1st Workshop
Experimental Opportunities - SERIES Project through Transnational Access

Reduced Scale Modelling
of geotechnical problems
in the centrifuge

Dr. Jean-Louis Chazelas – Laboratoire Central des Ponts et Chaussées – Nantes – FR
Dr. Gopal Madabhushi - Schofield Centre – University of Cambridge - UK
Introduction

Modern day Civil Engineer uses the following methods in design:

**For simple problems**
Empirical or Semi-empirical methods
Closed form solutions

**For complex problems**
Finite Element Analysis
Testing of Physical Models at Small Scale
Field Monitoring
For Geotechnical Problems, when using the FE method, we need to know the constitutive behaviour of soil i.e. the stress strain behaviour of the soil under the type of loading it experiences needs to be known.

If Yes, we can program this into the FE codes and proceed with the design

If No, ???

Let us look at the stress strain behaviour of soil
Stress - Strain behaviour of soil

Let us consider the shear stress Vs shear strain for loose and dense soils

Soil is highly NON-LINEAR and PLASTIC
Physical Modelling in Geotechnics

As soil is non-linear we cannot simply model our problem (say a caisson subjected to lateral load) at small scale.

We need to create prototype stresses and strains in our models !!!
Centrifuge Modelling Technique

Consider, for simplicity, a block structure of dimensions \( L \times B \times H \) sitting on a horizontal soil bed.

Principle of Centrifuge Modelling

- In a centrifuge a reduced scale model is subjected to centrifugal acceleration so that correct prototype stresses and strains are created in the model.

Stress under the block is given by

\[
\sigma = \frac{Mg}{LB} \quad \varepsilon = \frac{\delta L}{L}
\]
Centrifugal Acceleration:

The easiest way to create high gravity is by spinning our soil models in a centrifuge.

When the centrifuge is rotating with an angular velocity of ‘ω’, the centrifugal acceleration at any radius ‘r’ is given by

\[ \text{centrifugal acceleration} = r \times \omega^2 \]

We wish to match this centrifugal acceleration to be the same factor as the one we used to scale down our prototype by ie ‘N’ (geometrical scaling factor).

\[ \Rightarrow N \times g = r \times \omega^2 \]
For example, if we wish to scale a prototype problem at 100g, Using a centrifuge with working radius of 4.125 m We will be doing;

\[ 100 \times 9.81 = 4.125 \times \omega^2 \]

\[ \omega = \sqrt{\frac{100 \times 9.81}{4.125}} = 15.42 \text{ rad} / \text{s} \]

\[ \Rightarrow ..RPM \cong 147.3 \]
### Scaling laws

<table>
<thead>
<tr>
<th>Dynamic Fundamental Equation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$1/N$</td>
</tr>
<tr>
<td>Volume</td>
<td>$1/N^3$</td>
</tr>
<tr>
<td>Density</td>
<td>$1$</td>
</tr>
<tr>
<td>Stress</td>
<td>$1$</td>
</tr>
<tr>
<td>Stain</td>
<td>$1$</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$N$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$1/N$</td>
</tr>
<tr>
<td>Displacement</td>
<td>$1/N$</td>
</tr>
<tr>
<td>Force</td>
<td>$1/N^2$</td>
</tr>
<tr>
<td>Time</td>
<td>$1/N$</td>
</tr>
<tr>
<td>Frequency</td>
<td>$N$</td>
</tr>
<tr>
<td>Darcy's law with water</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>$1/N^2$</td>
</tr>
<tr>
<td>Darcy's law with viscosity N*water</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>$1/N$</td>
</tr>
</tbody>
</table>
Cambridge Centrifuge Facility

Turner Beam Centrifuge - University of Cambridge
Acceleration fields in the Centrifuge

The beam Centrifuge at LCPC
Radius 5.50 m
2T in the basket at 100 g
Reducing scales - Limits

Size effect

Shallow foundation diameter / grain size > 35
Pile diameter / grain size = 45 or 60

Silo effect

Width = 35 cm
σ = 33 kPa in the center
σ = 23 kPa against the wall
σ = 28 kPa at 5 cm from the wall

Boundary effect

Neutralized zones
Ratio size/width

IJPMG Vol.7, n°3, 2007
**G is radial**

Problem in little centrifuges
(error on surface 0.7% at 5.1m and box 0.8 m)

\[ Gc = \omega^2 R \]

**G centrifuge function of z**

G at 1/3 of the total depth: error ~ 2%?

