Model Testing of Circular Flat Footings
on Uncemented Loose Carbonate Sand:
Experimental data

by

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The University of Oxford

SUMMARY
This report presents the factual results of a series of combined load tests on a circular flat footing on extremely loose uncemented carbonate sand. These tests were conducted to explore the concepts of work hardening plasticity theory applied to the behaviour of foundations. Similar tests have been completed on clays and dense silica sand. This set of data is to provide empirical evidence of performance on another material. The main intention of the report is to present the results in a systematic manner consistent with previous reports.

INTRODUCTION
Recent studies of footings subjected to combined loads have successfully described the elasto-plastic deformation behaviour of the footing by the use of work hardening plasticity models (Tan, 1990; Martin, 1994; Gottardi et. al., 1997). Essentially the postulate is that after a given footing penetration a yield surface is established within \(\{V, M/2R, H\}\) space. Any footing behaviour within this surface is assumed to be elastic, whilst elasto-plastic behaviour occurs once the load point reaches the yield surface. This approach can be traced back to Roscoe and Schofield (1956) in their analysis of foundations for steel frames. Batterfield (1980, 1981) developed the idea further and more recent interest has been evident from several research groups world-wide. Primarily this interest has been concentrated on medium to dense silica sands, and clays of increasing strength with depth. This report concentrates on a material with vastly different properties to either of these, and the results serve to illustrate the ease with which the plasticity concept could be adapted to other materials.

EXPERIMENTAL SET-UP
To test the hypothesis it is essential to establish (i) the shape of the yield surface, (ii) the mechanism of hardening of the surface, (iii) a flow rule or plastic potential and (iv) the elastic behaviour within the surface. Studies of this kind normally use eccentric inclined loads (Gottardi et. al., 1993), or simply look at the two dimensional cases \(\{V, H\}\) and \(\{V, M/2R\}\) (Nova and Montrasio, 1991). At the University of Oxford a loading rig was developed, initially to explore the behaviour of spudcan footings on clay (Martin, 1994). It has undergone several stages of modification and it is adaptable to any soil medium. The unique feature of this apparatus is that any combination of displacement path can be applied to the model footing using computer controlled stepper motors. The response of the footing is determined by measuring the resultant loads using a 'Cambridge' load cell. The displacements are applied using stepper motors, via a stepper motor control unit, with accurate foundation displacements measured using a system of LVDTs. The primary advantage of using this displacement controlled apparatus is the ability to explore post peak behaviour. Primitive load control can also be maintained though the use of feedback on the stepper motors from the load cell, however, the low frequency data logger available during the testing precluded the use of any sophisticated control software. Figure 1 shows the loading rig, further details of which can be gained from Martin (1994) and Gottardi et al (1995). Throughout the tests loading rates not exceeding 0.01 mm/s or 0.01°/s were
used so that any effects of rate became negligible (footing performance was assumed to be rate independent).

The material used for the testing was obtained from a grab sample at the Goodwyn site off the North West Shelf of Western Australia. Carbonate sands can have in-situ void ratios of up to two, and are problematic soils in that upon shearing there can be large volume contraction. For this testing programme the decision was taken to test the material at its loosest state, primarily to maximise the diversity with other data. The material, which had been stored in a saturated state, was firstly dried, then broken up before being sieved to remove the larger shell particles. The sieving process involved two phases, firstly through a 2.36mm sieve to remove any large shell particles, before being passed through a 1mm sieve. Each individual sample was prepared by carefully allowing the material to fall slightly from a scoop into the test container. This method had been used previously in the laboratory for the preparation of uniform loose samples - any slight sample inhomogeneities are averaged out by the large footing displacements that are associated with loose material. A repeatable mean density of 9.32 kN/m$^3$ was obtained. The sample surface was levelled using a vacuum technique, prior to the test sequence. The material possesses a minimum density of 9.22 kN/m$^3$, a maximum density of 11.35 kN/m$^3$, and a grading curve as shown in Figure 2.

