THE HONG KONG GEOTECHNICAL CENTRIFUGE AND ITS UNIQUE CAPABILITIES

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ABSTRACT

Recently there has been rapid development in geotechnical centrifuge modelling technology world-wide, and centrifuge testing is now commonly used for reduced-scale physical modelling of geotechnical and geo-environmental systems. In this paper, a new 400 g-ton state-of-the-art geotechnical centrifuge facility in Hong Kong is introduced and some of its unique and advanced capabilities such as in-flight bi-axial shaker, 4-axis robotic manipulator, and data acquisition and control system are described. This facility is dedicated to serve not only the University but also the entire geotechnical community in Hong Kong and around the world.

KEYWORDS: Geotechnical centrifuge, bi-axial shaker, robotic manipulator, geophysical modelling

1. Introduction

As illustrated in Figure 1, geotechnical centrifuge modelling has now become a widely-used modelling tool to complement more conventional numerical analysis and field testing or monitoring (Schofield, 1980 & 1998; Ko, 1988; Van Laak et al., 1994; Ng & Springman, 1994; Ellis et al., 1995; Ng et al., 1998a & b; Kimura, 1998). Each approach has its own advantages in terms of quality of result, time and cost. Particularly in cases where there are uncertainties in the applicability of a proposed design methodology, use of more than one approach permits calibration of results against each other and verification of conclusions drawn.

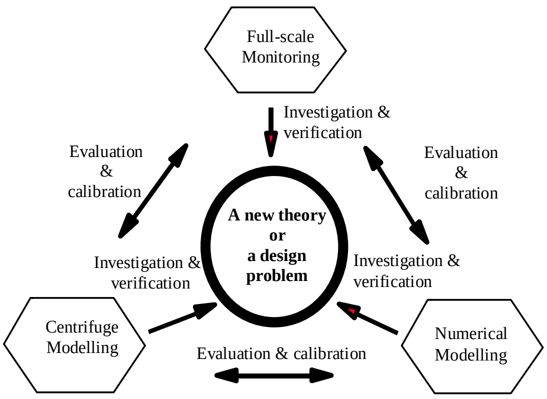

Figure 1 The inter-relationships between field monitoring, numerical and centrifuge modelling

2. Basic principle of geotechnical centrifuge modelling

For most applications in civil engineering, the major and fundamental difference in engineering behaviour between soil and steel (or concrete) is that the behaviour of the former material is strongly dependent on stress state and stress path, whereas the latter is generally not. This implies that any laboratory or field test involving soils which fails to correctly model stress state and stress path will likely produce incorrect results. In particular, small-scale geotechnical model tests conducted under one gravity (9.81 m/s^2) can be very misleading because the stress field within the prototype is not modelled accurately, leading to incorrect dilative instead of contractive behaviour at low stresses. How to create a correct stress field effectively and economically for physical modelling of geotechnical problems has been a major challenge for engineers and researchers for many years.

The basic principle of centrifuge modelling is to recreate the stress conditions which would exist in a full-scale construction (prototype), using a model on a greatly reduced scale. This is done by subjecting the model components to an enhanced body force, which is provided by a centripetal acceleration of magnitude *ng*, where *g* is the acceleration due to the Earth gravity (i.e. 9.81 m/s^2). Stress replication in an *n*th scale model is achieved when the imposed "gravitational" acceleration is equal to *ng*. Thus, a centrifuge is suitable for modelling stress-dependent problems. Moreover, reduction of time for model tests such as consolidation time can be achieved by using a reduced size model.

Figure 2 shows a plan view of a model earth dam rotating at a constant angular velocity ($d\theta/dt$) in a centrifuge test. For a typical static model test, $r(d\theta/dt)^2$ provides the artificial "gravitational" acceleration *ng*, which is used to increase the body force of the model.

2.1 Scaling Laws

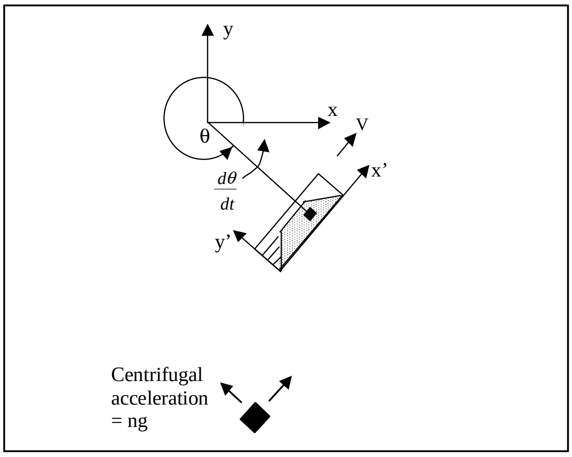

Figure 2 A plan view of model dam in a centrifuge test

For centrifuge model tests, model laws are generally derived through dimensional analysis, from the governing equations for a phenomenon, or from the principles of mechanical similarity between a model and a prototype. Some commonly used scaling laws are summarised in Table. 1.

