SINGLE BUOY MOORINGS INC., Monaco

LCPC Laboratoire Central des Ponts et Chaussées

INP Grenoble

3S LABORATOIRE SOLS, SOLIDES, STRUCTURES

Physical modelling of the behaviour of vertically loaded plate anchors in deep sea sediments: laboratory, centrifuge and field tests

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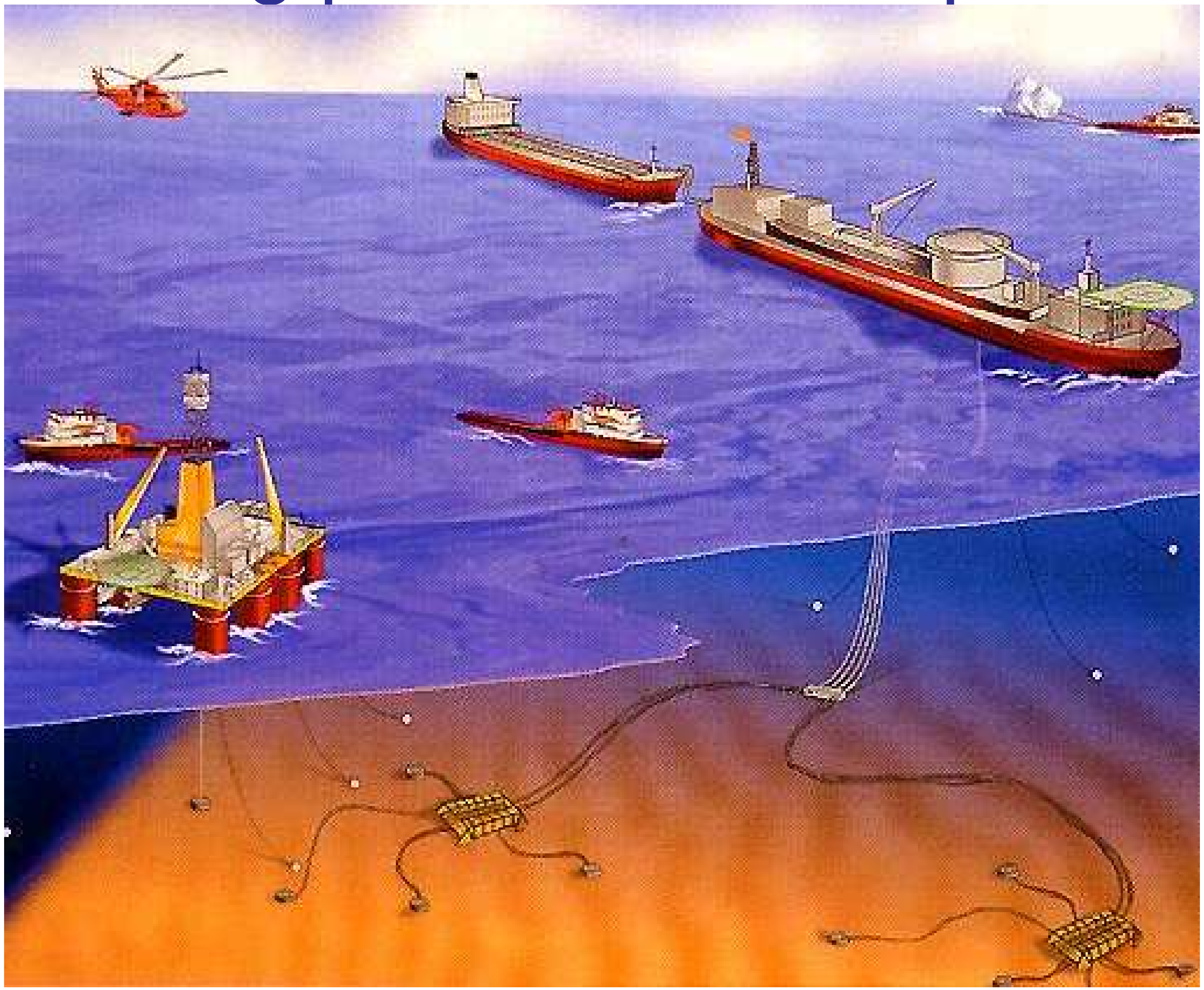
Outline

- Introduction
- Research program
- Laboratory model tests
- Half-scale onshore field tests
- Centrifuge tests
- Numerical modelling
- Conclusions

Anchoring problems in deep offshore



Introduction

- Plate anchors as an alternative to suction caissons in deep sea sediments
- VELPA developed by SBM for deepwater Taut Moorings (S.Alhayari DOT Conf. Marseille 2003)
- Explore the possibility of installation
- Evaluate the ultimate pullout capacity. Previous work (Forest et al 1995): holding factors Nc =9 (long term) and 15 (short term)
- Effect of soil suction ?

Suction anchors

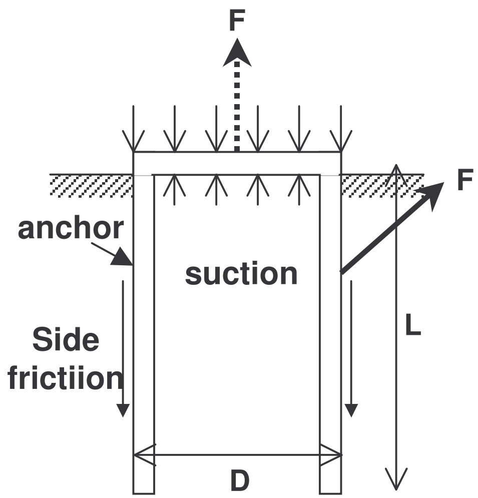
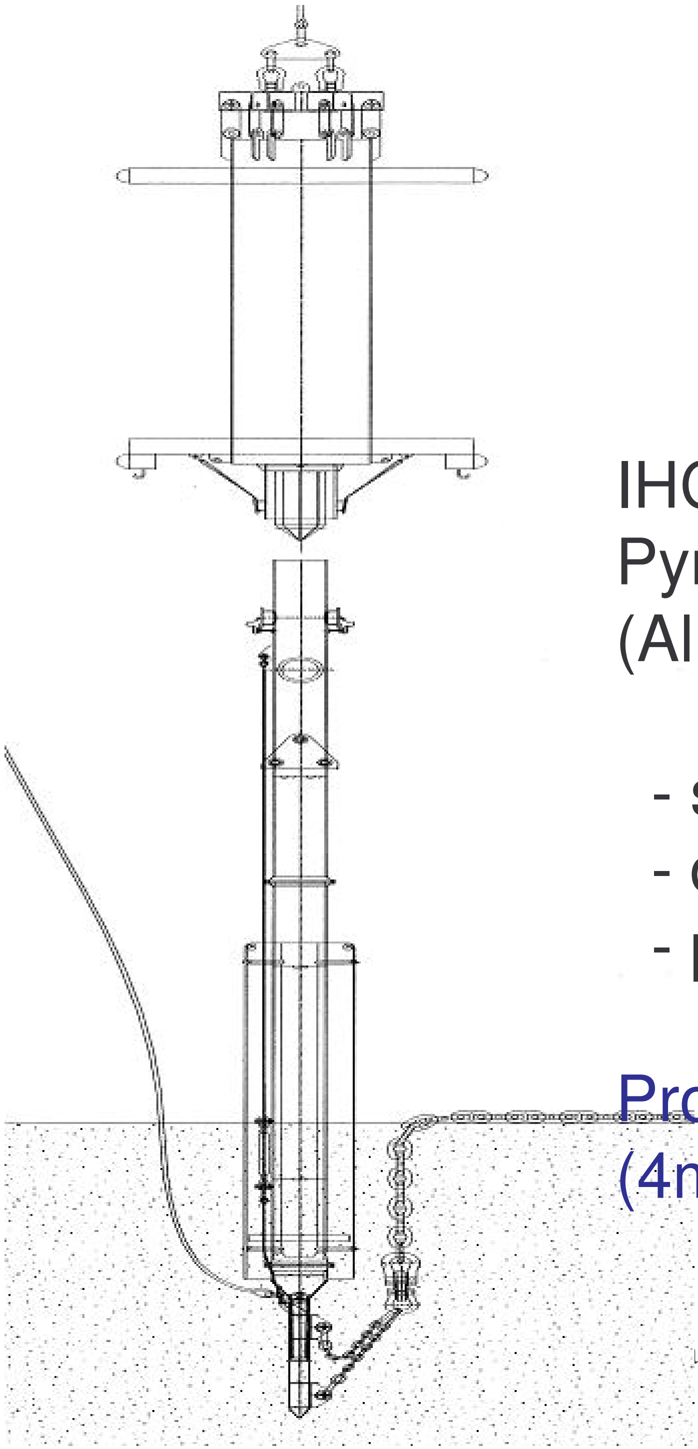


Plate anchors

VLA Anchors

SEPLA

VErtically Loaded Plate Anchor (VELPA) for Deepwater Taut Moorings SBM, inc.



Installation of the VELPA

IHC Hydrohammer
Pyrodriver (combustion hammer)
(Alhayari & Van Foeken 2003)

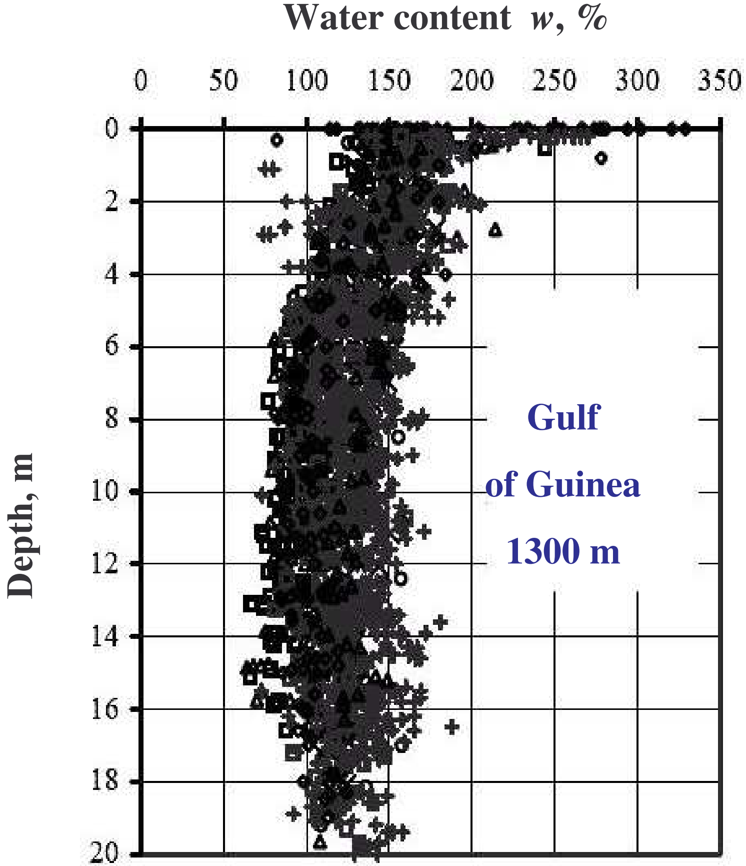
- self-penetration with follower
- driving of the anchor
- pretension and rotation

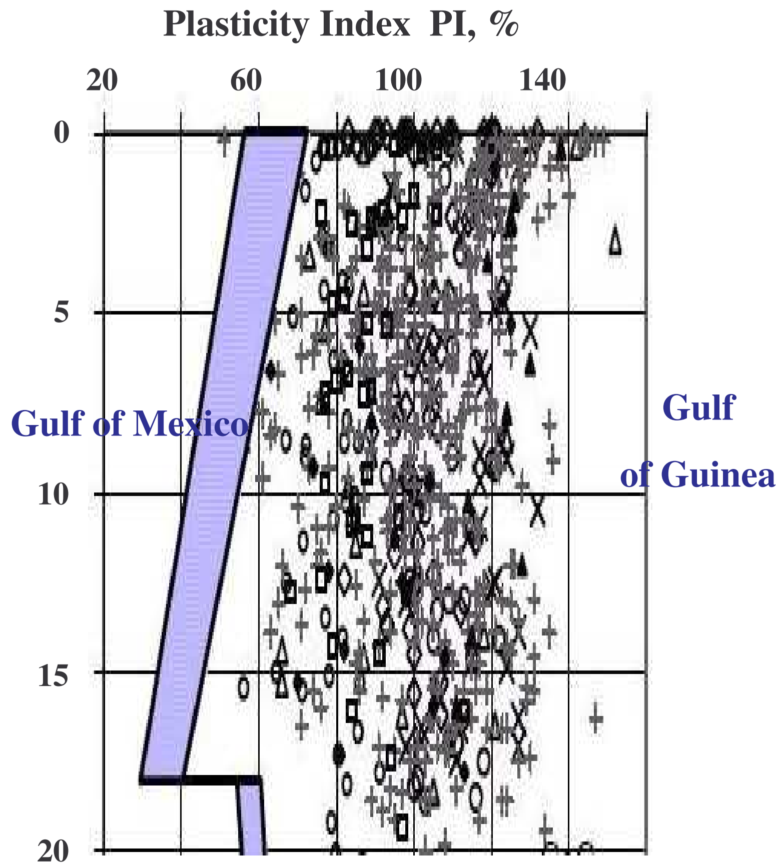
Prototype : 4, 8 and12m²
(4m in height x 3m in width for 12m²)