Vertical section
Limits: fundamental equation unknown = scaling rules

Example: internal erosion within embankment

⇒ preliminary tests for empirical evaluation of leading parameters
Reference: Non-Cohesive Soil

- LCPC : fine Fontainebleau sand
  or Hostun Sand

- UCAM : Fraction D or E, (Leighton Buzzard 52/100 or 100/120 sands)
  or Hostun Sand (from France)

Reference: Cohesive Soil

LCPC : Speswhite Kaolin

UCAM : Speswhite Kaolin clay
  or E-grade Kaolin clay
  (higher Permeability, so faster consolidation)
UCAM - Team for earthquake experimenting

Gopal Madabhushi  Reader in Geotechnical Engineering
Stuart Haigh     University Lecturer
Ulas Cilingir    Research Associate
Mark Stringer   Research Student
Darren Chian    Research Student
Jenny Haskell   Research Student
Charles Heron  Research Student

Technician team

John Chandler   Centrifuge Operator & Mechanical
Kristian Pather Centrifuge Operator & Mechanical
Chris McGinnie  Electronics Support
David Yates     Instrumentation Support
Anama Lowday    Schofield Centre Administrator
Earthquake simulation – Device in Cambridge

- Mechanical system
- Simple, cheap and robust
- Tone bursts of desired frequency (0~5 Hz)
- Earthquakes of desired duration (0~100 seconds)
- Earthquakes of desired intensity (up to 0.4g at bedrock)
Cambridge - New Servo-Hydraulic Shaker

- Commissioning in March/April 2010
- Will model realistic earthquake motions such as Kobe motion or Northridge motion
- PGA of 0.6g
- Max operational g level 100g
Model Containers for Dynamic Testing

Laminar Box

Dimensions:
1g → Depth = 226 mm; Length=560 mm; Width=250 mm
100g → Depth = 22.6 m; Length=56.0 m; Width=25.0 m
Model Containers for Dynamic Testing

Small ESB Box

Dimensions:
1g → Depth = 200 mm; Length=560 mm; Width=250 mm
100g → Depth = 20.0 m; Length=56.0 m; Width=25.0 m
Model Containers for Dynamic Testing

Large ESB Box

Dimensions:

- $1g \rightarrow$ Depth = 427 mm; Length=673 mm; Width=253 mm
- $100g \rightarrow$ Depth = 42.7 m; Length=67.3 m; Width=25.3 m
Model Containers for Dynamic Testing

Window Box

Dimensions:
1g → Depth = 360 mm; Length=560 mm; Width=236 mm
100g → Depth = 36.0 m; Length=56.0 m; Width=23.6 m
Example Project: Soil-Structure Interaction of Tunnels

Model container and fast camera system on swing ready for centrifuge flight

View of the square tunnel model in model container

*Ulas Cilingir & Gopal Madabhushi*
Typical Data

Measured accelerations around tunnel

Typical dynamic earth pressure – time history

Normalized lining accelerations at the crown of circular tunnels relative to the invert for tunnels with different flexibility ratios

Soil and lining deformations from Particle Image Velocimetry (PIV) analysis

Ulas Cilingir & Gopal Madabhushi
Example Project: Response of Pile Groups during Earthquakes

Schematic layout of the pile group testing

Pile group driven into the soil before centrifuge flight

Mark Stringer & Gopal Madabhushi
Example Project: Response of Pile Groups during Earthquakes

- Shaft friction
- Pore pressure on the tip of the pile and settlement of the pile group
- Change of shaft friction after the earthquake
- Post-earthquake pore pressure response

Mark Stringer & Gopal Madabhushi
Example Project: Dam-Reservoir-Foundation Interaction

Cross-section of the model

Plan view taken in-flight during Earthquake loading

Sadia Saleh & Gopal Madabhushi
Typical data

Acceleration and pore pressure-time histories were recorded at several locations.
Example Project: Reluis Project - Propped Cantilever Retaining walls

View of the retaining wall model

Views of the propped retaining wall model

*Ricardo Conti, Giulia Viggiani & Gopal Madabhushi*
Example Project: Reluis Project - Tunnels

Ricardo Conti, Guilia Viggiani & Gopal Madabhushi
RELUIS Project - Tunnels

**BM9**

**HS10**

**ACC**

Instrumented Tunnel to measure hoop stress and bending stresses.

