson bars. (a) S3 incident and transmission bar strain pulses. (b) S8 incident and transmission bar strain pulses. (c) S9 incident and transmission bar strain pulses.

internal friction. As the clay was a unified entirety, the structure of the soil in the distance continued to resist so that the pressure of the end face of the wave guide bar reaches its peak value.

At this stage, the specimens had a strong plastic deformation capacity. The high consolidation stress in the early stage caused a great change in the internal structure of the specimen, which made it hard to break. Therefore, the cohesive force and internal friction of the soil particles were greatly enhanced, and the dynamic compressive strength of the specimen was significantly improved under the impact effect.

In the end, the whole structure of the clay specimens were destroyed by the impact pressure, and after the strain reached a certain value, the stress was sharply reduced, and the specimens were destroyed.

The process of the specimen impact has been captured by the high speed photography. The whole process of the specimen from the beginning to the completion of a shock is shown in Fig. 5. Around 133 μs the specimen completed the elastic compaction, and on the left end micro cracks began to appear. It is a sign that the near end of the soil structure has yield plastic deformation. Later between 133 μs and

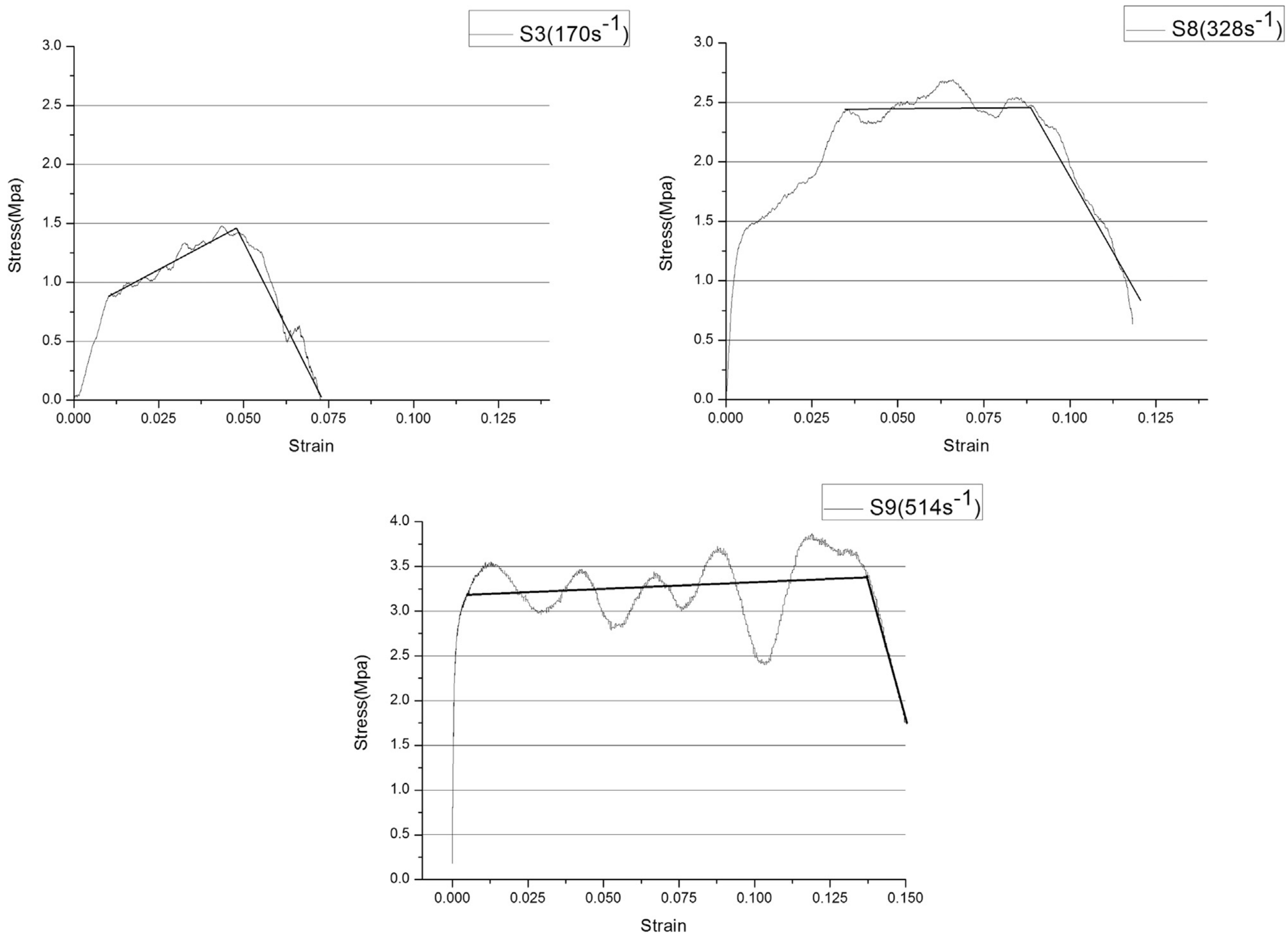


Fig. 4. Stress strain curves of examples.

664 μs the micro cracks expanded until the whole specimen was penetrated. At this point, the fine micro cracks began to consolidate and expand, and new crack was generated. Clay specimen failure eventually happens..

3.2.2. The effect of strain rate on dynamic properties of clay

As for clay specimens under high consolidation stress, the dynamic properties in different strain rates were studied. In order to compare the differences of the response of clay specimens under different impact loads, some experimental data are listed in Table 1, and the corresponding dynamic stress-strain curves with failure strain been marked are shown in Fig. 6.

Failure strain, as the target value, is to be analyzed. Fig. 7 shows in the range of strain rates from 60 s^{-1} to 600 s^{-1}, the failure strain increases with the increase of the strain rate at approximately $k=2.42\times10^{-4}$ slope linear. It shows the strain rate correlation between dynamic properties of clay materials.

3.2.3. The effect of consolidation on dynamic properties of clay

