Laboratoire Central des Ponts et Chaussées

From Modelling to Practice in Geotechnical Engineering

THE BRITISH GEOTECHNICAL ASSOCIATION

Comité Français de Mécanique des Sols et de Géotechnique

Soil-footing interaction of a building submitted to lateral cyclic loading : centrifuge modelling

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Paris, BGA / CFMS joint meeting

25th november 2005

Outline

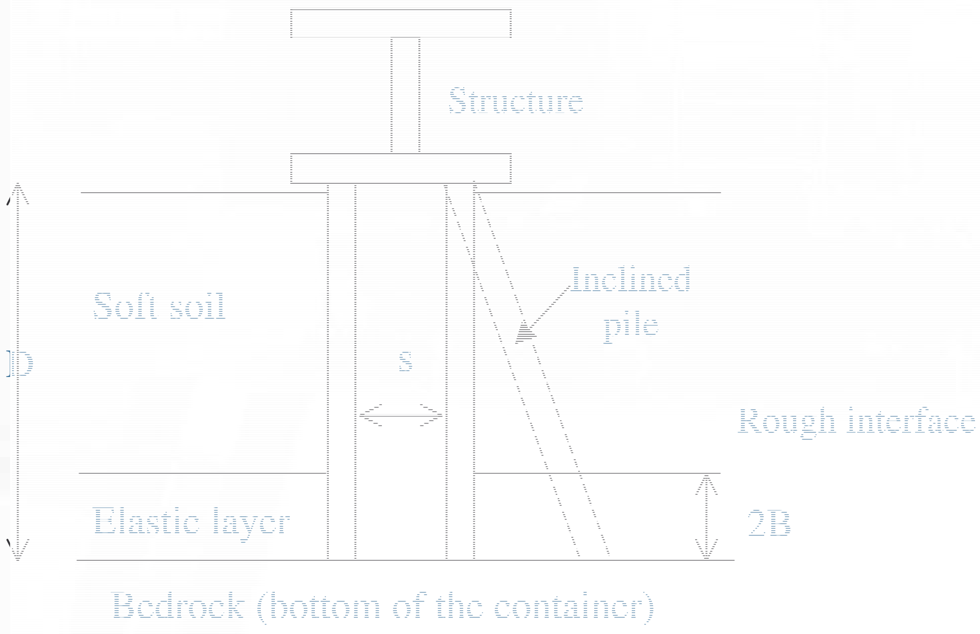
- Introduction
- Case History
- Centrifuge test programme
- Experimental setup
- Results
- Conclusions and prospects

Introduction

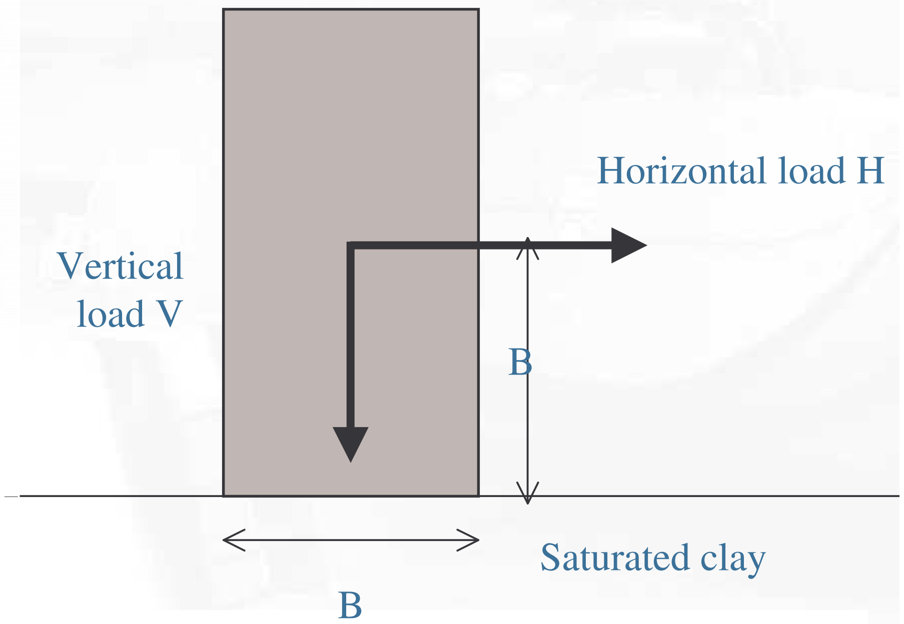
Topic A : Fault-Rupture Soil Structure Interaction

<u>Topic B:</u> Strong Seismic Response of Composite Foundation Systems

Effect of pile inclination



QUAKER B2 : Non linearity of soil-footing interaction

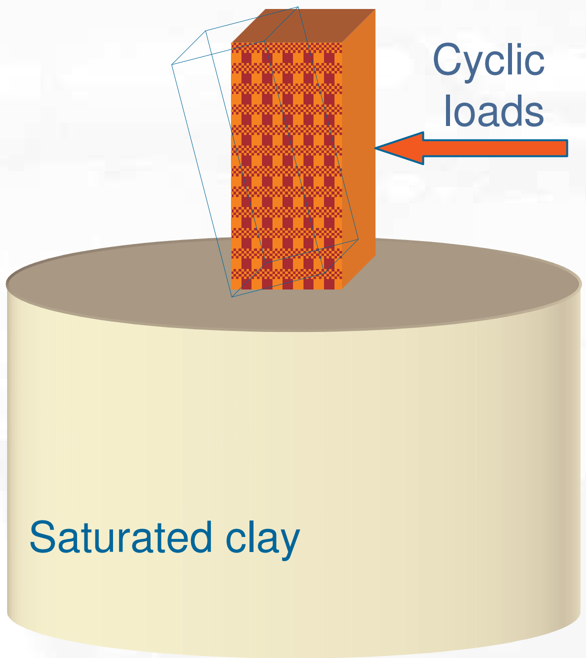


Introduction : Objectives

Main objectives

Determine the relationship between the horizontal load and the rotation of the foundation under static and cyclic horizontal loading

Rotation of buildings on shallow footings (cyclic overturning moments)



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Case History (1)

Izmit (Turkey), 17th august 1999
[AFPS picture]

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Case History (2)

Izmit (Turkey), 17th august 1999
Tigcilar District, Adapazari [Gazetas et al. 2003]

Centrifuge test programme (1)

1 - Building

- Geometry : square footing (B = 10 m)
- Vertical load = Dead weight
  Two buildings
- *2 – Soil*

  Soft saturated clay : Undrained shear strength increasing linearly with depth (CPT tests)

3 – Loading programmes

- Vertical monotonic loading to failure (→ Determination of vertical bearing capacity)
- Horizontal monotonic loading to failure (with constant vertical dead weights M1 or M2)
- Cyclic horizontal loading under self weight (with and without a sand layer below the footing)

Centrifuge test programme (2)

- Seven containers (Tub1 to Tub7), fifteen tests (T1 to T15)

