Research on hydraulic servo control system for field test of ground motion parameters

Bin Qian¹*, Bingyi Li², Yanbo Fan², Mingqiao Fan², and Weijie Gu¹

¹Geotechnical Engineering Department, Nanjing Hydraulic Research Institute, Nanjing, Jiangsu, 210002, China
²Geotechnical Research Institute, Hohai University, Nanjing, Jiangsu, 210098, China
*Corresponding author’s e-mail: bqian@nhri.cn

Abstract. The hydraulic servo control system of the ground motion parameter field test system is introduced in this paper. The hydraulic servo control system mainly includes the seismic wave generating equipment system and the servo control system. And the equipment system consists of the P-wave and the S-wave generator. The main advantage of the hydraulic servo control system is that P-wave and S-wave generator can generate both p-wave and S-wave. The seismic waves produced are characterized by strong stability and high energy, which can overcome the shortcomings of instability, less energy and poor repeatability of the on-site wave generating device. It is necessary to generate the waveform of different types of seismic waves, such as sine wave, cosine wave, square wave and random wave. The vibration frequency of the seismic wave can be controlled to meet the actual demand of the seismic wave in engineering. The hydraulic servo control system can be run stably for a long time, without interference and unreliable operation in various environments and states, which can be of great significance for the seismic safety evaluation of the engineering site.

1. Introduction

Frequent earthquake disasters are disturbing problems over the world. In recent decades, there have been some disastrous earthquakes in China. The earthquake zone was almost in ruins, and the tragedy of the disaster was shocking. It is vital to evaluate the seismic safety of the engineering site. Nowadays, seismic safety evaluation is mainly based on the dynamic characteristic parameters of engineering soil and combined with the experience of engineering practice. Therefore, the dynamic characteristic parameters of the soils become the most important content of seismic safety evaluation.

At present, the study of soil dynamic parameters is mainly carried out by laboratory tests. The dynamic modulus and damping ratio are two important parameters for studying the soil dynamic problems. The experimental study of dynamic modulus and damping ratio of soil was very complicated[1-2], because there are more than 13 influence factors related to dynamic modulus and damping ratio. Yasuhara et al. considered that the frequency of load and vibration had no significant effect on the dynamic strength and deformation modulus of cohesive soil[3]. Zhang et al. carried out that the variation curves of equivalent linear modulus with dynamic strain of saturated sand under different the vibrational frequencies were not significantly different[4]. Chen et al. considered that the vibration frequency had an obviously effect on dynamic modulus and damping ratio of dynamic compacted loess, while the magnitude of frequency was inversely proportional to the effect[5]. Wang et al. found that the vibration frequency had little effect on the dynamic elastic modulus of undisturbed loess, but it had dramatically effects on the damping ratio. It could be seen that the dynamic modulus
and damping ratio of soil under different states varied greatly with the influence factors[6]. Xu et al. tested the dynamic characteristics of silty clay in the hinterland of permafrost zone on the Qinghai-Tibet Plateau by using MTS-100 cyclic dynamic triaxial test. By the experimental data, it was concluded that negative temperature was the most important factor to affect the damping ratio of permafrost[7]. By cyclic torsional shear tests on saturated soils under unconsolidated-undrained conditions, Qi et al. studied the effects of loading mode and cyclic stress affinity on dynamic shear modulus and damping ratio under large strain[8]. By laboratory dynamic triaxial tests on clay and EPS particulate mixed light soil (LCES), Li et al. found that the loading rate increased with the growth of vibration frequency, which increased the effective stress of the soil, and ultimately the dynamic modulus and dynamic strength of the soil[9]. Lai et al. illustrated that the loess high filling site formed after mountain cutting had a great influence on the characteristics of seismic parameters, which can provide reference for seismic safety evaluation and structural seismic design of high filling site[10]. It could be found that most of the current indoor experiments were on remolded soil samples, even using undisturbed soil, but disturbance to the soils was not avoided under the transport and the preparation of the laboratory sample. Thus, the data and results may not really demonstrate the actual state of the soil. Therefore, it is very necessary to carry out in-situ dynamic test of soil.