Research Program

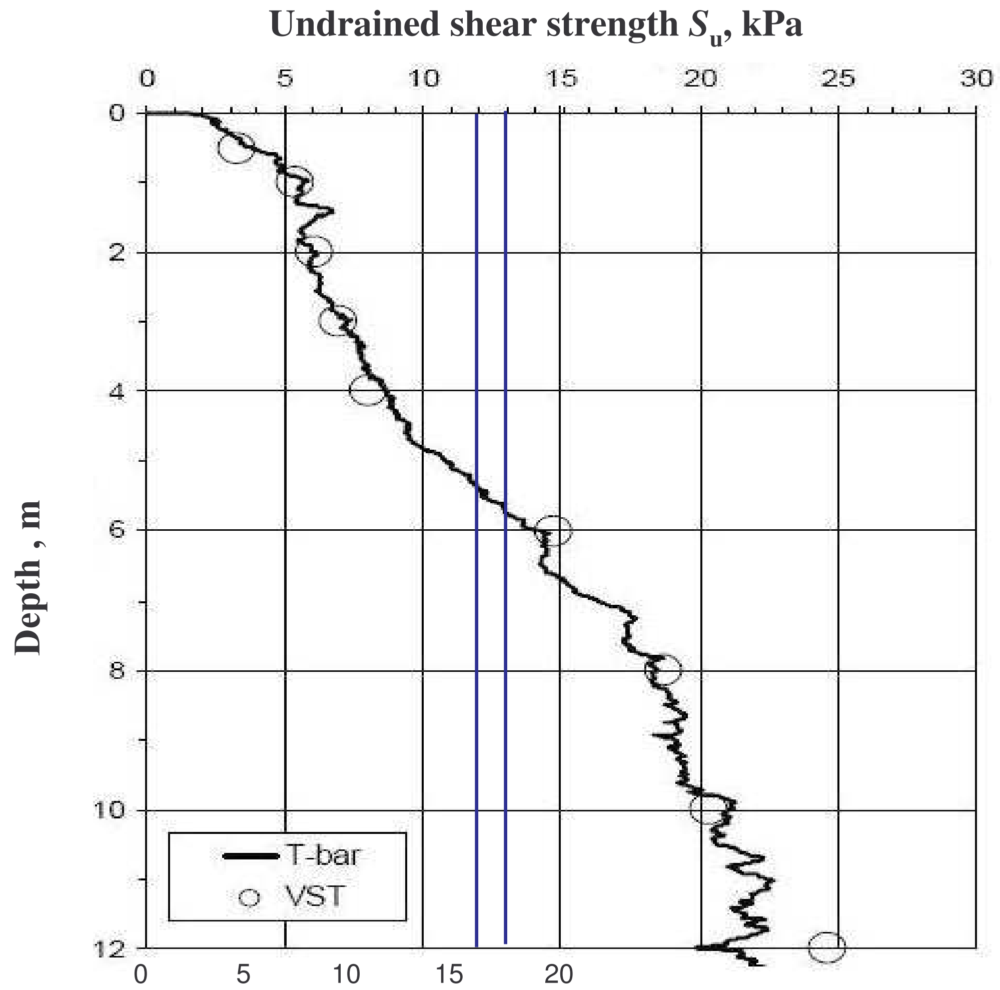
- Physical modelling of the anchor combined with numerical modelling
- Reproduce the different phases of installation, pretension and pullout of anchors
- Reproduce the deep sea soil conditions
- Laboratory tests (models at scale 1/15)
- Field Tests (scale 1/6)
- Centrifuge Tests (scale 1/100)
- Numerical modelling

Deep sea soil properties





Typical deep sea soil profile



Laboratory tests

•Laboratory tank:
2m x 1m x1m

•Homogeneous clay:

1st Tank : Su = 1kPa
2nd Tank: Su = 4 kPa
3rd Tank: Su = 20 kPa

•6 to 9 tests in each tank

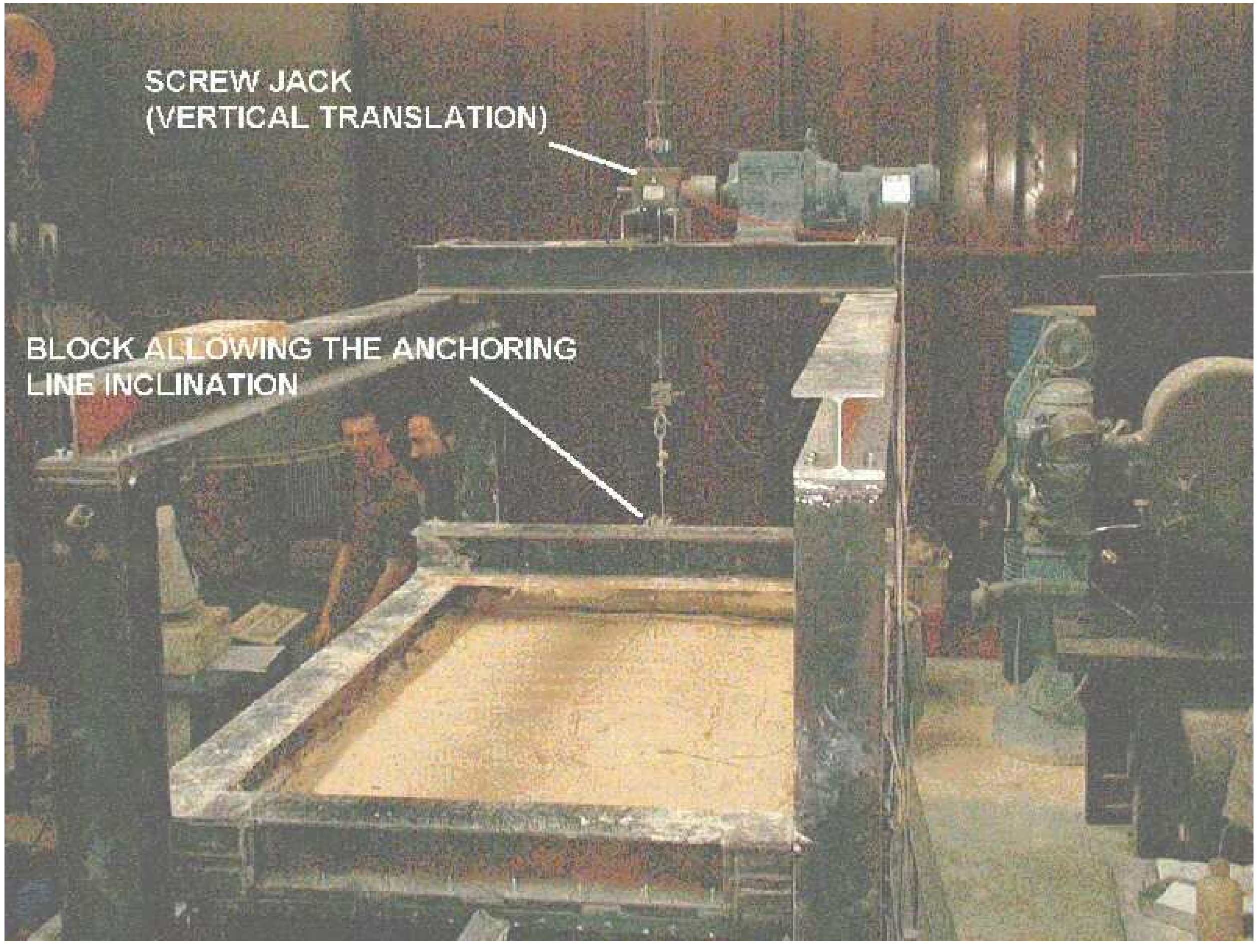


Plate Anchor Scale Model

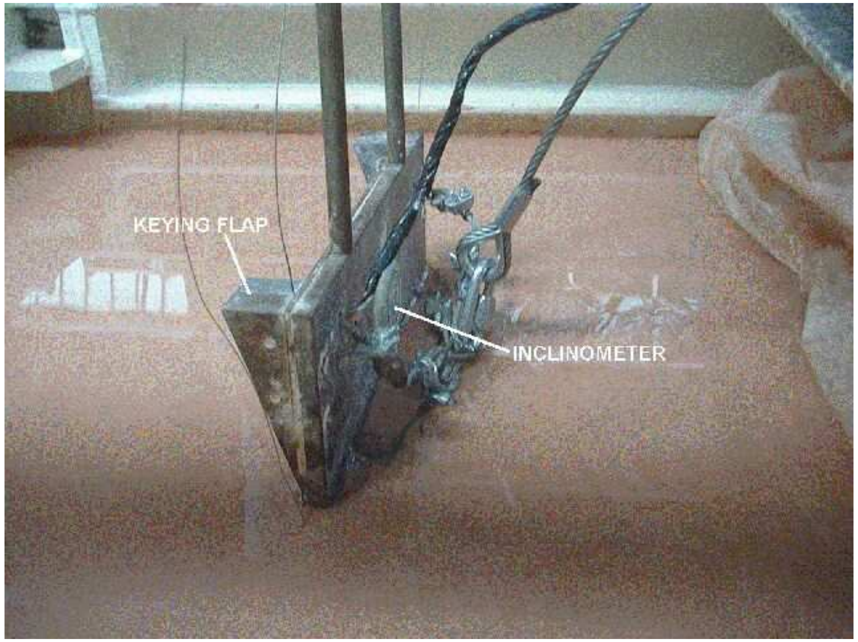
• Dimensions of the model plate:
- height : 20 cm
- width : 30 cm
-thickness : 1.4 cm

•Efficient anchorage surface 6.10^{-2} m^2.