- Vertical bearing capacity : Four tests in Tub1, Tub2 & Tub3

- Horizontal monotonic loading

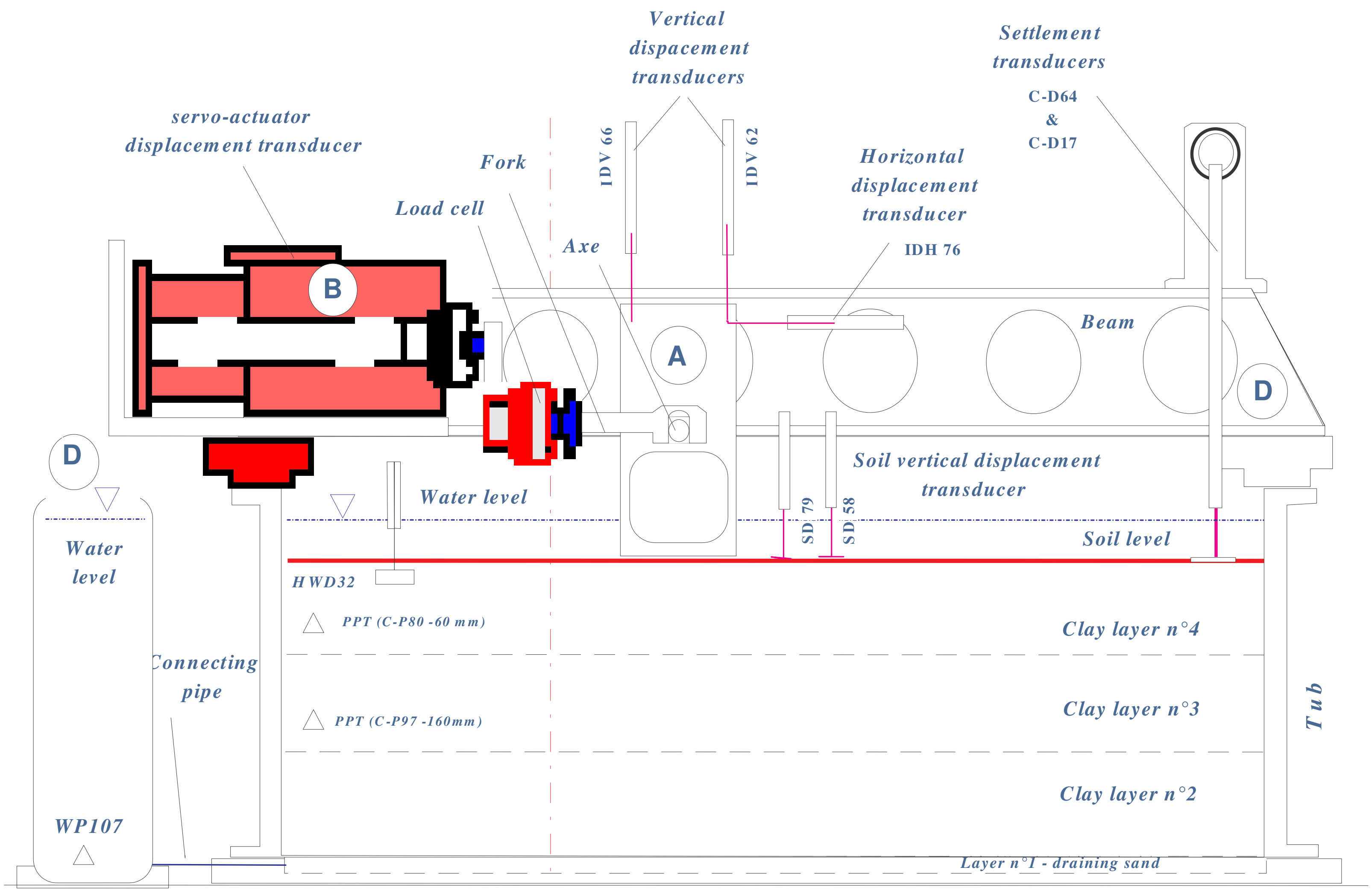
-Without sand layer	Building M1 : 4 tests (T7, T9, T10, T14) Building M2 : 1 test (T12)
-With a sand layer	Building M1 : 1 test (T13) Building M2 : 1 test (T15)

- Horizontal cyclic loading

-Without sand layer	Building M1 : 2 test (T9, T10) Building M2 : 1 test (T11)
-With a sand layer	Building M1 : 1 test (T13) Building M2 : 1 test (T15)

Experimental set-up

Lateral cyclic loading under constant vertical load



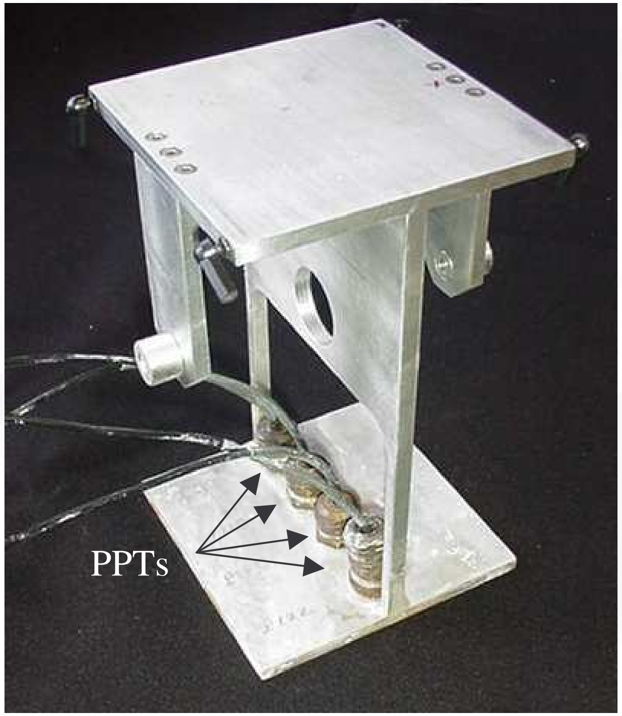
Experimental set-up : Model building

Two model buildings (100G tests)

- Heavy building M1 (Weight 1370 t) Vertical load = 60% of vertical bearing capacity
- Light building M2 (Weight 580t) Vertical load = 26% of vertical bearing capacity

Square footing: 10m x 10m

Model building M1



Model building M2

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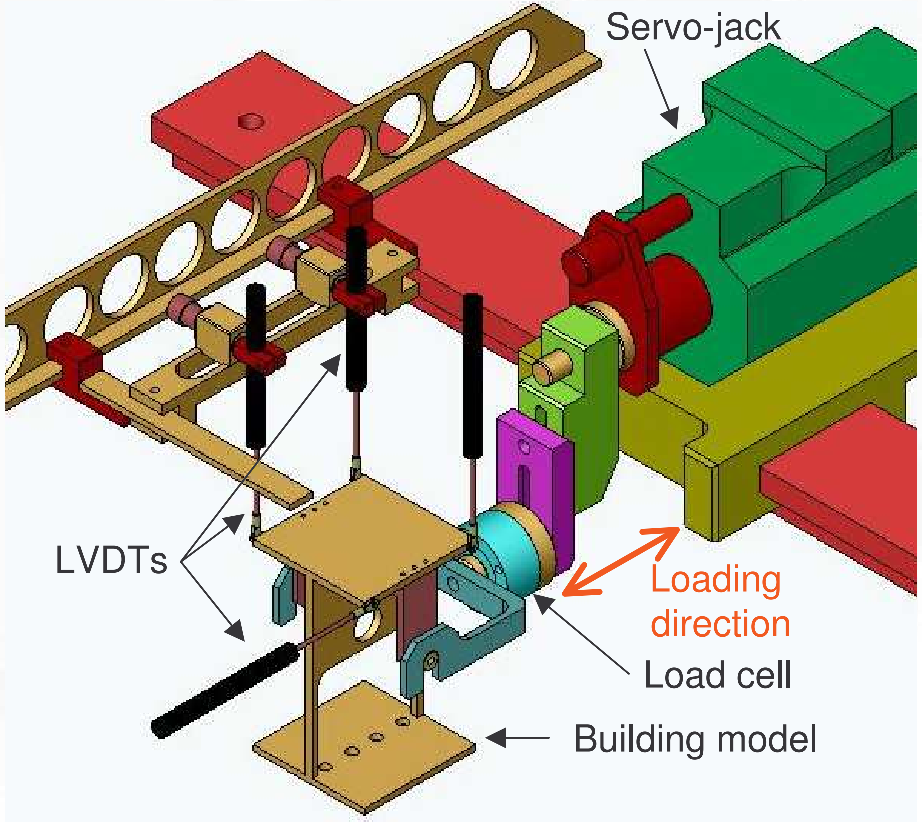
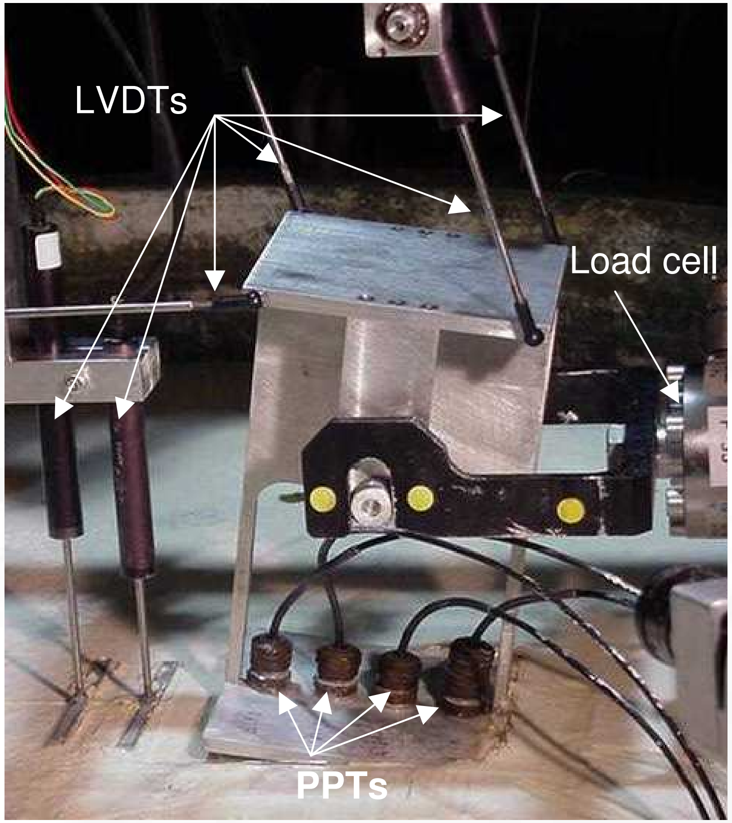
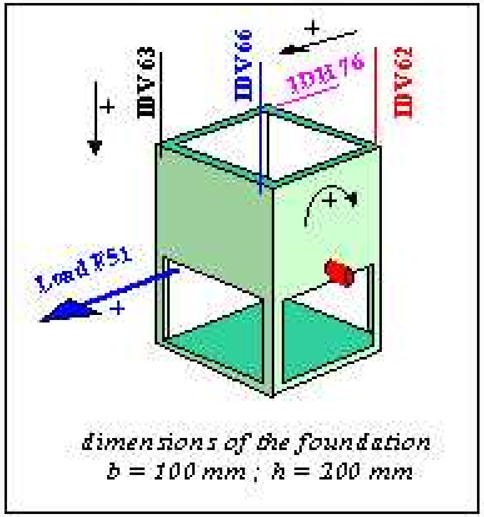
Experimental set-up : lateral loading device