RESULTS

A programme of five different test types was undertaken (based on those used by Gottardi et al., 1995) in order to explore the yield surface shape and the mechanisms associated with yield surface expansion due to hardening. A long capacity displacement transducer system was used, compromising slightly the resolution of the displacement measurements, though entirely necessary due to the quite large displacements that prevailed throughout the testing. This system was used during all tests except for the elasticity tests, where a smaller more accurate measurement system was used to capture the elastic behaviour. The large transducer system necessitates the need to account for the stiffness of the rig between the measured locations and the footing via a $3 \times 3$ rig stiffness matrix, [RSM];

$$\begin{bmatrix}
\delta V \\
\delta h \\
2R\delta \theta_{footing}
\end{bmatrix}
= \begin{bmatrix}
\delta V \\
\delta h \\
2R\delta \theta_{measured}
\end{bmatrix}
+ \begin{bmatrix}
V \\
H \\
M / 2R
\end{bmatrix}
\begin{bmatrix}
5.09E-04 & -1.07E-04 & 8.92E-06 \\
1.72E-06 & -2.06E-03 & 2.49E-04 \\
8.31E-04 & 3.83E-03 & -1.81E-03
\end{bmatrix}
$$

[where $[RSM]$ is defined as;

$$\begin{bmatrix}
5.09E-04 & -1.07E-04 & 8.92E-06 \\
1.72E-06 & -2.06E-03 & 2.49E-04 \\
8.31E-04 & 3.83E-03 & -1.81E-03
\end{bmatrix}
\begin{cases}
\text{for } H > 0 \\
\text{for } H < 0,
\end{cases}$$

with the displacements are in mm and forces in N.

From a plasticity point of view the use of the large LVDTs was justified as the vertical soil stiffness ratios, $v_p/V_p$, were typically greater than 50, which suggested that any load path tracked during the constant penetration tests would in fact closely approximate a yield surface. The effect of rig stiffness on the shape of this tracked yield surface could also be assumed to be negligible. A footing of diameter 150mm, and side-wall of 70mm, was used which, when loaded to 1600N, displaced to a vertical penetration of about 60mm - an indication of the compressibility of the soil.

Table 1 displays the 18 tests completed (grouping them within specific test types), whilst Table 2 gives a complete listing of all the available data files corresponding to each test.
The data files contain fully processed data including the incorporation of the effect of rig
stiffness on footing displacements, as well as correction of the vertical and horizontal load
for rotation of the footing. The data in each file are ordered as (note that the moment loads
and rotational displacements are normalised by 2R):

<table>
<thead>
<tr>
<th>Column 1 Time</th>
<th>Column 2 Vertical Load V</th>
<th>Column 3 Horizontal Load H</th>
<th>Column 4 Moment Load M/2R</th>
<th>Column 5 Vertical Displacement dw</th>
<th>Column 6 Horizontal Displacement du</th>
<th>Column 7 Rotational Displacement 2R/θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Seconds</td>
<td>Newtons</td>
<td>Newtons</td>
<td>Newtons</td>
<td>millimetres</td>
<td>millimetres</td>
<td>millimetres</td>
</tr>
</tbody>
</table>

The co-ordinate systems, sign conventions and notations for the loads and displacements
are shown in Figure 3 following that set out by Butterfield et. al. (1997). The load
reference point was located at the centre of the base of the footing (i.e. mudline) as defined
in Figure 3, consistent with previous work conducted on flat footings at Oxford University.

The data are presented graphically in this report in two forms. Figure 4 through to Figure
21 depicts the time histories of the various tests. Figure 22 through to Figure 69 depicts the
stress/strain relationships, load paths, and displacement paths followed during the specific
events of each test.

**CONCLUSIONS**

This report has presented the results from 18 general loading tests on a circular footing on
a loose un cemented carbonate sand. The tests were specifically completed to complement
tests performed on dense silica sand in order to provide proof of the versatility of a
plasticity formulation of response. Whilst specific interpretation of the results have not
been carried out in this report it is clear that enough information will be available to
determine parameters for a suitable plasticity model.

**ACKNOWLEDGEMENTS**

The first author would like to gratefully acknowledge the generous support of the Rhodes
Trust. This work could not have been completed if it were not for Phillip Watson and
Gerard Dyson of the University of Western Australia who, whilst visiting the Civil
Engineering group at Oxford, helped with carrying out the testing and preparatory work.

**REFERENCES**

Butterfield, R. 1980. *A simple analysis of the load capacity of rigid footings on granular

Technology*, CISM, Udine, Italy.

Butterfield, R., Houlsby, G.T. and Gottardi, G. 1997. *Standardised sign conventions and


Gottardi, G. and Houlsby, G.T. 1995. *Model tests of circular footings on sand subjected to
combined loads*. *Report No OUEL 2071/95*. Oxford University Engineering
Laboratory, UK.

footings on sand under general planar loading*. *Report No OUEL 2143/97*. Oxford
University Engineering Laboratory, UK.


