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Development and Application of an Integrative Direct Shear Apparatus for Multi-scale Rock Mass Discontinuity

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Abstract: Variation of shear strength scale-effect of rock mass discontinuity need to be tested on a special integrative direct shear apparatus, where the stable mechanical shear strength parameters can be gotten. A new integrative direct shear apparatus has been developed by two devices. It meets a group of multi-scale rock masses which cross section are from 10×10 to 100×100 cm^2. Specimen overlay region and load overlay region are set up to check the accuracy of two devices, where common upper or lower specimens and its corresponding load values can be tested in respective device. The integrative direct shear apparatus has been manufactured and applied. It has been gotten good performances and met the precision and testing requirements. It can be summarized as the following characteristics: (1) It can achieve the transmission, location, directional shearing and restoration of multi-scale specimens, (2) The reliability of the test results and the service life of core components have been verified under precision requirements. Rock mass discontinuity has the peak shear strength and the nearly linear variation for the peak and residual strengths which are consistent with theoretical results and (3) The whole test process is convenient. It has the capability of automatic collection and real-time graphics by self-developed software. The integrative direct shear apparatus has provided a good platform to research shear strength of multi-scale rock masses.

Key words: Integrative direct shear apparatus, multi-scale specimen, rock mass discontinuity, scale-effect

INTRODUCTION

Shear strength of rock mass discontinuity is a key parameter used to evaluate stability of engineering rock and draw up reinforcement scheme. However, Due to the existing discontinuities, mechanical parameters of jointed rock mass are featured with inhomogeneity, anisotropy and scale effect. Scale effect has become an essential characteristic of rock mass mechanical parameters. To get stable shear strength of rock mass discontinuity, a series of rock specimens with different sizes should be tested by a special integrative direct shear apparatus.

Rock mechanics workers Zhou *et al.* (2001), Yang and Xu (2004), Barton and Bandis (1980), Krahn and Morgenstern (1979) and Bandis *et al.* (1981), at home and abroad, usually adopt direct shear test and engineering geological surveys data to get shear strength of structural plan. However, most existing direct shear apparatuses only test specimen which is less than 50×50 cm^2. In order to overcome the shortages of the existing instrument, the shear strength parameters are artificially low (Reduction coefficients is usually defined as 70%) and use them to engineering rock mass.

How to get shear strength scale-effect of rock mass discontinuity and mechanical parameters has been concerned, but the problem is unsolved up to now. So it is very urgent to develop a special integrative direct shear apparatus used to test multi-scale rock mass.

DEVELOPMENT OBJECTIVES AND TECHNICAL PROBLEMS OF INSTRUMENT

At present, many scholars have been studying how to design a more advanced and reasonable direct shear apparatus and putting forward many improved methods. (Min *et al.*, 2006; Cai *et al.*, 2010; Liu *et al.*, 2006, 2010). Working mode of conventional direct shear apparatus can be categorized into two types (Fig. 1): Upper half or lower part of specimen is applied tangential load under a constant normal loading.

The disadvantages of two types are obvious. As can be seen from the type of Fig. 1a, it has been deviated between the center of upper half of specimen and the center of normal load after relative movement of specimen happens which affects the service life of the servo some key parts, such as servo cylinder and force sensor. As

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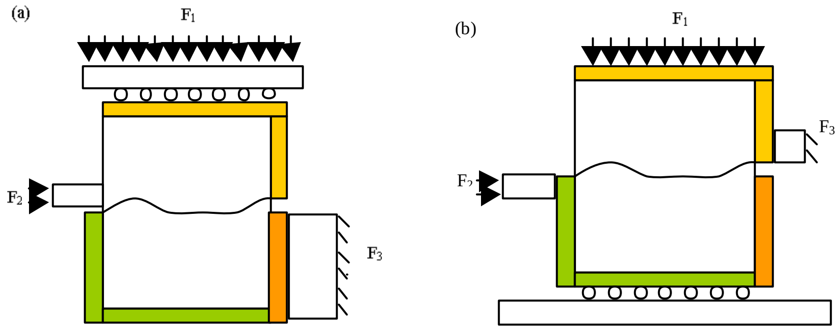

