Module 7:
Lecture - 8 on Geotechnical Physical Modelling
The technique of testing scaled models at different $g$ levels with the aim of verifying the scaling laws is called modelling of models. The modelling of models technique is used whenever we are trying to model a new physical phenomenon in the centrifuge and the scaling laws for one or more parameters cannot be derived easily.
Test programme for modeling of models

Test programme of concentric loading tests of circular footings on a uniform dry sand ($e = 0.565; d_{50} = 0.3 - 0.6$ mm)

After Taylor (1995)
Normalized load-settlement curves for modeling of models

All tests correspond to $d_p = 1m$

After Taylor (1995)
Values of bearing capacity for different g-levels

Indicates the modeling of models holds well.
Conflict of scale factors for diffusion and dynamic events

- Prototype
- Centrifuge model (with model pore fluid)
- Centrifuge model (with water)
Qualities of an Ideal Substitute Pore Fluid

• Density very close to that of water
• Surface tension same as water
• Newtonian fluid
• Chemically polar
• Available in wide range of viscosities
• Stable and its properties should not change in the time frame of experimental preparation
• Easy to manufacture
• Non-toxic and soluble in water
• Inert
Different pore fluids for dynamic tests

- **Silicone oil** - Drawbacks
  - Classified as a hazardous waste,
  - Resistant to most solvents, and thus determination of the dry density of saturated soil with silicone oil and the clean up of equipment is difficult
  - Unit weight is less than that of water necessitating corrections to be implemented
  - Relatively expensive.

- **Delft pore fluid**
  - Composition not revealed by its originators
  - Evaluated through physical, permeability and monotonic and cyclic triaxial test and showed promising results
Different pore fluids for dynamic tests

- **Glycerin**
  - Non-toxic
  - Easily mixible with water in any concentration

- **Methylcellulose**
  - Biodegradable and relatively easy to clean up
  - Available in wide range of viscosities
  - Unit weight of the solution almost identical to pure water
  - Components are inexpensive, readily available, and not subject to proprietary protection.
Variation of permeability with g-level

- For water as pore fluid: $k \uparrow$ with g-level; increase was linear.

- For Metolose as pore fluid: $k_{1g} \approx k_{Ng}$; Very marginal variation.

After Dewoolkar et al. (1999)
Properties of Metolose

- The chemical name of metolose is hydroxypropyl methylcellulose. It is a water-soluble cellulose ether.

- It is in the form of a fine white powder. Metolose is tasteless, odorless, and physiologically harmless.

- Metolose solutions of desired viscosities can be prepared by dissolving certain amounts of metolose powder by weight in warm, distilled, deaired water.
Effect of concentration and age, and on the viscosity of metolose

After Dewoolkar et al. (1999)
Effect of temperature on the viscosity of metolose

After Dewoolkar et al. (1999)
Effect of metolose on constitutive behaviour of the sand

- Strain-controlled, CU triaxial compression tests were performed on water- and 60-cSt metolose-saturated specimens of sand at 70% RD.
- Three cell pressures 69 kPa, 138 kPa and 207 kPa
Effect of metolose on constitutive behaviour of the sand

After Dewoolkar et al. (1999)

The stress-strain behaviour and pore pressure generation with water and metolose were very similar.

After Dewoolkar et al. (1999)
Effect of metolose on constitutive behaviour of the sand

- The stress paths were very similar with water and metolose.
- Thus, the overall constitutive behaviour (stress-strain behaviour, pore pressure generation, and the friction angle) of sand was not altered significantly by the use of metolose instead of water as the pore fluid.

After Dewoolkar et al. (1999)
A level ground experiment was conducted to demonstrate the importance of a substitute pore fluid in seismic centrifuge modelling of saturated cohesionless structures.

After Dewoolkar et al. (1999)
The effects of the pore fluid on the model behaviour

• With water as the pore fluid, the accumulation of excess pore pressures was reduced due to high permeability.

• However, with metolose, due to slower dissipation, high excess pore pressures were generated.

• The rate of pore pressure dissipation with metolose was considerably smaller than that with water.

After Dewoolkar et al. (1999)
Time histories of acceleration

After Dewoolkar et al. (1999)

Prof. B V S Viswanadham, Department of Civil Engineering, IIT Bombay
Based on these observations, it is clear that neither the accelerations nor the excess pore pressures indicated occurrences of liquefaction in the water-saturated soil model.