<table>
<thead>
<tr>
<th>Test Group</th>
<th>Test Notes</th>
<th>Test Names</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Loading</td>
<td>As far as possible with unload-reload cycles</td>
<td>FUF01, FUF02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Up to V = 1600N, with unload-reload cycles at V = 1000N</td>
<td>FUF05, FUF06, FUF08, FUF09, FUF10, FUF11, FUF13, FUF14, FUF15, FUF16, FUF23</td>
<td></td>
</tr>
<tr>
<td>Swipe</td>
<td>From V = 1600N</td>
<td>FUF05 (H, 0)</td>
<td>$\text{atan}(2\delta V / \delta u) = 0.03$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF06 (0, M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 89.6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF08 (H, M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 69.1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF09 (H, -M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 69.4$</td>
</tr>
<tr>
<td></td>
<td>From V = 50N after V = 1600N</td>
<td>FUF10 (H, 0)</td>
<td>$\text{atan}(2\delta V / \delta u) = 0.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF11 (0, M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 89.7$</td>
</tr>
<tr>
<td></td>
<td>Multiple values of V</td>
<td>FUF21 (H, 0) from V = 400N, 800N, 1200N, 1600N and 1800N</td>
<td></td>
</tr>
<tr>
<td>Constant V</td>
<td>At V = 1600N</td>
<td>FUF13 (H, 0)</td>
<td>$\text{atan}(2\delta V / \delta u) = 1.2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF14 (0, M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 87.9$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF15 (H, M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 87.9$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FUF16 (H, -M)</td>
<td>$\text{atan}(2\delta V / \delta u) = 72.9$</td>
</tr>
<tr>
<td>Monotonic Radial Displacement</td>
<td>Each test taken as far as possible</td>
<td>FUF17, FUF18, FUF19, FUF20</td>
<td>$\delta u / \delta w = 0.997$, $\delta u / \delta w = 1.509$, $2R\delta V / \delta w = 0.491$, $2R\delta V / \delta w = 2.556$</td>
</tr>
<tr>
<td>Elastic Cycles</td>
<td>At V = 800N after V = 1600N</td>
<td>FUF23</td>
<td>$V \pm 100N$ excursion, $H \pm 100N$ excursion, $M/2R \pm 50N$ excursion</td>
</tr>
</tbody>
</table>