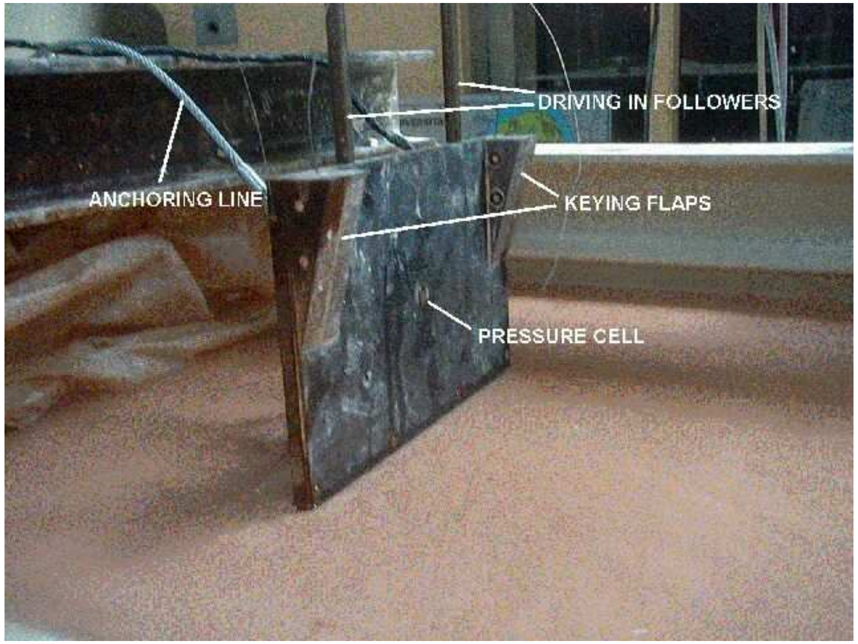
•Scale: 1/15

•Instrumentation:
  inclinometer
  pore pressure

Front face

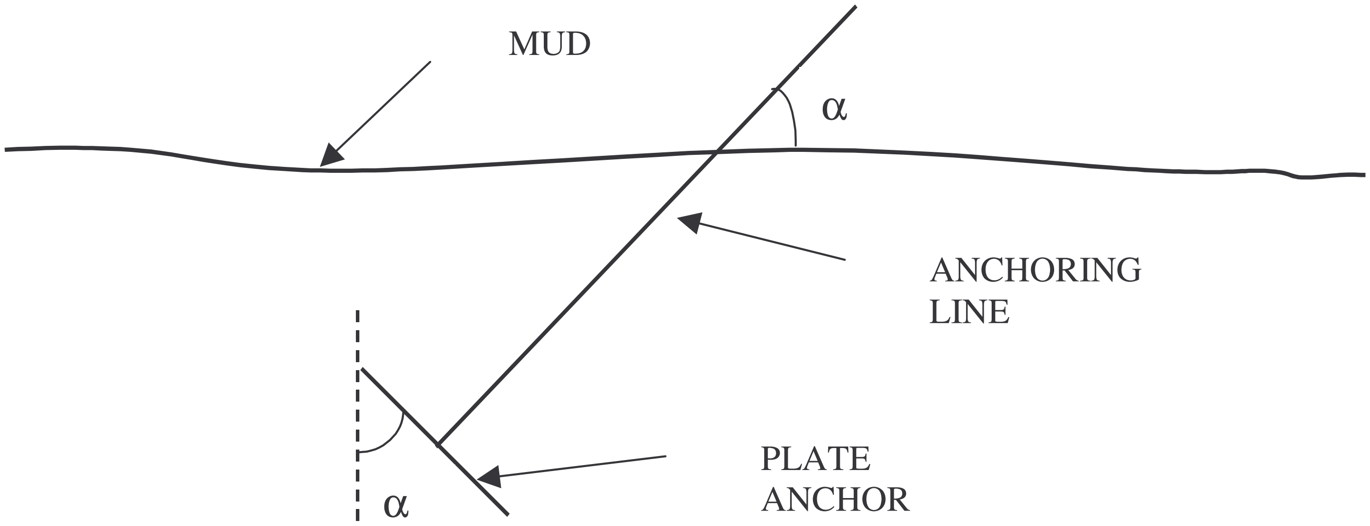


Rear face



Driving of the plate + pretension at 80°

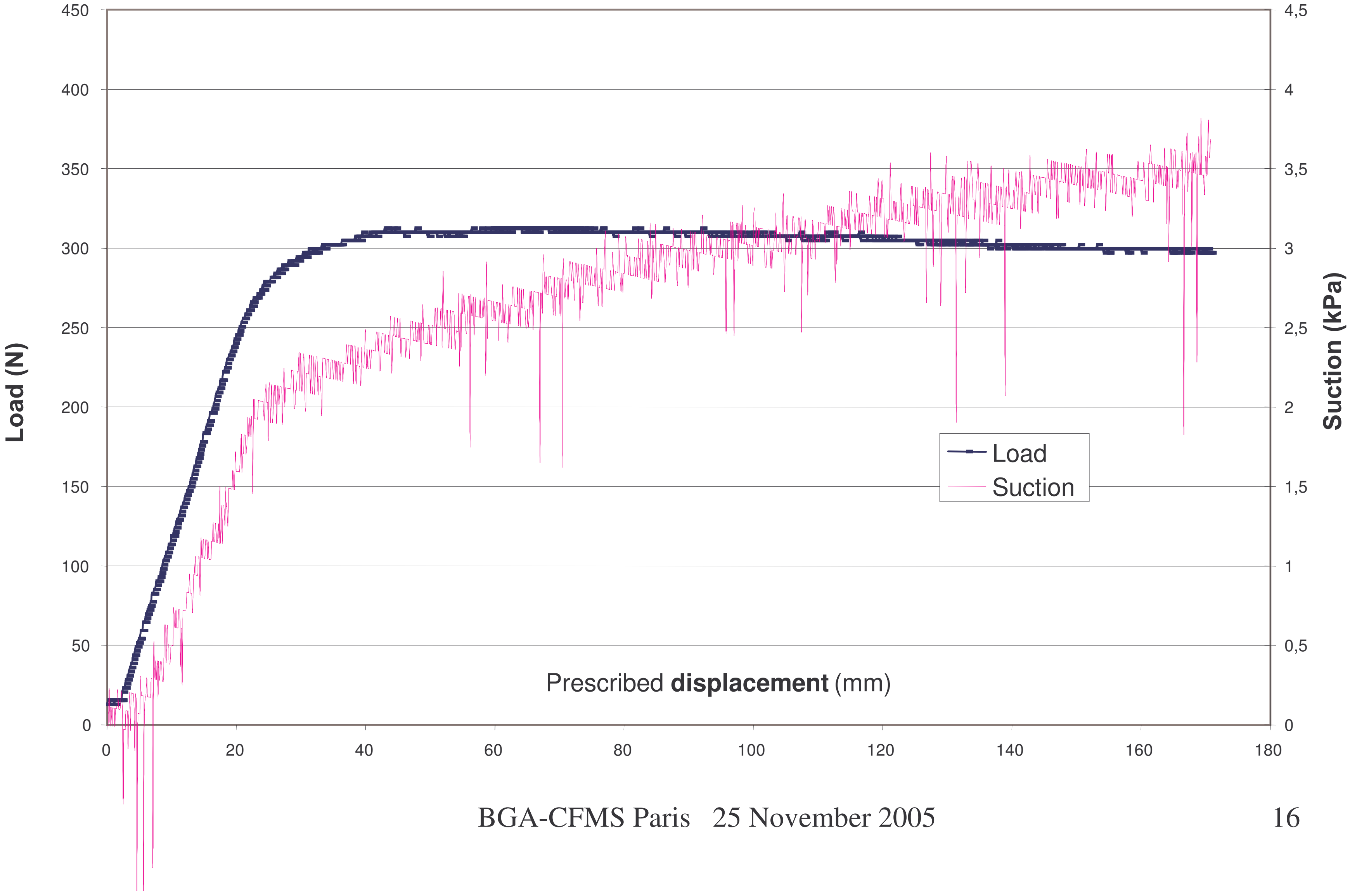
Pullout Tests



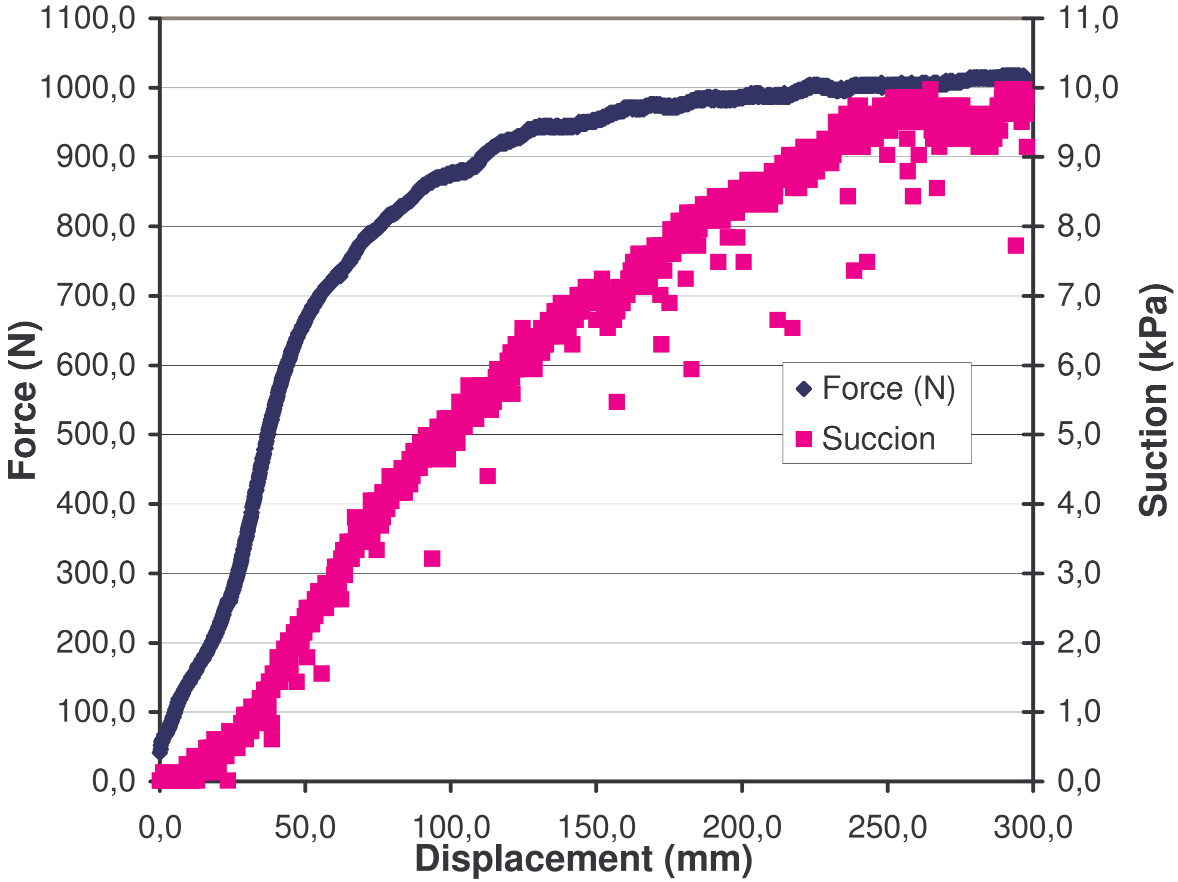
Sketch – Definition of the anchoring angle α

- Initial depth of the anchor between 40 cm and 70 cm
- Anchoring angles varied from 25° to 90°
- Loading rate: 4mm/min

Pullout test 3 in lab tank n°1 – load and suction curves
Inclination of the anchor : 60°



Pullout Test 7 in Tank n°2. Load and Suction curves. Inclination of the anchor $\alpha = 45°$



Summary of Laboratory Results

Tank n°	Su (kPa)	Ultimate Pullout capacity (N)	Holding Factor Nc	Suction Contribution
1	0.8-1.1	300 - 460	**5.4 - 7.8**	**73%**
2	3.5-4.5	917 - 1150	**4 - 4.8**	**61%**
3	**20**	7400 - 11600	**6.2 – 9.5**	**20%**

Ultimate Pullout Capacity = Su x Effective area x Nc
Suction contribution = (Δu x Effective area)/ Total Load

- Relatively low values of Nc
- Drainage paths observed
- Successful pretension and rotation phase