Currently there are relatively few field tests on dynamic properties conducted, because of the lack of test equipment for field dynamic characteristics. Upon this situation, we have developed a state-of-art test system for ground motion parameters, which can conveniently detect dynamic response behaviour of foundation. Then parameters such as dynamic shear modulus and liquefaction resistance of foundation soil can be collected. Through the field test system for ground motion parameters, the site dynamic response parameters can be obtained in the laboratory. And the test errors caused by sample disturbance can be eliminated, which made the test results more consistent with the actual situation of soil. The hydraulic pressure servo control system is the core part of the field test system for ground motion parameters. At the same time, generation of different seismic waveform, which is the key content of in-situ ground motion test.

This paper focus on the hydraulic pressure servo control system for the field test on ground motion parameters. The seismic wave system and its working principle, as well as the advantages of the private service control system would be introduced. The system can generate stable and high-energy seismic waves. And different types of seismic waves can be generated, such as sine wave, cosine wave, square wave, random wave, etc. Meanwhile, the vibration frequency can be controlled to meet the requirement of engineering seismic waves to a large extent.

2. Technical scheme of field test system for ground motion parameters
The field test system for ground motion parameters has been independently developed by the group. The device consists of movable devices, dynamic loading devices, dynamic response measurement system and data analysis system, etc., as shown in Figure 1.

By adjusting the frequency and amplitude of dynamic loads, the work principle of the device is to apply dynamic loads on the foundation under certain static loads,. Then the in-situ dynamic characteristics of the soil can be obtained, as shown in Fig. 2.
Sensors such as seismic geophones are located under the shaking table and at a certain position on the side to obtain the corresponding dynamic response of the soil, which is ultimately used to measure the dynamic shear modulus and other dynamic characteristics parameters of the foundation soil. In the dynamic shear modulus experiment, by adjusting the soil strain from $10^{-4}\%$ to more than $0.05\%$, the respective shear modulus $G$ reduction curve can be obtained, as shown in Figure 3. The results of dynamic shear modulus test showed that for cohesionless soil, the $G$ value of shear modulus curve was larger than that of laboratory, but for cohesive soil, the corresponding experimental relationship become more complex.

![Figure 3. Dynamic shear modulus of foundation.](image)

The pore water pressure of foundation can be measured by liquefaction sensors and pore water pressure gauges. The liquefaction resistance of natural sedimentary soils can be directly evaluated by measuring the variation curves of pore water pressure and non-linear shear modulus. Finally, the liquefaction degree of natural soils under seismic load can be evaluated.

3. Seismic wave generating equipment system

3.1 Composition of Seismic Wave Generating Equipment System

In this paper, the hydraulic servo control system is mainly introduced in the field test system of ground motion parameters. The hydraulic servo control system has two vibration control modes: the pressure control and the displacement control. It can not only generate the vibration frequency, but also generate P-wave and the S-wave of variable forms such as sine wave, cosine wave, square wave and random wave according to the demand. These functions are mainly achieved by function generator, which contacts with the master computer by parallel communication. In addition, the memory of the generator is 32K. The data on the hard disk can be directly reproduced by function generator. Therefore, seismic wave can be simulated and tested. The system expansion function provides a convenient and practical method of test and measurement. The system can overcome the shortcomings of the existing seismic generator devices, such as low energy, instability, poor repeatability, and low safety. Therefore, the system can be of great significance for the application of seismic waves in geotechnical engineering and geophysical engineering.

The hydraulic servo control seismic wave generating device includes the P-wave generating device and the S-wave generating device, as shown in Fig. 4. A shock absorber air bag and an actuator fixing bracket are placed between the ground-touching board and the bearing plate of the S-wave generating device. An actuator is arranged on the actuator fixing bracket while a guide rail fixing bracket is arranged on the ground-touching board. The actuator is placed between the ground-touching board and the bearing plate of the P-wave generating device when the pressure sensor is arranged at one end of the actuator. The bearing plate is fixed on a counterforce pile which is inserted into the foundation in order to provide sufficient power for actuator. Both the P-wave generating device and the S-wave generating device use hydraulic source to provide hydraulic pressure for actuator. Actuator, pressure sensor and displacement sensor are connected to the computer. The hydraulic source is controlled by
the computer, while the output index of hydraulic pressure is changed due to the different forms of wave and vibration frequency.