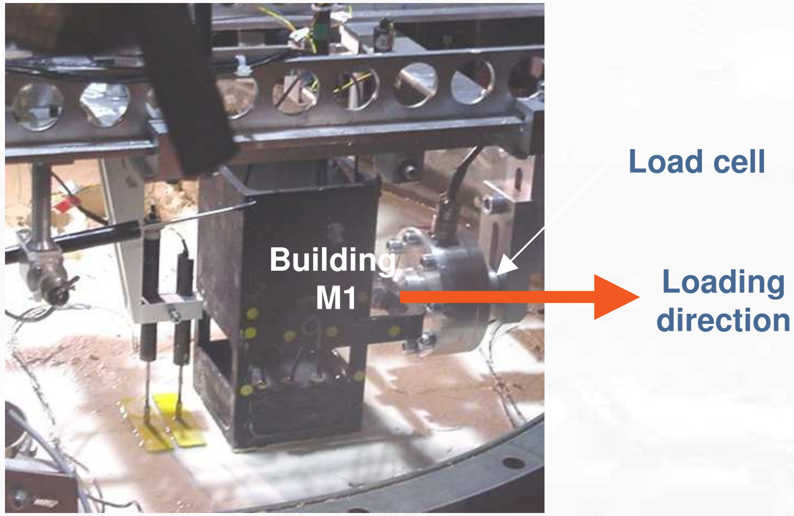


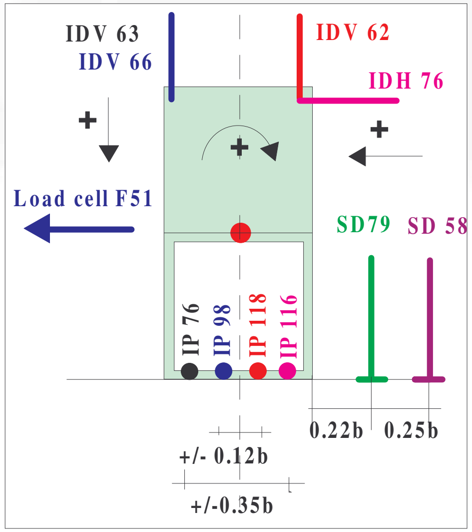


Experimental set-up : Instrumentation

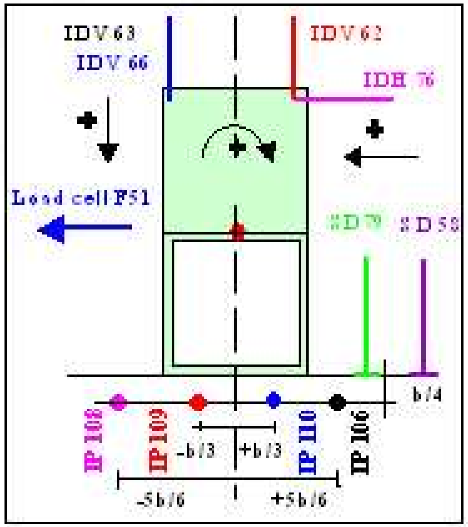


Vertical and horizontal displacements





Pore pressure at the base



Pore pressure below the footing

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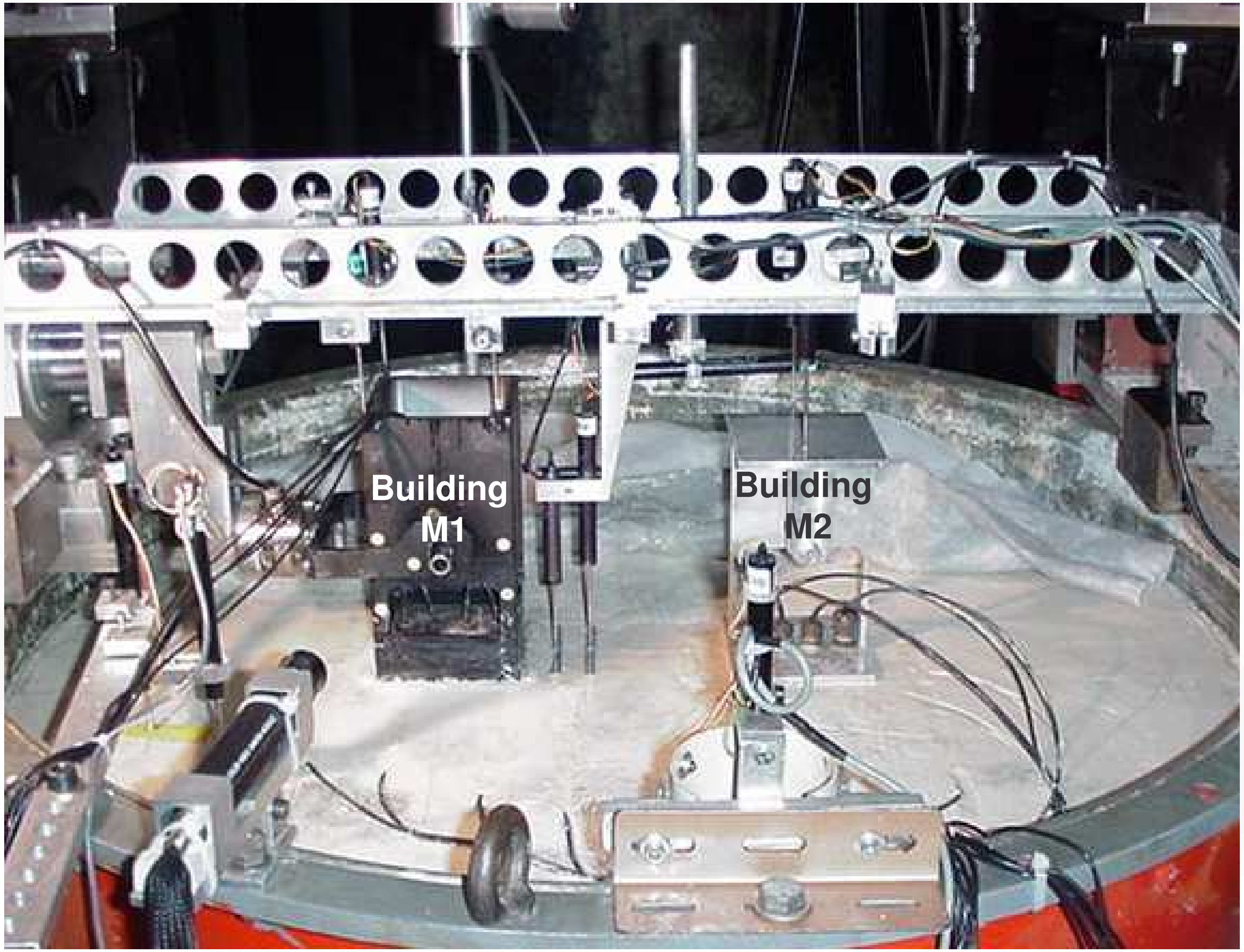
Experimental set-up : In the Centrifuge



Results : Vertical undrained loading tests

Comparison between theoretical and experimental data

1-Undrained shear strength c_u

$$c_u = 0.19\sigma'_v \, OCR^{0.59}$$

Shear strength at depth z = 15m (about 1.5B to 2B)