According to previous literature, there exist differences between deep clay and surface soil in physical and mechanical properties. In the practical engineering applications such as tunnel blasting, chamber excavation, high-speed rail and so on, the location of clay, the preconsolidation stress, stress relief need to be considered in dynamic design. Fig. 8 shows the conclusions on dynamics of clay at present: Compared with the quasi static loading, the dynamic strength and failure strain of the clay are greatly improved; the clay used in He's experiment [6] was without consolidation. The density was 2.24 g/cm3, Zhu [12] also used non-consolidated clay specimens with density 1.699 g/cm3. which two kinds had small strain and high compressive strength under high strain rates. The samples didn't have yield stage apparently during failure process. The patterns of failure happened to be tensile failure. Liu [7] used mudstone crushed soil whose diameter was 20 mm, degree of compaction from 93% to 100%. He studied changing degree of compaction has little effect on the dynamic peak stress and peak strain of the compacted cohesive soil under high strain rate. The linear relationship between the strain rate and strain is similar to the conclusions in this paper. However, because of the size effect, the yield stress is different. In summary, in comparison with the experimental results of clay specimens in other literatures, the initial stress state and degree of consolidation of specimens affect the impact results..

According to this paper, after 3.2 MPa consolidation test the strain rate needed to achieve the same failure strain reduces by about 60%, and the strain rate needed to achieve the same peak value reduces by about 40%. After high consolidation stress, the uniformity and density of the clay samples are greatly improved which are similar to the true environment of the clay. Thus at high strain rate, it can withstand greater fracture strain and dynamic peak stress.

4. Conclusions

Under impact load, the clay specimens have three stages in turn: elastic compression–plastic flow–extreme failure. The results have regularity and can be referred to for dynamic load design with the same clay conditions.

The dynamic properties of clay have strain rate correlation. Within the strain rate of 60–600 s^{-1} and after 3.2 MPa consolidation, the failure strain increases with the increase of the strain rate at approximately $k=2.42\times10^{-4}$ slope linear.

