Application of centrifuge modeling

TNA Workshop on Centrifuge Modelling – 3/4 March 2011

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London Underground Limited (LUL) - Project

- LUL has about 400 km of embankments that were constructed at the turn of last century.
- Construction was by ‘end-tipping’ from cuttings or borrow pits.
- The embankments are starting to suffer slope failures causing the railway track to settle.
- Every night between 1 am and 4.30 am the tracks at certain locations have to be jacked up several inches and re-ballasted.
Retrofit Design options

To mitigate the situation several designs were proposed:

A. Use of micro-piles through the slopes of the embankment with a running beam on the top
B. Use of continuous soldier piles through the length of the embankment
C. Improved drainage

Question: Which design is the cheapest and offers maximum protection against track settlement?
Centrifuge Testing

- Centrifuge tests were commissioned at the University of Cambridge to evaluate the design of the micro-piles with a running beam at the top.
- Two series of tests were conducted:
  - First to reproduce the problem of the settlement of the embankments.
  - Second to evaluate the design of the micro-piles and measure the loads seen by these piles and observe the reduction in settlement.

I can show you the results from the first series but not from the second due to the client confidentiality.

Cost of Centrifuge testing was about £40,000/-
London Underground Embankments

Modeled in 10m beam centrifuge
Model with displacement targets
Displacement after equivalent of 9.3 years
Pipe Uplift Problem

- Buried pipe lines are used to transport oil and gas
- These pipes can suffer uplift under various conditions
  - axial loading due to thermal stresses can cause buckling
  - land slides/ground movement can force the pipe to shorten axially and therefore lead to uplift
  - weak backfill on the buried pipe
  - Earthquake induced liquefaction softens the backfill soil and pipe becomes buoyant
  - lateral spreading of soil following liquefaction can cause the pipe to buckle out of ground
Pipeline Uplift
Pipeline Uplift

In all these cases we wish to know the uplift resistance offered by the soil.

The analysis often considers Simple Limit Equilibrium equations.

It turns out it is the soil strains around the pipe, deformation patterns that are more important – thereby rendering limit equilibrium analysis less useful for this problem.

This can be done effectively in a centrifuge.
Centrifuge Modelling

- The repair costs and the down time costs due to pipe uplift are prohibitive to oil industry
- A series of centrifuge tests were commissioned at Cambridge for over a year
- Average centrifuge testing fees in the last few years has been around £30000/-
- The results from the tests have led to good
  - understanding of soil flow around pipe lines
  - development of PIV technology to obtain strain/displacement fields from digital images
Clay Samples

Re-consolidated slurry

Pelletised sample
Pipe pullout mechanisms in sand

Coloured sand layers

Resistance response

![Graph showing pullout resistance vs. displacement](image)
Offshore Caisson Project

- An offshore caisson was deployed April 2002 off the Egyptian Coast
- The depth to the sea bed is 450 metres
- The caisson is to support a manifold structure weighing about 100 tons + hydrodynamic wave loading of about 200 tons
- The sea-bed is normally consolidated clay
- Piling is too expensive at these depths, so the preferred option is installation by diver-less, remotely controlled methods
Offshore caisson foundations

Added Mass
210 T @ 4.2m
Two rival designs were proposed
a) a 28 m deep steel caisson of 6 m diameter
b) a 10 m deep steel caisson of 6 m diameter

Lateral loading (hydrodynamic+thermal) due to waves and heat of the gas is a problem

Need to establish the lateral capacity of the caisson

The offshore company obviously wants to know if the second option will do the job!

Also the difference is hiring a ship that drives the caisson to 28 m as opposed to 10m is about US$ 100,000/- per day

This area is also liable to earthquakes – this aspect will be covered separately!
Costs

- The company has already purchased steel for the longer caisson, but cost of steel is negligible compared to the installation costs.
- Long term performance without failure is essential.
- Caisson must be deployed by end of April 2002.
- Quick answers were needed – centrifuge testing to be done in two weeks from word ‘go’!!
- Cost of Centrifuge modelling was £20,000/-.
10m caisson

28m caisson
Centrifuge model and Prototype

![Image of centrifuge model and prototype]
Cross-section of the centrifuge model
Numerical prediction of failure mode
Comparison of Centrifuge Results and numerical predictions

![Graph showing Static Capacity of Foundation](image-url)
Dynamic response of Caisson

10m caisson

28m caisson

Added Mass
210 T @ 4.2m
Cross-section of the centrifuge model
Dynamic response of Caisson

Short Caisson

Long Caisson

Base

Soil surface

Superstructure
Dynamic response of Caisson

• Both caisson configurations would give static lateral capacities greater than that required by the designers
• The short caisson benefited by the attenuation of acceleration through the very soft normally consolidated clay layer
• The shear capacity of the clay does not allow transfer of the large accelerations to the overlying soil resulting in progressive attenuation as we move towards the soil surface
• The caisson obviously has the shear capacity to transfer the shear waves and hence the superstructure sees much the same acceleration as the soil at the caisson’s base
• The short caisson thus has to cope to much lower accelerations and hence forces than the long one
• Dynamic centrifuge modelling has proved that the short caisson is preferable not only for economic reasons, but also due to its better performance under strong earthquake loading
Results

- The centrifuge test results show that the ultimate lateral capacity of the 10m caisson is well over the designers estimate – client is happy!

- The centrifuge results also show that while the ultimate capacity is large, the lateral displacement required to mobilise this capacity is larger than predicted by numerical analyses

- This has implications in the design of the manifold superstructure and amount of flexibility needed in the gas pipes coming from the oil wells