It can be readily deduced from Table 1 that the stress level of a 100m tall slope can be correctly modelled by using a 1-metre slope model when it is subjected to an elevated "gravitational" acceleration of 100g (i.e., *n=100*). Also, a four-hour centrifuge modelling at 100g can correctly simulate a prototype soil settlement problem consolidated for more than 4.5 years (i.e., $4xn^2$ or $4x100^2$ hours). Substantial time reduction and hence cost savings can be achieved by adopting the centrifuge modelling technique.

3. Development of the Hong Kong Geotechnical Centrifuge Facility

One of the largest and most advanced geotechnical centrifuges in the world is being commissioned on the campus of the Hong Kong University of Science & Technology (HKUST). Figure 3 shows the comparisons of capacity between the HKUST centrifuge and others in the world.

Table. 1 Some common scaling laws for centrifuge tests

Parameter	Scale (model/prototype)
Acceleration	n
Linear dimension	1/n
Area dimension	$1/n^2$
Volume dimension	$1/n^3$
Stress	1
Strain	1
Mass	$1/n^3$
Density	1
Unit weight	n
Force	$1/n^2$
Bending Moment	$1/n^3$
Bending Moment / unit width	$1/n^2$
Flexural stiffness / unit width	$1/n^3$
Time (dynamic)	1/n
Time (consolidation/ diffusion)	$1/n^2$
Time (creep)	1
Pore fluid velocity	n
Concentration	1
Velocity (dynamic)	1
Frequency	n

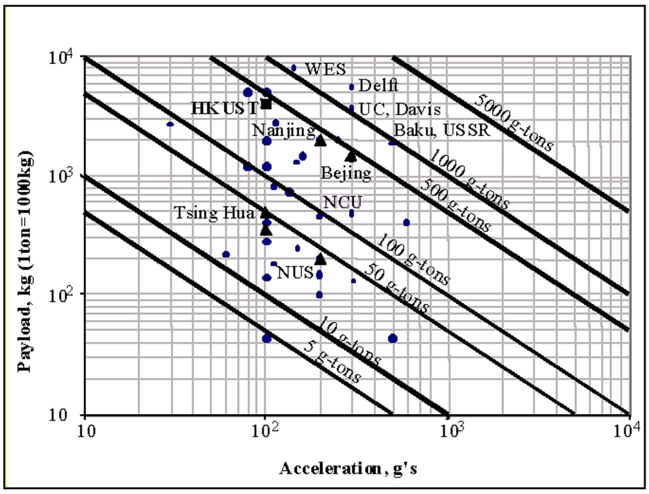

Figure 3. Capacities of major geotechnical centrifuges in the world

The centrifuge is installed in a new building, located a short distance from the main academic building on campus. The centrifuge facility has a total of 255 m^2 of office and general laboratory space. In the main laboratory area, a 20 tonne capacity overhead gantry crane is available to move the pre-cast concrete panels above the centrifuge enclosure and to load and unload the centrifuge model containers. The crane is also used to interchange the static platform and shaker when required. The unused platform or shaker is stored in a recess in the floor of the centrifuge enclosure. The centrifuge is monitored using CCTV cameras and microphones, and an intercom is used to communicate between the centrifuge chamber and control room during model checkout. The hydraulic power supply is located below the main laboratory area in a room adjacent to the centrifuge.