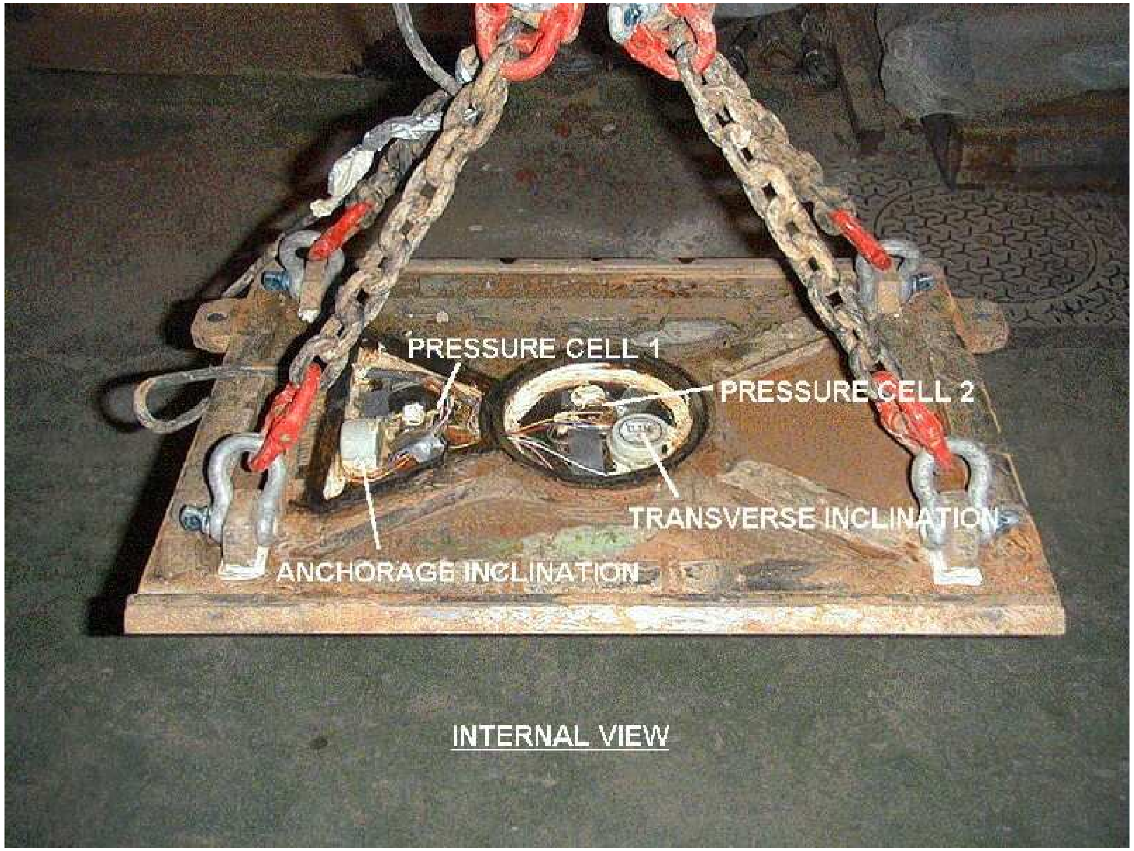
Half scale onshore field tests

•Bourget du Lac site:
Homogeneous clay
over 6m deep

•Average shear strength:
Su = 33 kPa

•Dimensions of the plate:
Height: 0.675m
Width: 0.5m
Thickness: 3.3 cm

•Scale: 1/6



Anchor before installation

Driving Follower

•Driving of the plate to 4.5m deep

•Initial depth of middle point after pretension and rotation:
3.75m and 4.25 m

Pullout Loading

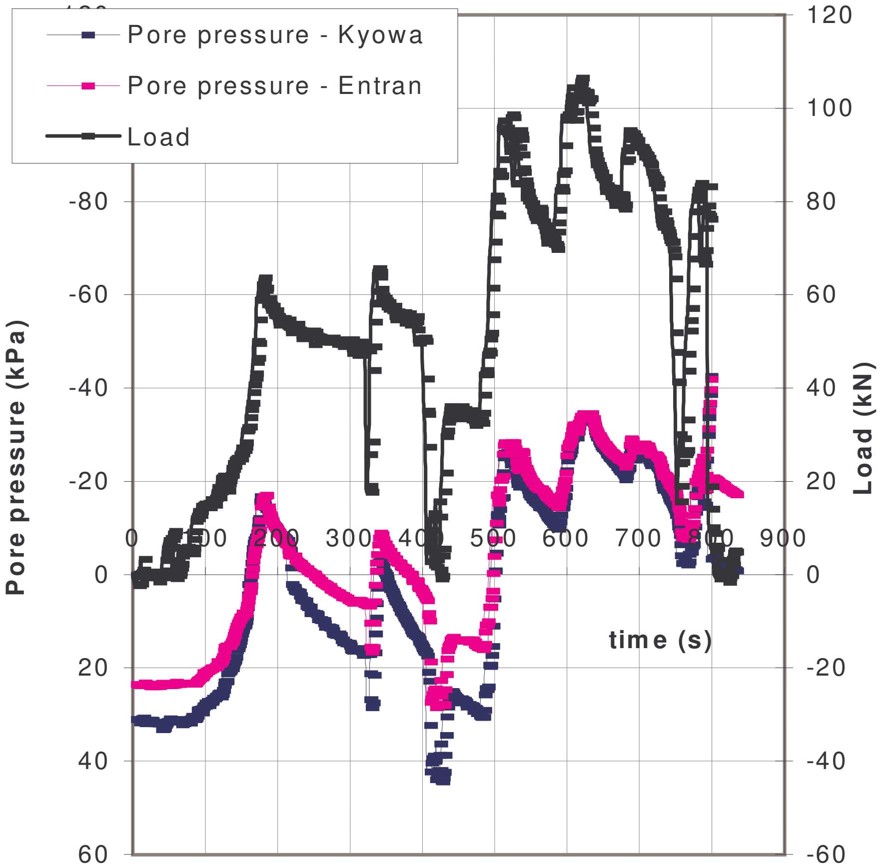
•5 complete tests

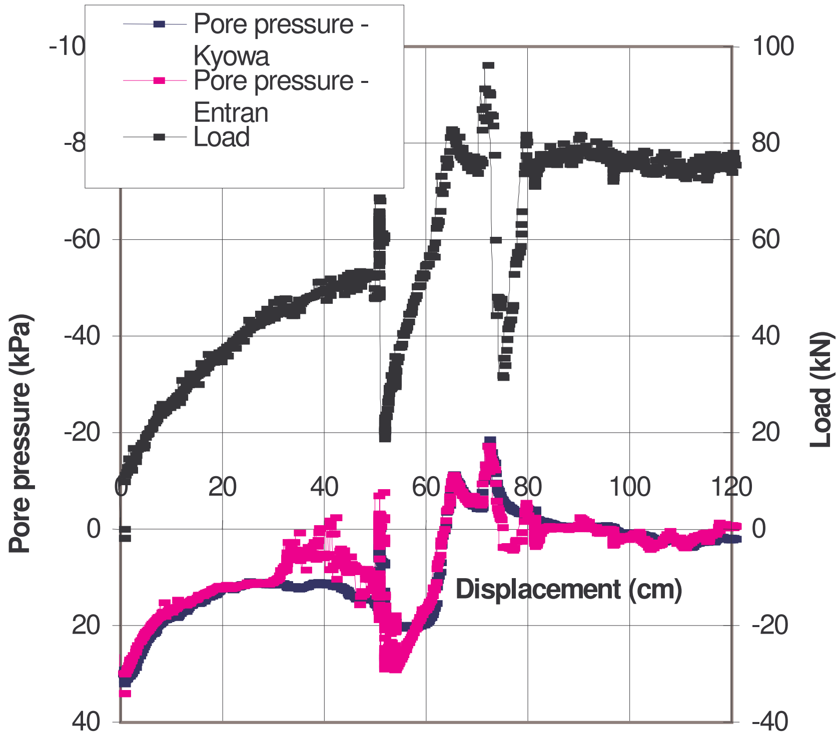
•Inclination angles:
35°, 38°, 40 °, 45°, 53°

•Unloading steps and strong changes in the pullout rate were applied to simulate storm conditions

Anchor after complete pullout test

Typical pullout results





Summary of Field Results

- Ultimate pullout capacities: 80 to 100 kN
- Holding capacity factors Nc = 7.5 to 9.3
- Suction values up to 40 kPa, corresponding to 15% to 20% of the total load, nearly constant (continuous loading or fast loading)
- Possible drainage paths
- The anchoring depth may be not sufficient to develop a complete deep failure mechanism
- Technical success for all the phases of installation, pretension/rotation and pullout.

Centrifuge Tests (LCPC Nantes)

Centrifuge testing program

- Consolidation of kaolin « Speswhite clay » in order to reproduce the in-situ gradient in undrained shear strength Su = 0.8 z
- Soil properties control with in flight CPT tests
- First series of tests on pre-embedded anchors positioned at an inclination of 45°
- Second series of complete tests (driving, pretensioning at 80° and pullout at 45°
- Third series of installation and pretension tests (control of the plate rotation)

Sample preparation

Sample consolidation

Installation of the pre-embedded anchors

Container configuration for tests with pre-embedded anchors

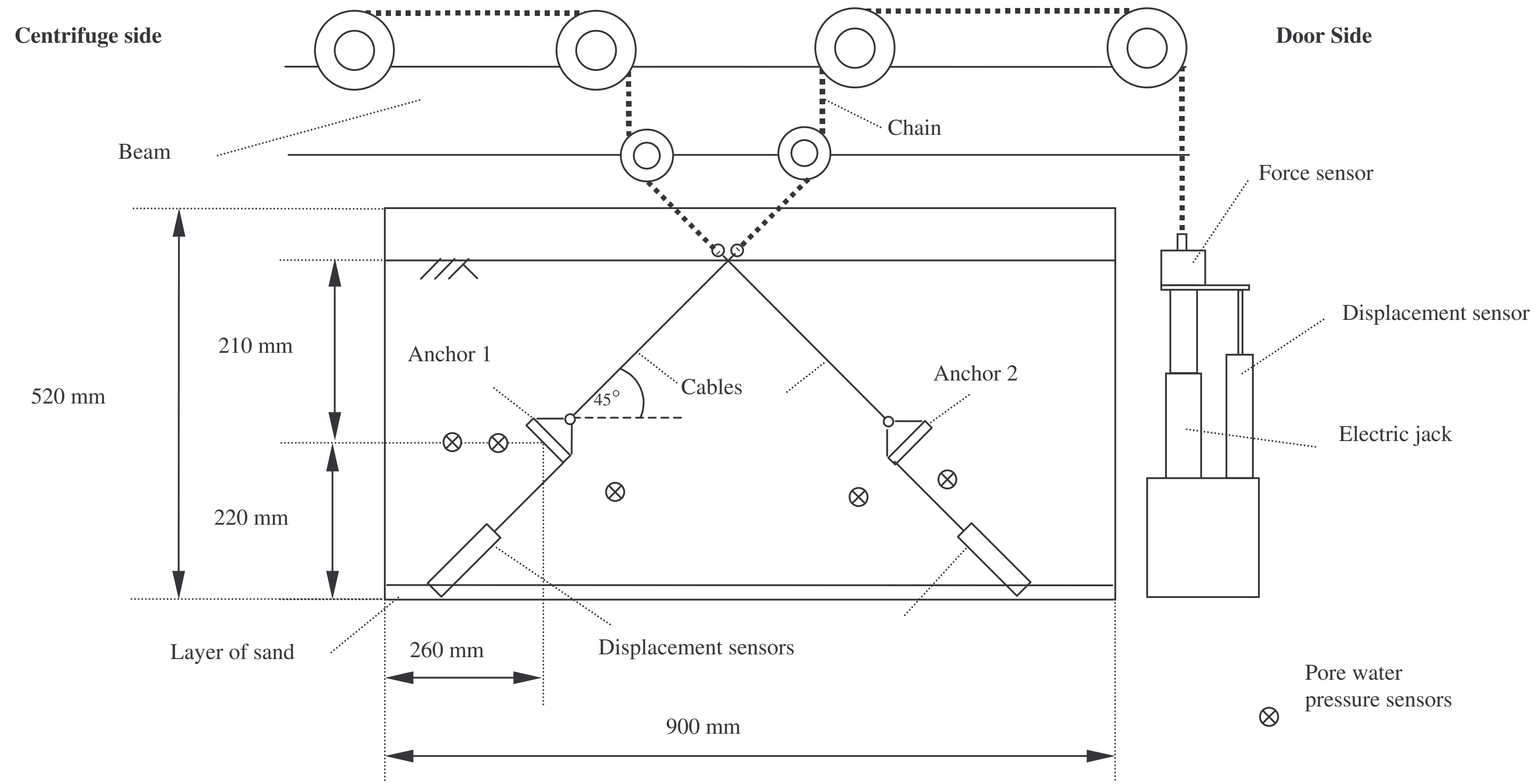
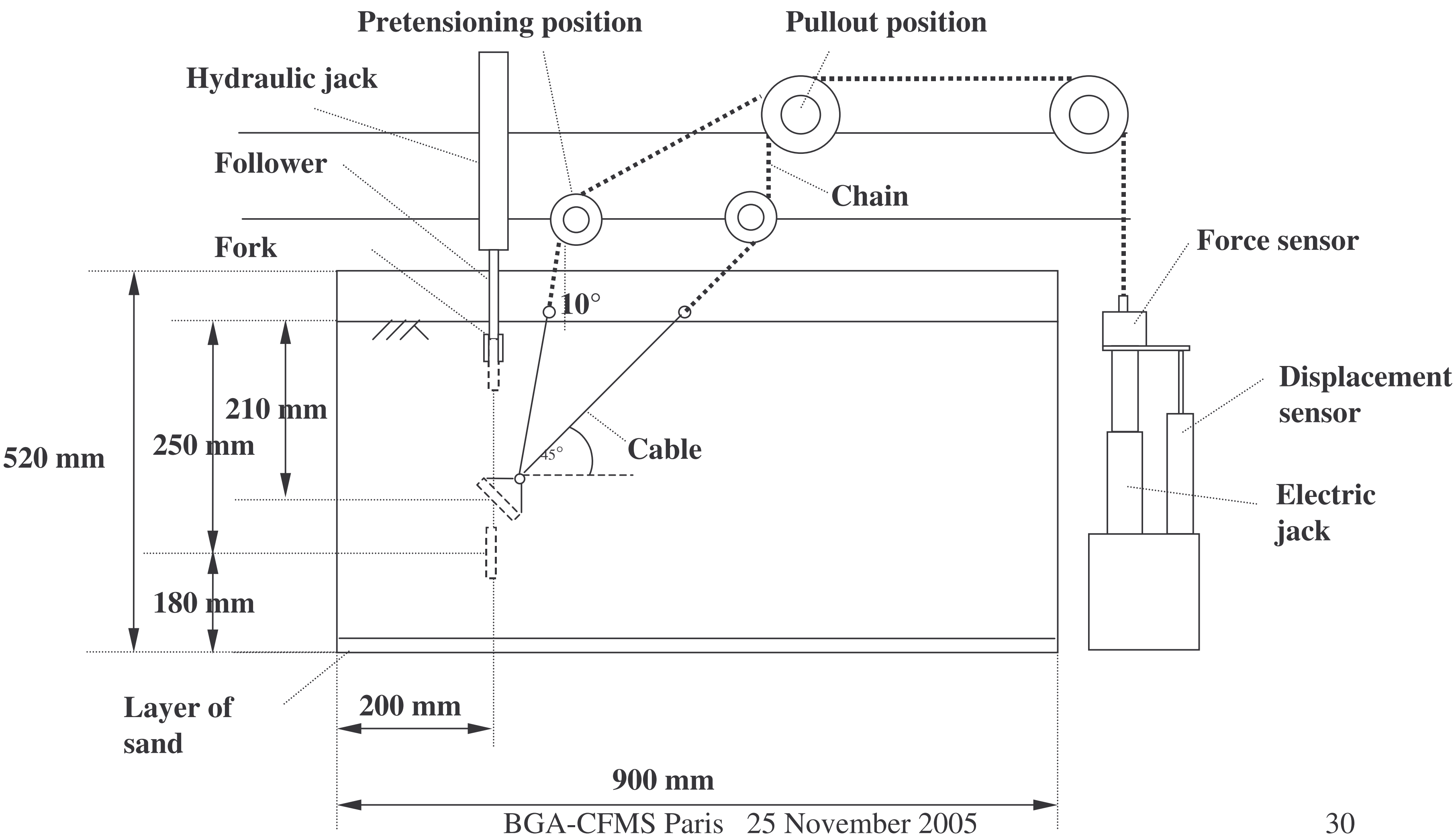
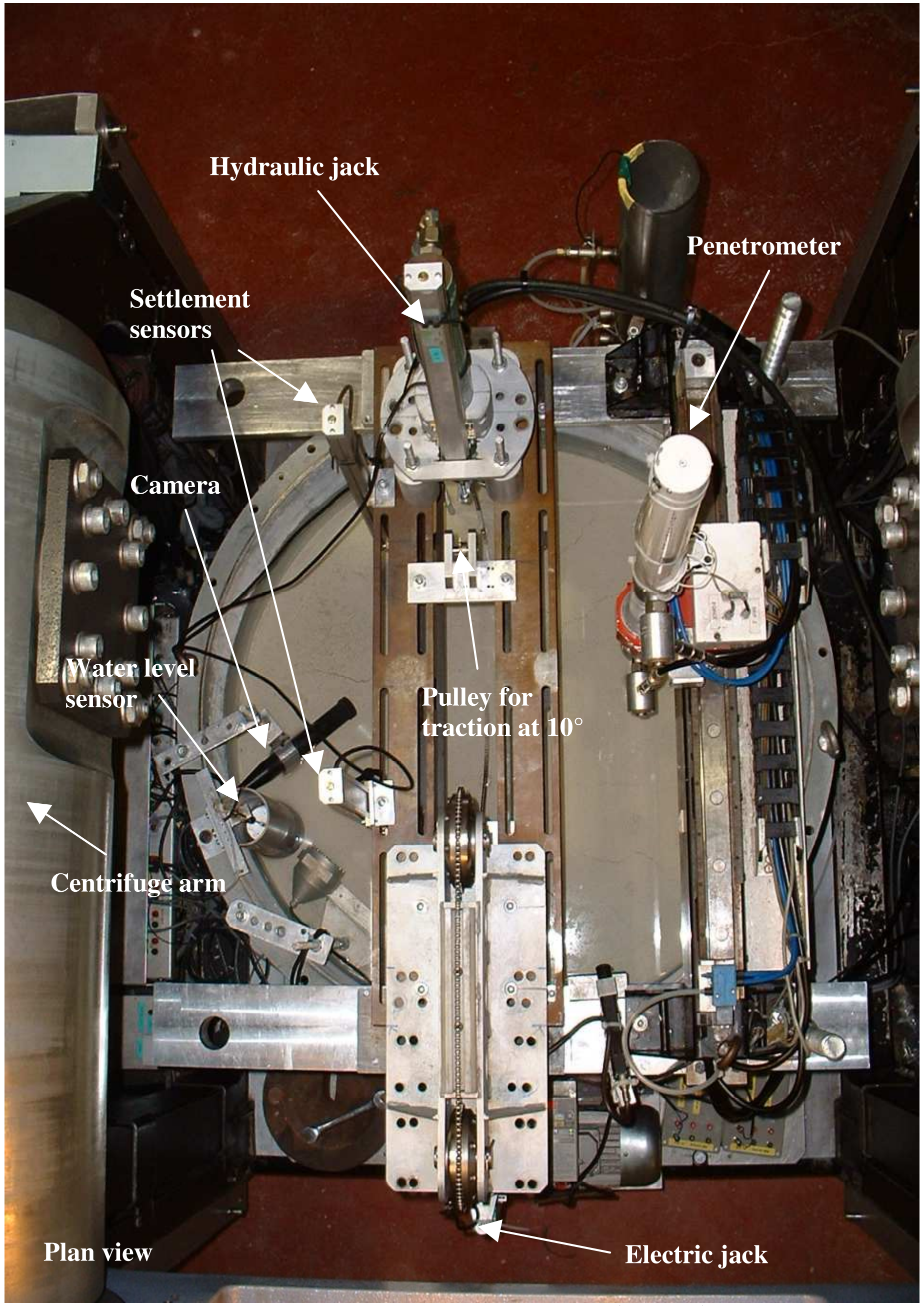
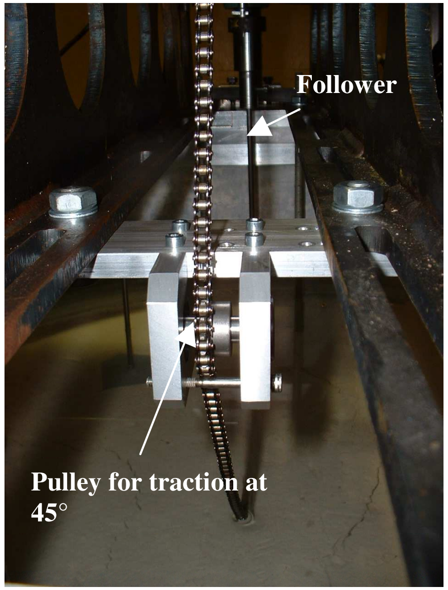