Fig. 1: Working mode of traditional direct shear apparatus, F_1: Normal load, F_2: Tangential load and F_3: Support load

Table 1: Development objectives

Parameters	Quotas
Specimen range	10×10~100×100 cm^2
Range of normal load	2~1000 KN
Range of tangential load	2~1000 KN
Indicating accuracy	±1%
Loading rate	0.2~20 kN Sec^{-1}
Displacement rate	0.5~50 mm min^{-1}

can be seen from the type of Fig. 1b, ascending motion has been hindered because of existing friction (Between F3 and upper half of specimen). In addition, the reset operation is complicated, especially for large rock specimen.

The traditional direct shear apparatus is limited to the lager-scale and multi-scale rock mass. The change of shear strength scale-effect of rock mass discontinuity cannot be analyzed by the traditional testing result. Mainly, the following problems are difficult to solve: it can't achieve the transmission, location, directional shearing and restoration of multi-scale specimens (The cross section size of rock masses are from 10×10 cm^2 to 100×100 cm^2); Testing precision is hard to guarantee large range of load values (Load values are from 2 to 1000KN).

Ten discrete specimens (from 10×10 to 100×100 cm^2) have been adopted and maximum normal pressures of every specimen are respectively applied as 0.2, 0.4, 0.6, 0.8 and 1 Mpa. Note that some testing procedures of many criterions are written as follows: the maximum normal loading of every specimen should load by 5 load steps; the maximum load must be greater than engineering load. Development objectives of the direct shear apparatus can be seen inTable 1.

DESIGN OF INTEGRATIVE DIRECT SHEAR APPARATUS

Grading of the apparatus: System error caused by components, controller resolution and sensor precision, forms an overall accuracy and testing range. It usually

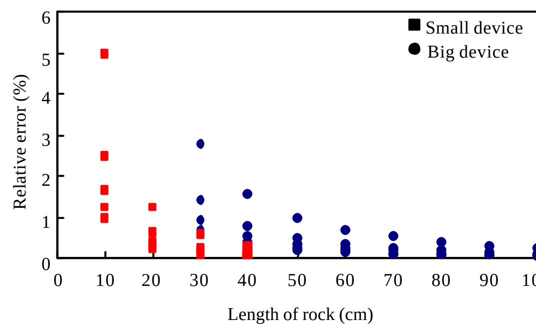

Fig. 2: Maximum relative error of force sensor of two devices

Table 2: Grading of apparatus

	Small device	Big device
Classified load	0.2~200 KN	10~1000 KN
Classified specimen	10×10 cm^2	-40×40 cm^2
	30×30 cm^2	-100×100 cm^2
Maximum quantum of force sensor	200KN	1000 KN

can't achieve all the testing remands when load ratio (Minimum load is divided by the maximum load) reaches more than 100. So, an apparatus can't meet the testing for a series of multi-scale specimens when the maximum load is 1000 KN and the maximum load is 2 KN. How to certain the amount of devices is critical.

Sensor precision is an important parameter to solve the problem. On the basis of the existing technical level, the precision of force sensor can reaches 0.05% and the testing range of force sensor can reaches 1-100%. It can infer that two devices can meet the testing demands. Reasonable grading of apparatus has been gotten in Table 2. The maximum relative error of force sensor of two devices can be gotten in Fig. 2. However, precision correction should be done to meet overall measurement accuracy, especially the part of testing load is less than

