The ISMGE Seismic Geotechnical Centrifuge

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ABSTRACT: The ISMGE seismic geotechnical centrifuge (ISGC) is a medium size beam centrifuge, made up of a symmetrical rotating arm with a diameter of 6 m. The centrifuge has the potential of reaching an acceleration of 600g at a payload of 4 kN. In 2010 it was equipped with a 1-degree of freedom shaking table. The table works under an acceleration field up to 100g, it can provide excitations at frequencies up to 1000 Hz and acceleration up to 50g and it is able to reproduce real earthquakes at the model scale. The main features of the table and example of applications in two research projects are described in this paper.

1 INTRODUCTION
The geotechnical centrifuge of the Istituto Sperimentale Modelli Geotecnici (ISMGE, formerly ISMES – Italy) is a beam centrifuge made up of a symmetrical rotating arm with a diameter of 6 m, a height of 2 m and a width of 1 m, which gives it a nominal radius of 2 m. The arm holds two swinging platforms, one used to carry the model container and the other the counterweight; during the test, the platforms lock horizontally to the arm to prevent transmitting the working loads to the basket suspensions. An outer fairing covers the arm and they concurrently rotate to reduce air resistance and perturbation during flight.

The centrifuge has the potential of reaching an acceleration of 600g (g = gravity acceleration) at a payload of 400 kg. The maximum dimensions of the model are: length = 1 m, height = 0.8 m, with = 0.5 m; further details can be found in Baldi et al. (1988). Figures 1 and 2 show a scheme and a picture of the centrifuge.

The unusual shape of the arm offers the following advantages:
• small distortion of the centrifugal field in the model, since its main dimension is parallel to the rotation axis;
• low deflection of the support plane of the swinging basket;
• easy location of instruments close to the rotation axis because of the absence of a central shaft across the arm.

From 2010 the centrifuge, hereafter simply called ISGC, houses a single degree of freedom shaking table, which is able to reproduce real strong motions at the model scale. The axis of motion of the shaker is parallel to the centrifuge rotational axis, thus problems related to Corioli’s acceleration are avoided. The shaker is not integrated into the swinging platform, but it is directly connected to the rigid arm: the platform which holds the model container is moved into contact with the table in flight and released before dynamic excitation starts. The shaker excitation is transferred from the slip table to the model container entirely through mechanical coupling. The table works under an acceleration field up to 100g, it can provide excitations at frequencies up to 1000 Hz and acceleration up to 50g (depending on the driving load).

This paper presents the main characteristics of the table and examples of applications in two research projects carried out:
• the modelling of a shallow landslide stabilization with large-diameter rigid shafts in static and dynamic conditions;
• the seismic response of an embankment simulating the seismic behavior of the right bank of the Po river.

2 THE ISMGE SHAKING TABLE
2.1 Mechanical features
The shaker installed in the ISGC was designed by TEAM corporation. Its main characteristics are given in Table 1. The operating map of peak accelerations is shown in Figure 3.

The shaker is capable of reproducing single degree of freedom strong motions at the model scale. Unlike most centrifuge shaker solutions, where the shaker is integrated into the swinging basket (Derkx
et al., 2006, Imamura et al., 1998, Ma et al., 2006, Matsuo et al., 1998, Shen et al., 1998, Van Laak et al., 1998), the ISGC shaker was designed specifically to fit on the centrifuge arm (see Figure 4). The symmetric arm is of a particularly rigid construction, which makes it suited as reaction base for the shaker. The model container is moved into contact with the shaker slip table in flight and released before model dynamic excitation starts; the shaker forces are transferred from slip table to model container entirely by friction.

Two dynamically matched back-to-back mounted integrated shakers drive the slip table. These consist in an actuator driven by a two-stage V-100 servovalve, and pressure and return side accumulators that improve frequency response. The actuator pistons are coupled, through hydrostatic pad bearings that allow rotation and lateral sliding between contact surfaces, to sliding beams fixed to the slip table. This configuration was chosen to maximize load capacity and actuator force in a compact construction that can fit into the available space. Hydrostatic T-film bearings support the slip table vertically by an oil film on the top surface of the T-film bearing housings and actuator bodies and restrains it axially with sliding beams running in hydrostatic bearing T-slots. This bearing system gives very low friction and high dynamic stiffness. All bearings are unsealed to improve reliability and reduce maintenance, which creates a major leakage flow collected in the shaker moat.

Pressure transducers located in the actuator chambers give pressure feedback and an LVDT mounted on the actuator body and connected to the sliding beam gives position feedback.

The external view of the table is shown in Figure 5. The table without the slip plate is shown in Figure 6: the T-Film bearings are located at the four corners, the Integrated Shakers are located between the bearings.