Figure 4 : Container configuration (Pullout tests)

Container configuration for complete tests







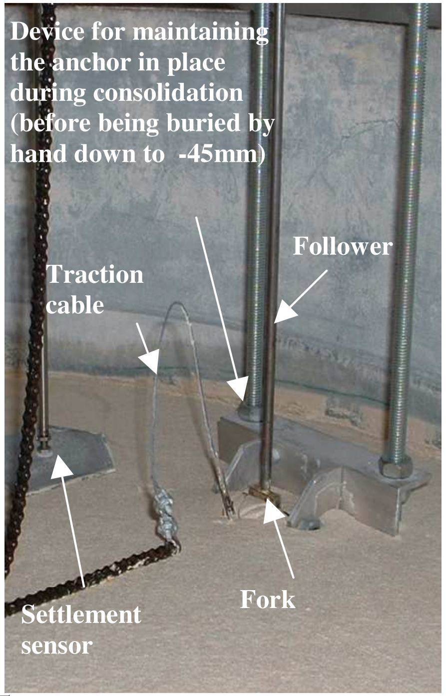
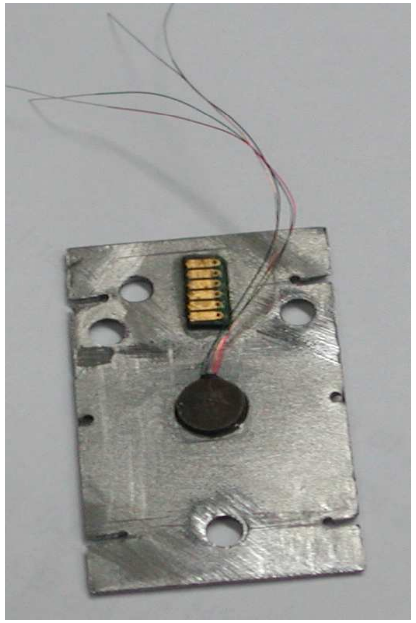


Figure 9 : Container configuration (Complete tests)

Instrumented model plates



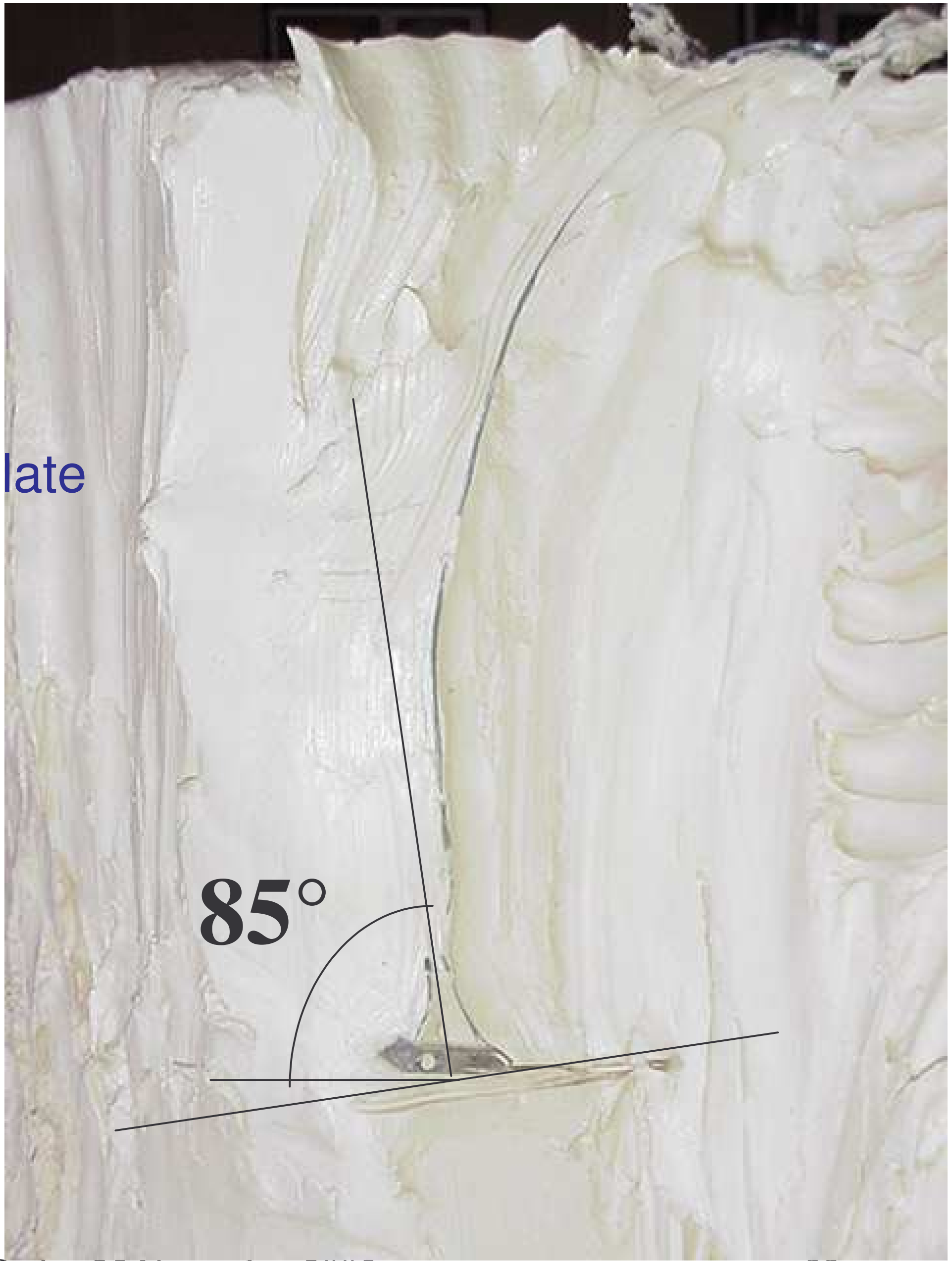


Dimensions: 4x 3x 0.4cm (scale 1/100)

Pretension tests

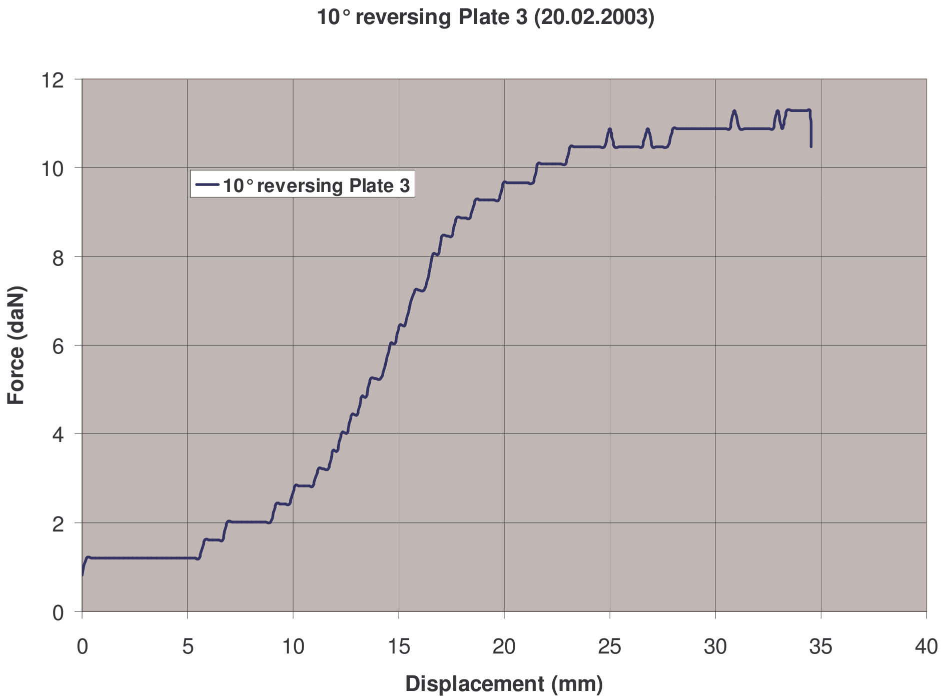
• Verification of the orientation of the plate after pretension.