Theoretical value: σ'_c=560kPa σ'_v=15x7=105kPa c_u=54kPa

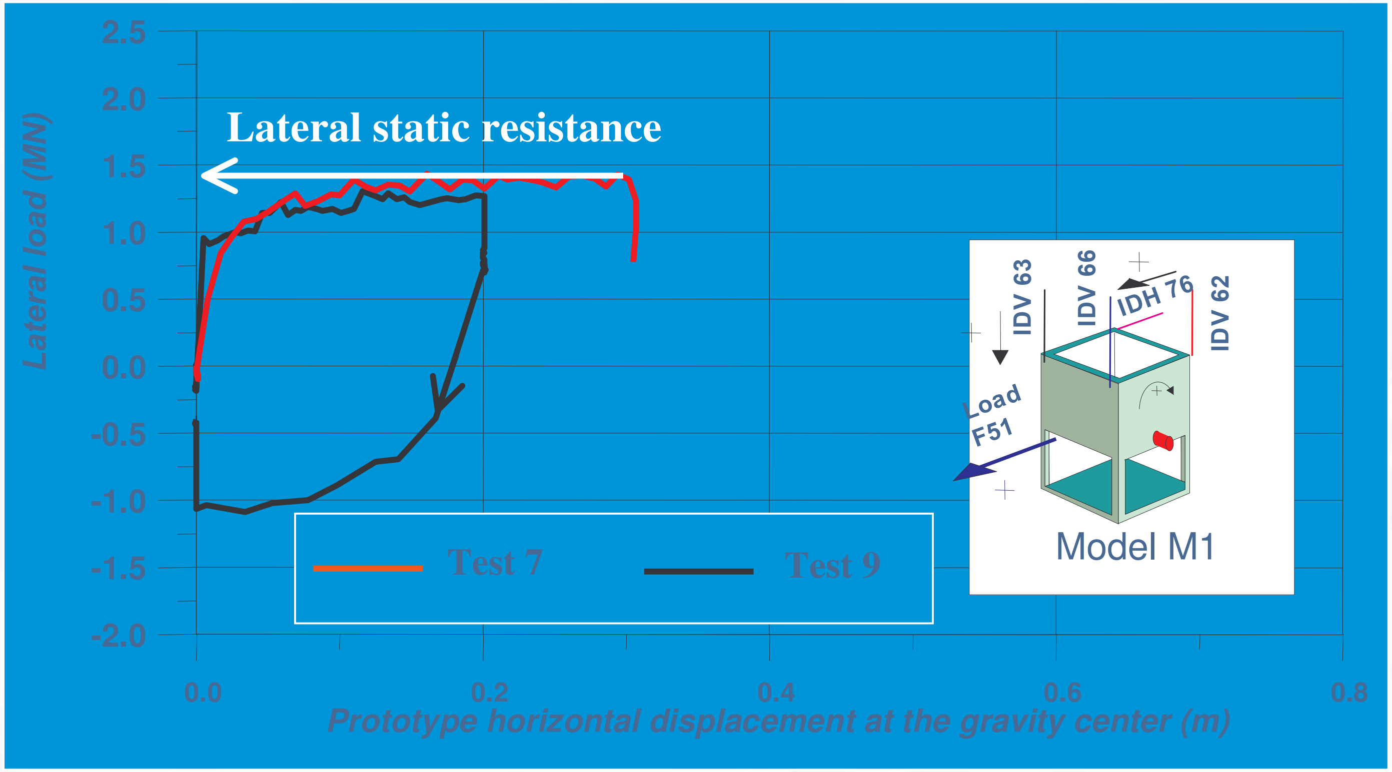
Experimental values (100G CPT tests):

- Tub01 c_u= 64kPa
- Tub03 (1st consolidation) c_u= 81kPa
- Tub04 (last consolidation) c_u= 66kPa
- Tub05 (last consolidation) c_u= 75kPa

2-Vertical bearing capacity q_r

Tub & Test	q_r (kPa) Exper.	q_c (kPa)	Ncz (Tables JPG)	q_r (kPa) Theor.
Tub01-Test01	156	12.5+3.24z	9.49	141
Tub02-Test03	258	No CPT test	???	???
Tub02-Test04	240	No CPT test	???	???
Tub03-Test06	220	18.5+4.24z	9.83	216

Results : Monotonic lateral loading



Results of monotonic lateral loading on building M1 (Tests 7 and 9)

Ultimate monotonic resistance <u>before cyclic loading</u> (H_R & M_R)

Building M1	H_R = 1.4 MN	(M_R = 14 MN x m)
Building M2	H_R = 0.75 MN	(M_R = 7.5 MN x m)

Results : Horizontal cyclic loading (1)

Building M2 without sand layer

Cyclic sequences (LC) :

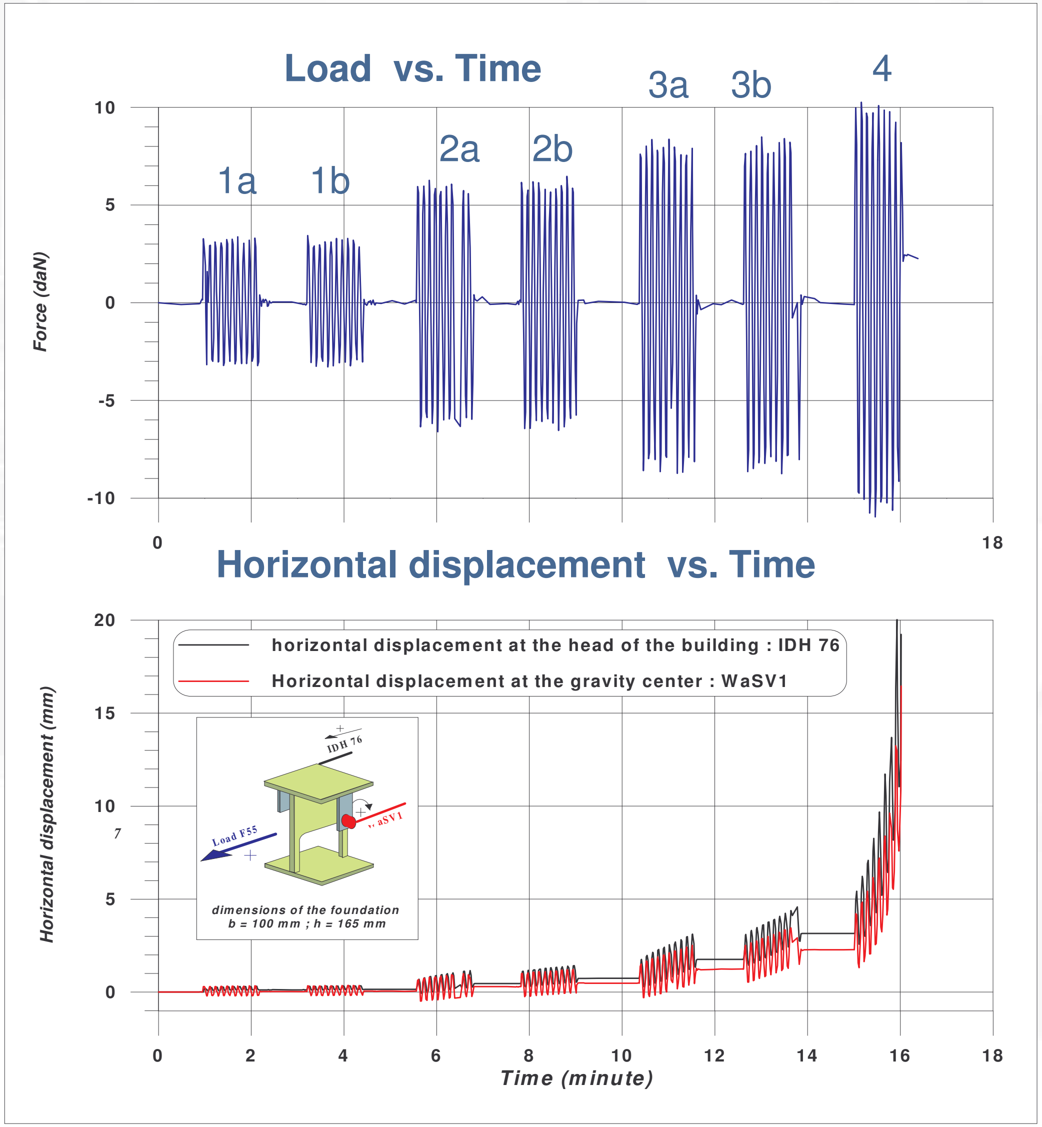
1a & 1b – 1st cyclic sequence :
2 x 10 cycles at 0.16 HZ ± 3 daN

2a & 2b – 2nd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 6 daN

3a & 3b – 3rd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 8 daN

4 – 4th cyclic sequence :
8 cycles at 0.16 Hz ± 10 daN

→ Failure under the 4th cyclic loading sequence :
H_R ~ 1MN prototype scale



(Test T11, Tub 5)

Results : Horizontal cyclic loading (2)

Building M2 without sand layer

Cyclic sequences (LC) :