2.2 Control system

Driving a slip table with more than one actuator with separate lines of action requires that the actuators operates at the same force and in phase throughout the frequency band, to avoid the generation of a moment. The T-film bearings to which the slip plate is mounted have a very high dynamic load capacity. The bearings prevent large dynamic cross axis motions and their presence eases the requirement for precise phase and amplitude control.

In the ISGC the two actuators are driven by a two-stage servo-valves, the first is master, controlled by a T-2200 servo-controller, and the second is slave. The actuators need to be closely synchronized to avoid application of static moments to the sensitive hydrostatic T-film bearings. This is accomplished by force control. As the actuators are double-acting, force is equal to the actuator piston cross-
Figure 4. Lateral view of the centrifuge arm with shaker installed.

Figure 5. Picture of the shaking table.

Figure 6. Slip Plate removed, view along axis of motion.

\[ F_{\text{actuator}} = A_{\text{piston}} \Delta p \]

Hence, by monitoring the \( \Delta p \), the actuators can be dynamically matched. To this end four pressure transducers are installed, one for each actuator chamber, that give feedback to the servo-controllers. The servo-controller has an “outer” position control loop using the LVDT as feedback, and “inner” force control loop using the \( \Delta p \) feedback.

The design of the shaker control system includes:
- Multi-Actuator Force Synchronization Circuit (MASC) that provides an ulterior servo-loop on the \( \Delta p \) balance between actuators, \( \Delta \Delta p \).
- Monitoring and display of HPS pressure switches.
- Control of HPS solenoid valves and servo-controllers.
- Emergency stop.

The core of the shaker control and data acquisition system is an onboard industrial PC with two National Instruments PCI-6229 DAQ interface boards:
- Analog Inputs: 32 SE/16 DI, 250 kS/s, 16 bits
- Analog Outputs: 4, 833 kS/s, 16 bits
- Digital I/O: 48 DIO, 1 MHz
- Counter/Timers: 2, 32 bits, 80 MHz

One of the boards interfaces with the signal conditioning unit and the other is used for control of the shaker and hydraulic supply. In order to interface the PCI-6229 boards with solenoid valves and pressure switches on the HPS, NI SCB-68 terminal boards connected to Grayhill DC Input and Output modules are used.

The shaker control software is located on the onboard industrial PC, which is remote-controlled by a control room Laptop PC via a Gigabit LAN network. The interface between the centrifuge side rotating part of the network and the control room side fix part of the network is accomplished by electrical rotary joints both for power (higher level) and signals (lower level). The remote control configuration minimizes time lag in the control system and guarantees a controlled shutdown even if the network should be interrupted.

2.3 Data acquisition system

The signal conditioning is provided by an onboard National Instruments Chassis with modules containing:
- 24 channels of strain/bridge signal conditioning
- 16 channels of ICP accelerometer signal conditioning
- 8 channels of LVDT conditioning
- 32 channels of general purpose programmable amplifiers

The data acquisition software is located on the onboard industrial PC and remote-controlled from the control room PC via the Gigabit LAN network.

2.4 Waveform replication software

Motion is controlled by a Signal Star Vector controller produced by Data Physics Corp, which provides a comprehensive system satisfying all modes of vibration testing: Random, Sine, Resonance Search and
Dwell, Classical Shock, SRS, Transient, Sine on Random vibration testing, Random on Random, and FFT Analysis.

The shaker is a nonlinear dynamic system. The input – output relationship is therefore function of excitation frequency, amplitude and payload. In order to accurately replicate acceleration time histories, an algorithm is needed to compensate for nonlinearities in the system. The mapping of the input – output relationship in the form of a Frequency Response Function (FRF) is accomplished by performing tests on a dummy model with dynamic properties similar to the real test model. The FRF is then saved to a library for future use. For the rest of the test series, this motion may be recalled and applied directly onto new models, eliminating the need to calibrate for every test. Example data from a calibration is shown in Figures 7, both in the frequency and time domain of acceleration. In the Figure the target spectrum and time history are represented with green lines while the motion reproduced by the table is represented with a blue lines.

3 EXAMPLES OF APPLICATIONS

3.1 Static and dynamic centrifuge modeling of landslide stabilization with large-diameter shafts

A series of static and dynamic centrifuge tests was carried out to investigate the stabilization of shallow landslides by rigid shafts (Lai et al. 2012). The project was commissioned by the Italian Department of Civil Protection to EUCENTRE (European Centre for Training and Research in Earthquake Engineering) and it consisted in the combined use of advanced physical and numerical modeling: the former was aimed at identifying the mechanisms controlling the response of a stabilized slope under both static and dynamic loading and to calibrate an advanced numerical model of the system. The latter was aimed at performing parametric analyses at a prototype scale in order to develop a simplified methodology for the design of large diameter shaft systems to reinforce unstable slopes under various geological and geotechnical conditions.

