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Decommissioning of Offshore Piles Using Vibration

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ABSTRACT
This paper reports on an investigation of the feasibility of decommissioning offshore tubular piles with vibration. A series of 1g model pile tests using a scaled vibration source and a 400mm long open-ended steel pile were conducted in loose and dense dry sand. Under forced vibration, the pull-out load of the pile was reduced by 36% in dense sand and to the self-weight of the pile in loose sand. Back-calculation reveals a correlation between the lower tensile capacity of the pile and reduced interface friction angles during the application of vibration indicating that such a method may be valuable in future decommissioning projects.

KEYWORDS
Decommissioning; vibration; pile; extraction; tensile capacity

INTRODUCTION
Decommissioning the infrastructure used in the production of oil and gas is fast becoming an important field of activity and research as some of the World's most prolific oil and gas fields approach the limit of economic production. The North Sea, with infrastructure in place since 1967 { ADDIN EN.CITE <EndNote><Cite><Author>Oil and Gas Authority</Author><Year>2016</Year><RecNum>492</RecNum>< DisplayText>(Oil and Gas Authority, 2016)</DisplayText><record><rec-number>492</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1470205805">492</key></foreign-keys><ref-type name="Web Page">12</ref-type><contributors><authors><author>Oil and Gas Authority,</author></authors><secondary-authors><author>Oil and Gas Authority,</author></secondary-authors></contributors><titles><title>Table of Current Platforms</title></titles><number>03/06/2016</number><dates><year>2016</year></dates><work-type>MS Excel Database</work-type><urls><related-urls><url>https://www.gov.uk/guidance/oil-and-gas-infrastructure</url></related-urls></urls><access-date>03/06/2016</access-date></record></Cite></EndNote>}{}{} is one such area, with many installations approaching or exceeding their 25-year design life { ADDIN EN.CITE <EndNote><Cite><Author>Stacey</Author><Year>2008</Year><RecNum>466</RecNum><DisplayText>(Stacey et al., 2008)</DisplayText><record><rec-number>466</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1467562107">466</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Stacey, A</author><author>Birkinshaw, M</author><author>Sharp, JV</author></authors></contributors><titles><title>Life extension

issues for ageing offshore installations</title><secondary-title>ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering</secondary-title></titles><pages>199-215</pages><dates><year>2008</year></dates><publisher>American Society of Mechanical Engineers</publisher><urls></urls></record></Cite></EndNote>}.

The decommissioning of these structures is regulated by UK law and by the OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations { ADDIN EN.CITE <EndNote><Cite><Author>OSPAR Commission</Author><Year>1998</Year><RecNum>349</RecNum ><DisplayText>(OSPAR Commission, 1998)</DisplayText><record><rec-number>349</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1458595698">349</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>OSPAR Commission,</author></authors></contributors><titles><title>Decision 98/3 on the Disposal of Used Offshore Installations</title><secondary-title>Ministerial Meeting of the OSPAR Commission, Sintra</secondary-title></titles><dates><year>1998</year></dates><urls></urls></record></Cite></EndNote>}. Currently, the removal of offshore piles is not required under legislation. Instead, the piles are cut below the seabed, at a distance deemed appropriate in preventing any remaining pile becoming uncovered { ADDIN EN.CITE <EndNote><Cite><Author>DECC</Author><Year>2013</Year><RecNum>93</RecNum><DisplayText>(DECC, 2013)</DisplayText><record><rec-number>93</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455571165">93</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>DECC</author></authors><contributors><titles><title>Guidance Notes: Decommissioning of Offshore Oil and Gas Installations and Pipelines under the Petroleum Act 1998</title></titles><dates><year>2013</year></dates><urls></urls></record></Cite></EndNote>}. Anecdotally, this distance is around three metres below the natural seabed, in line with current well abandonment procedures. Severance of the piles is normally achieved by abrasive waterjets or mechanical cutting techniques { ADDIN EN.CITE <EndNote><Cite><Author>Orszulik</Author><Year>2016</Year><RecNum>465</RecNum><DisplayText>(Orszulik, 2016)</DisplayText><record><rec-number>465</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx"

