Use of containment walls as a liquefaction remediation method for existing buildings – Data report on centrifuge tests WA1P, WA1F and WA3

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1. Introduction

This report describes three centrifuge tests carried out as part of the NEMISREF project, at 50g, to investigate the behaviour of containment walls as a liquefaction remediation measure for existing buildings. The complete set of results is presented. Both rigid and flexible containment walls were used in the centrifuge tests to try and gain an insight into the factors affecting the performance of these walls. In order to assess the effectiveness of the containment walls tested, the results can be compared with those from centrifuge tests on similar unimproved soil profiles. These results can be found in technical report CUED/D-SOILS/TR.342 and full analysis, comparison and discussion of the results is given in Mitrani 2006, PhD thesis, University of Cambridge.

2. Description of centrifuge models

The model structure used in this series of centrifuge tests was a single degree of freedom (SDOF) frame structure with a natural frequency of 1.52Hz (prototype, 76Hz model scale) and a bearing pressure of 58kPa. This structure is shown in figure 1, at prototype scale.

![Figure 1: Diagram of SDOF structure](image-url)
Centrifuge test WA1P was carried out on a model consisting of the SDOF structure founded on a deep (15.75m, 315mm) homogeneous bed of liquefiable sand. A partial-depth rigid containment wall around the base of the structure was used as a liquefaction remediation method. The containment wall was constructed from aluminium and was 5m (100mm) deep and 162.5mm (3.25mm) thick. This had an equivalent stiffness to a prototype concrete wall approximately 240mm thick. The instrument layout for centrifuge test WA1P is shown in figure 2, at prototype scale.

Figure 2: Instrument layout for centrifuge test WA1P

Figure 3: Instrument layout for centrifuge test WA1F

Figure 3 above shows the instrument layout for centrifuge test WA1F, at prototype scale. This centrifuge test was similar to WA1P, except a full-depth rigid containment wall, of the same properties as that used in centrifuge test WA1P, was adopted.

Centrifuge test WA3 was carried out on a model with a layered sand profile. This profile consisted of a loose layer of liquefiable sand 7m (140mm) deep, overlying a dense layer of the same sand, 5m (100m) deep. A flexible containment wall around the base of the structure was adopted, which extended through the full depth of the liquefiable layer. This wall was constructed from 0.1mm thick high density polyethlyene (HDPE) sheet. The instrument layout for centrifuge test WA3 is shown in figure 4, at prototype scale.
Three types of instruments were used in all the centrifuge tests: accelerometers to measure soil and structural accelerations, pore pressure transducers (PPTs) to measure pore pressures in the soil bed and linear variable differential transformers (LVDTs) to measure displacements of the structure and the sand surface.

The connection detail between the top of the containment walls and the base of the structure is thought to be an important factor which affects the behaviour of the structure and contained soil. In each of the three centrifuge tests this connection was different. In centrifuge test WA1P, the structure rested on top of the containment walls and was connected by means of water-tight silicon seal. In centrifuge test WA1F, the walls were positioned around the edge of the structure, with a 250mm (5mm) clearance between them and the structure base. This gap was sealed using Rowntree’s jelly but it is thought that the seal failed during the course of the centrifuge test. Finally, in centrifuge test WA3, the HDPE sheet was attached firmly between the two base-plates of the structure (see figure 1), creating a water-tight seal. More details about these connections are given in Mitrani 2006.
3. Model Preparation

Each model was prepared in essentially the same way. Hostun S28 sand was air pluviated from an over-head hopper into the deep ESB box. A large orifice was used to produce the loose layers, and a small orifice, low flow rate and sieves were used to pour the dense layer in centrifuge test WA3. After completion of sand pouring and placement of the instruments and containment walls, the models were saturated under vacuum from the base, using 50cS methylcellulose. Following saturation, the structure was placed on the sand surface and connected to the containment walls. This was done after each model was loaded onto the centrifuge, to minimise structural settlement before testing. Placement of the containment walls and formation of this connection was slightly different for each model and full details of the preparation method for each can be found in Mitrani 2006.

It should be noted that the dimensions and instrument positions shown in figures 2 to 4 represent the geometry that was aimed for during construction of the models. However, due to the difficulties of making precise models by hand, the actual prototype dimensions were often different. The actual properties of the sand layers in centrifuge tests WA1P, WA1F and WA3 at prototype scale are shown in table 1.

| Table 1: Properties of sand layers in models for centrifuge tests WA1P, WA1F and WA3 |
|-------------|----------------|----------------|----------------|
|             | WA1P            | WA1F            | WA3            |
|             | layer thickness (m) |                 |                |
|             | 15.27                | 14.93                | 7.70  | 3.53 |
| $\gamma_{\text{dry}}$ (kN/m$^3$) | 14.2                | 14.7                | 14.6  | 16.8 |
| $\gamma_{\text{sat}}$ (kN/m$^3$) | 18.7                | 19.0                | 18.9  | 20.3 |
| $D_r$ (%)    | 40                | 53                | 44  | 100 |