**Table 2 - Summary of the tests undertaken during study.**
<table>
<thead>
<tr>
<th>Test</th>
<th>Density (kN/m³)</th>
<th>Description</th>
<th>Datafiles</th>
<th>Lines</th>
<th>Description</th>
<th>Velocity Data (Actual velocities and distances)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUF01</td>
<td>9.389</td>
<td>Vertical loading test</td>
<td>fuf01_1.dat</td>
<td>822</td>
<td>All data logged during test</td>
<td>$v_d = 0.01$ mm/s $v_a = 0.005$ mm/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=500N</td>
<td>fuf01_2.dat</td>
<td>653</td>
<td>Total test postscript file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=1000N</td>
<td>fuf01_3.dat</td>
<td>2528</td>
<td>Vertical load data file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=1600N</td>
<td>fuf01.ps (4)</td>
<td>4003</td>
<td>Vertical load postscript file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf01.dat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf01e.ps (22, 23)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUF02</td>
<td>9.235</td>
<td>Vertical loading test</td>
<td>fuf02_1.dat</td>
<td>1979</td>
<td>All data logged during test</td>
<td>$v_d = 0.01$ mm/s $v_a = 0.005$ mm/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=500N</td>
<td>fuf02_2.dat</td>
<td>1979</td>
<td>Total test postscript file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=1000N</td>
<td>fuf02.ps (5)</td>
<td></td>
<td>Vertical load data file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=1600N</td>
<td>fuf02e.dat</td>
<td></td>
<td>Vertical load postscript file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf02e.ps (24, 25)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUF05</td>
<td>9.245</td>
<td>(H,0) swipe at V=1600N</td>
<td>fuf05_1.dat</td>
<td>964</td>
<td>All data logged during test</td>
<td>$v_d = 0.01$ mm/s $v_a = 0.005$ mm/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unload-reload at V=1000N</td>
<td>fuf05_2.dat</td>
<td>896</td>
<td>Total test postscript file</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>fuf05_3.dat</td>
<td>1541</td>
<td>Datafile for swipe from V=1600N</td>
<td>$v_b = 0.0097$ mm/s (15.12 mm)</td>
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<tr>
<td></td>
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<td>fuf05.ps (6)</td>
<td>1398</td>
<td>Postscript file for swipe from V=1600N</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>fuf05.dat</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf05e.ps (26, 27)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>FUF06</td>
<td>9.237</td>
<td>(0,M) swipe at V=1600N</td>
<td>fuf06_1.dat</td>
<td>924</td>
<td>All data logged during test</td>
<td>$v_d = 0.01$ mm/s $v_a = 0.005$ mm/s</td>
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<tr>
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<td></td>
<td>Unload-reload at V=1600N</td>
<td>fuf06_2.dat</td>
<td>653</td>
<td>Total test postscript file</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>fuf06_3.dat</td>
<td>998</td>
<td>Datafile for swipe from V=1600N</td>
<td>$v_b = 0.025$ mm/s (27.99 mm)</td>
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<td></td>
<td></td>
<td></td>
<td>fuf06.ps (7)</td>
<td>844</td>
<td>Postscript file for swipe from V=1600N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf06.dat</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>fuf06e.ps (28, 29)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FUF08</td>
<td>9.452</td>
<td>(H,M) swipe at V=1600N</td>
<td>fuf08_1.dat</td>
<td>20</td>
<td>All data logged during test</td>
<td>$v_d = 0.01$ mm/s $v_a = 0.005$ mm/s</td>
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<tr>
<td></td>
<td></td>
<td>Unload-reload at V=1000N</td>
<td>fuf08_2.dat</td>
<td>888</td>
<td>Total test postscript file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf08_3.dat</td>
<td>678</td>
<td>Datafile for swipe from V=1600N</td>
<td>$v_b = 0.0097$ mm/s (7.85 mm)</td>
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<td></td>
<td>fuf08.dat</td>
<td>880</td>
<td>Postscript file for swipe from V=1600N</td>
<td>$v_b = 0.026$ mm/s (20.56 mm)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>fuf08e.ps (30, 31)</td>
<td>726</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Numbers in brackets correspond to the figure number in this report.
<table>
<thead>
<tr>
<th>Test</th>
<th>Density (kN/m³)</th>
<th>Description</th>
<th>Datafiles</th>
<th>Lines</th>
<th>Velocity Data (Actual velocities and distances)</th>
</tr>
</thead>
</table>
| FUF09 | 9.402           | (H.-M) swipe at V=1600N Unload-reload at V=1000N | { all data logged during test  
  } Total test postscript file  
  Datafile for swipe from V=1600N  
  Postscript file for swipe from V=1600N | 1202  | \( v_d = 0.01 \) mm/s  
  \( v_a = 0.005 \) mm/s  
  \( v_h = 0.0096 \) mm/s (7.72 mm)  
  \( v_{250} = 0.025 \) mm/s (-20.52 mm) |
| FUF10 | 9.288           | (H,0) swipe at V=50N after V=1600N Unload-reload at V=1000N | { all data logged during test  