timestamp="1467562045">465</key></foreign-keys><ref-type name="Book">6</ref-type><contributors><authors><author>Orszulik, Stefan T</author></authors></contributors><titles><title>Environmental technology in the oil industry</title></titles><dates><year>2016</year></dates><publisher>Springer</publisher><isbn>1402054726</isbn><urls></urls></record></Cite></EndNote>}. This treatment of piles is currently seen as the most beneficial approach regarding cost, technical ability and environmental impact { ADDIN EN.CITE <EndNote><Cite><Author>Ekins</Author><Year>2006</Year><RecNum>51</RecNum><DisplayText>(Ekins et al., 2006)</DisplayText><record><rec-number>51</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455570980">51</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Ekins, P.</author><author>Vanner, R.</author><author>Firebrace, J.</author></authors></contributors><auth-address>Policy Studies Institute, PSI, 50 Hamson Street, London W1W 6UP, UK. p.ekins@psi.org.uk</auth-address><titles><title>Decommissioning of offshore oil and gas facilities: a comparative assessment of different scenarios</title><secondary-title>J Environ Manage</secondary-title></titles><periodical><full-title>J Environ Manage</full-title></periodical><pages>420-38</pages><volume>79</volume><number>4</number><keywords><keyword>Conservation of Natural Resources</keyword><keyword>Environmental Monitoring</keyword><keyword>*Petroleum</keyword></keywords><dates><year>2006</year><pub-dates><date>Jun</date></pub-dates></dates><isbn>0301-4797 (Print)0301-4797 (Linking)</isbn><accession-num>16373078</accession-num><urls><related-urls><url>http://www.ncbi.nlm.nih.gov/pubmed/16373078</url></related-urls></urls><electronic-resource-num>10.1016/j.jenvman.2005.08.023</electronic-resource-num></record></Cite></EndNote>}, although this may not always be the case and pile extraction may become necessary or prove to be beneficial in some instances where future structures are designed to be fully recoverable.

Deep tubular piles are a preferred solution in many offshore installations. In water depths up to four hundred metres { ADDIN EN.CITE <EndNote><Cite><Author>Randolph</Author><Year>2005</Year><RecNum>222</RecNum><DisplayText>(Randolph et al., 2005)</DisplayText><record><rec-number>222</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455621314">222</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Randolph, Mark</author><author>Cassidy, Mark</author><author>Gourvenec, Susan</author><author>Erbrich, Carl</author></authors></contributors><titles><title>Challenges of offshore geotechnical engineering</title><secondary-title>16th international conference on soil mechanics and geotechnical engineering</secondary-title></titles><pages>123-176</pages><number>1</number><dates><year>2005</year></dates><pub-location>Osaka</pub-location><urls></urls></record></Cite></EndNote>}, steel jacket platforms are the most common offshore structure ({ ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Yu</Author><Year>2015</Year><RecNum>16</RecNum><DisplayText>Yu et al. (2015)</DisplayText><record><rec-number>16</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455570812">16</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Low Chong Yu</author><author>Lim Soo King</author><author>Alex Teo Cher Hoon</author><author>Patrick Chai Chee Yean</author></authors></contributors><titles><title>A Review Study of Oil and Gas Facilities for Fixed and Floating Offshore Platforms</title><secondary-title>Research Journal of Applied Sciences, Engineering and Technology</secondary-title></titles><periodical><full-title>Research Journal of Applied Sciences, Engineering and Technology</full-title></periodical><pages>672-679</pages><volume>10</volume><number>6</number><dates><year>2015</year></dates><urls></urls></record></Cite></EndNote>}, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Randolph</Author><Year>2005</Year><RecNum>222</RecNum><DisplayText>Randolph et al. (2005)</DisplayText><record><rec-number>222</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455621314">222</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Randolph, Mark</author><author>Cassidy, Mark</author><author>Gourvenec, Susan</author><author>Erbrich, Carl</author></authors></contributors><titles><title>Challenges of offshore geotechnical engineering</title><secondary-title>16th international conference on soil mechanics and geotechnical engineering</secondary-title></titles><pages>123-176</pages><number>1</number><dates><year>2005</year></dates><pub-location>Osaka</pub-location><urls></urls></record></Cite></EndNote>}) and are fixed to the seabed via piles installed through sleeves on the jacket legs. At least one pile is required at each leg of the jacket, with some large structures requiring many more. For example, the CNR International, Murchison platform in the northern North Sea used eight piles at each leg of the jacket { ADDIN EN.CITE <EndNote><Cite><Author>Corcoran</Author><Year>2014</Year><RecNum>343</RecNum><DisplayText>(Corcoran and Nazaruk, 2014)</DisplayText><record><rec-number>343</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1458494129">343</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>M Corcoran</author><author>K Nazaruk</author></authors></contributors><titles><title>Murchison field decommissioning programmes</title></titles><dates><year>2014</year></dates><publisher>CNR International</publisher><isbn>MURDECOM-CNR-PM-REP-00232</isbn><urls></urls></record></Cite></EndNote>}. When the total of 556 fixed steel piled jackets { ADDIN EN.CITE <EndNote><Cite><Author>Oil and Gas UK</Author><Year>2012</Year><RecNum>164</RecNum><DisplayText>(Oil and Gas UK, 2012)</DisplayText><record><rec-number>164</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455571580">164</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>Oil and Gas UK,,</author></authors></contributors><titles><title>The decommissioning of steel piled jackets in the north sea region</title></titles><dates><year>2012</year></dates><urls></urls></record></Cite></EndNote>} installed in the North Sea are considered, it becomes apparent that a very large number of piles exist in this area alone. Therefore, any future requirements to extract these piles will necessitate an efficient and effective method which does not significantly contribute to the expected decommissioning costs of £46 billion for the United Kingdom Continental Shelf (UKCS) by 2040 { ADDIN EN.CITE <EndNote><Cite><Author>Oil and Gas