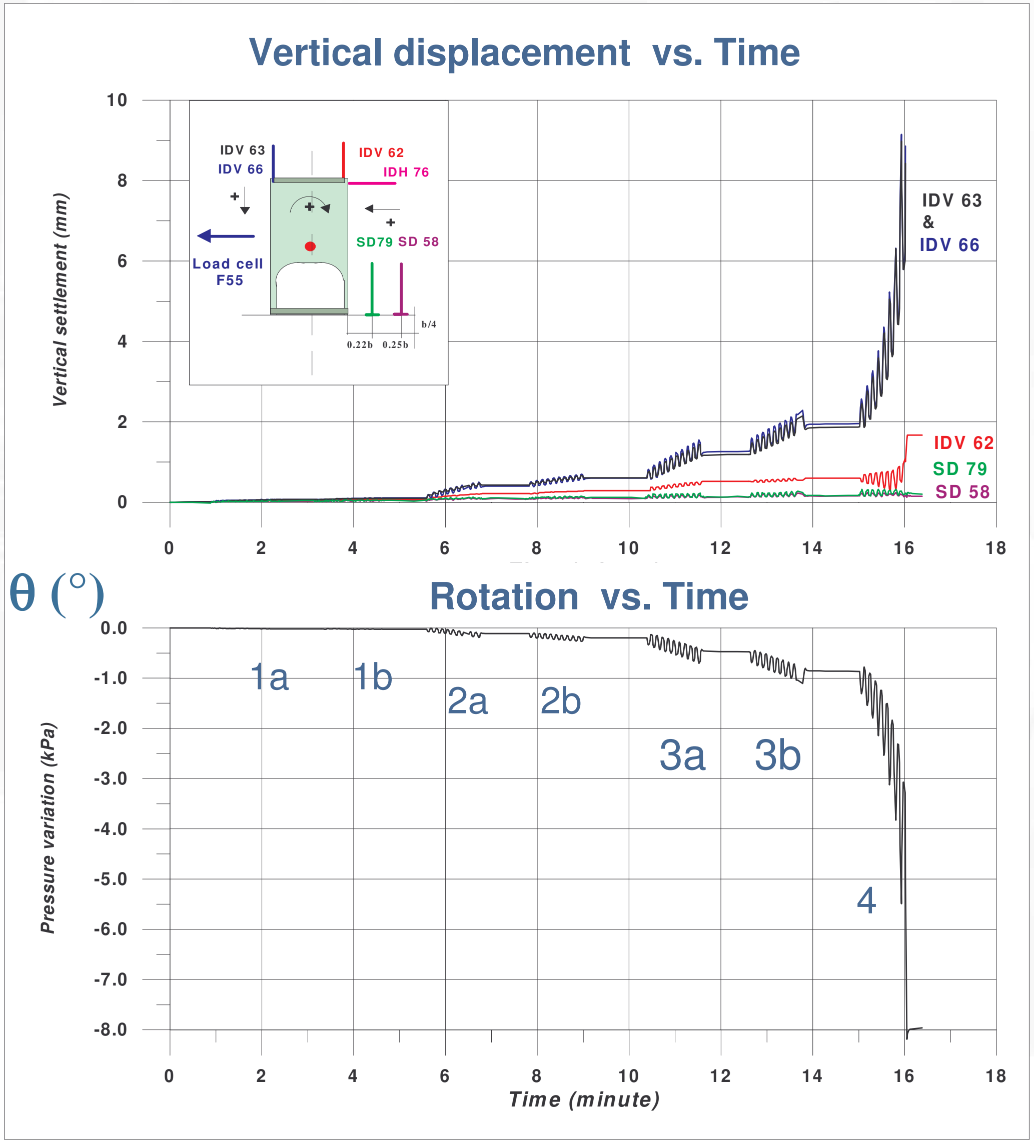
1a & 1b – 1st cyclic sequence :
2 x 10 cycles at 0.16 HZ ± 3 daN

2a & 2b – 2nd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 6 daN

3a & 3b – 3rd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 8 daN

4 – 4th cyclic sequence :
8 cycles at 0.16 Hz ± 10 daN

→ Failure under the 4th cyclic loading sequence (H_R ~ 1MN)



(Test T11, Tub 5)

Results : Horizontal cyclic loading (3)

Building M2 without sand layer

Cyclic sequences (LC) :

1a & 1b – 1st cyclic sequence :
2 x 10 cycles at 0.16 HZ ± 3 daN

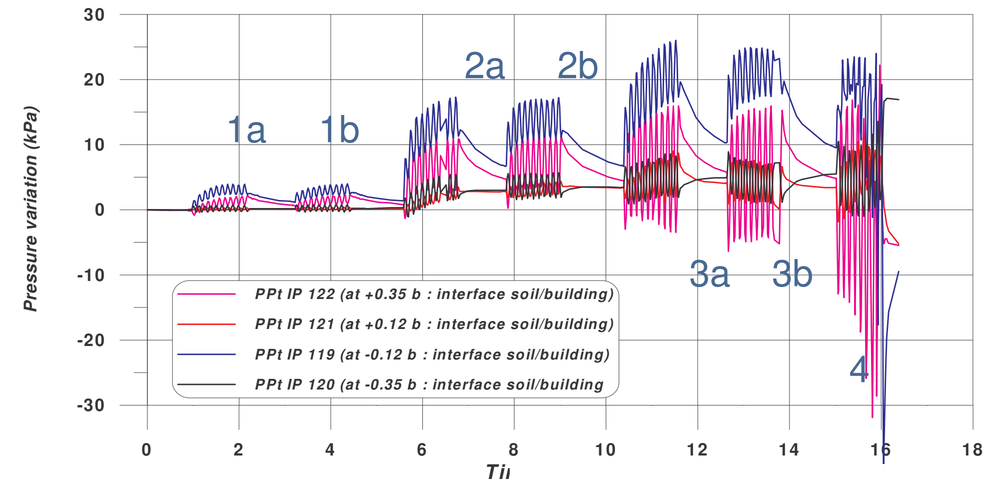
2a & 2b – 2nd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 6 daN

3a & 3b – 3rd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 8 daN

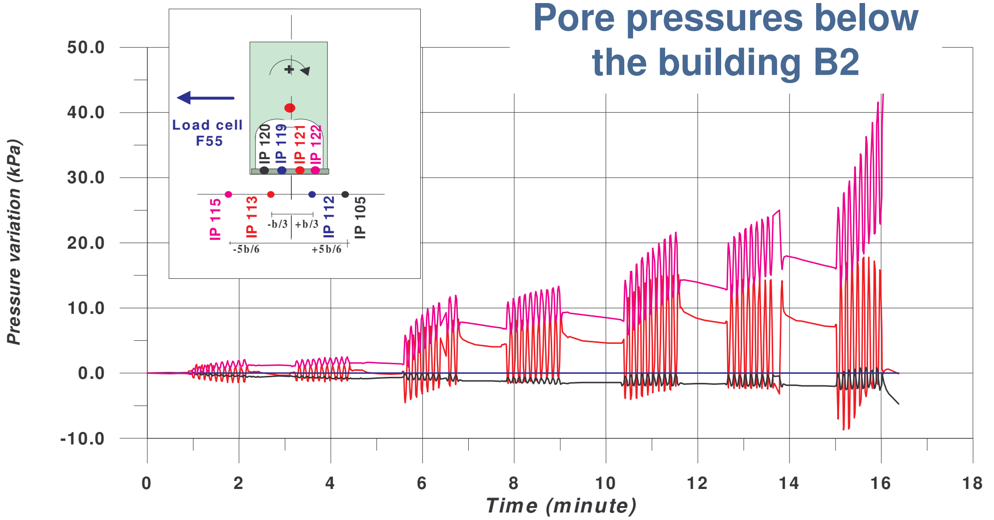
4 – 4th cyclic sequence :
8 cycles at 0.16 Hz ±10 daN

Failure under the 4th cyclic loading sequence (H_R ~ 1MN)

Pore pressures at the interface soil building vs. Time



Pore pressures below the building B2



(Test T11, Tub 5)

Results : Horizontal cyclic loading (4)

Building M2 without sand layer

Cyclic sequences (LC) :