The electro-hydraulic servo actuator includes a cylinder, a moving piston, hydraulic distributor integrated valve group, servo valve, force sensor, displacement sensor and other components with high precision and high sensitivity, which is the action execution part of the test system when loading and obeying control orders.

![Figure 4. Hydraulic servo control seismic wave generator.](image)

3.2 Procedure of S-wave Generator
Step 1. According to the demand of the field test in geotechnical engineering and geophysical engineering, the control mode and waveform of seismic wave are determined.

Step 2. Due to the control mode and waveform from the step 1, the hydraulic feed actuator is controlled by the computer to ensure the output of different waveforms and vibration frequencies from the hydraulic source.

Step 3. The actuator performs stretching behaviours of the corresponding waveform under the hydraulic pressure of different waveforms and vibration frequency.

Step 4. The actuator is rigidly connected with the actuator support when the actuator drives the actuator support to perform stretching behaviours.

Step 5. The actuator support drives ground-touching board to perform stretching behaviours.

Step 6. Eventually, ground-touching board performs stretching behaviours to produce the S-wave of the corresponding waveform.

Step 7. Dynamic data of actuator, the pressure sensor and displacement sensor are fed back to computer through data line in real time.

Step 8. According to the feedback of step 7, the computer makes further adjustments to the control mode, the waveform and the vibration frequency of the hydraulic source.

During the work steps of the S-wave generator, in order to ensure the vibration stability of the shear wave generator, the load of corresponding weight should be set on the bearing plate according to the actual demand.

3.3 Procedure of P-wave Generating Device
Step 1. According to the demand of the field test in geotechnical engineering and geophysical engineering, the control mode and waveform of seismic wave are determined.

Step 2. The hydraulic power is controlled by the computer to output different waveforms and vibration frequencies according to the control modes and waveforms determined in step 1.

Step 3. The actuator performs stretching behaviour of the corresponding waveform under the hydraulic pressure of the different waveforms and the different vibration frequency.

Step 4. The actuator is rigidly connected with the ground-touching board and the actuator drives the ground-touching board to perform stretching behaviours.

Step 5. The ground is vibrated by the ground-touching board to generate the corresponding P-wave.

Step 6. The top of the actuator is rigidly connected with the bearing plate, and the actuator transfers the force to the bearing plate.
Step 7. The bearing plate is rigidly connected with the counterforce pile, and the bearing plate transfers the force to the counterforce pile.

Step 8. The counterforce pile is fixed on the ground to provide reaction force for actuator.

Step 9. The dynamic data of actuator, pressure sensor and displacement sensor are fed back to computer through data line in real time.

Step 10. The computer makes further adjustments to the control mode, waveform and vibration frequency of the hydraulic source according to the feedback of step 9.

The work steps of the S-wave and P-wave generating devices are set in accordance with the demand. In step 5 and step 6, the movement of the ground-touching board is carried out along the lead rail when the stretching behaviour of the ground-touching board performs, which ensures the stability of the movement of ground-touching board. The load of corresponding weight should be set on the bearing plate to ensure enough reaction according to the facts.

4. Advantages of the Servo Control System

4.1 Guarantee for high reliability of coordinated loading
With the digital signal processing technology, the real-time test signals are collected, transformed, filtered, estimated, enhanced, compressed and recognized by computer in digital format. The multiple microprocessors are applied to accomplish multi-parameter control, data acquisition and other tasks independently, which are decentralized and then centralized processing with multi-computer parallel and coordination processing. The system works in low failure rate and high reliability.

