The ISMGEO geotechnical centrifuge (formerly ISMES Geotecnica)

The ISMGEO geotechnical centrifuge (IGC) is a beam centrifuge with a symmetric rotating arm that holds two swinging basket, that contain the model and the counterweight (fig. 1). An outer fairing, which rotates with the arm, has an aerodynamic purpose of limiting the air friction in reaching the limit speed with low power consumption (Baldi et al., 1988). The IGC is a medium size centrifuge with a capacity of 240 g-ton, which has designed to reach a limiting speed of 600g with a payload of 400 kg. The unusual shape of the arm (fig. 2 a) provides the following advantages:

- relatively 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 baskets;
- easy location of instruments close to the rotation axis due to the absence of a central shaft across the arm;
- dynamic excitation of the model in the direction parallel to the rotation axis, thus eliminating the Coriolis acceleration problem.

The nominal radius of the model is 2 m, and its maximum dimensions are: length 1000 mm, height 600 mm and width 500 mm. As centrifuge acceleration increases, the swinging baskets rotate from a vertical position at rest to a horizontal one, and then move radially to rest against the arm in order to prevent transmitting working loads to the suspension system. The propulsion system is a 300 kW D.C. electric motor.

The centrifuge is equipped with a set of hydraulic slip rings, for the oil at high pressure (250 MPa max), water and air (20 MPa max), and electrical slip rings for the power supply (7 A) and electrical signals.

Special signal conditioners, specifically developed by ISMES, have been mounted in the centre of the arm, and are programmable from the control room in terms of type of transducer to be supplied, transducer supply voltage, offset and sampling frequency; the signal conditioners are equipped with both analogical and digital outputs. A 14 bit A/D converter is employed, with a maximum sampling rate, for digital acquisition, of 100 Hz per channel for a total number of 32 channels. All operations can be completely remote controlled from the centrifuge control room.

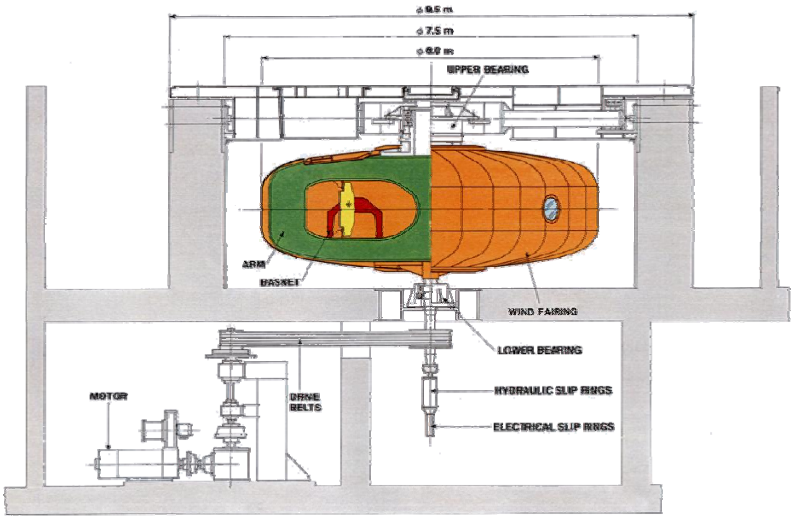
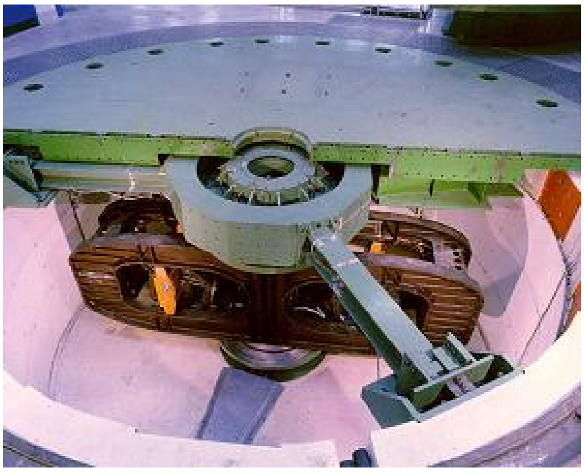
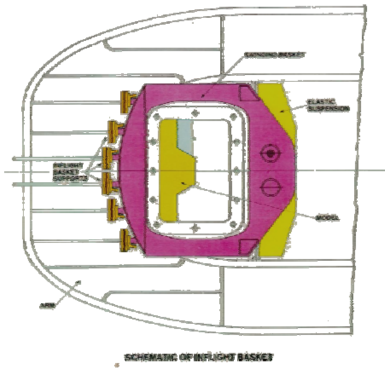