SERIES General Committee Meeting - Iasi, July 15th 2009
Distributed Testing

UK - NEES Project Meeting

- Bristol
- New Zealand
- Oxford
- Cambridge

Powerpoint Presentation from NZ
Proof of Concept: Distributed testing

Apart from the simple, tele-participation tests carried out so far, the scope for distributed testing is enormous.
As part of UK-NEES project, University of Cambridge is committed to test a bridge pier foundation.
Live demonstration of distributed testing to be given at Institution of Civil Engineers, London.
   Centrifuge running at Cambridge
   Shaking table test at Bristol
   Sub-structure testing at Oxford
UK-NEES Project: Distributed Testing

Prototype structure:

- Large-scale test of pier: Bristol
- Test of piled foundation: Cambridge

Interface forces/displacements passed between substructures via internet
UK-NEES Project: Distributed Testing

h, v and $\theta$ sent from Cambridge to Bristol

H, V, M demands from Bristol to Cambridge

Centrifuge model in flight at Cambridge
UK-NEES Project

Prototype structure:

Distributed test set-up:

- FE model of deck and bearings: Oxford
- Full-scale test of bearing: Oxford
- FE model of pier: Oxford
- Test of piled foundation: Cambridge
- Interface forces/displacements passed between substructures via internet

Large-scale test of pier: Bristol
UK-NEES Project - Typical data
Earthquake Simulator at LCPC

Actidyn QS80 Shaker

Electro-hydraulic system
Tone burst from 20Hz – 200 Hz model « real earthquakes » 20-300 Hz model
Pga = 0,5g prototype

In the centrifuge basket
Earthquake Simulator at LCPC

Dynamic Equilibrium
The payload and the counteweight as a moving set de-coupled from the basket

Control
Closed loop below 120 Hz on LVDT
Open loop over 120 Hz up to 400 Hz
# LCPC - Shaker Specifications

## Specifications for full load sine tone burst

<table>
<thead>
<tr>
<th></th>
<th>Model Scale</th>
<th>Prototype scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 D Shaking</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payload mass</td>
<td>400 kg</td>
<td>25 600 T/40 gc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>91 200 T/80 gc</td>
</tr>
<tr>
<td>Centrifuge acceleration range</td>
<td>10 to 80 gc</td>
<td>1 g</td>
</tr>
<tr>
<td>Peak displacement</td>
<td>5 mm</td>
<td>20 cm/40 gc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 cm/80 gc</td>
</tr>
<tr>
<td>Peak velocity</td>
<td>1 cm/s</td>
<td>1 cm/s</td>
</tr>
<tr>
<td>Peak acceleration</td>
<td>0.5 gc &amp; &lt; 40 gc</td>
<td>0.5 g</td>
</tr>
<tr>
<td>Controlled frequency range</td>
<td>20 – 200 Hz</td>
<td>0.5 – 5 Hz (40 gc)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25 – 2.5 Hz (80 gc)</td>
</tr>
<tr>
<td>Duration of the sine earthquake</td>
<td>1 s</td>
<td>40 s / 40 gc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 s / 80 gc</td>
</tr>
<tr>
<td>Spurious acceleration</td>
<td></td>
<td>&lt; 10 % Y acceleration</td>
</tr>
</tbody>
</table>

## Specifications for full load real reference earthquakes

<table>
<thead>
<tr>
<th>Event</th>
<th>Characteristics</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landers - 1992 - Lucerne Valley Station – Comp. N09E</td>
<td>Short – Strong amplitude in low frequencies – 1 spike</td>
<td>0 dB</td>
</tr>
<tr>
<td>Kobe 1995 – DAISG – Comp. N43W</td>
<td>Long span and high amplitudes of acceleration</td>
<td>- 3 dB at 50 g</td>
</tr>
<tr>
<td>Mexico - 1985 - Sec. Com. Y Transport Station – Comp. 090</td>
<td>Long span – Rich spectrum in low frequencies</td>
<td>0 dB</td>
</tr>
<tr>
<td>Northridge - 1994 - Tarzana Station – Comp. 90</td>
<td>Very impulsive. Very high acceleration peaks</td>
<td>- 8.5 dB at 50 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 5.6 dB at 80 g</td>
</tr>
</tbody>
</table>
LCPC - Shaker performances