On the other hand, the metolose-saturated soil liquefied completely. Thus, it was shown that the conflict between the dynamic and consolidation time exists, and, hence, the results from seismic centrifuge tests on water saturated soil models could underestimate the consequences of an earthquake.

A substitute pore fluid was necessary.
Method of saturation

Sucking water into the soil with a vacuum pump.
Method of saturation

Fluid percolation in a vacuum chamber
Laminar Container

Saturated Sand

In-flight Earthquake Shaking System

Swing Basket

H = Thickness of sand layer; Suffix m: model; p: prototype

Typical Shaking system mounted on Swing basket
Centrifuge shaker during flight

After Kutter, 2007
Shaking systems

Generating earthquake-like shaking of a model in flight requires a power source or actuator.

- The actuator will require high frequency excitation and high force.
- The duration of shaking will be short, the actuator must be capable of delivering peak energy flow almost instantaneously.
- The centrifuge itself could be subjected to unacceptable dynamic stresses if appropriate reaction masses are not designed into the system.
- The actuator must be compact in size and of minimum mass and should be able to vary amplitude and frequency content.
Common types shaking systems

- Mechanical actuators - Bumpy road system UC, UK

- Piezo electric system - UC Davis, USA

- Electromagnetic shaking system - Shimazu Centrifuge, Japan

- Hydraulic actuator - U Colorado, USA
Bumpy road actuator
Example problem and solution

\[ V_m = 3 \times 10^{-2} \text{ m}^3 \]

10 cycles at a \( f_m = 100 \text{ Hz} \);
\( a_m = 1.5 \text{ mm}; \ t_m = 0.1 \text{ s} \)

\( (\text{Acc.})_m = \left(\frac{1.5}{1000}\right) \times 4\pi^2 \times (100)^2 \)

= 592 \text{ m/s}^2 = 60.3 \text{ g} 

\[ V_p = 3 \times 10^3 \text{ m}^3 \]

10 cycles at a \( f_p = 1 \text{ Hz} \);
\( a_p = 0.15 \text{ m}; \ t_p = 10 \text{ s} \)

\( (\text{Acc.})_p = (0.15) \times 4\pi^2 \times (1) \)

= 5.92 \text{ m/s}^2 = 0.6 \text{ g}
Example problem and solution

Check for Coriolis effect:

\[ V = 30 \text{ m/s} \]

\[ v = a_m (2\pi f_m) = 1.5 \times 10^{-3} \times 2\pi \times (100) \]

\[ = 0.94 \text{ m/s} < 0.05 V \]

Error due to Coriolis effect = \( \frac{2 \times 0.94}{30} \times (100) = 6.2 \% < 10 \% \)

⇒ Coriolis effect is negligible
Cam-shaft shaking table
Electromagnetic shaking system
Electromagnetic shaking system

Schematic diagram of the electromagnetic system
Electromagnetic shaking system

An electro-magnetic shaker, Shimizu Co., Japan
Hydraulic shaker for Nishimatsu centrifuge

Hydraulic shaker

servo valve

actuator

shaking table

Hydraulic shaker for Nishimatsu centrifuge

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In-flight shaking table at Tongji University, China

After Ma et al. 2006
In-flight shaking table at Korea Water Resources Corporation KOWACO, South Korea

After Ha et al. 2006
Boundary effects - Earthquake modeling experiments

- Centrifuge models are enclosed within finite boundaries provided by a model container. The artificial boundaries of the model container may distort the stress and strain fields and generate P-waves among other superfluous wave reflections in the model that are not present in the prototype.

- Realistic boundary conditions at the boundary of the model produce accurate model simulations of soil seismic behaviour that reflect the behavior observed in semi-infinite soil layers in the field.
Boundary effects - Earthquake modeling experiments

Centrifuge model with rigid container →

Soil layer

S waves

← Prototype

P waves

S waves
Boundary effects - Earthquake modeling experiments

In a semi-infinite half space

After Lee et al. 2012
Boundary conditions during 1-D shaking

If the end walls are smooth, stress dissimilarities would occur because of the lack of complementary shear stress on the elements A and B.

In a centrifuge model within a rigid smooth wall container

After Lee et al. 2012
Laminar containers

- Stack-ring devices, originally developed for simple shear tests, have been increasingly used to simulate free boundary conditions in earthquake modelling of soil deposits.

- This type of container is a laminar container. The design concept of laminar containers is that the container should have a limited contribution to the response of the soil system.

- Laminar containers are constructed from stacked lightweight rings separated by bearings that permit relatively free movement of the soil and rings during shaking.
View of laminar container at the onset of earthquake during centrifuge test