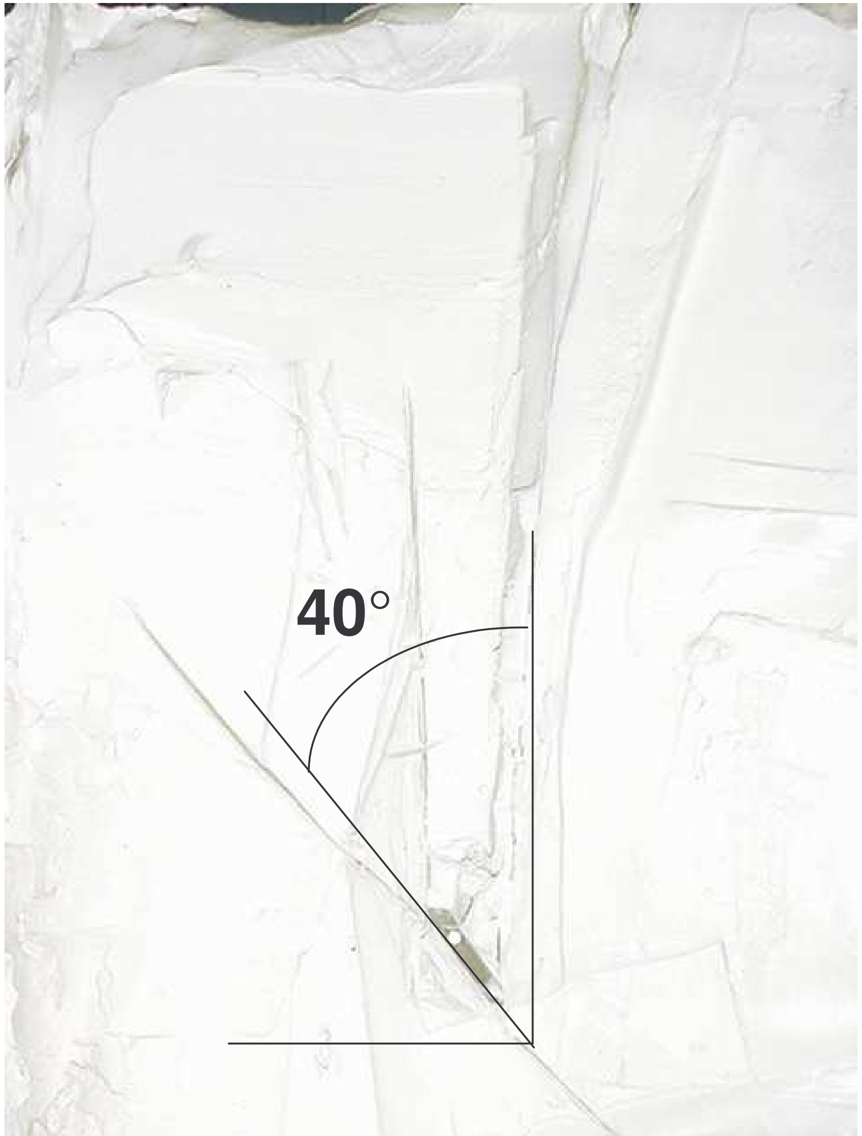
•Final orientation determined by the orientation of the anchoring line



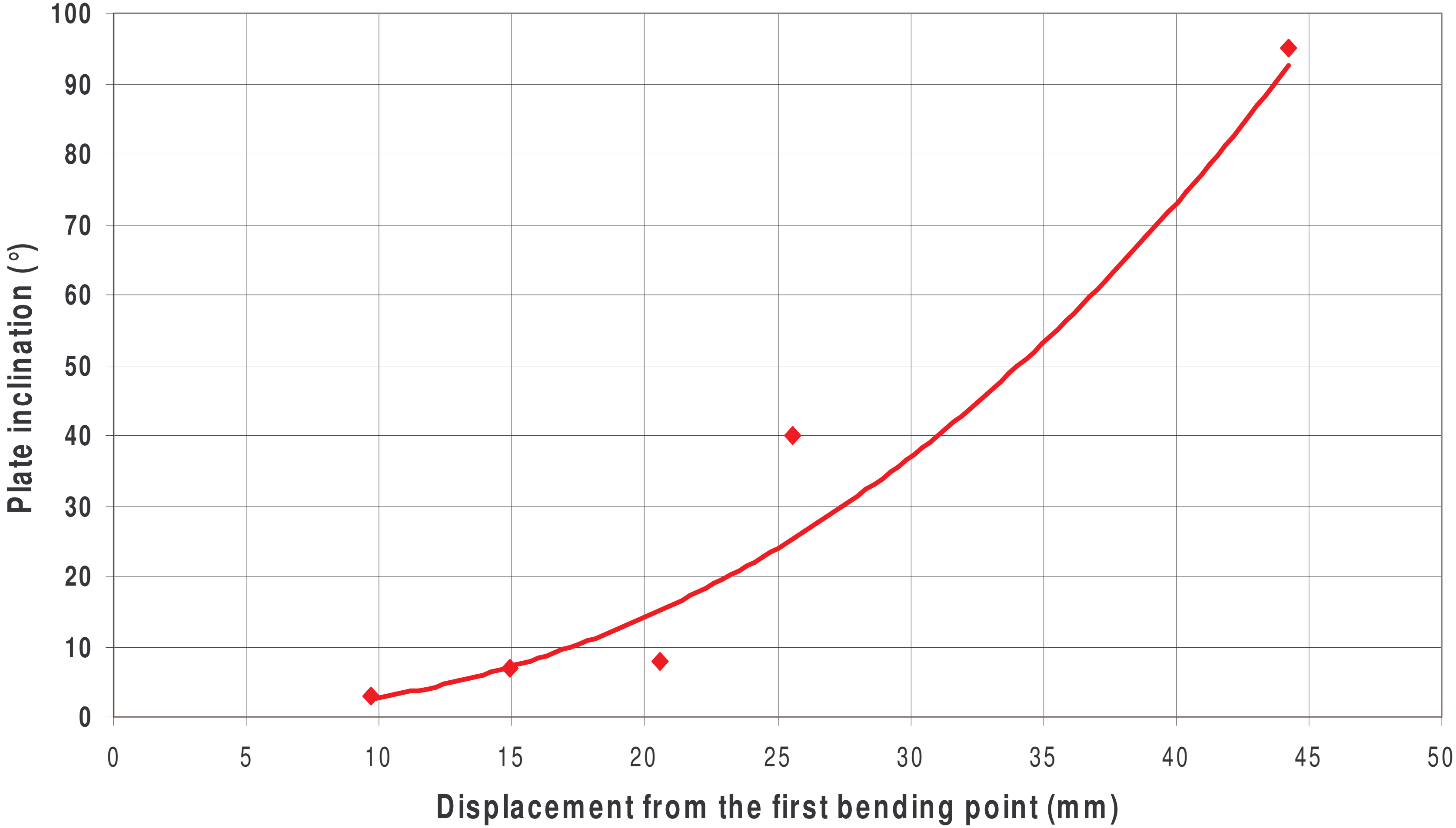
Pretension tests

- Control of the plate orientation after a pretension test

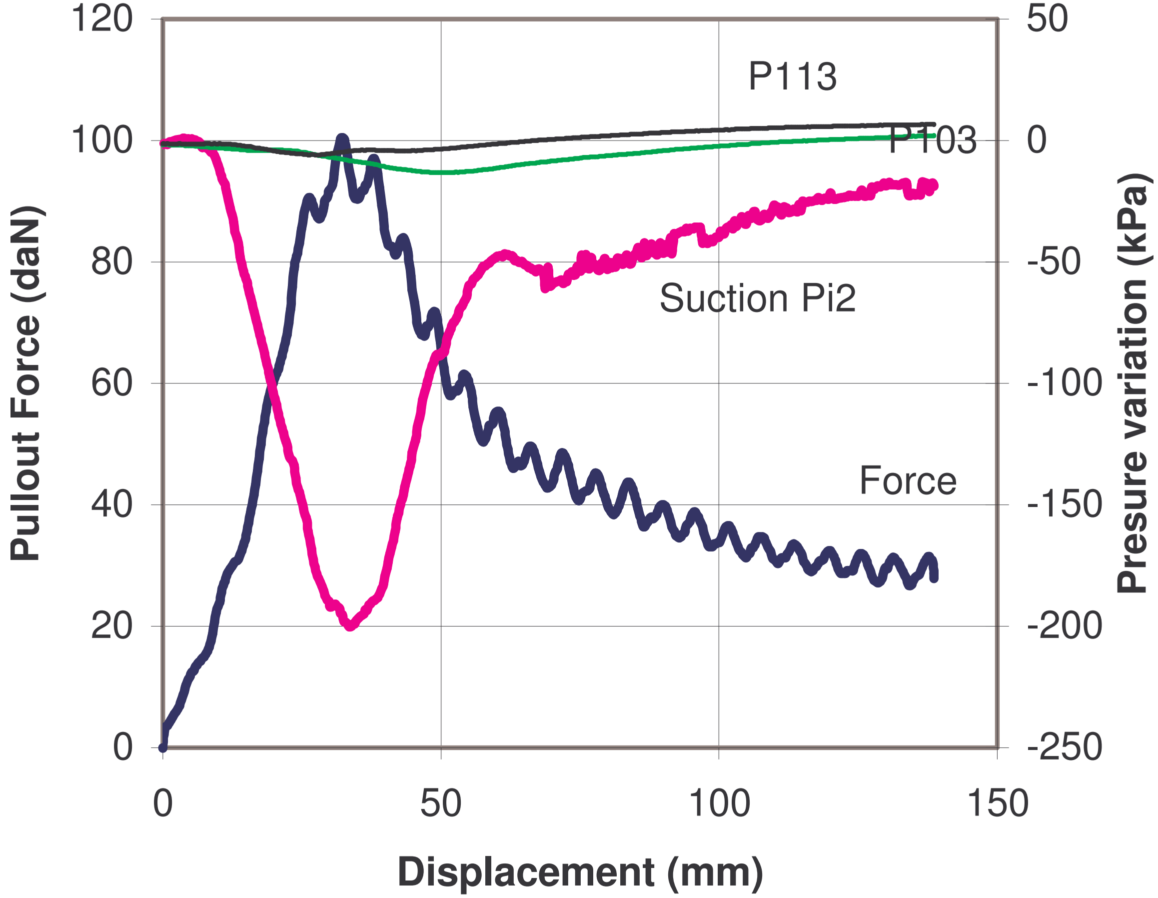




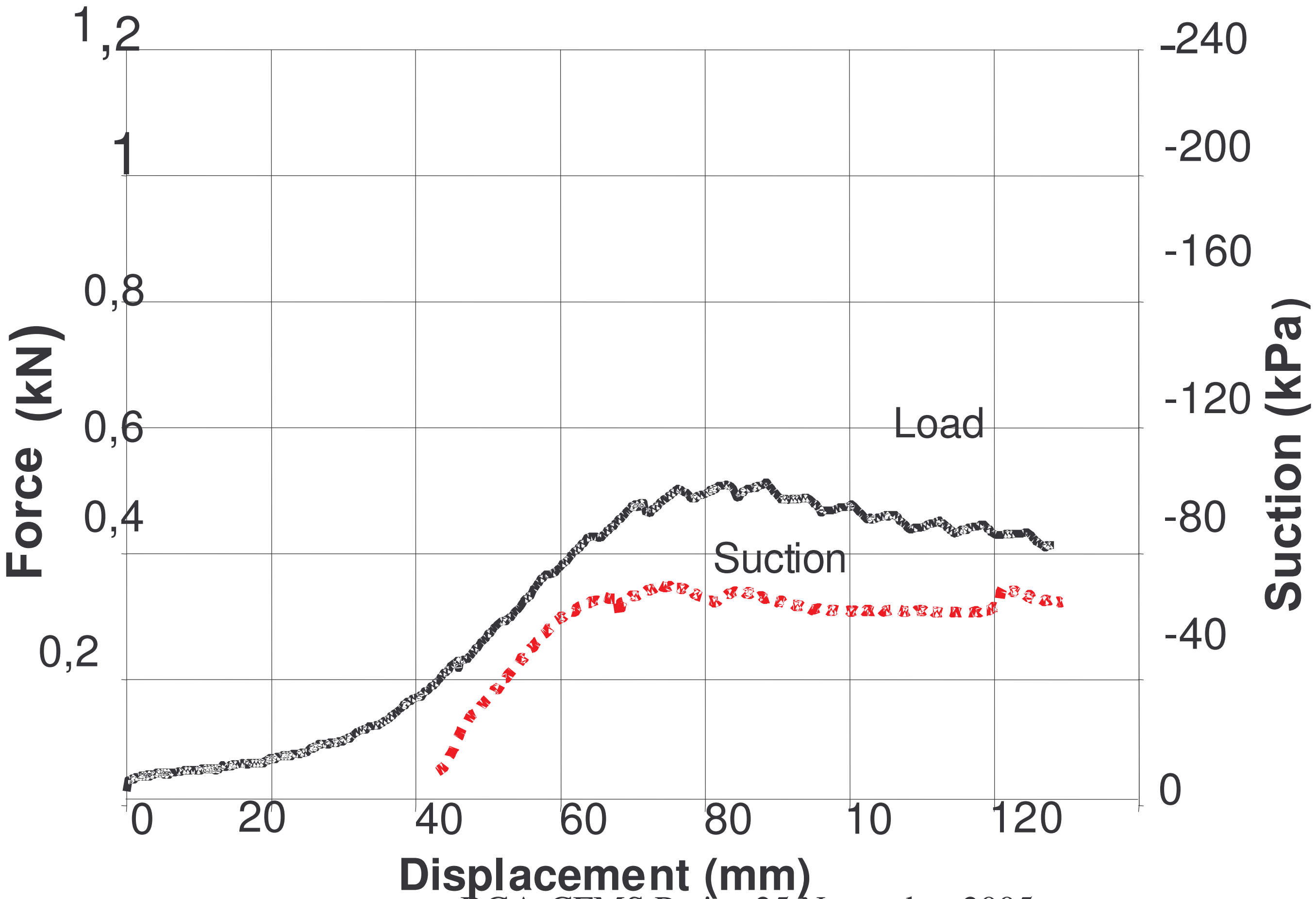
Pretension of the plate: displacement criteria