The centrifuge models reproduced a shallow landslide on a rock slope 32° steep, reinforced by 3.5 m diameter shafts. The adopted geometrical scaling factor of the models was N=50. Three models were tested, both under static and dynamic loading conditions: the unreinforced landslide and the landslide reinforced with one or three aligned piers. During the tests one model shafts was instrumented with strain gauges to measure bending moments.

In the static tests, the shallow landslide was triggered by a displacement-controlled piston which pushed down the top of the slope through a rigid slab which imposed uniform displacements along the slope direction. During the tests the displacements of the sliding mass were monitored through a series of potentiometers. The effect of the insertion of one or three piers was estimated comparing the displacement field of the landslide with and without the reinforcing shafts. In the dynamic tests a real, properly-scaled time history was applied to the models using the ISGC shaking table. Five accelerometers were embedded into the physical models to measure the seismic excitation and response. An additional accelerometer measured the acceleration in the shaking direction at the rigid base of the models. Figure 8 shows a cross section and a plane view of the unreinforced and stabilized models used in the dynamic tests. As input motion a real, properly scaled acceleration time history was applied to the models using the ISGC shaking table. Five accelerometers were fitted on the models to measure the seismic excitation and response.

The motion was selected from a set of 7 compatible spectra specified for Garfagnana territory, in Tuscany region, Italy (Lai et al. 2008). The time history of acceleration and the pseudo-acceleration spectrum of the input motion are represented in Figure 9 (a) and (b), respectively.

The pseudo-acceleration spectra PSA of the motions measured during the tests with three aligned piers are plotted at the prototype scale in the Figure 10. The PSA of the applied earthquake, measured by the accelerometer ACCB (at the rigid substratum), is compared with the PSA of the record measured

![Figure 7](image-url) Reference time history (green line) and motion reproduced by the table (blue line).

![Figure 8](image-url) Layout of the dynamic tests (model scale): cross section and plane of (a) the unreinforced model, (b) the stabilized model. All dimensions are in mm.
within the sand downstream (ACC5) and upstream (ACC4). The reinforced slope resulted stable under the earthquake loading while the test results clearly show evidence of ground amplification within the soil mass.

3.2 Centrifuge tests to evaluate the Po river bank seismic response

On behalf of the Italian Department for the Civil Protection, the Po River Basin Authority carried out a research project to evaluate the seismic hazard of about 90 km of the right bank of the Po river, from Boretto (Reggio Emilia Province) to Ro (Ferrara Province). The project consisted in the evaluation of 1) the regional seismic risk of the areas under study, 2) the bank and foundation soil properties, 3) the local seismic response of the ground foundation, 4) the liquefaction risk and 5) the evaluation of the static and dynamic bank stability. Centrifuge tests were carried out on model embankments to study their seismic response and dynamic stability (Giretti et al. 2012).

The physical model tests were carried out using the ISGC. The bank models were reconstructed using silty and sandy soils retrieved in situ during the boreholes realized at one of the investigated sites (Casaglia, Ferrara Province), which was assumed as reference site. Four different models were tested: two geometries and two soil profiles of the levees were adopted, as evidenced in Figure 11. For each model four tests were carried out, using four different input motions, applied at the bottom of the model levee. The input motions were the results of a seismic ground response analysis carried out referring to the Casaglia site. The adopted geometrical scaling factor of the models was N=50. The models were reconstructed within a rigid container under plain strain conditions. The models were instrumented with six miniaturized accelerometers, one installed at the container bottom (ACCX B) and five embedded within the model banks, at variable heights from the bottom (ACCX 1-5). The results of the test on the model M1-1, subjected to one of the input earthquake are reported in Figure 12; all the results are plotted at the prototype scale. Figure 12 shows the time histories of acceleration along the height of the bank and evidences that the amplification increased as the distance from the base increases, due to amplification effects of the embankment. The amplification effects are also evidenced in Figure 13 where the Fourier amplitude spectra of acceleration are reported. The amplification is significant in the range of frequency of 2.5 – 25 Hz and increases from the base towards the crest. The measures of top accelerometers (ACCX 4 and ACCX 5) evidence slightly higher amplification effects at the crest center than at the edge.

4 REFERENCES


Figure 11. Model configurations and dimensions. All dimensions in mm.

Figure 12. Model M1-1. Time histories of the acceleration along the bank height for one of the input motions.

Figure 13. Model M1-1. Time histories of the acceleration along the bank height for one of the input motions.