Figure 1: Cross section of the ISMES-GEO Geotechnical Centrifuge (Fioravante, 1994)





(a) (b)

Figure 2: (a) view of the machine with the deck partially removed and without the wind fairing (Baldi et al., 1988), (b) schematic of the in-flight basket (Fioravante, 1999)

Scaling laws in centrifuge modelling

The various similarity conditions between models and prototypes that have to be fulfilled in geotechnical model testing have been examined by many researches (e.g. Roscoe, 1968; Rowe et al., 1977; Schofield, 1980; Baldi et al., 1989a, Taylor, 1995; Butterfield, 1999; 2000).

For all quantities that describe static and dynamic phenomena in soil mechanics, the following ratio is defined as scale factor:

$$X^* = \frac{(X)_{prototype}}{(X)_{model}} \tag{1}$$

where X stands for a generic physical quantity (e.g. length, mass, density, or time).

If the length, the mass density, the acceleration field and the strain (also stiffness instead of strain is possible) are assumed as independent quantities, the other quantities can be expressed as functions of the independent quantities.

The critical similarity relationships between a centrifuge model and a prototype state that if a model in which each linear dimension is reduced by a factor N is subjected to a centrifuge acceleration of N x g (where g is the gravity field), it achieves the equivalent vertical stress as the full scale prototype, on condition that a material with the same unit weight is used. As the stresses derive from the density of the soil and gravitational acceleration:

$$\delta\sigma' = \rho \cdot g \cdot \delta z \quad \Rightarrow \sigma^* = \rho^* \cdot g^* \cdot L^* \tag{2}$$

If

$$g^* = N,\ L^*=1/N \text{ and } \rho^* = 1 \tag{3}$$

hence

$$\sigma^* = 1 \tag{4}$$

If the same soil is used for the model and the prototype, the stress strain behaviour of the model is the same as that of the prototype. This also means that a similarity of strain is achieved (i.e. $\varepsilon^*=1$). A summary of scaling factors for the main physical quantities of interest is given in table 1.

QUANTITY	SCALE FACTOR
Length	N
Area	N^2
Volume	N^3
Velocity (cone penetration)	1/N
Acceleration	1/N
Mass	N^3
Force	N^2
Energy	N^3
Stress	1
Strain	1
Mass Density	1
Energy density	1
Time (Dynamic)	N
Time (Diffusion)	N^2
Time (Creep)	1
Frequency	1/N

Table.1: Scale factors in an artificial gravity field

Mechanics of centrifuge modelling

The acceleration field in a centrifuge varies through the model. The centrifugal acceleration is a function of the radial distance as follows:

$$a_c = n \cdot g = R_S \cdot \omega^2 \qquad (5)$$

where:

$g = 9.81\ m/s^2$ = earth gravitational acceleration

$n = a_c/g$ = ratio between centrifuge acceleration and earth's gravity at free surface

ω = angular velocity

R_S = radial distance of the free surface of the model from the rotational axis

In equation 5, the ratio of centrifugal-to-earth gravity acceleration refers to the free surface of the model.

If, for sake of simplicity, a homogeneous soil is assumed (i.e. soil density constant with depth), the result of the previous integral is:

$$\sigma'_v = \rho \cdot g \cdot z \qquad (6)$$

Model preparation

The soil models can be reconstituted by pluvial deposition in air with constant height of fall (figure 3). This is the most reliable and repeatable technique used to achieve a homogeneous soil sample (Fretti et al., 1995; Garnier, 2001, 2002a).

The target soil density can be obtained by selecting the drop of height, the size of the hopper and the speed of the travelling hopper. The relative density can be measured before and after flight because the acceleration field slightly increases the density reached by pluvial deposition; the value of the relative density after flight will be adopted as the test soil density.