Figure 6 shows details of an elevation view of the centrifuge. The centrifuge arm is supported on a vertical drive shaft running on a pair of pre-loaded tapered

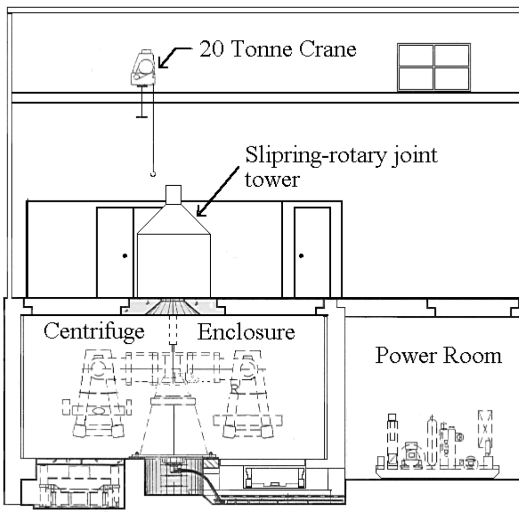

Figure 4. Elevation view of the centrifuge facility

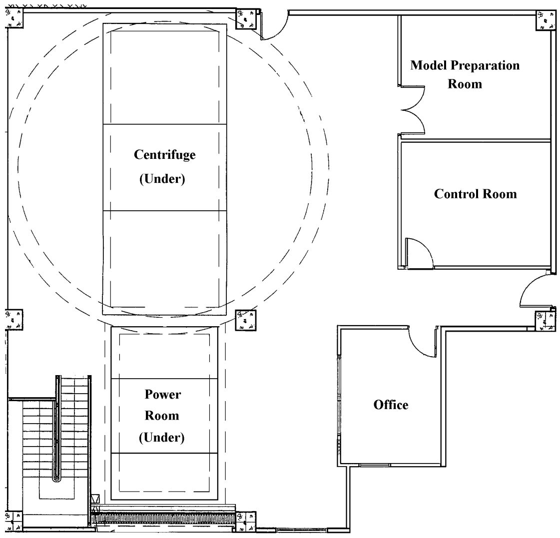

Figure 5 Plan view of the centrifuge facility

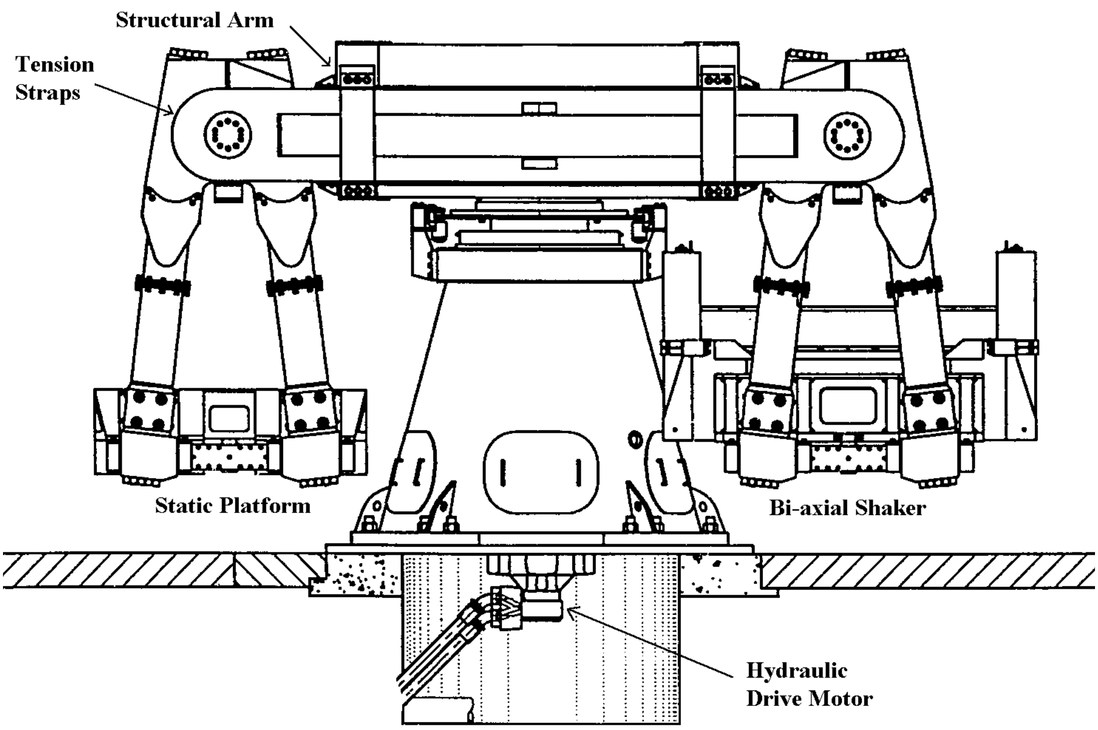

Figure 6 The HKUST 400 g-ton Centrifuge

roller bearings. It is driven by a hydraulic radial piston motor directly coupled to the lower end of the vertical drive shaft. Balancing of the centrifuge is accomplished using weights of various sizes placed on the platform not used for the model container. Careful bookkeeping is used to ensure the centrifuge is closely balanced to maintain stresses within structural limits and to prolong bearing life.