  } Total test postscript file  
  Datafile for swipe from V=50N  
  Postscript file for swipe from V=50N | 436   | \( v_d = 0.01 \) mm/s  
  \( v_a = 0.005 \) mm/s  
  \( v_h = 0.0096 \) mm/s (9.78 mm) |
| FUF11 | 9.339           | (0,0) swipe at V=50N after V=1600N Unload-reload at V=1000N | { all data logged during test  
  } Total test postscript file  
  Datafile for swipe from V=50N  
  Postscript file for swipe from V=50N | 1055  | \( v_d = 0.01 \) mm/s  
  \( v_a = 0.005 \) mm/s  
  \( v_{250} = 0.025 \) mm/s (25.56 mm) |
| FUF13 | 9.388           | (H,0) at constant V=1600N Unload-reload at V=1000N | { all data logged during test  
  } Total test postscript file  
  Datafile for swipe at V=1600N  
  Postscript file for swipe at V=1600N | 1675  | \( v_d = 0.01 \) mm/s  
  \( v_a = 0.005 \) mm/s  
  \( v_h = 0.0089 \) mm/s (9.07 mm) |
| FUF14 | 9.334           | (0,0) at constant V=1600N Unload-reload at V=1000N | { all data logged during test  
  } Total test postscript file  
  Datafile for swipe at V=1600N  
  Postscript file for swipe at V=1600N | 1282  | \( v_d = 0.01 \) mm/s  
  \( v_a = 0.005 \) mm/s  
  \( v_{250} = 0.025 \) mm/s (14.19 mm) |
<table>
<thead>
<tr>
<th>Test</th>
<th>Density (kN/m³)</th>
<th>Description</th>
<th>Datafiles</th>
<th>Description</th>
<th>Lines</th>
<th>Velocity Data (Actual velocities and distances)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUF15</td>
<td>9.245</td>
<td>(H,M) at constant V=1600N Unload-reload at V=1000N</td>
<td>fuf15_1.dat, fuf15_2.dat, fuf15_3.dat, fuf15.ps (14), fuf15.dat, fuf15e.ps (42, 43)</td>
<td>} All data logged during test</td>
<td>536</td>
<td>$v_0 = 0.01$ mm/s</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>} Total test postscript file</td>
<td>1194</td>
<td>$v_s = 0.005$ mm/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datafile for swipe at V=1600N</td>
<td>647</td>
<td>$v_h = 0.0094$ mm/s (4.94 mm)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Postscript file for swipe at V=1600N</td>
<td>461</td>
<td>$v_{2R} = 0.024$ mm/s (12.68 mm)</td>
</tr>
<tr>
<td>FUF16</td>
<td>9.422</td>
<td>(H,-M) swipe at constant V=1600N Unload-reload at V=1000N</td>
<td>fuf16_1.dat, fuf16_2.dat, fuf16.ps (15), fuf16.dat, fuf16e.ps (44, 45)</td>
<td>} All data logged during test</td>
<td>1561</td>
<td>$v_0 = 0.01$ mm/s</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>} Total test postscript file</td>
<td>675</td>
<td>$v_s = 0.005$ mm/s</td>
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<td>Datafile for swipe at V=1600N</td>
<td>444</td>
<td>$v_h = 0.0076$ mm/s (3.86 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Postscript file for swipe at V=1600N</td>
<td>-</td>
<td>$v_{2R} = 0.025$ mm/s (-12.61 mm)</td>
</tr>
<tr>
<td>FUF17</td>
<td>9.260</td>
<td>Monotonic radial displacement Du/dw = 1</td>
<td>fuf17_1.dat, fuf17_2.dat, fuf17_3.dat, fuf17.ps (16), fuf17.dat, fuf17e.ps (46, 47)</td>
<td>} All data logged during test</td>
<td>5</td>
<td>$v_0 = 0.0091$ mm/s (41.06 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>} Total test postscript file</td>
<td>50</td>
<td>$v_s = 0.0091$ mm/s (40.97 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datafile for radial displacement</td>
<td>1011</td>
<td>$v_h = 0.0094$ mm/s (46.91 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Postscript file for radial displacement</td>
<td>-</td>
<td>$v_{2R} = 0.0062$ mm/s (31.08 mm)</td>
</tr>
<tr>
<td>FUF18</td>
<td>9.502</td>
<td>Monotonic radial displacement Du/dw = 1.5</td>
<td>fuf18_1.dat, fuf18_ps (17), fuf18.dat, fuf18e.ps (48, 49)</td>
<td>All data logged during test</td>
<td>1233</td>
<td>$v_0 = 0.0094$ mm/s (46.97 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total test postscript file</td>
<td>-</td>
<td>$v_s = 0.0094$ mm/s (46.91 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datafile for radial displacement</td>
<td>1184</td>
<td>$v_h = 0.0046$ mm/s (23.08 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Postscript file for radial displacement</td>
<td>-</td>
<td>$v_{2R} = 0.0094$ mm/s (46.97 mm)</td>
</tr>
<tr>
<td>FUF19</td>
<td>9.427</td>
<td>Monotonic radial displacement 2rdq/dw = 0.5</td>
<td>fuf19_1.dat, fuf19.ps (18), fuf19.dat, fuf19e.ps (50, 51)</td>
<td>All data logged during test</td>
<td>1457</td>
<td>$v_0 = 0.0073$ mm/s (11.77 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total test postscript file</td>
<td>-</td>
<td>$v_s = 0.0073$ mm/s (11.77 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datafile for radial displacement</td>
<td>1184</td>
<td>$v_h = 0.017$ mm/s (27.73 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Postscript file for radial displacement</td>
<td>-</td>
<td>$v_{2R} = 0.017$ mm/s (27.73 mm)</td>
</tr>
<tr>
<td>FUF20</td>
<td>9.381</td>
<td>Monotonic radial displacement 2Rdq/dw = 2.35</td>
<td>fuf20_1.dat, fuf20.ps (19), fuf20.dat, fuf20e.ps (52, 53)</td>
<td>All data logged during test</td>
<td>568</td>
<td>$v_0 = 0.0073$ mm/s (11.77 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total test postscript file</td>