UK</Author><Year>2015</Year><RecNum>350</RecNum><DisplayText>(Oil and Gas UK, 2015)</DisplayText><record><rec-number>350</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1458597132">350</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>Oil and Gas UK,,</author></authors></contributors><titles><title>Activity Survey</title></titles><dates><year>2015</year></dates><urls></urls></record></Cite></EndNote>}.

{ ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Overy</Author><Year>2007</Year><RecNum>473</RecNum><DisplayText>Overy (2007)</DisplayText><record><rec-number>473</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469111854">473</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Overy, Robert</author></authors></contributors><titles><title>The use of ICP design methods for the foundations of nine platforms installed in the UK North Sea</title><secondary-title>Offshore Site Investigation and Geotechnics: Confronting New Challenges and Sharing Knowledge</secondary-title></titles><dates><year>2007</year></dates><publisher>Society of Underwater Technology</publisher><isbn>0906940494</isbn><urls></urls></record></Cite></EndNote>} highlights the tendency for jacket structures operated by Shell in the North Sea to be founded on medium-sized piles of 0.6 to 2.1m diameter embedded 26 to 87m below the seabed with rated axial compressive capacities between 14 and 100MN respectively. Assuming a tensile capacity 30% lower than the compressive capacity ({ ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>De Nicola</Author><Year>1993</Year><RecNum>276</RecNum><DisplayText>De Nicola and Randolph (1993)</DisplayText><record><rec-number>276</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455632826">276</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>De Nicola, Anthony</author><author>Randolph, Mark F</author></authors></contributors><titles><title>Tensile and compressive shaft capacity of piles in sand</title><secondary-title>Journal of Geotechnical Engineering</secondary-title></titles><periodical><full-title>Journal of Geotechnical Engineering</full-title></periodical><pages>1952-1973</pages><volume>119</volume><number>12</number><dates><year>1993</year></dates><isbn>0733-9410</isbn><urls></urls></record></Cite></EndNote>}, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Overy</Author><Year>2007</Year><RecNum>473</RecNum><DisplayText>Overy (2007)</DisplayText><record><rec-number>473</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469111854">473</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Overy, Robert</author></authors></contributors><titles><title>The use of ICP design methods for the foundations of nine platforms installed in the UK North Sea</title><secondary-title>Offshore Site Investigation and Geotechnics: Confronting New Challenges and Sharing Knowledge</secondary-title></titles><dates><year>2007</year></dates><publisher>Society of Underwater Technology</publisher><isbn>0906940494</isbn><urls></urls></record></Cite></EndNote>}) to perform a rudimentary illustrative

calculation of the pull-out load of such piles, shows that a force of up to 71.6MN might be required to extract a typical pile. Notwithstanding the inherent danger of such an operation, there are very few heavy lift vessels available on the current market which can handle such massive lifts (e.g. the Heerema Thialf { ADDIN EN.CITE <EndNote><Cite><Author>Heerema Marine Contractors</Author><Year>2016</Year><RecNum>493</RecNum><DisplayText>(Heerema Marine Contractors, 2016)</DisplayText><record><rec-number>493</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1470206127">493</key></foreign-keys><ref-type name="Web Page">12</ref-type><contributors><authors><author>Heerema Marine Contractors,</author></authors></contributors><titles><title>Thialf</title></titles><pages>Heerema Marine Contractors > Fleet > Thialf</pages><number>05/06/2016</number><dates><year>2016</year></dates><work-type>Website</work-type><urls><related-urls><url>https://hmc.heerema.com/fleet/thialf/</url></related-urls></urls></record></Cite></EndNote>}) and with day rates reaching hundreds of thousands of dollars, these are very expensive to operate. Reducing the pull-out load would decrease the size of the lifting equipment required and potentially lower the financial cost to the operator.