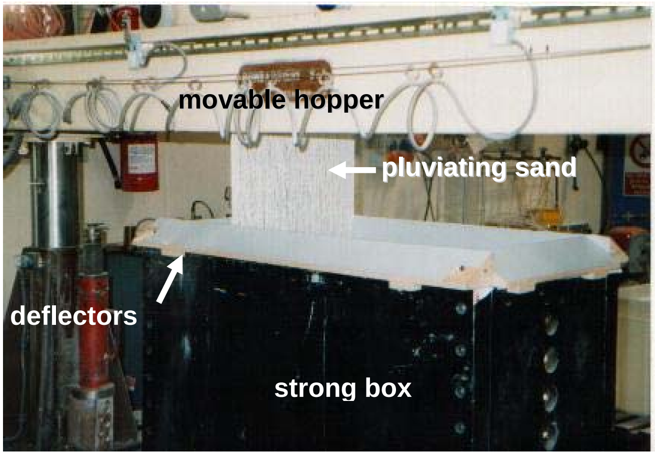


Figure 3: Movable sand hopper used for the soil sample preparation

In-flight cone penetration tests

Figure 4 shows a scheme of the ISMES-GEO in-flight cone penetrometer mounted onto a cylindrical strong-box. The cone has a diameter B = 11.3 mm, and a total area A = 100 mm^2. It has a 60° cone tip with a load cell to measure tip forces up to 9.8 kN and a 370 mm long 11mm diameter shaft, which connects to an upper section that contains a 9.8 kN load cell, that is used to measure cone shaft friction. The ISMES-GEO cone has a Druck PDCR42 pressure transducer (35 bar capacity) for interstitial pressure measurements. The system feed unit is a hydraulic ram whose rod is the penetrometer bar. The maximum load that can be attained with the actuator is 11.8 kN.

In general, penetration rates from 2 to 20 mm/s, seems to have negligible effects in dry sand samples (Garnier, 2002a).

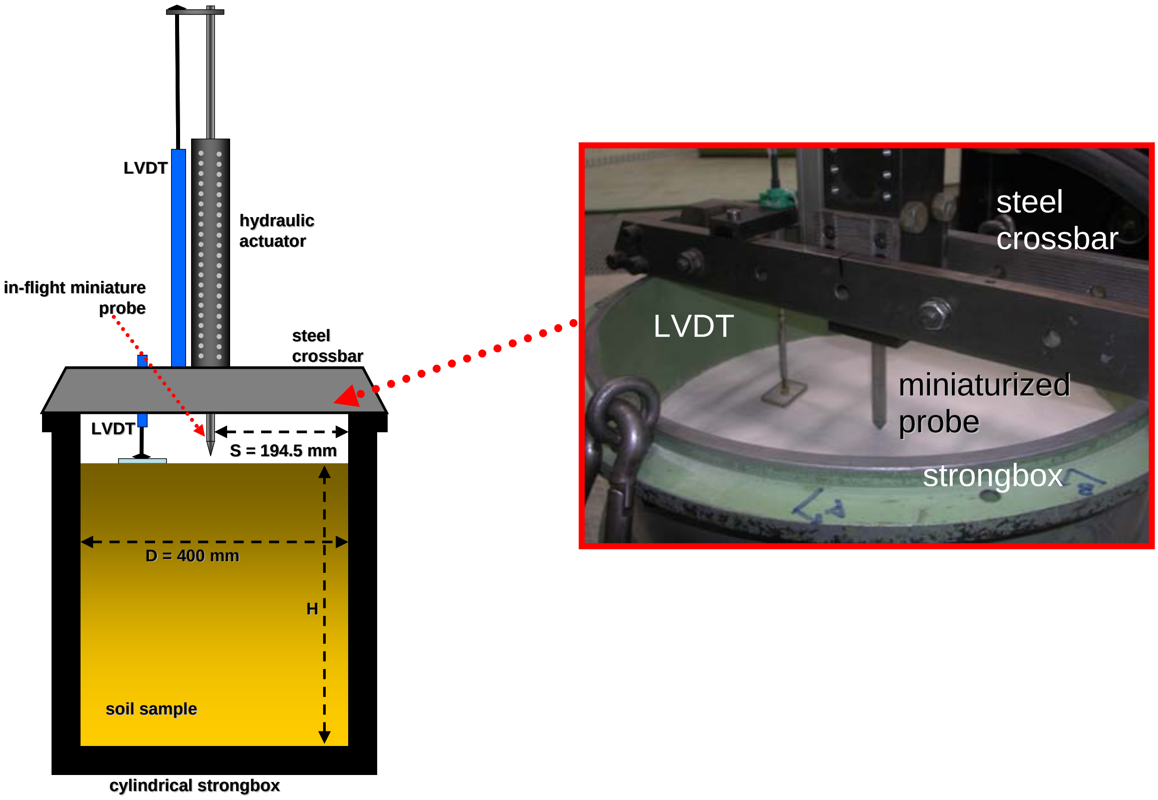


Figure 4: ISMGEO in flight cone penetrometer

Application Example

Several series of tests have been performed on various material. As an example, Figure 5 shows a series of test results performed in Toyoura sand