<td>-</td>
<td>$v_s = 0.0073$ mm/s (11.77 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Datafile for radial displacement</td>
<td>568</td>
<td>$v_h = 0.017$ mm/s (27.73 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Postscript file for radial displacement</td>
<td>-</td>
<td>$v_{2R} = 0.017$ mm/s (27.73 mm)</td>
</tr>
<tr>
<td>Test</td>
<td>Density (kN/m³)</td>
<td>Description</td>
<td>Datafiles</td>
<td>Description</td>
<td>Lines</td>
<td>Velocity Data (Actual velocities and distances)</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------</td>
<td>-------------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>FUF21</td>
<td>9.407</td>
<td>(H,0) multiple swipes at V=400N, 800N, 1200N, 1600N and 1800N</td>
<td>fuf21_1f.dat</td>
<td>{ }</td>
<td>242</td>
<td>$v_d = 0.01 \text{ mm/s}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_2f.dat</td>
<td>{ }</td>
<td>259</td>
<td>$v_h = 0.009 \text{ mm/s} (2.27 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_3f.dat</td>
<td>{ All data logged during test}</td>
<td>2541</td>
<td>$v_s = 0.0088 \text{ mm/s} (2.22 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_4f.dat</td>
<td>{ }</td>
<td>14</td>
<td>$v_h = 0.0084 \text{ mm/s} (2.56 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_5f.dat</td>
<td>{ }</td>
<td>829</td>
<td>$v_h = 0.0087 \text{ mm/s} (3.48 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_6f.dat</td>
<td>{ }</td>
<td>523</td>
<td>$v_h = 0.0082 \text{ mm/s} (2.34 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21.ps (20)</td>
<td>Total test postscript file</td>
<td>-</td>
<td>$v_h = 0.009 \text{ mm/s} (2.27 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_1.dat</td>
<td>Datafile for swipe from V=400N</td>
<td>225</td>
<td>$v_s = 0.0088 \text{ mm/s} (2.22 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_2.dat</td>
<td>Datafile for swipe from V=800N</td>
<td>223</td>
<td>$v_h = 0.0084 \text{ mm/s} (2.56 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_3.dat</td>
<td>Datafile for swipe from V=1200N</td>
<td>271</td>
<td>$v_h = 0.0087 \text{ mm/s} (3.48 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_4.dat</td>
<td>Datafile for swipe from V=1600N</td>
<td>358</td>
<td>$v_h = 0.0082 \text{ mm/s} (2.34 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_5.dat</td>
<td>Datafile for swipe from V=1800N</td>
<td>352</td>
<td>$v_h = 0.0082 \text{ mm/s} (2.34 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_1.ps (54, 55)</td>
<td>Postscript file for swipe from V=400N</td>
<td>-</td>
<td>$v_h = 0.009 \text{ mm/s} (2.27 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_2.ps (56, 57)</td>
<td>Postscript file for swipe from V=800N</td>
<td>-</td>
<td>$v_h = 0.0084 \text{ mm/s} (2.56 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_3.ps (58, 59)</td>
<td>Postscript file for swipe from V=1200N</td>
<td>-</td>
<td>$v_h = 0.0087 \text{ mm/s} (3.48 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_4.ps (60, 61)</td>
<td>Postscript file for swipe from V=1600N</td>
<td>-</td>
<td>$v_h = 0.0082 \text{ mm/s} (2.34 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21_5.ps (62, 63)</td>
<td>Postscript file for swipe from V=1800N</td>
<td>-</td>
<td>$v_h = 0.0082 \text{ mm/s} (2.34 \text{ mm})$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf21all.ps (64, 65)</td>
<td>Postscript file for all swipe events</td>
<td>-</td>
<td>$v_h = 0.0082 \text{ mm/s} (2.34 \text{ mm})$</td>
</tr>
<tr>
<td>FUF23</td>
<td>9.342</td>
<td>Elastic cycles at V=800N after V=1600N Unload-reload at V=1000N 2 sets of cycles about V=800N</td>
<td>fuf23_1f.dat</td>
<td>{ }</td>
<td>767</td>
<td>$v_d = 0.01 \text{ mm/s}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_2f.dat</td>
<td>{ All data logged during test}</td>
<td>1570</td>
<td>$v_s = 0.005 \text{ mm/s}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_3f.dat</td>
<td>{ }</td>
<td>1495</td>
<td>Elasticity Cycles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_4f.dat</td>
<td>{ }</td>
<td>1621</td>
<td>$v_s = 0.0008 \text{ mm/s (± 100 N)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_5f.dat</td>
<td>{ }</td>
<td>9</td>
<td>$v_h = 0.00032 \text{ mm/s (± 100 N)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23.ps (21)</td>
<td>Total test postscript file</td>
<td>-</td>
<td>$v_{280} = 0.0027 \text{ mm/s (± 54 N)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_1.dat</td>
<td>Datafile for first set of cycles</td>
<td>1311</td>
<td>$v_h = 0.009 \text{ mm/s (2.27 mm)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_2.dat</td>
<td>Datafile for second set of cycles</td>
<td>1289</td>
<td>$v_h = 0.0084 \text{ mm/s (2.56 mm)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_1.ps (66, 67)</td>
<td>Postscript file for first set of cycles</td>
<td>-</td>
<td>$v_h = 0.0087 \text{ mm/s (3.48 mm)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fuf23_2.ps (68, 69)</td>
<td>Postscript file for second set of cycles</td>
<td>-</td>
<td>$v_h = 0.0082 \text{ mm/s (2.34 mm)}$</td>
</tr>
</tbody>
</table>