4. Centrifuge Test Procedure

All three centrifuge tests were carried out at 50g. Five earthquakes were fired in centrifuge tests WA1P and WA3 but only three in centrifuge test WA1F, due to a problem with the SAM actuator (see Mitrani 2006 for more details). The earthquakes were of difference size and frequency to investigate the behaviour of the structure thoroughly. The main details of the earthquakes fired in each test are shown in table 2, at prototype scale. It should be noted that in centrifuge tests WA1F and WA3, the order of the frequency sweep earthquake and earthquake 4
was reversed. The earthquakes were fired in order of increasing magnitude and frequency to try and minimise the effects of firing multiple earthquakes on a single model. Further details can be found in Mitrani 2006.

Table 2: Details of earthquakes fired in centrifuge tests WA1P, WA1F and WA3

<table>
<thead>
<tr>
<th></th>
<th>frequency (Hz)</th>
<th>duration (s)</th>
<th>max. base acc. (g)</th>
<th>no. of cycles</th>
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<td></td>
<td></td>
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<td>WA1F</td>
<td>WA3</td>
</tr>
<tr>
<td>EQ1</td>
<td>0.6</td>
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<tr>
<td>EQ3</td>
<td>1</td>
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<td>54</td>
<td>28</td>
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<tr>
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<td>-</td>
<td>≈181</td>
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<tr>
<td>EQ4</td>
<td>1</td>
<td>27</td>
<td>-</td>
<td>28</td>
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5. Results

5.1 Centrifuge test WA1P, earthquake 1

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures around structure base
5.2 Centrifuge test WA1P, earthquake 2

Soil and structural displacements

Accelerations on and under structure

<table>
<thead>
<tr>
<th>TEST WA1P</th>
<th>Scales: Prototype 8th order Butterworth Filter at 500Hz</th>
<th>Earthquake</th>
<th>Figure No.</th>
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<tr>
<td>FLIGHT 1</td>
<td>Long-Term Time Records</td>
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Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures around structure base
5.3 Centrifuge test WA1P, earthquake 3

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures around structure base
5.5 Centrifuge test WA1P, frequency sweep earthquake

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures around structure base
5.4 Centrifuge test WA1P, earthquake 4

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures around structure base
5.6 Centrifuge test WA1F, earthquake 1

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures at sides of structure base and near containment walls
5.7 Centrifuge test WA1F, earthquake 2

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base

TEST WA1F  |  Flights: Prototype  
FLIGHT 1  |  8th order Butterworth Filter at 500Hz  
Short-Term Time Records  |  Earthquake  
2  |  Figure No.

TEST WA1F  |  Flights: Prototype  
FLIGHT 1  |  8th order Butterworth Filter at 500Hz  
Long-Term Time Records  |  Earthquake  
2  |  Figure No.
Free field excess pore pressures

Excess pore pressures at sides of structure base and near containment walls
5.8 Centrifuge test WA1F, earthquake 3

Soil and structural displacements

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Accelerations on and under structure

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<th>acc 8112</th>
<th>Time(s)</th>
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</tbody>
</table>
Free field soil accelerations and box (input) acceleration

Excess pore pressures under centre of structure base
Free field excess pore pressures

Excess pore pressures at sides of structure base and near containment walls
5.9 Centrifuge test WA3, earthquake 1

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under structure base
Free field excess pore pressures

Excess pore pressures near containment walls
5.10 Centrifuge test WA3, earthquake 2

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under structure base
Free field excess pore pressures

Excess pore pressures near containment walls
5.11 Centrifuge test WA3, earthquake 3

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under structure base
Free field excess pore pressures

Excess pore pressures near containment walls
5.12 Centrifuge test WA3, earthquake 4

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under structure base

TEST WA3
FLIGHT 1
Short-Term Time Records

Earthquake
Figure No.
4

TEST WA3
FLIGHT 1
Long-Term Time Records

Earthquake
Figure No.
4
Free field excess pore pressures

Excess pore pressures near containment walls
5.13 Centrifuge test WA3, frequency sweep earthquake

Soil and structural displacements

Accelerations on and under structure
Free field soil accelerations and box (input) acceleration

Excess pore pressures under structure base

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TEST WA3
FLIGHT 1
8th order Butterworth filter at 500 Hz
Long-Term Time Records
Earthquake sweep
Figure No.

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Notes:
- Scales: Prototype
- Scale: Prototype
- 8th order Butterworth filter at 500 Hz
- Long-Term Time Records
- Earthquake sweep
- Figure No.

43
Free field excess pore pressures

Excess pore pressures near containment walls

TEST WA3
FLIGHT 1

Scales: Prototype
8th order Butterworth Filter at 500Hz
Long-Term Time Records
Earthquake sweep
Figure No.

Scales: Prototype
8th order Butterworth Filter at 500Hz
Long-Term Time Records
Earthquake sweep
Figure No.