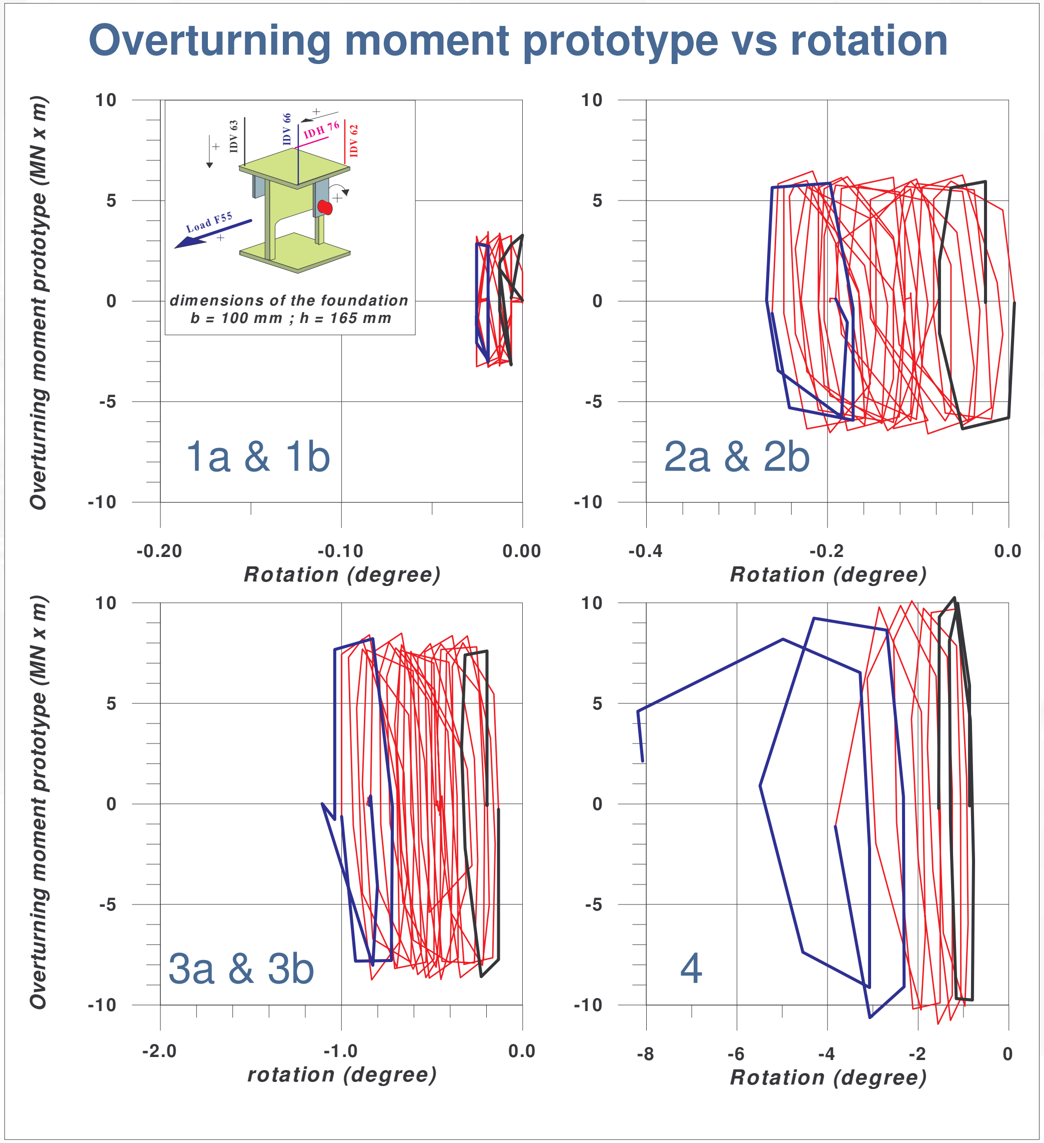
1a & 1b – 1st cyclic sequence :
2 x 10 cycles at 0.16 HZ ± 3 daN

2a & 2b – 2nd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 6 daN

3a & 3b – 3rd cyclic sequence :
2 x 10 cycles at 0.16 Hz ± 8 daN

4 – 4th cyclic sequence :
8 cycles at 0.16 Hz ±10 daN

Failure under the 4th cyclic loading sequence (H_R ~ 1MN)



(Test T11, Tub 5)

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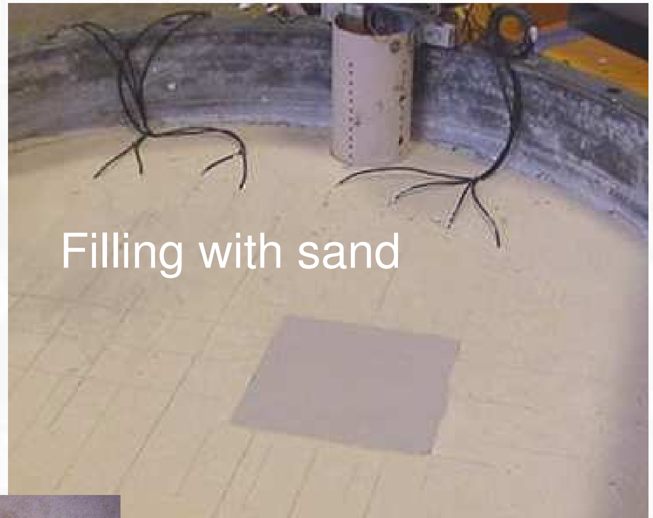
Results : Horizontal cyclic loading (5)

Effect of a sand layer below the footing (e=0.05B)


Excavation in the clay

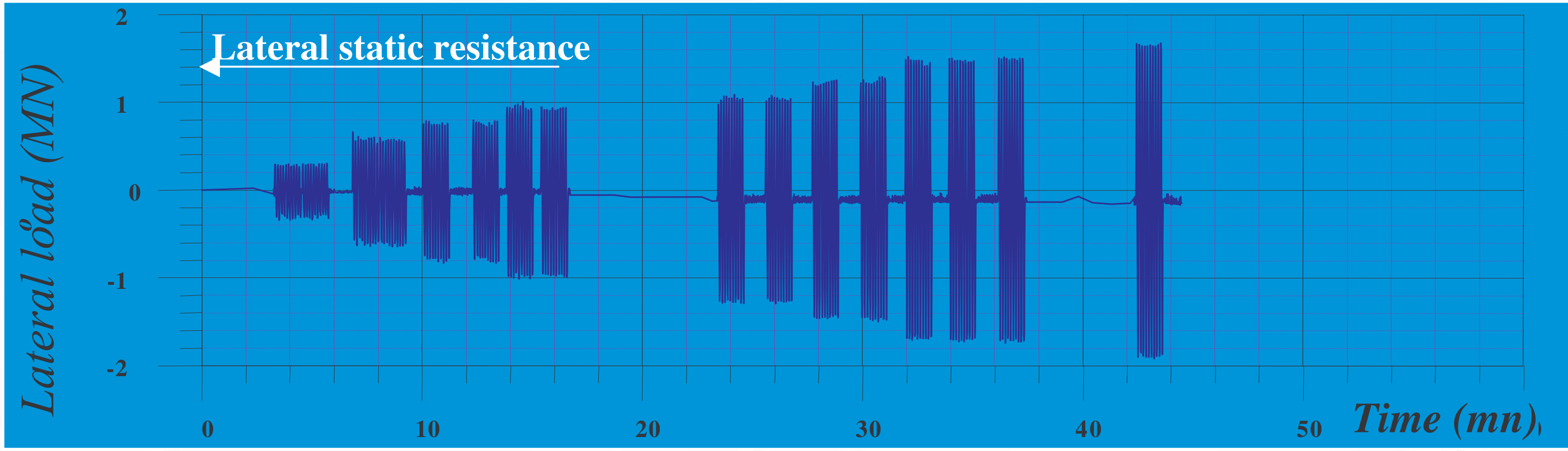

Filling with sand


View after loading the test

Two tests with a sand layer
- Building M1 (Test T13)
- Building M2 (Test T15)

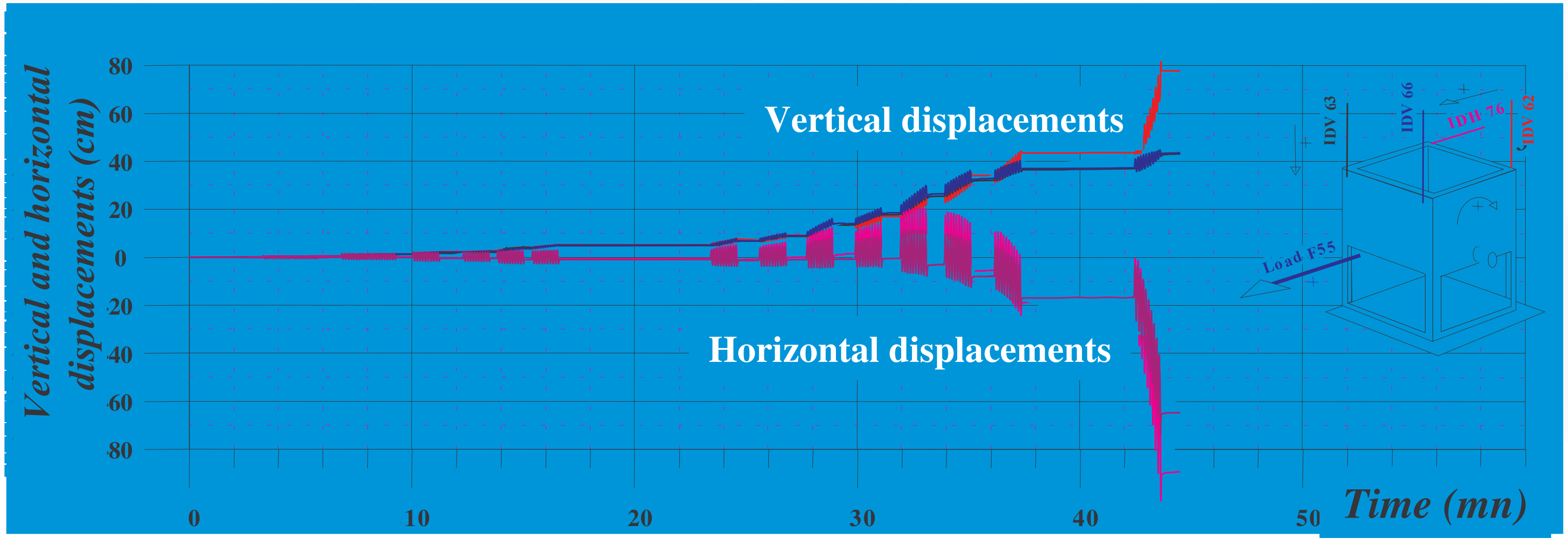
Results : Horizontal cyclic loading (6)