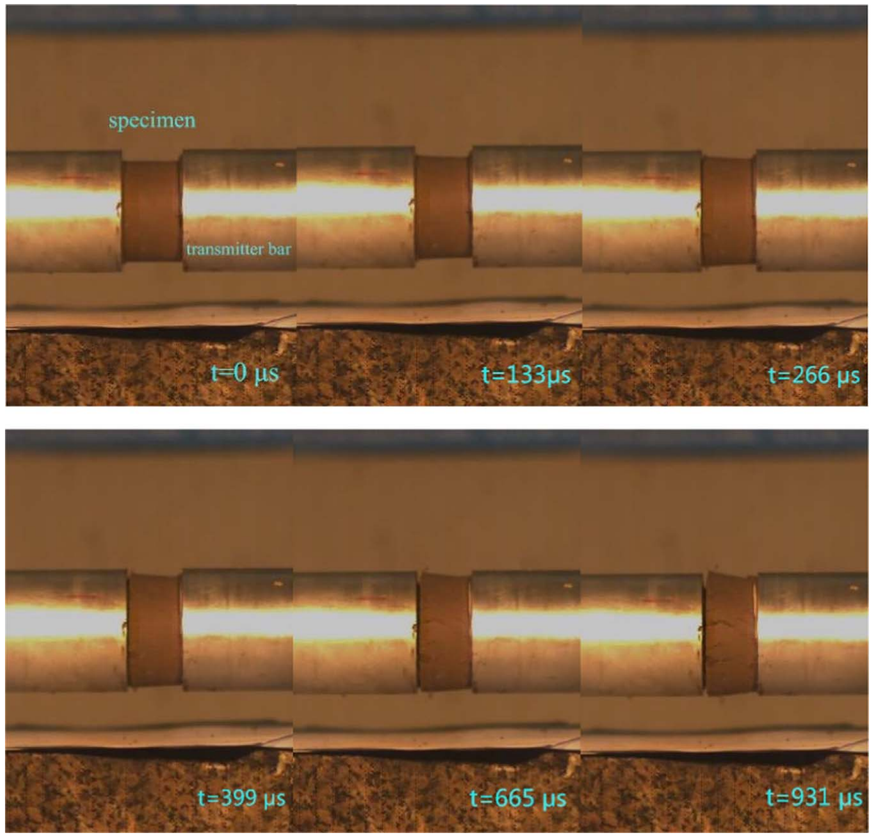


Fig. 5 **High-speed video of SHPB test showing the initiation of fracture (7500 frames/s).**

Table1
Summary of the dynamic compression test.

Test ID	Diameter (mm)	Length (mm)	Average strain rate (1/s)	Peak strain rate (1/s)	Peak compressive strength (MPa)	Failure strain	Deformation Modulus (MPa)
S1	61.8	35.70	62.32	88.63	1.21	0.016	75.63
S2	61.8	35.68	63.19	86.12	1.15	0.017	67.65
S3	61.8	35.62	170.10	183.45	1.48	0.049	30.20
S4	61.8	36.23	231.61	253.54	2.02	0.064	31.56
S5	61.8	36.20	275.86	308.44	2.35	0.085	27.65
S6	61.8	36.55	296.46	367.78	2.37	0.082	28.90
S7	61.8	35.14	306.73	375.46	2.58	0.073	35.34
S8	61.8	35.07	328.76	393.15	2.91	0.086	33.84
S9	61.8	35.42	514.30	644.11	3.88	0.134	28.96
S10	61.8	34.16	641.97	771.18	3.36	0.156	21.54

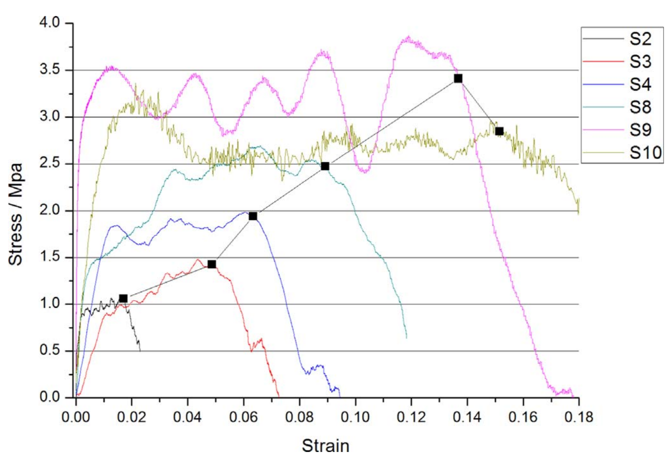


Fig. 6. Comparison of dynamic stress-strain curves for different specimens.

