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Dynamic multiaxial strength and failure criterion of dam concrete

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HIGHLIGHTS

- The failure modes of dam and wet-screened concretes under dynamic multiaxial loading are presented.
- The strengths and DIF of strengths of dam and wet-screened concretes under dynamic multiaxial loading are described.
- The dynamic failure criterion is developed in the octahedral stress space.

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ABSTRACT

Dynamic multiaxial strength experiments on both dam and wet-screened concretes were carried out by using a large static and dynamic triaxial electro-hydraulic servo testing machine. The dynamic strength under uniaxial compression (C), uniaxial tension (T), biaxial compression–compression (C–C), biaxial compression–tension (C–T), triaxial compression–compression–tension (C–C–T) and triaxial compression–compression–compression (C–C–C) are presented in the paper. The influence of strain rate (ranging from 10^{-5}/s to 10^{-2}/s) and stress ratio on the failure modes and dynamic strength of dam and wet-screened concretes is analyzed. It is found that the failure modes of both dam and wet-screened concretes were mainly dependent on the stress ratio, but independent of the strain rate. The ultimate strengths of dam and wet-screened concretes are found to increase with the increase of strain rate. Particularly, the dynamic increasing factor (DIF) increases obviously when the tensile stress is included. It is noted that the maximum DIF existed in the triaxial C–C–T stress state and the minimum DIF corresponded to the triaxial C–C–C state. The octahedral normal and shear stresses are increased but the similar angle is kept constant with the increase of strain rate in the octahedral stress space. The dynamic failure criterion is developed after analyzing the effect of octahedral normal stress and similar angle on the dynamic strength.

1. Introduction

Due to the stochastic nature of earthquake, it is possible for concrete dams to subject to strong earthquakes that may exceed the specifications factored into their design. A lot of studies performed numerical simulation of antiknock performance and failure modes of concrete gravity dams under dynamic loading [1–3]. It is shown that the failure process of structures under dynamic loading is much more complicated than that under static loadings. Once concrete dams suffer from strong earthquakes, they may develop cracks. Cracks can penetrate through these massive structures, and the entire dam may break into several blocks. Therefore, it is important to fully understand the mechanical characteristics of dam concrete under dynamic loading to predict the structure response, especially when tensile stress is included.

It is well known that the mechanical response of concrete depends on the loading rate. The research of rate dependency of concrete started in 1917 with Abrams' dynamic compressive experiment [4]. Since then, several reviews of the properties of concrete in both compression [5,6] and tension [7,8] under dynamic loading have been completed recently. They concluded that the strengths of plain concrete under dynamic loading had been found to be higher than that under the static loading. A great number of experimental researches on strength of ordinary concrete under multiaxial stress state have been carried out [9–11]. It is pointed out that the strength of plain concrete under multiaxial stress state is quite complicated, and many failure criteria for concrete are proposed in terms of several material constants varying from one to five independent parameters. Some studies have been carried out to investigate the strength characteristics

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of plain concrete under dynamic biaxial and triaxial loads [12–15]. They confirmed that both the strain rate and stress ratio influence the strength of concrete under multiaxial stress state. The strength of plain concrete increases with the strain rate, but the magnitude of increment decreases with the confining pressure.

Due to the practical difficulties in performing a full size specimen test, dam concrete is usually wet-screened to remove aggregates larger than 40 mm when casting, which is called wet-screened concrete. Compared to the dam concrete, the mix proportion of wet-screened concrete has been changed. Aggregate that exhibits a good bond, which minimizes the difference in stiffness with the surrounding mortar matrix, have a good impact resistance. Consequently, comparison of the mechanical properties of dam concrete using larger size specimens with the wet-screened concrete by small size specimens is very important. Many researchers [16–20] have paid much attention to the strength characteristics of dam and wet-screened concretes under uniaxial compressive and tensile loading. The present experimental data indicated that the type of aggregate used for concrete is known to affect the influence of strain rate on the dynamic compressive strength. The strength decreases as the size of aggregate increases, and increases with the strain rate. Large concrete structures, especially hydraulic abundant gravity dams and arch dams, generally work under multiaxial stress state. Therefore, the effect of aggregate size on dynamic strength of concretes under multiaxial stress state needs further investigations.

For this reason, a few experimental investigations for the effect of coarse aggregate on concrete strength under dynamic multiaxial loading were carried out previously. Wang and Song [21] reported that the enhancement effect of compressive strength of the dam concrete under biaxial C–C becomes stronger than that in the wet-screened specimens. Vu and Daudeville [22] focused on identifying the effect of coarse aggregate size and cement paste volume on concrete behavior under high triaxial C–C–C. The experiments results of dam concrete under biaxial C–T and triaxial C–C–T [23] showed that compressive and tensile strengths were lower than that under uniaxial stress state, and it was revealed that the relative strength decrease for dam concrete was a little larger than for wet-screened concrete at the same stress ratio. However, there is very little attention that has been paid to the strength of dam and wet-screened concretes under dynamic multiaxial stress state, especially biaxial C–T and triaxial C–C–T state. Moreover, the wide use of finite element method in the design and analysis of dam structure makes it necessary to establish the failure criterion of dam concrete subjected to dynamic loading. Obviously, these types of study have not yet been reported because of the shortage of experimental data.

