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Design and validation of a new dynamic direct shear apparatus for frozen soil

Jiankun Liu *, Yinghui Cui, Pengcheng Wang, Peng Lv

Department of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China

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ABSTRACT

The dynamic parameters of frozen soil are important for both engineering design and numerical simulation, which directly affect the accuracy of calculations. This paper describes the development of a new dynamic direct shear apparatus and provides a comprehensive analysis of its capability, measurement and control systems. The calibration test results show that this dynamic direct shear apparatus is suitable for studying the dynamic characteristics of frozen soil and interfaces behavior between different materials.

1. Introduction

In recent years, construction on the Qinghai-Tibet Plateau has been increasing, including the Qinghai-Tibet railway and highway, the oil pipeline from Golmud to Lhasa, and etc. However, tectonic activity in the Qinghai-Tibet Plateau is very frequent, which can be detrimental to all engineered structures. Since 2003, 7–8 magnitude earthquakes have occurred in succession, especially in the West Kunlun Pass and Yushu area. This seismic activity and increasing traffic load may cause damage to transportation infrastructure, especially for subgrade on slopes in warm permafrost, cannot be ignored in cold regions.

The dynamic parameters of frozen soil are important factors for both engineering design and numerical simulation in seismic active zone, which directly affect the accuracy of calculations. Compared with the studies on statics of frozen soil, researches on dynamic characteristics of frozen soil started relatively late. In the 1960s, scholars began the frozen soil experiments under different parameters like temperature, moisture, soil type, confining pressure, loading frequency, amplitude, and other aspects of dynamic loads, and proposed new results on dynamic stress–strain relationships and dynamic strength.

Currently, most dynamic parameters of frozen soil are obtained by conducting dynamic triaxial test. Vinson and Li (1980) studied Young's modulus and Poisson's ratio of frozen soil subjected to different confining pressures and temperatures with dynamic triaxial tests. Jessberger and Jordan (1982) discussed the influence of temperature and frequency on the elastic and plastic deformation by cyclic triaxial loadings tests. Shen and Zhang (1997) conducted experiments under constant strain amplitude dynamic mode and revealed the relationship between dynamic strength and static effective normal stress. Xu et al. (1998) used a triaxial MTS-810 to study the stress–strain relationship of frozen soil, the dynamic elastic modulus, and a dynamic Poisson's ratio with negative temperature vibration. Wu et al. (2004) studied dynamic constitutive models of remolded frozen Lanzhou loess and variation laws of the dynamic elastic modulus at different temperatures (−2 °C, −5 °C, −7 °C, and −10 °C) based on triaxial tests under seismic loads. Zhao et al. (2003) conducted dynamic triaxial tests under dynamic loads of constant amplitude and found that the dynamic elastic modulus increased with increasing frequency or decreasing temperature, while the damping ratio of frozen soil showed an opposite trend. Wang et al. (2012) investigated the dynamic strain induced by train loading with laboratory dynamic triaxial tests, and documented the effects of the numbers of cyclic loadings, freezing temperature, and water content on resilient and accumulative plastic strains of frozen silt clay. Zhang et al. (2008) found that frozen soil dynamic strength was not only affected by vibration times, but also had a relationship with the effective energy absorbed by the soil under cyclic action.

As for the apparatus, Da Re et al. (2003) designed a high-pressure, low-temperature triaxial testing system to study the physical mechanisms controlling the strength-deformation behavior of frozen sands. The computer controlled system is capable of performing high-stress monotonic triaxial compression tests on specimens and incorporates advanced technology for temperature, strain rate, and loading control, here the static test can only be conducted. Fox et al. (2006) developed a large direct shear machine for static and dynamic shear strength testing of geosynthetic clay liners (GCLs) and GCL liner systems, but it is not temperature controlled. Ross et al. (2011) developed a large-scale dynamic direct shear apparatus to study the interface shear strength between a textured geomembrane (GMX) and a needle-punched geosynthetic clay liner (NP GCL) under cyclic loading with

* Corresponding author. Tel./fax: +86 10 51684096.
E-mail address: jkliu@bjtu.edu.cn (J. Liu).