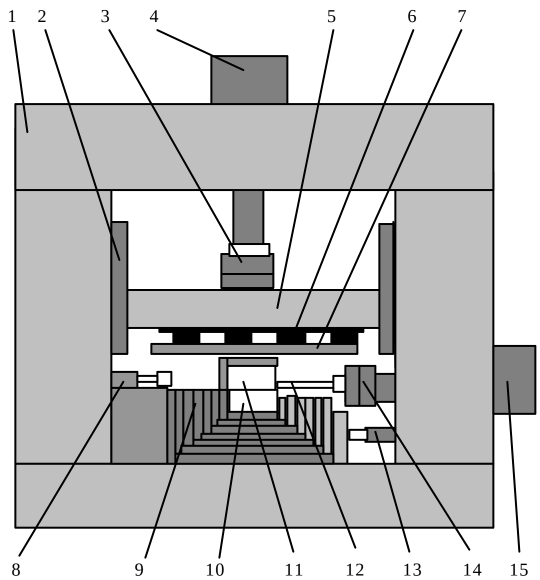

Fig. 3: Structure of integrative direct shear apparatus, 1: Frame, 2: Guide, 3: Force sensor, 4: Servo cylinder, 5: Bearing frame, 6: Roller, 7: Loading plate, 8: Resetting device, 9: Pad, 10: Upper half of specimen, 11: Lower half of specimen, 12: Force transmission block, 13: Compressing device, 14: Force sensor, 15: Servo cylinder

10% of maximum load. Load overlay region between small device and big device is 10-200 KN. Specimen overlay region is 30×30-40×40 cm^2. Overlay region provides a checkout for test results. So, the two devices form an integrative direct shear apparatus.

Structure of apparatus: The structure of big device (Fig. 3), belongs to the integrative direct shear apparatus, is similar to small device. It is made of normal loading mechanism, tangential loading mechanism, frame, subsidiary mechanism, hydraulic system and control system. Normal loading mechanism (made of servo cylinder, force sensor, bearing frame, roller and loading plate) is used to load normal loading and tangential loading mechanism (made of servo cylinder, force sensor and force transmission block) is used to load tangential loading. In order to improve the accuracy and reliability of apparatus, subsidiary mechanism has been used as described follows:

- Every lower half of specimen with different size is elevated to the same height by way of placing a number of pads. So the height of tangential loading mechanism can be fixed. In addition, the extended distance of servo cylinder in the normal direction can be reduced
- Different length of force transmission block can be changed according to the specimen size. So the extended distance of servo cylinder in the tangential direction can be reduced
- Guides are used to bear tangential load and moment;
- Compressing device is used to compact the lower half of specimen
- Resetting device is used to reset upper half of specimen

In addition, the specimen has been transported by handcart installed four retractable wheels.

Working principle of the integrative direct shear apparatus can be described as follows: A number of pads according to the size of specimen are placed on handcart. Then, specimen is placed on the top of pads. Next handcart is pushed to designated spot of apparatus and its wheels are retracted to make sure that the baseboard of handcart is up-close contact to the frame. Then, a number of pads according to the size of specimen are placed on the side of specimen and they are compacted by compressing device. Then, normal loading is loaded by 5 load steps and kept on a constant value. Then tangential loading is loaded by 10 levels until the obvious relative movement happens between upper half of specimen and lower part of specimen. At last, the curves and data are output by self-developed software.

Hydraulic circuit: Loading power source is provided by a designed hydraulic system (Fig. 4). The characteristics can be described below:

- Electromagnetic relief valve is used to change system pressure. Solenoid valve in electromagnetic relief valve attracts when servo cylinder is not working. So, oil directly returns to tank through electromagnetic relief valve which can reduce the caloric of hydraulic power unit
- Servo valves are used to control the working pressure and working speed. Loop feedback system, made of PC, force sensor, displacement sensor, has been used to adjust the state of servo valves according to loading and rate all the time
- Accumulators are installed on oil channel to get stable pressure in the testing process by absorbing or adding pressure
- The radiator is installed to reduce the caloric of hydraulic power unit in order to meet long time work for device

Control system: The Controller has a load channel with a resolution of ±180,000 steps and an incremental position channel with a controlled ±10Volt output for power amplifiers. It has been designed for static and dynamic testing instruments by way of controlling servo valve. The frame of control system has been showed in Fig. 5.