Pre-embedded anchor
Pullout test – inclination 45°



Driven and pretensioned anchor final inclination 45°

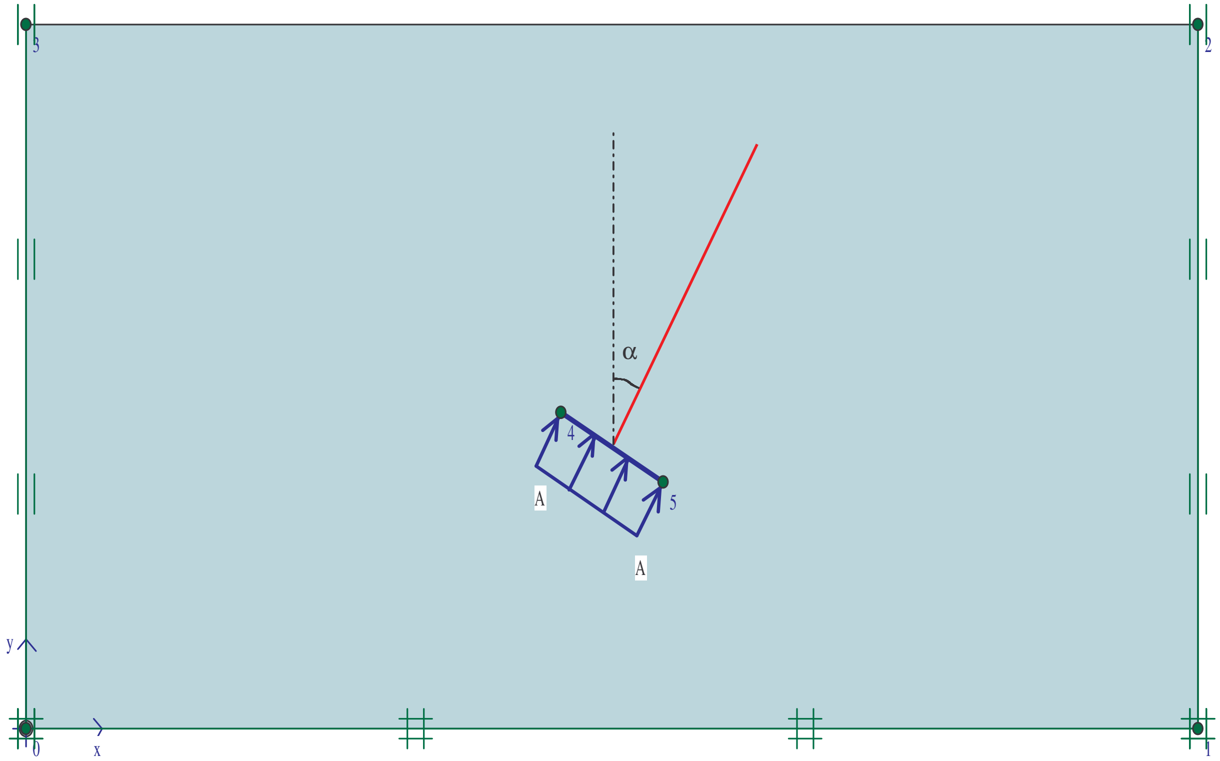


Summary of centrifuge tests results

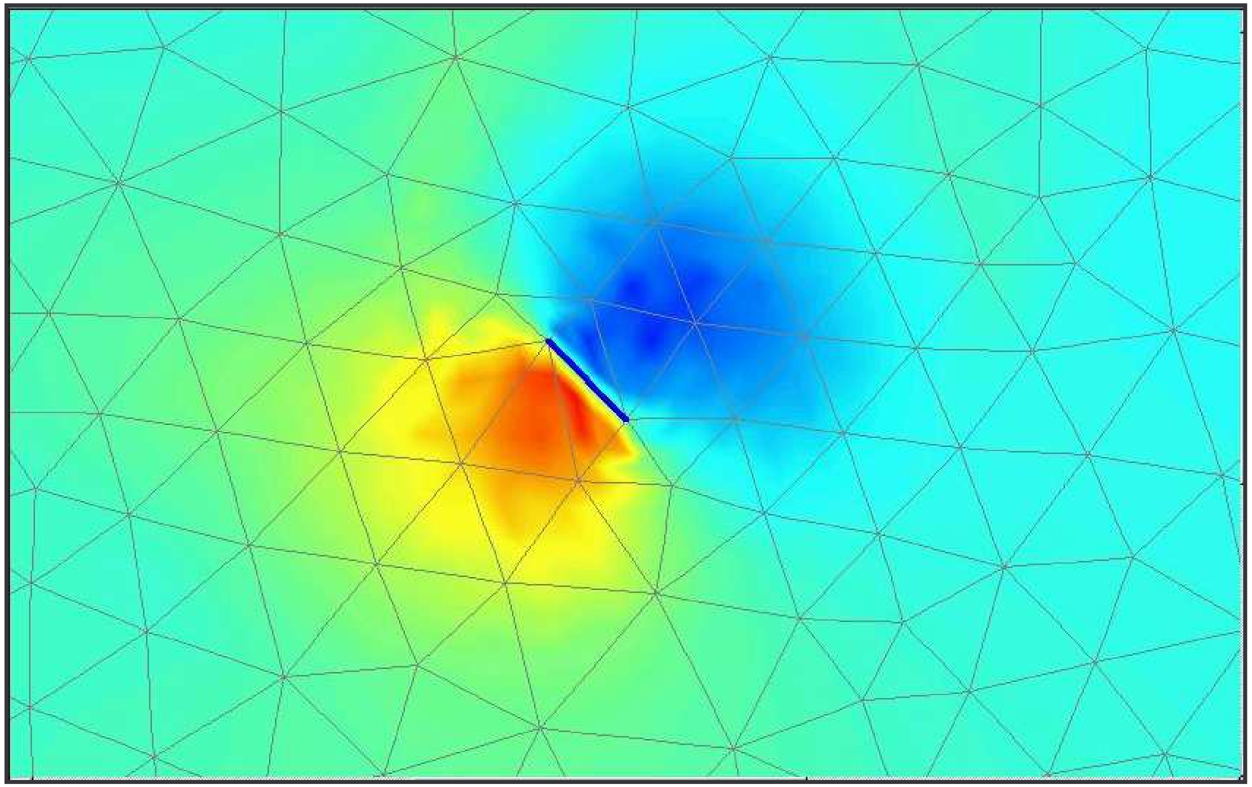
	Ultimate Pullout capacity (MN)	Holding Factor Nc	Suction (kPa)	Suction Contribution
Pre-embedded anchors	Anchor 1: 6.1	**28 (res.15)**		
Driven and pretensioned anchors	Anchor 1: 6.6 Anchor 2: 4.9	**31** **24**	**60**	**14%**

- High values of Nc, slightly lower for driven plates (effect of soil remoulding after installation ?)
- Peak/residual values for pre-embedded plates
- « Plateau » values of UPC and suction for driven plates
- Successful pretension and rotation phase