Control over harmonics in sine ~ 10% of reference
Control over spurious movements ~ 10% of reference
LCPC - Shaker performances

Typical simulation of a « real earthquake - Northridge 1994 - LCPC

Northridge – 50 gc – Référence – 6,2 dB

Kobe – 70 gc – 3.2 dB below reference

Control over spurious movements

Repeatability
LCPC - Team for earthquake experimenting

Jean-Louis Chazelas  Senior Researcher
Sandra Escoffier  Researcher
Gérard Rault  Research Engineer

Technical team

Patrick Gaudicheau  C.O. - mechanics, hydraulics support
Alain Néel  C.O. - electronics, hard & software, network support
Claude Favraud  C.O. - mechanical design of model and devices
Philippe Audrain  C.O. - electroméchanics, hydraulics support
X  Metrology - Dynamics

C.O. : Centrifuge Operator
LCPC - other devices

ESB Box

Prototype dimensions:
- 40 gc: 32 x 14 x 16 m
- 60 gc: 48 x 21 x 24 m

0.80 x 0.35 x 0.41 m model

Data Acquisition System: LMS – 72 channels

Fs = 100 Hz to 25 kHz
72 Channels Voltage or ICP accelerometers
48 Channels Strain Gauge, Voltage, ICP accelerometers

Electromagnetic impact generator

Saturation Device end 2009
Laminar Box for liquefaction tests end 2009
**LCPC recent studies**

Soil – Pile Interactions: Isolating inertial and kinematics

**Bending moment profiles**

**Dynamic PY loops**

(PhD M. H. Bonab - LCPC - Univ Rouen 2002
PhD Chenaf - LCPC - Univ Nantes 2007)
ACI CAT' NAT' - Show evidence of Structure - Soil - Structure Interactions

Free Field

Earthquake

Passive building $d = 7.50$ m

Impacted building

Time - s

Passive building $d = 2.50$ m

Impacted building

Time - s

SERIES General Committee Meeting - Iasi, July 15 2009
B1 12 m from B2

B1 12 m from B1 angle

B2 23 m from B1

M2 38 m from M1 angle

B1 embedded angle

B2 12 m from B1

B1 embedded

B2 23 m from B1

B2 12 m from B1 angle

B1 embedded angle

B2 23 m from B1

B1 embedded angle

B2 23 m from B1

B1 embedded
LCPC recent studies

FP6 - QUAKER – Inclined piles under horizontal dynamic load

- **Frequency response**
  behavior: more complex
  translation – rocking mode of vibration: stiffer

- **Pile cap movement**
  reduction of the horizontal dynamic displacement (2 – 3)

- **Bending moment**
  below soil surface: decreased
  at the pile/cap connection: increased in back pile

- **Axial load**
  both piles: increased (X 2)

LCPC recent studies

Bearing Capacity of shallow foundations on clay

(PhD Chadzigogos – LMS X - GDS - 2008)

accelerometers

Pore Pressure Transducer
Description of TNA Service

Orienting proposals

- Beginning by the simplest situation

- Opening the range of possibilities

- Co-defining the process of demonstration

- Influence of the process on the modelling
Description of TNA Service

Experimental design

Design of model
- Reduction scale,
- Soil characteristics – Saturation liquid
- Computation: FEM, Modal tuning, Soil Characterisation
- Process of setting up the model

Design of instrumentation
- Sensors
- Position
- Reference

Free field response
- Soil acceleration, amplification, starting of liquefaction
- Border effect characterisation (sensors)

Input signal design
- Filtering, tuning amplitude
- Sequence & Cumulative effect of repeated earthquakes
Description of TNA Service

Performing the experiment

Soil Preparation
Choice and calibration of sensors
Setting up of the model
Setting up the instrumentation
Consolidation process
Shaker Drives tuning
Driving
  the centrifuge
  the shaker
  the data recorders
Data examination
Experiment reporting