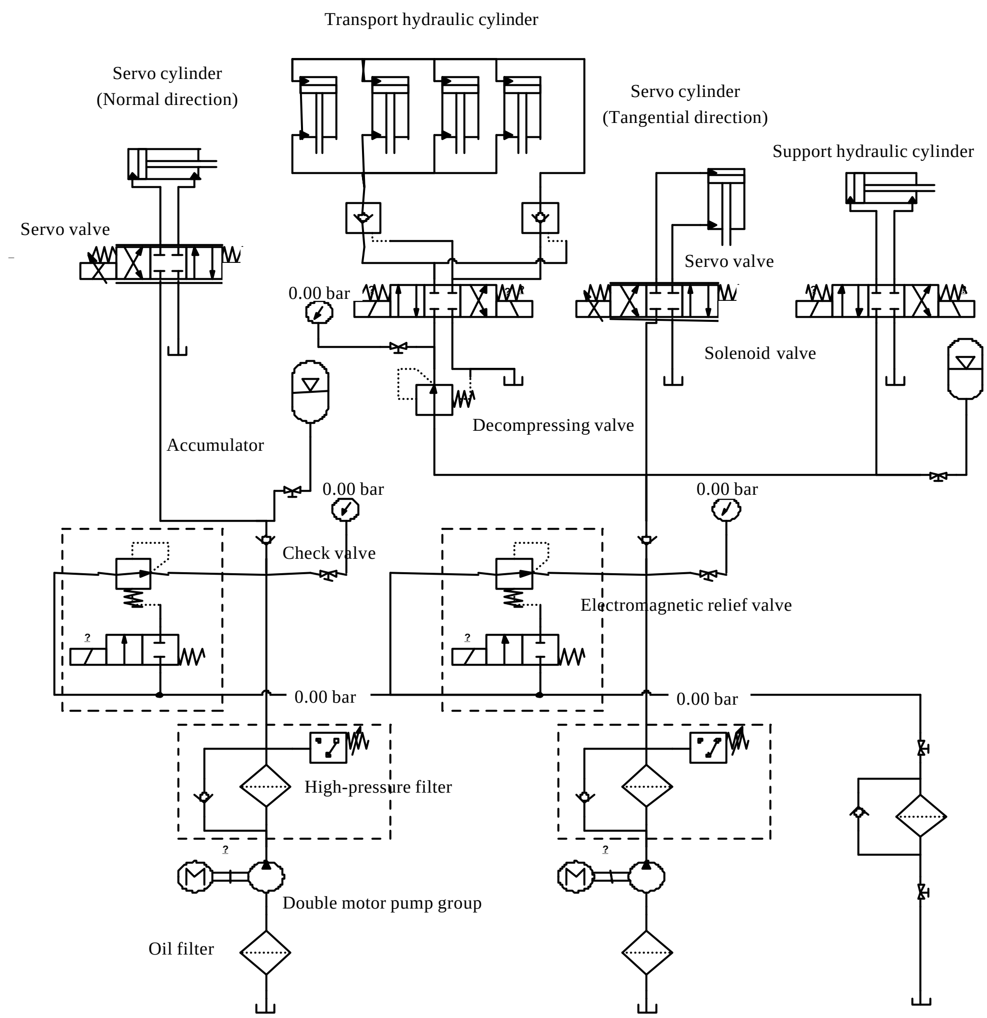

Fig. 4: Hydraulic circuit of the big device

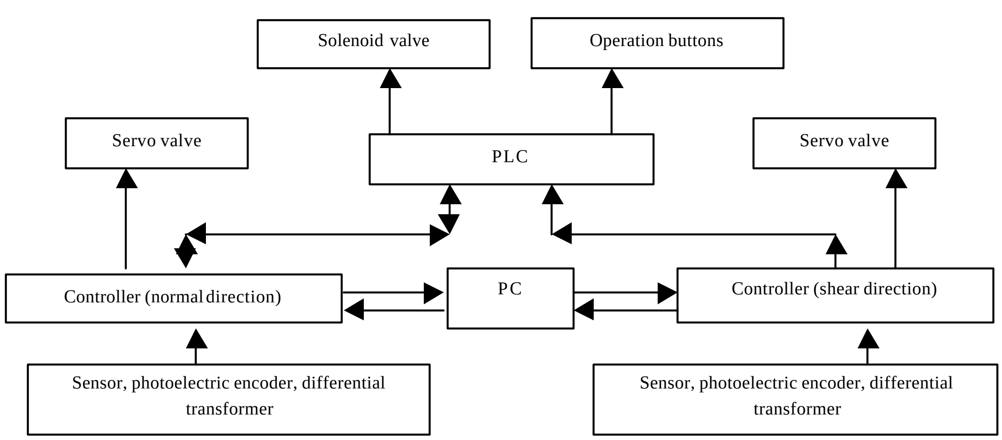

Fig. 5: Frame of control system

The control precision requirements of normal load and tangential load are achieved by way of the digital PID fuzzy control method. The data processing is achieved by computer. Displacement control is achieved by photoelectric encoder. Load control is achieved by sensor. Deformation control is achieved by differential transformer.

The whole control process includes force control and displacement control. Force control means that servo cylinder loads and keeps to a constant value. Displacement control means that the piston rod of servo cylinder moves at a constant speed. It belongs to force control before obvious relative motion happens between upper half of specimen and lower half of specimen. Otherwise, it belongs to displacement control. How to change from force control to displacement control or how to obtain the peak load is a key technology. Peak point can be set up in advance according to the experience. Namely, once load control reaches and gotten the peak point, the control system automatically converts to displacement control.

EQUIPMENT MANUFACTURE AND TESTING

In order to verify the reasonableness of the integrative direct shear apparatus, it has been manufactured and tested. The performance has been verified and gotten good results. Multi-scale specimens have been showed in Fig. 6. The prototype has been showed in Fig. 7.

One random and maximum rock mass which cross section is 100×100 cm^2, is used to illustrate the performance of the big device. It has been loaded by 5 load steps and kept to 1000KN in normal direction. Then it has been loaded to 1000 KN in 10 steps by tangential loading before obvious relative motion happens between upper and lower half of specimen. Once load value in tangential direction reaches the peak point, the control system automatically converts to displacement control. It can be gotten from the curve showed in Fig. 8. Shear load with the variation of shear displacement also can be gotten in Fig. 9. Another random and maximum rock mass which cross section is 30×30 cm^2, is also tested in big device. The results have been showed in Fig. 10. The results show that rock mass discontinuity has the peak shear strength and the nearly linear variation for the peak and residual strengths which is consistent with theoretical results. The performance of small device is also verified and gotten good results.

The accuracy of integrative direct shear apparatus reaches user requirements by a number of testing results within a year.