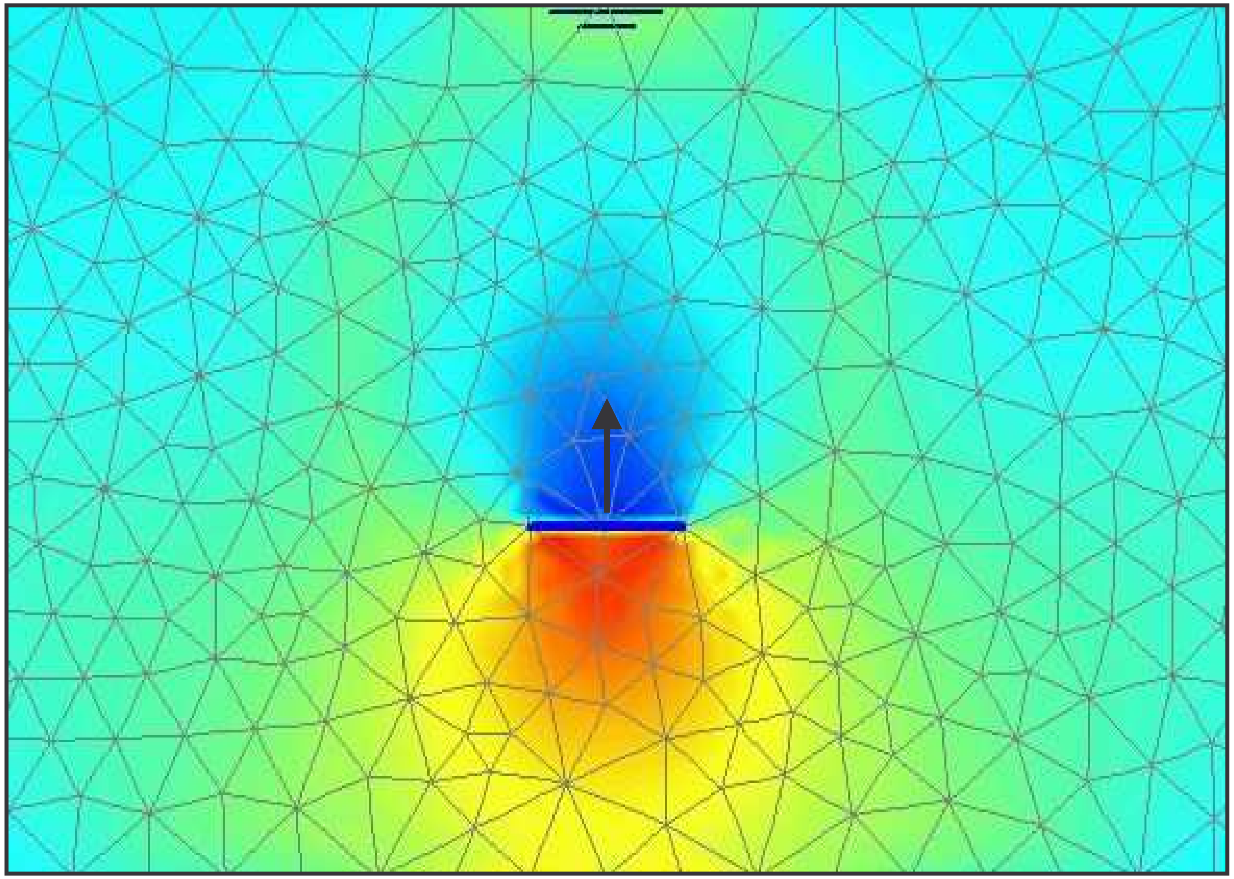
Numerical modelling: Plaxis



Plaxis calculation- undrained conditions: evidence of succion effect

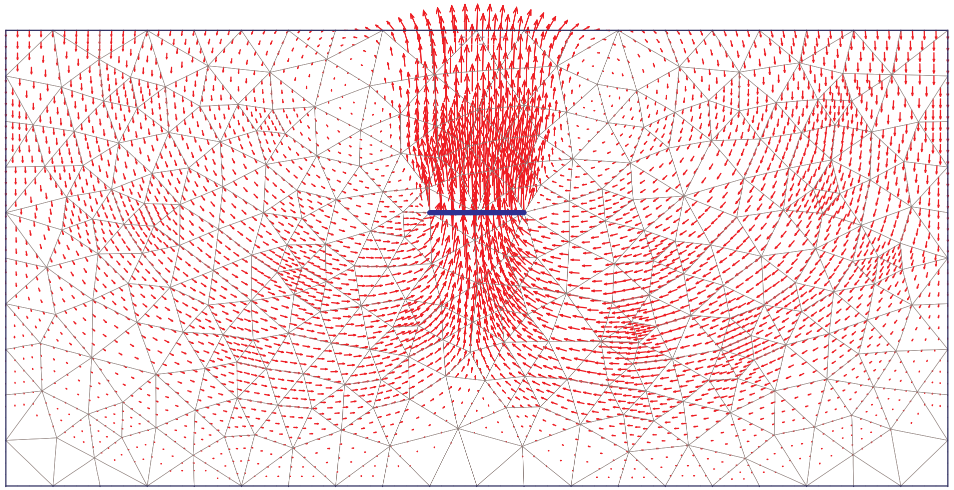


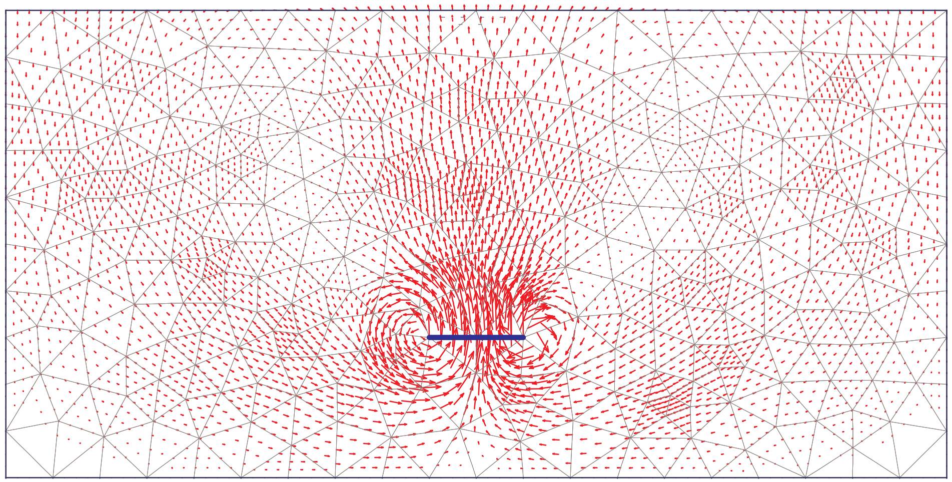
Plaxis calculation_Anchor at 90°



Effect of embeddement depth on the failure mechanism

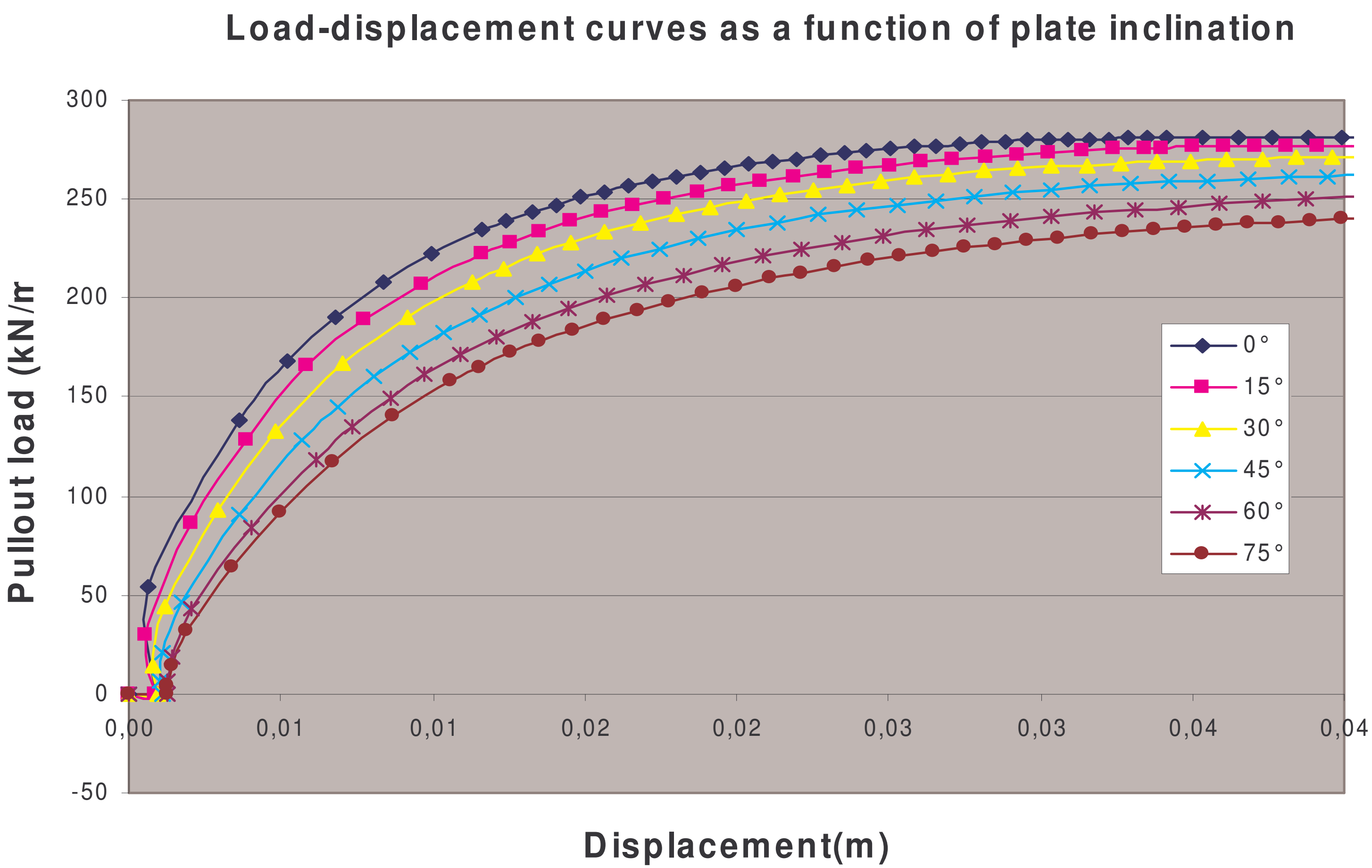
Low depth: heave of the soil surface





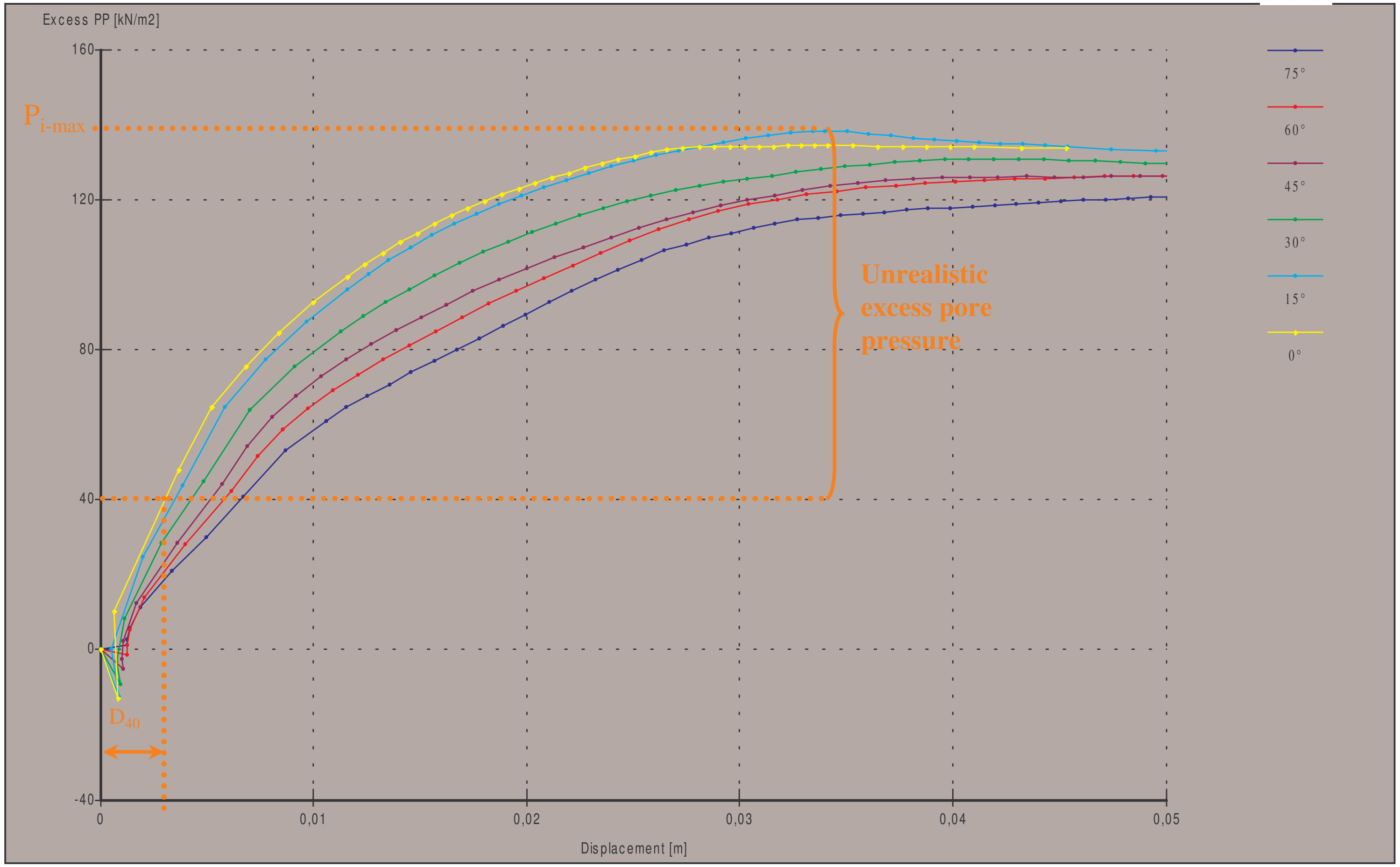
Large depth: deep failure mechanism

Influence of load inclination



Simulation of laboratory tests

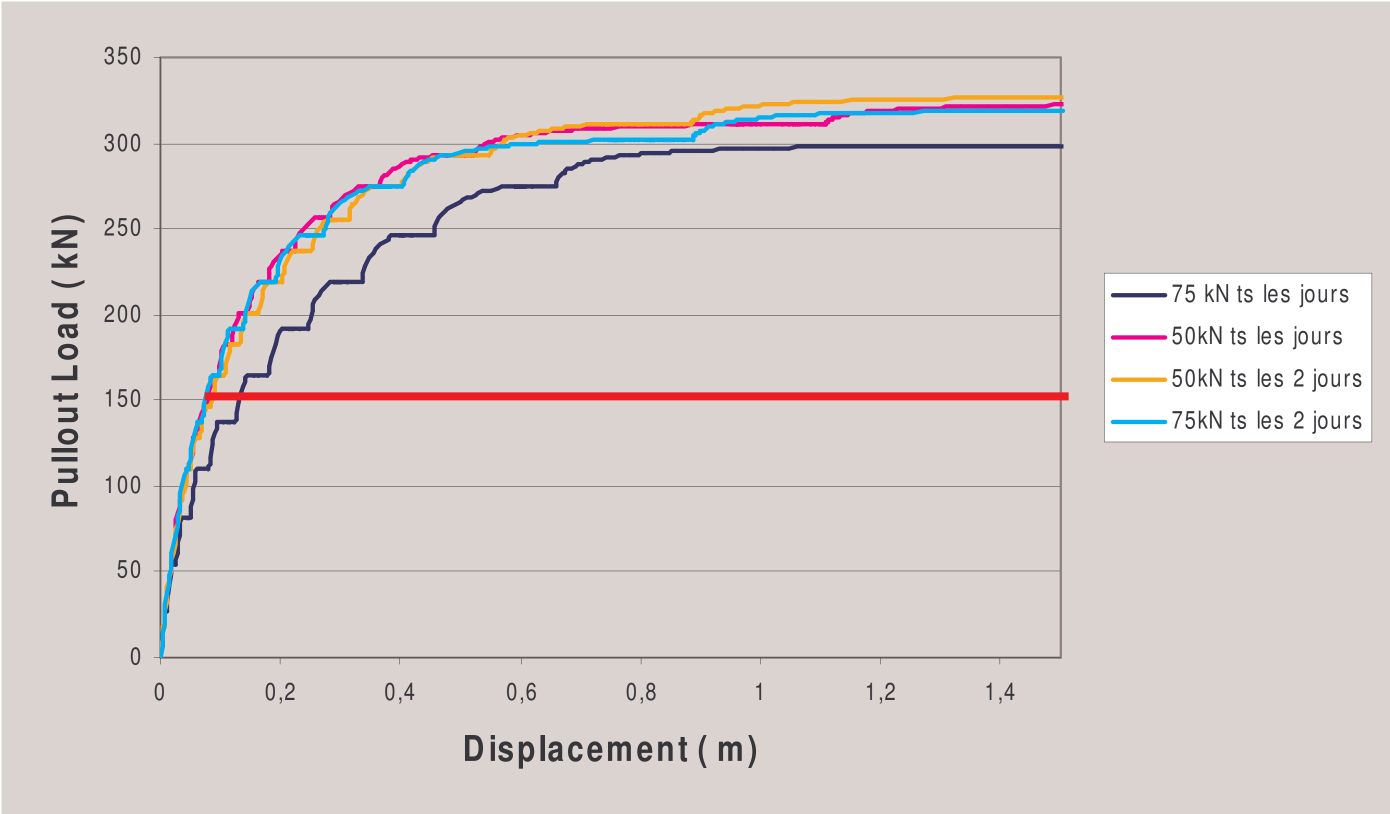
Inclination – Suction effects



Simulation of field conditions

Estimation of long term capacity by step loading

Ultimate undrained pullout capacity



Simulation of field conditions summary

	Ultimate Pullout capacity (MN)	Holding Factors Nc	Suction (kPa)	Suction Contribution
Anchor at 2Om, 45°	4 - 6	15 - 17	100 kPa	30%

Conclusions (1)

- Pretension method using quasi-vertical inclination of the anchoring line gave a satisfactory start of rotation
- Final inclination of the anchor controlled by the inclination of the anchoring line
- Suction contribution of 15% to 20% of the total capacity in most of the tests. This was confirmed by numerical analysis.
- Holding factors N_c higher than 15 were observed, provided the anchoring depth is sufficient to develop a deep failure mechanism

Conclusions (2)

- Interesting complementarity between:
  - Laboratory tests
  - Field tests
  - Centrifuge tests
  - Numerical models

Further research

- Effect of long term loading/dissipation of the suction
- Displacements under working load
- Effect of cyclic or shock loading ?
- Local setup effects ?
- Full Scale tests in offshore conditions
- 3D numerical analysis

Thank you for your attention