Table 3 - Summary of data files associated with the testing.
Figure 1 - Photograph of the three degree of freedom loading rig located at The University of Oxford.

Figure 2 - Grading curve for the Goodwyn Carbonate sand utilised during the experiments.
Figure 3 - Sign convention and notation (after Butterfield et al, 1997)
Oxford University: Carbonate Sand Footing Tests
Test FUF02: Vertical Loading Test

Figure 5
Figure 6

Oxford University: Carbonate Sand Footing Tests
Test FUF05: (H,0) Swipe from V=1600N
Oxford University: Carbonate Sand Footing Tests
Test FUF06: (0,M) Swipe from V=1600N
Figure 8

Oxford University: Carbonate Sand Footing Tests
Test FUF08: (H,M) Swipe from V=1600N

2000.
V (N)

0.
160.

-40.
H (N)

180.

-20.
80.

M/2R (N)

-20.

δw (mm)

0.
9.00

δu (mm)

-1.00
25.00

2Rδθ (mm)

0.00
0.

Time (s)

18000.
Figure 9

Oxford University: Carbonate Sand Footing Tests
Test FUF09: (H,M) Swim from V=1600N

![Graph](image-url)
Oxford University: Carbonate Sand Footing Tests
Test FUF10: (H,0) Swipe from V=50N after V=1600N

- V (N)
- H (N)
- M/2R (N)
- δw (mm)
- δu (mm)
- 2Rδθ (mm)

Time (s)
Figure 11

Oxford University: Carbonate Sand Footing Tests
Test FUF11: (0, M) Swipe from V=50N after V=1600N
Oxford University: Carbonate Sand Footing Tests
Test FUF13: (H,0) Swipe at Constant $V=1600$N

- $V$ (N)
- $H$ (N)
- $M/2R$ (N)
- $\delta w$ (mm)
- $\delta u$ (mm)
- $2R\delta \theta$ (mm)

Time (s) 0.0 18000
Oxford University: Carbonate Sand Footing Tests
Test FUF14: (0,M) Swipe at Constant V=1600N

Figure 13
Oxford University: Carbonate Sand Footing Tests
Test FUF15: (H,M) Swipe at Constant V=1600 N

![Graph showing force, displacement, and rotation over time](image-url)
Figure 15

Oxford University: Carbonate Sand Footing Tests
Test FUF16: (H,-M) Swipe at Constant V=1600N

2000.

V (N)

0.

450.

H (N)

-50.

40.

M/2R (N)

-160.

140.

δw (mm)

-60.

4.50

δu (mm)

-0.50

-1.25

2Rδθ (mm)

-13.75

0.

Time (s)

18000.
Oxford University: Carbonate Sand Footing Tests
Test FUF17: Radial Displacement \((du/dw)=1\)
Oxford University: Carbonate Sand Footing Tess
Test FUF18: Radial Displacement \( (du/dw)=1.5 \)
Oxford University: Carbonate Sand Footing Tests
Test FUF19: Radial Displacement \(2R \delta q/dw\)=0.5

\(V (N)\)
- 2000.
- 160.
- 0.

\(H (N)\)
- 90.
- 80.
- 70.
- 60.
- 50.
- 40.
- 30.
- 20.
- 10.
- 0.

\(M/2R (N)\)
- 80.
- 70.
- 60.
- 50.
- 40.
- 30.
- 20.
- 10.
- 0.