The 400 g-ton centrifuge has a rotating arm of 3.4 metres nominal radius. In total, three swinging platforms have been manufactured. Two platforms are identical and are designed for non-shaking tests. Each of these 'static platforms' can accommodate a model of up to 1.5m x 1.5m x 1m in size and up to 40,000 N in weight. The third platform comprises the bi-axial shaker and associated structural supports, hydraulic manifolds and reaction mass. The shaker slip-table can accommodate payloads of up to 0.6m x 0.6m x 0.4m and up to 3000 N in weight.

Table 2 summaries some key specifications for the centrifuge. Note that for static tests, the centrifuge can be operated at up to 150g whereas for dynamic tests, the bi-axial shaker is designed to operate at up to 75g.

The centrifuge drive uses a variable volume pressure compensated pump driven by 150 kW electric motor. A computer is used to control the centrifuge and the shaker. Besides controlling the speed of the centrifuge, the computer is used to monitor operational parameters such as imbalance forces in the arm, temperature of the main bearings, hydraulic fluid temperature and pressure, and status of safety interlocks. The computer is also used to implement the sequence of valving operations required for operating the shaker system during shaking tests. Input data and measured parameters from each run are automatically logged to the computer hard disk to facilitate long-term monitoring of machine performance and scheduling of routine maintenance.

A fluid rotary joint is provided for supplying pressurized air, water, and hydraulic fluid to instrumentation mounted on the centrifuge during spinning. An electrical slip ring assembly is provided for transmitting electrical power and signals to and from centrifuge instrumentation, for control of various devices and acquisition of experimental data. Some specifications for the assemblies are given in Table 3.

4. The bi-axial shaker

The HKUST centrifuge incorporates a bi-axial servo-hydraulic shaker, to be used for simulated seismic excitation. In consideration of the facts that earthquake motions are multi-directional in nature and that many uni-directional centrifuge earthquake simulators are already available, HKUST decided to develop a bi-axial shaker in order to simulate earthquake motions in two horizontal directions simultaneously.

Because large shaking forces in two directions are possible with this shaker, development of the centrifuge and the shaker was carried out simultaneously, with the shaker designed as an integral part of the centrifuge. This integrated approach to the design was adopted in order to isolate the shaking forces from the centrifuge to as large an extent as possible and to produce high quality shaking motions.

To facilitate installation and maintenance, and to permit operation of the centrifuge at accelerations greater than 75 g for static tests, the shake table and its bucket form a single assembly that is removable from the suspension arms and replaceable by an optional static bucket.

With a payload weight of 3000N, the total moving weight (payload and shake table hardware) is about 10,000N. To optimize the dynamic behaviour of the in-flight shaker, a large reaction mass (4000 kg) has been incorporated into the design. The shake table is supported by hydrostatic self-aligning pad bearings, and utilizes two pairs of servo-actuators for each of the shaking directions (one pair in the tangential direction of the centrifuge rotation and the other in the direction of bucket swing-up). Each pair of actuators is located on opposite sides of the shaking platform and corresponding pairs are

Table 2. Technical specifications for the centrifuge.

Key item	Specification
Payload capacity	400 g-tons
Arm radius	4.2 m to the base of the swinging platform
Maximum acceleration	150g (Static tests) 75g (Dynamic tests)
Payload size	1.5mx1.5mx1m for static tests, 0.6mx0.6x0.4m for dynamic tests

Table 3. Specifications of slip ring and rotary joint assembly.

Key item	Specification
Slip rings	32 for analog signals, 8 for analog return, 16 for power
Co-axial cable channels	8 for video, and high frequency equipment, 4 high quality for digital signals (computer network)
Air ports	2 at 700 kPa, 0.05 m^3/min
Water ports	2 at 1400 kPa, 40 liters/min