4.2 Excellent real-time response of the coordinated loading system
Instruction system is a pipeline operation. A test instruction is decomposed into several sub-tasks. In servo control system, each sub-task is performed by several microprocessors in a way of parallel, overlap and coordinating with each other, so as to realize high-speed dynamic data acquisition. Through high-performance real-time response capability and high throughput data processing capability, the instruction system can obtain satisfactory test control capability.

4.3 Automatic test of unmanned surveillance and strong self-adaptation
The working condition of the system can be adjusted by intelligent adaptive control system in real time, which can constantly adapt to the changing stiffness of the system during the experiment, track
deviation and maintain the best working state. In order to adapt the test system to accomplish the test task automatically under the condition of unmanned monitoring, a perfect self-diagnosis system is designed for the system, which can investigate the control and measurement system by itself and ensure the long-term stability, non-interference and reliable operation in various environments and states.

5. Conclusion
(1) The S-wave generator in the hydraulic servo control system introduced in this paper is mainly used to generate S-wave, including actuator, pressure sensor, displacement sensor, ground-touching board, shock absorber airbag, bearing plate and lead rail. The P-wave generator is mainly used to generate P-wave, including actuator, pressure sensor, displacement sensor, touching floor, bearing plate and counterforce pile.

(2) Pressure control and displacement control are mainly provided by the hydraulic servo control system. The state-in-art generating devices can be used to generate S-wave and the P-wave, which can solve the problems of instability, less energy and poor repeatability of current wave generating devices. Also, it can generate strong and energy seismic waves. Different types of seismic waveforms, such as cosine wave, square wave and random wave can be chosen according to the demand. Meanwhile, it can control the vibration frequency to meet the needs of seismic wave in engineering to a large extent.

(3) The hydraulic servo control system can be running under a stable condition for a long time, without interference and reliable operation in various environments and states, which can be a reference for the seismic safety evaluation of the engineering site.

Acknowledgement
This work was financially supported by the Special Fun of Chinese Central Government for Basic Scientific Research Operation in Commonweal Research Institutes (No. Y316007, No.318013 and No. 318015).

References
[1] Hardin, B.O., Drnevich, V.P. (1972) Shear modulus and damping in soils. Geotechnical Division of ASCE, 98(6): 603-624, 98(7): 667-692.
[2] Bai, B. (2016) Dynamic characteristics of soil and its application. China Construction Industry Publishing House, Beijing.
[3] Yasuhara, K., Yamanouchi, T., Hirao, K. (1978) Cyclic strength and deformation of normally consolidated clay. Soil and Foundations, 22(3): 77-91.
[4] Zhang, J.M., Wang, X.W. (1990) Effect of vibration frequency on dynamic characteristics of saturated sand soil shear modulus and damping in soils. Chinese Journal of Geotechnical Engineering, 1990(1): 89-97.
[5] Chen, C.L., Hu, Z.Q. (1998) Dynamic characteristics parameters and their relation to vibrofrequency of dynamically-compacted foundation loess. Journal of Xi’an University of technology, 14(2): 216-220.
[6] Wang, J.R., Zhang, Z.Z., etc. (1999) Effector vibration frequency on dynamic constitutive relationship of loess. China Earthquake Engineering Journal, 21(3): 310-314.
[7] Xu, X.Y., Zhong, C.L., etc. (1998) Research on dynamic characters of frozen soil and determination of its parameters. Chinese Journal of Geotechnical Engineering, 20(5): 77-81.
[8] Qi, J.F., Luan, M.T., etc. (2008) Dynamic shear modulus and damping ratio of saturated clay. Chinese Journal of Geotechnical Engineering, 30(4): 77-81.
[9] Li, B., Gao, Y.F., etc. (2008) Cyclic loading frequency effect and mechanism of lightweight clay-EPS beads soil. Rock and Soil Mechanics, 29(10): 2731-2734.
[10] Lai, C.J., Zhu, Y.P., etc. (2018) Characteristics of Ground Motion Parameters of Loess-high Filling Sites. China Earthquake Engineering Journal, 2018(6): 1168-1173.