Fig. 6: Multi-scale specimens

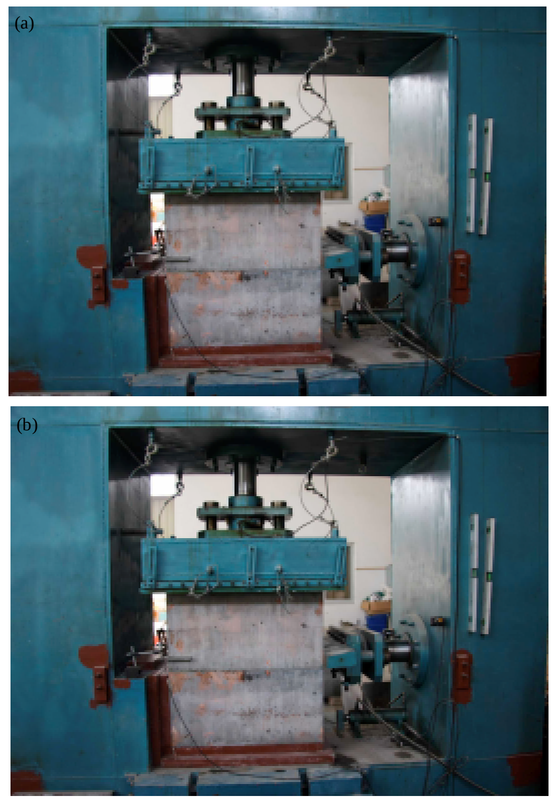

Fig.7: Integrative direct shear apparatus (a) Big device and (b) Small device

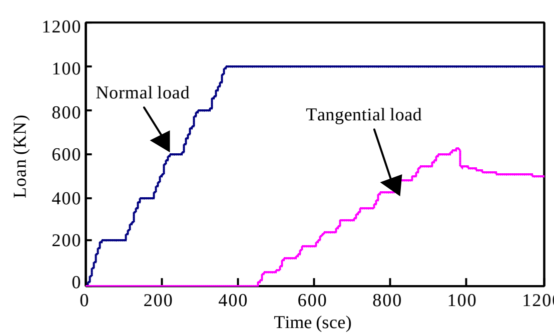

Fig. 8: Normal and tangential load variation

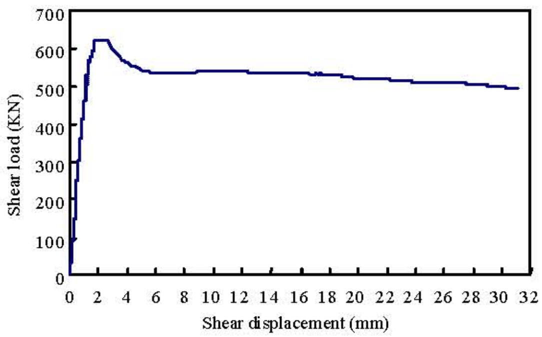

Fig. 9: Shear load with the variation of shear displacement

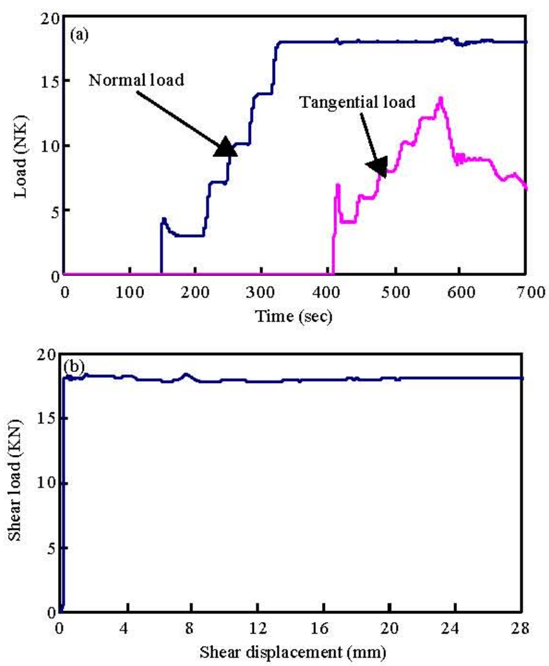

Fig. 10(a-b): Test results of a specimen with 30×30 cm^2

CONCLUSION

An integrative direct shear apparatus has been designed and manufactured to research scale-effect of rock mass discontinuity. The characteristics of apparatus can be summarized as follows:

- It meets the multi-scale rock mass discontinuity for 10×10 cm^2-100×100 cm^2 by two devices. To meet overall measurement accuracy, overlay region has been set up to check the accuracy of two devices, where common upper or lower specimens and its corresponding load values can be tested in respective device
- A large number of testing results show that the integrative direct shear apparatus has a good stability. Automatic gathering and recording have been realized by controller. Many kinds of curves, such as normal and tangential load variation, can be drawn automatically by self-developed software
- A number of testing results show that the accuracy of integrative direct shear apparatus reaches user requirements. For example, the curve of Shear load-shear displacement is consistent with the results tested by conventional direct shear apparatus.

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