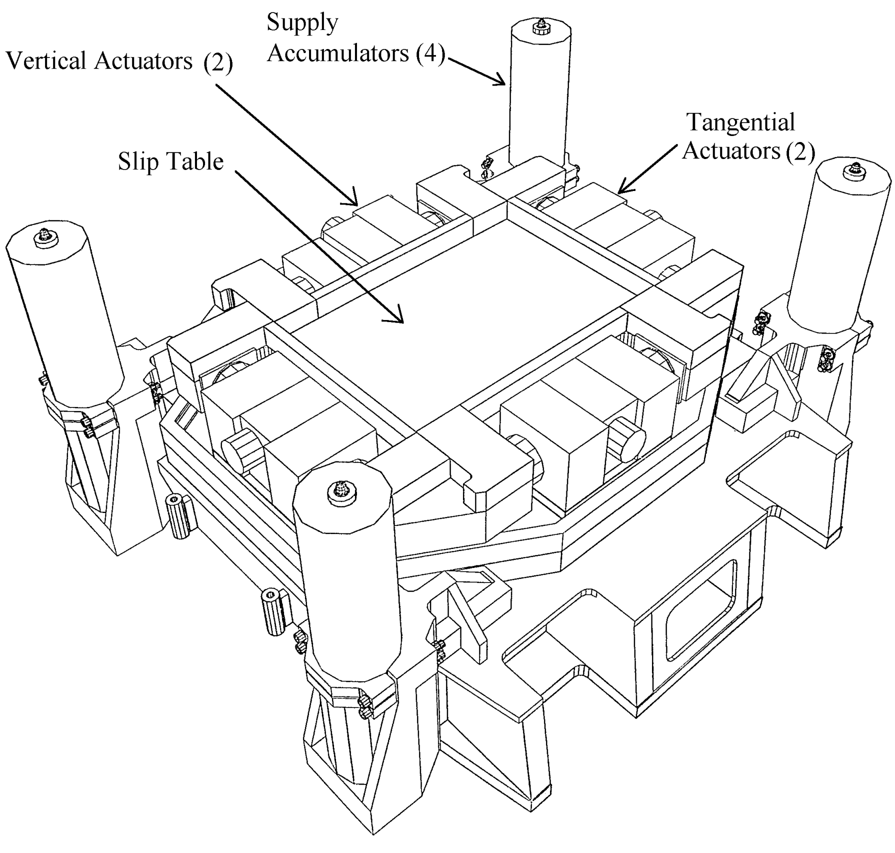

Figure 7 The bi-axial shaker

designed to act as a unit, applying identical forces to each side of the slip table. The motion of the slip table is then ostensibly a superposition of translations in the two orthogonal directions, with no rotations in the plane of shaking.

The shake table receives oil from a 10 gpm, 35 Mpa variable volume pressure compensated pump. This pump supplies oil to the shaker through a 35 Mpa hydraulic rotary joint mounted near the top of the centrifuge. Each pair applies a force of 32,000 kgf per axis. For the moving mass of just under 1000 kg, this force yields 35 g of acceleration in each shaking direction, and for a typical seismic signal, a shaking duration of 2 seconds for each accumulator charging is achievable. Several key technical specifications of the shaker are listed in Table 4.

To achieve the target shaking motions, a combined analog and digital control system is used. The analog portion of the controller is used primarily to eliminate the actuator redundancy by using pressure feedback to prevent actuator ‘fighting’. The digital shaking control system is implemented using a computer equipped with a high speed analog/digital interface. By using an error correction algorithm, the digital controller can accurately generate a variety of input shaking motions, including simple harmonic motions and scaled earthquake motions.

5. The 4-axis robotic manipulator

An advanced 4-axis robotic manipulator (second of its kind in the world) has been developed for simulating details of construction activities such as soil nailing, pile driving, tunnelling and excavation in-flight (Figure 8). The robot incorporates a standard tool changer to permit interchanging tools without need for stopping the centrifuge. It can operate either in accordance with a sequence of pre-programmed instructions, or in response to real-time commands from an operator, in a “fly-by-wire” mode of operation. Key specifications are listed in Table 5.

6. Data Acquisition and Control System

A new state-of-the-art distributed data acquisition and control system has been developed to support sophisticated modelling activities. The system uses multiple networked data acquisition servers to provide high-speed real time data acquisition on a large number of input channels. Custom-designed computer-controlled signal conditioning provides adjustable amplification of low-level signals from measurement transducers at the source, providing signals of very high signal-to-noise ratio and exceptionally high quality. A dedicated file server is used to archive experimental data. In addition, a relational database is used to store all information required to accurately interpret data acquired during testing.

An additional benefit of using a networked system is that it is possible to make test data available to researchers in widely dispersed geographical locations over the internet via a specially designed web page. This capability, which is currently being developed at HKUST, will make it possible for clients to view experimental data in nearly real-time and to interact with the centrifuge operator while a test is in progress. Once the test is finished, the complete experimental data set can be accessed remotely via the web page for further analysis.