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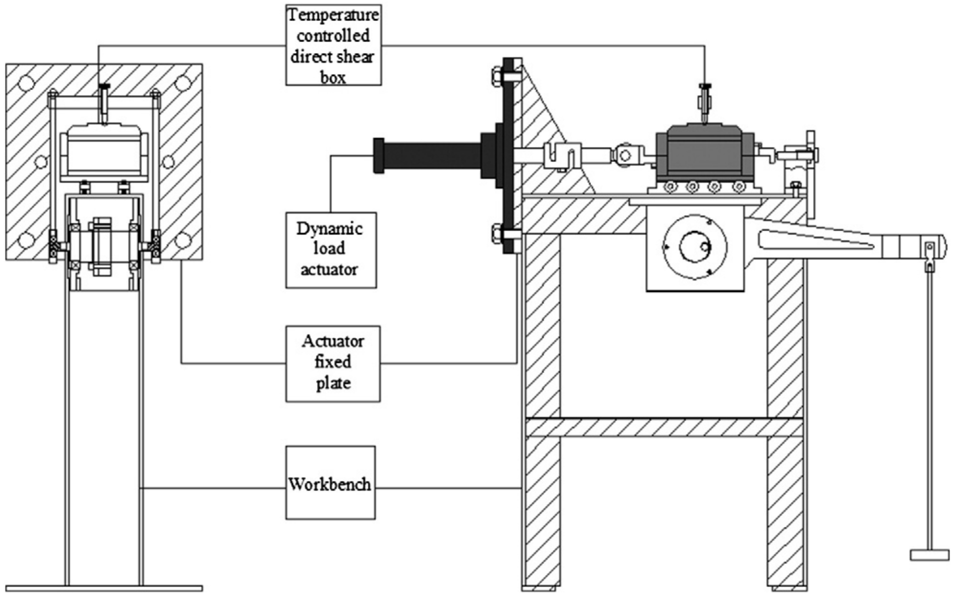

Fig. 1. Structure diagram of frozen soil dynamic direct shear apparatus.

no temperature control system. Yao et al. (2013) developed a temperature-controlled triaxial test system that can conduct Ko condition test and measure volumetric strain of frozen soils precisely, but only for static loading. So far, no temperature-controlled dynamic direct shear test system has been reported.

Direct shear apparatus has many advantages as easy operation, simple structure, faster consolidation, greater stiffness, clear physical meaning and so on, and is widely used in geotechnical engineering.

This paper aims to develop an efficient direct shear system that can apply dynamic shearing load of various forms and control temperature precisely, its designed structure, power system, measurement and control systems were introduced, and a series of temperature-controlled dynamic shearing tests were carried out to calibrate the device.

2. Main components of a new dynamic direct shear apparatus

A new dynamic direct shear apparatus was developed to measure the dynamic parameters both for frozen soil and interfaces between different materials. The entire dynamic direct shear system consists of the following main components: dynamic shearing loading system, temperature measuring and controlling instruments, a displacement measuring device, and a data acquisition system, as shown in Fig. 1. Each component of this device was designed by the authors.

2.1. Design of the dynamic actuator

A hydraulic power system provides the needed power, which is also the core of the whole system. Cooperatively working with the computer-controlled hydraulic pump, the actuator controlled by a valve can apply force to the bottom shear box. The signals of force and displacement are then fed back to the computer-controlled system by the measuring device integrated in the actuator, and all output of stress and strain will be recorded automatically. Thus, this hydraulic power loading system was designed with three aspects: pump performance, load-matching, and the hydraulic system.

Table 1
Performance parameters of dynamic loading system performance.

Design project	Load amplitude range (kN)	Piston stroke (mm)	Vibrational frequency (Hz)
Performance parameters	1–20	−50 to 50	0.5–4

2.2. Pump performance design

The original idea to develop this device was to study the dynamic shear strength of warm permafrost, especially at the frozen–thaw interface at the permafrost table, to obtain the parameters for slope stability analysis under dynamic loading, so the shearing force limit of the developed device should be estimated based on possible shear strength of warm frozen soil. According to Li et al. (2010), the dynamic shear strength of the frozen soil is around 1.5 MPa, based on this, the maximum shearing load limit of the actuator was set at 20 kN. According to Shen and Zhang (1997), the characteristic frequency of earthquakes is generally less than 4 Hz, so the vibrational frequency of the actuator was determined in the range of 0.5–4 Hz. The ultimate performance parameters of the power system are shown in Table 1. The vertical static load was applied by conventional equilibrium mass.

2.3. Load matching design

Based on the power system's bandwidth and piston stroke, the effective area of the hydraulic actuator was finally set as 3×10^{-3} m^2, and

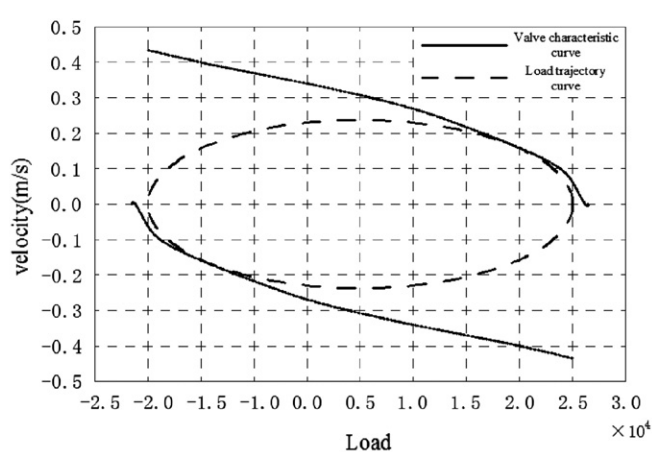

Fig. 2. Figure of load-matching.