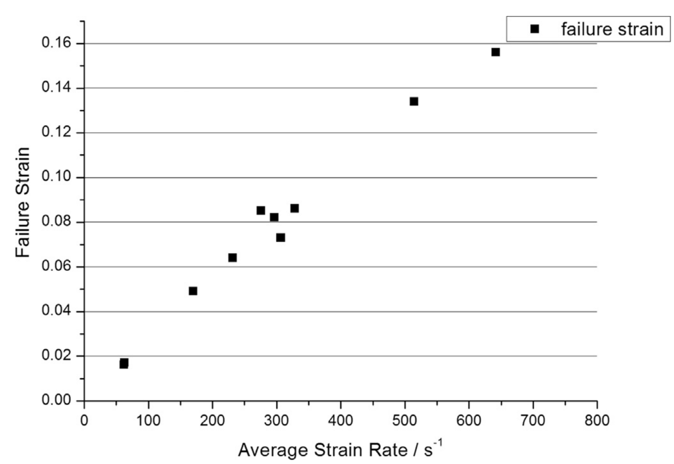
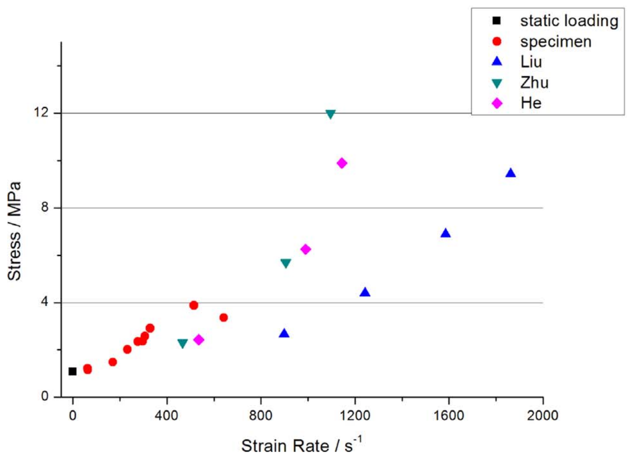


Fig. 7. Failure strain versus average strain rate.



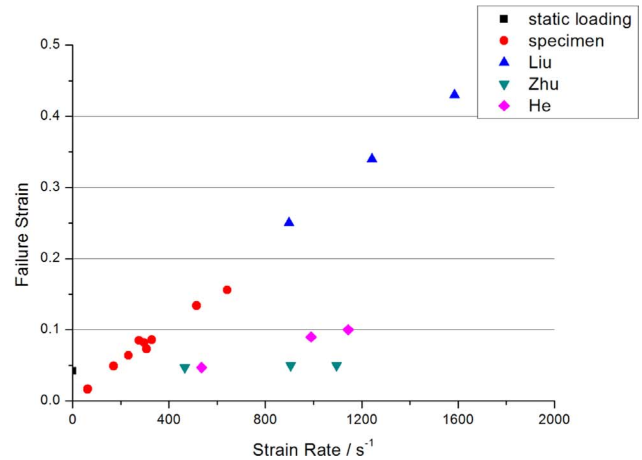


Fig. 8. Comparison of different dynamic compression tests of clay.

There exist great differences between deep soil and surface soil in dynamic properties. In long time high consolidation stress, deep soil has a stronger resistance load capacity and higher yield stress compared with surface soil, and there is an obvious linear relationship between failure strain and strain rate. In the SHPB dynamic test, it is necessary to consider the initial stress state and degree of consolidation. In this paper, 3.2 MPa consolidation tests of clay make a different result when comparing with the dynamic tests of surface soil in other literatures. Even though the effect of stress history of clay to the plastic deformation under dynamic loads has been proved, more abundant tests about other initial stress state and degree of consolidation need to be discussed.

Acknowledgments

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