7. Ancillary equipment

Several model containers have been developed. One is a rectangular aluminum container, designed for static tests, having inside dimensions of 1270mm x 1245mm x 850mm, and incorporating an optional acrylic window. The container has been designed to limit average strains within the model to 0.025% during spin-up. For dynamic tests, a laminar-type flexible walled container has been developed. This container is cylindrical in shape, with an inside diameter of 550mm and a height of 500mm. The container is constructed of fifty-two aluminum rings, with roller

Table 4. Technical specifications for the shaker.

Key item	Specification
Shaking direction	Two prototype horizontal directions
Maximum shaking acceleration	35g
Maximum shaking velocity	750 mm/sec
Shaking frequency	0-350 Hz

Table 5 Key specifications for the HKUST Robotic Manipulator

Key item	X-axis	Y-axis	Z-axis	θ-axis
Stroke	1.008m	0.839m	0.305m	270 °
Maximum Speed	6.67 cm/s	6.67 cm/s	3.47 cm/s	10 °/s
Accuracy	1.0 mm	1.0 mm	1.0 mm	1.0 °
Load Capacity	1000N	1000N	5000N	5 N-m

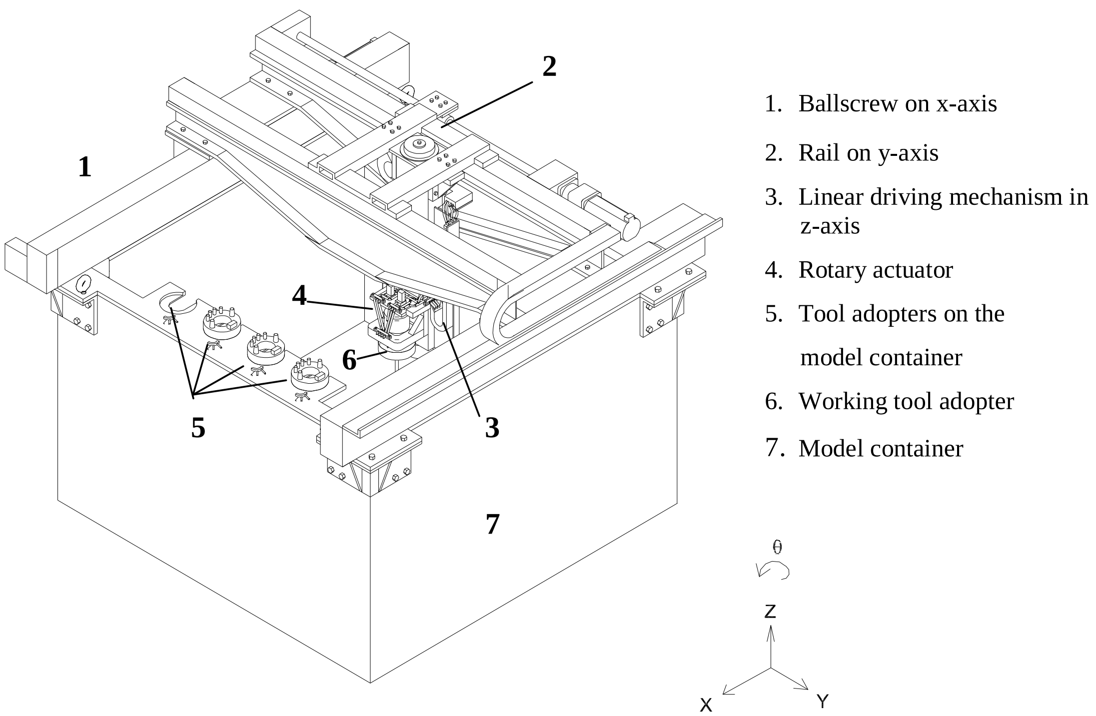

Figure 8 The 4-axis robotic manipulator

bearings used to provide the low-friction interface between adjacent rings. The laminar container has been designed to provide the necessary model boundary conditions for bi-directional shaking.

8. Summary

The state-of-the-art 400 g-ton geotechnical centrifuge at the Hong Kong University of Science and Technology is equipped with a unique bi-axial shaker, an advanced robotic 4-axis robotic manipulator and a modern data acquisition and control system. It represents a unique research facility that will be used to help academia and the construction industry advance their knowledge and technology in the 21st century.

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