The CPT tests on Toyoura sand were performed on specimens with three classes of density (DR≅45, 65, and 85%) and two acceleration levels (a/g= 30 and 80). Considering the height of the specimen and the boundary conditions, the maximum prototype depth investigated was approximately 25 m.

The measured tip resistance profiles, for a distance of the first 10 times the cone diameter depth, are not shown in figure 5, since the low embedment ratio gave rise to a non meaningful low cone resistance (De Nicola, 1996).

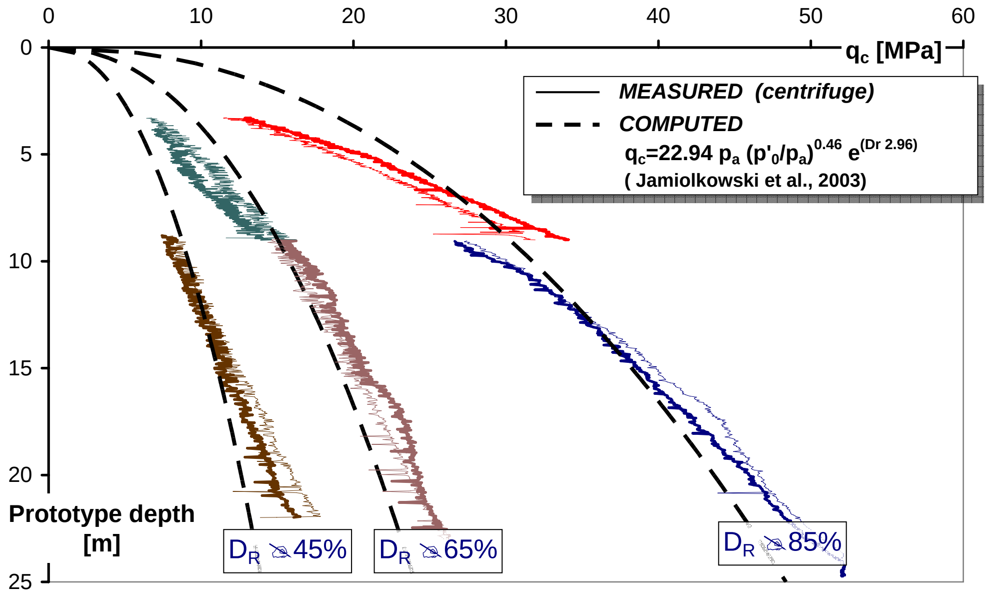


Figure 5: Cone tip resistance test results and interpretation – Toyoura sand

From figures 5 it can be seen that there is a good homogeneity and repeatability of the tested samples for Toyoura sands.

The test results were fitted by the function proposed by Jamiolkowski et al. (2003), based on the interpretation of an extensive database of cone penetration tests carried out in a calibration chamber:

$$\frac{q_c}{p_a} = C_0 \cdot \left(\frac{p'_0}{p_a}\right)^{C_1} \cdot e^{(D_R \cdot C_2)} \qquad (7)$$

where:

q_c = cone resistance
p_a = atmospheric pressure
p'_0 = mean effective stress at cone depth
D_R = relative density expressed as a number
C_0, C_1, C_2 = non dimensional empirical correlation factors

Unfavorable effects (Renzi et al 1994):

(A) Boundary effects:

1. The ratio Dcontainer/Dcone = 36 produces negligible boundary effects: for medium and dense specimens there is no apparent increase in q_c for a test done at Dcontainer/Dcone = 42, as compared to ratio of 85.
2. There is no effects in q_c measured at a distance from the rigid wall of 17.7, respect to the cone diameter, for medium and dense specimens.

(B) Grain size effects: data from modeling of models trials reveled that soil particle size does not affect the results for ratio dc/d50 > 50.

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