Effect of a sand layer below the footing



Load Control

Example of cyclic lateral loading sequences (Test 13)



(T13, M1)

Building displacements under the cyclic loading sequences (Test 13)

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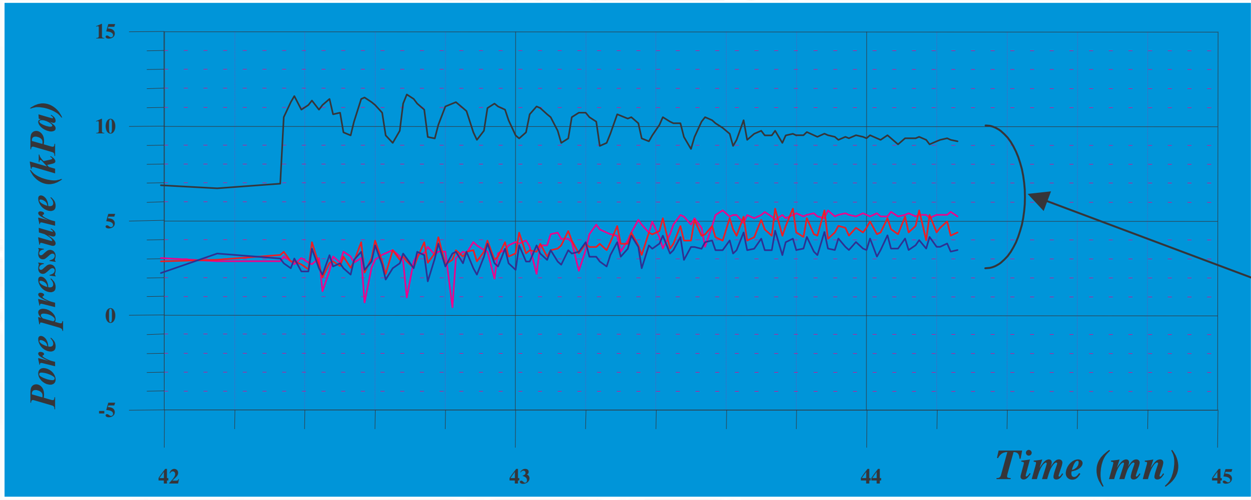
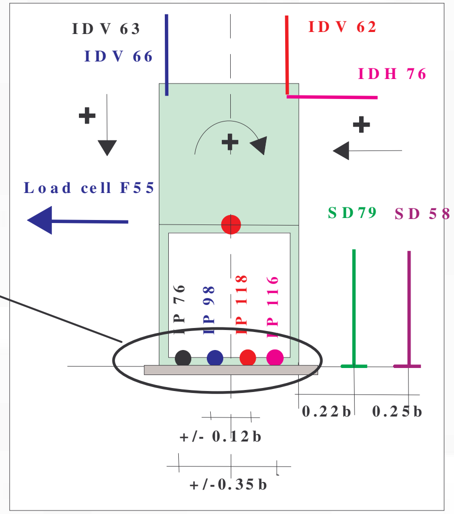
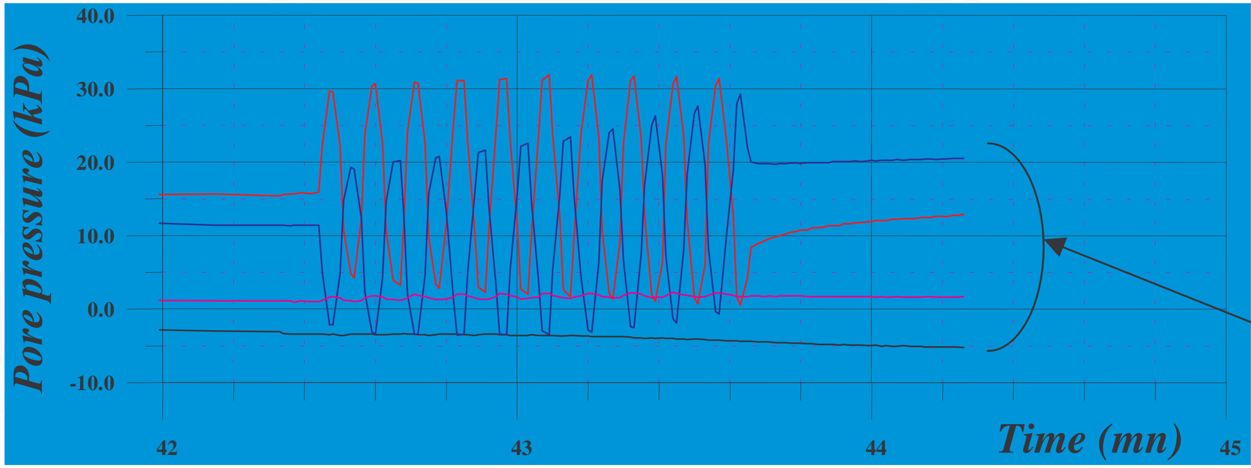
Results : Horizontal cyclic loading (7)

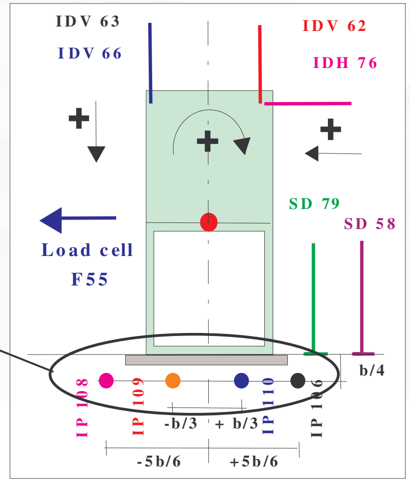
Effect of a sand layer below the footing





Pore pressure at the base (Test 13, last cyclic loading sequence)





Pore pressure below the footing at depth B/4 (Test 13, last cyclic loading sequence)