In the current paper, the dynamic performance of dam and wet-screened concretes was studied under seismic load that the range of strain rates was between 10^{-3}/s and 10^{-2}/s. In order to compare with the static responses (with strain rate of 10^{-5}/s), the dynamic strain rates were varied from 10^{-5} to 10^{-2}/s.

In the work presented here, the strengths of dam and wet-screened concrete under dynamic multiaxial stress state were studied experimentally based on about one thousand specimens. The dynamic strengths under uniaxial compression (C), uniaxial tension (T), biaxial compression–compression (C–C), biaxial compression–tension (C–T), triaxial compression–compression–tension (C–C–T), and triaxial compression–compression–compression (C–C–C) were presented. This investigation provides experimental fact on the failure behavior under dynamic complex stress state for dam and wet-screened concretes. The new dynamic failure criterion was developed after analyzing the effect of octahedral normal similar angle on dynamic strength.

2. Experimental program

2.1. Testing specimens and mix proportions

Mixture proportions for dam concretes are given in Table 1. To carry out this study, local materials were utilized. The cementations material used for this investigation is 32.5 Portland cement. The aggregate was crushed stone with diameter from 5 to 80 mm. The sand was natural river sand with fineness modulus of 2.6. The cement, sand, aggregate and fly ash were mixed for about 3 min, then water and water reducer were added, and mixed for two additional minutes. The specimens were vibrated to be dense and solid using a high frequency resistance vibrator. After vibration, part of the dam concrete was wet-screened to remove the aggregate size larger than 40 mm and was classified as wet-screened concrete.

There were four types of specimens casted in this program. In uniaxial C, biaxial C–C and triaxial C–C–C experiments, specimens were used for dam and wet-screened concretes with size 250 × 250 × 250 mm and 150 × 150 × 150 mm, respectively. In uniaxial T, biaxial C–T and triaxial C–C–T experiments, specimens were used for dam and wet-screened concretes with size 250 × 250 × 400 mm and 150 × 150 × 300 mm, respectively, which were depicted in Fig. 1. Steel molds were used for casting the wet-screened concrete and laminate plywood mold was used for the dam concrete. After 24 h, the specimens were removed from the molds and then cured in a condition of 20.73C and 95% RH (relative humidity) for 28 days.

The compressive loading platens were 245 × 245 × 55 mm and 145 × 145 × 45 mm for dam and wet-screened concretes, respectively. It can be seen from Figs. 1 and 2 that there are eight short steel bars embedded in both ends for the specimens connected with the tensile loading platens. The other surfaces were subjected to compressive loads. More detailed information for preparing the tensile specimens can be referred to Wang and Song [23].

In order to eliminate the restraint induced by the loading platens on the specimen surfaces, the friction-reducing pads were placed between the platens and the specimen for all compressive loading platens. The pads consist of three plastic membranes with two layers of butter between them.

2.2. Testing apparatus

The multiaxial experiments were conducted on the servo-hydraulic multiaxial testing system designed and built at Dalian University of Technology, which made notable contributions to the studies of concrete multiaxial constitutive and failure criterion [23–27]. This testing machine is capable of developing three independent compressive or tensile forces. The tensile and compressive loads can reach 1000 kN and 3000 kN, respectively. The loads are applied by means of six loading jacks that were equipped with spherical, self-aligning heads to obtain uniform distribution of stress on the specimens. Forces were measured by utilizing the calibrated loading-cells with the accuracy of 0.1%. Meanwhile, the deformation was measured by linear variable differential transformer (LVDT) with the accuracy of 0.001 mm. Two LVDTs were attached to the calm and used to measure the relative displacement between two opposite displacement.

Three closed loop servo-controls were available in the triaxial machine. The regulation circuit for a constant stress-ratio experiment with a constant displacement rate in the major loaded direction was used in the tests. In order to obtain the stable failure modes in the descending stage, the displacement from the output of two LVDTs was employed in computation of strain of the specimen and also used as the feed-back signal to each specimen. The direction of σ_3 was in displacement control in uniaxial C and biaxial C–C and triaxial C–C–C experimental tests, while the other directions were loaded in force control, proportional to the major compressive stress σ_3. Corresponding to uniaxial T, biaxial C–T and triaxial C–C–T experimental tests, the direction of σ_1 was in displacement control, and the other two directions were loaded in force control, proportional to the tensile stress σ_1.

The displacement rates for dam concrete were set as 0.005 mm/s, 0.05 mm/s, 0.5 mm/s and 5 mm/s, whereas for wet-screened concrete, they were 0.003 mm/s, 0.03 mm/s, 0.3 mm/s, and 3 mm/s, which corresponding to the strain rates of 2×10^{-5}/s, 2×10^{-4}/s, 2×10^{-3}/s and 2×10^{-2}/s, respectively. A minimum amount of three specimens were tested for each combination of strain rate and stress ratio to ensure the repeatability of experimental results. In this paper, tensile stress is denoted as positive, and the three principle stresses are expressed as $\sigma_1 > \sigma_2 > \sigma_3$.

Table 1
Mix proportion of dam concrete (unit: kg/m^3).

Water	Cement	Fly ash	Sand	Water reducer	Aggregate (mm)		
					5–20	20–40	40–80
120	214	53	549	0.214	442.5	442.5	590