\(\delta w (mm)\)
- 0.
- 0.64

\(\delta u (mm)\)
- 0.16

\(2R \delta \theta (mm)\)
- 0.00

Time (s)
0.
18000.
Figure 19

Oxford University: Carbonate Sand Footing Tests
Test FUF20: Radial Displacement ($2Rdq/dw$) = 2.35
Oxford University: Carbonate Sand Footing Tests
Test FUF05 : (H,0) Swipe from V=1600N : Event
Oxford University: Carbonate Sand Footing Tests
Test FUF05: (H,0) Swipe from V=1600N Event
Oxford University: Carbonate Sand Footing Tests
Test FUF06 : (0,M) Swipe from V=1600N : Event
Figure 29

Oxford University: Carbonate Sand Footing Tests
Test FUF06: (0,M) Swipe from V=1690N: Event

Graphs showing:
- H(N) vs. V (N)
- M/2R (N) vs. V (N)
- δu (mm) vs. δw(mm)
- 2Rδθ (mm) vs. δu (mm)
Oxford University: Carbonate Sand Footing Tests
Test FUF08: (H,M) Swipe from V=1600N: Event
Oxford University: Carbonate Sand Footing Tests
Test FUP09: (H,-M) Stroke from V=1600N: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF09: (H,-M) Swipe from V=1600N: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF10: (H,0) Swipe from V=50N after V=1600N: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF10 : (H,0) Swipe from V=50N after V=1600N : Event
Oxford University: Carbonate Sand Footing Tests
Test FUF11: (0, M) Swipe from $V=50N$ after $V=1600N$: Event

$V(N)$

$H(N)$

$M/2R(N)$

$\delta w (mm)$

$\delta u (mm)$

$2R\delta \theta (mm)$
Oxford University: Carbonate Sand Footing Tests
Test FUF11: (0,M) Swipe from V=50N after V=1600N: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF13 : (H,0) Swipe at Constant V=1600N : Event
Oxford University: Carbonate Sand Footing Tests
Test FUF13: (H,0) Swipe at Constant V=1600N: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF14 : (0,M) Swipe at Constant V=1600N : Event
Oxford University: Carbonate Sand Footing Tests
Test FUF15 : (H,M) Swipe at Constant V=1600N : Event
Oxford University: Carbonate Sand Footing Tests
Test FUF16 : (H,-M) Swipe at Constant V=1600N : Event

Figure 44
Figure 45

Oxford University: Carbonate Sand Footing Tests
Test FUF16 : (H,-M) Swipe at Constant V=1600N : Event

H(N)

M/2R (N)

V (N)

δu (mm)

2Rδθ (mm)

δw(mm)
Oxford University: Carbonate Sand Footing Tests
Test FUF17: Radial Displacement \((du/dw)=1\): Event

![Graphs showing relationships between various parameters]
Oxford University: Carbonate Sand Footing Tests
Test FUF17: Radial Displacement (du/dw)=1: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF18: Radial Displacement (du/dw)=1.5: Event

Figure 48
Oxford University: Carbonate Sand Footing Tests
Test FUF18: Radial Displacement (du/dw)=1.5: Event
Figure 50

Oxford University: Carbonate Sand Footing Tests
Test FUF19: Radial Displacement (2Rdq/dw)=0.5: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF19: Radial Displacement (2Rdq/dw)=0.5: Event
Oxford University: Carbonate Sand Footing Tests
Test FUF20: Radial Displacement (2Rδθ/dw)=2.35: Event

Figure 52
Oxford University: Carbonate Sand Footing Tests
Test FUF20: Radial Displacement \(2R\theta/dw=2.35\): Event
Oxford University: Carbonate Sand Footing Tests
Test FUF21 : (H,0) Swipe from V=400N : Event
Figure 55

Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Swipe from \( V=400 \text{N} \): Event
Oxford University: Carbonate Sand Footing Tests
Test FUF21 : (H,0) Swipe from V=800N : Event
Oxford University: Carbonate Sand Footing Tests
Test FUF21 : (H,0) Swipe from V=800N : Event

![Graph](image-url)
Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Swipe from \( V=1200 \)N : Event

![Graphs showing V(N), H(N), and M/2R(N) vs. \( \delta w \) and \( \delta u \) in millimeters.](image)
Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Swipe from V=1200N: Event
Figure 60

Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Swipe from V=1600N: Event
Figure 61

Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Swipe from V=1600N; Event
Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Swipe from V=1800N: Event

Figure 63
Oxford University: Carbonate Sand Footing Tests
Test FUF21 : (H,0) Multiple Swipes from Various Loads
Figure 65

Oxford University: Carbonate Sand Footing Tests
Test FUF21: (H,0) Multiple Swipes from Various Loads
Oxford University: Carbonate Sand Footing Tests
Test FUF23: Elastic Cycling at V=800N after V=1600N: Event 1
Oxford University: Carbonate Sand Footing Tests
Test FUF23: Elastic Cycling at V=800N after V=1600N: Event 1
Oxford University: Carbonate Sand Footing Tests
Test FUF23: Elastic Cycling at V=800N after V=1600N: Event 2

Figure 68
Oxford University: Carbonate Sand Footing Tests
Test FUF23: Elastic Cycling at V=800N after V=1600N: Event 2