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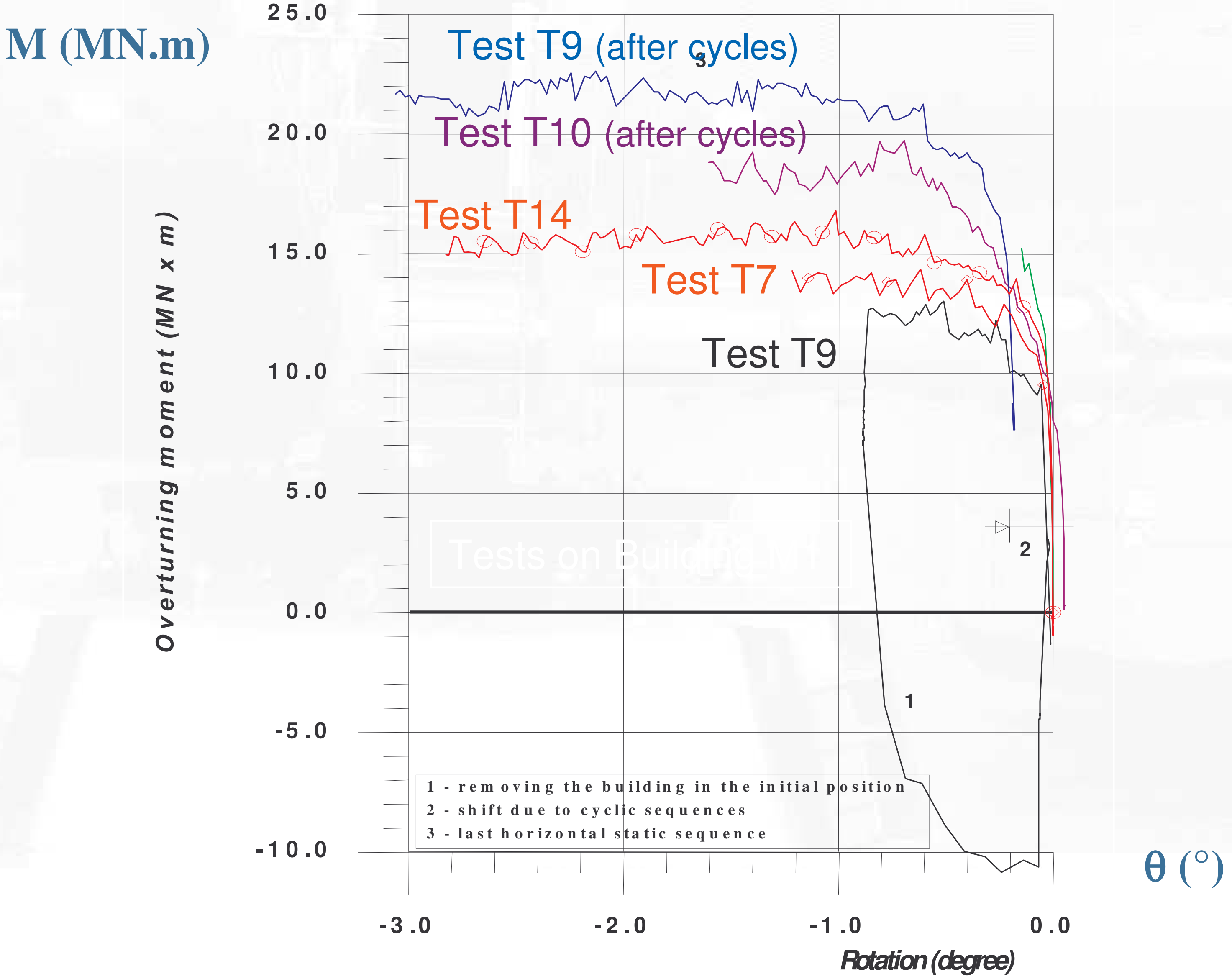
Results : Effect of cyclic sequences on lateral resistance



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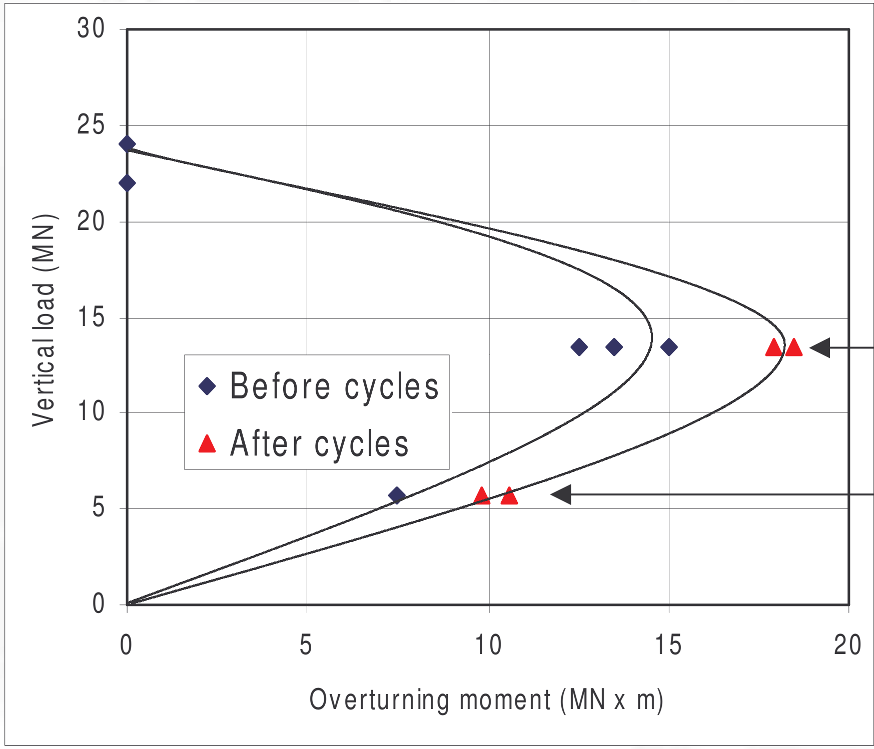
Results : Effect of cyclic sequences on lateral resistance (2)

V (MN)



Building M1

Building M2

M (MN.m)

Failure envelope from the centrifuge tests

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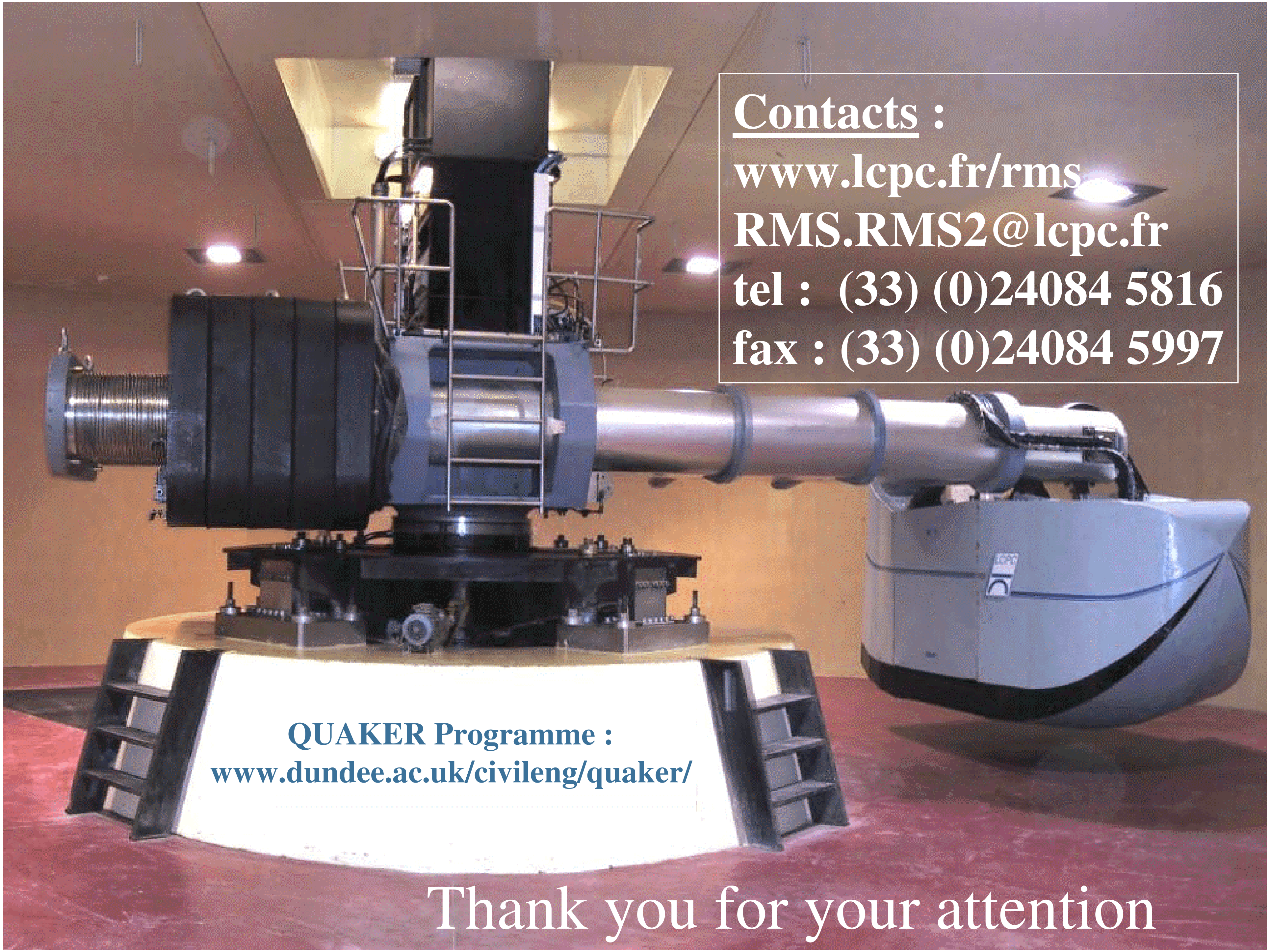
Conclusions & prospects

- Non-linear load-displacement behaviour
- Strain accumulation : settlement & rotation
- Large amount of work being dissipated in the foundation (M-θ curve)
- Effect of a draining layer at the base of the footing
  - Development (or not) of “suction” on the soil-foundation interface
  - Smaller and more localised variations of pressure below the foundation
- Effect of two vertical weight => failure envelope

- Comparison with numerical analysis (collaboration with University of Athens)
- Soil reinforcement below the foundation (e.g. piled embankment)
- Seismic loading (e.g. with the LCPC Shaker)



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