In the onshore environment, it is common practice to extract and re-use sheet piles and temporary casings via different methods, which include the application of vibration { ADDIN EN.CITE <EndNote><Cite><Author>FPS</Author><Year>2010</Year><RecNum>542</RecNum><DisplayText>(FPS, 2010)</DisplayText><record><rec-number>542</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1471733272">542</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>FPS</author></authors><tertiary-authors><author>Federation of Piling Specialists</author></tertiary-authors></contributors><titles><title>Notes for guidance on the extraction of temporary casings and temporary piles within the piling industry</title></titles><edition>1st</edition><dates><year>2010</year></dates><urls></urls></record></Cite></EndNote>}, usually utilising the same or a similar vibro-hammer used during installation of the pile. This process, although commonly reported by onshore and near-shore civil engineering contractors and equipment manufacturers, is not recorded in academic literature or typically applied in the offshore environment in the context of offshore oil and gas installations. Previous experimental work at the University of Dundee found vibration was also of benefit in other offshore applications for instance, testing of a scaled model offshore pipeline plough increased the ploughing depth in dense sand by up to 39%, without increasing tow force requirements { ADDIN EN.CITE <EndNote><Cite><Author>Zefirova</Author><Year>2012</Year><RecNum>186</RecNum><DisplayText>(Zefirova et al., 2012)</DisplayText><record><rec-number>186</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455571686">186</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Conference Paper">47</ref-type><contributors><authors><author>Zefirova, A</author><author>Brown, MJ</author><author>Brennan, AJ</author><author>Boyes, S</author></authors></contributors><titles><title>Improving The Performance Of Offshore Pipeline Ploughs Using Vibration</title><secondary-title>7th International Conference on Offshore Site Investigation and Geotechnics: Integrated Technologies - Present and Future</secondary-title></titles><dates><year>2012</year><pub-dates><date>12–14 September 2012</date></pub-dates></dates><pub-location>Royal Geographical Society, London</pub-location><publisher>Society of
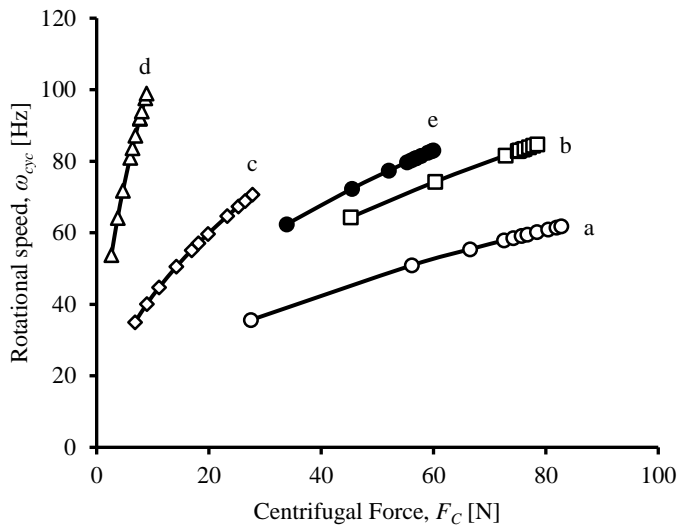
Underwater
Technology</publisher><urls></urls></record></Cite></EndNote>}.

To assess the validity of the application of vibration in aiding the extraction of offshore piles driven into sand, a programme of 1g laboratory testing of scaled models was undertaken. Preliminary experiments were conducted at a scale of 1:50 with full consideration given to scaling issues on grain size and boundary effects when selecting the sand, testing container and model pile. The effectiveness of the vibro-extraction method was investigated in loose and dense dry sand through a series of tests which established the pull-out loads of the model pile. Additionally, elements of the custom designed vibrator were varied to determine the effects of both frequency and amplitude of vibration on the extraction force.

EXPERIMENTAL INVESTIGATION

A model scale vibration source ({ REF _Ref471463848 \h * MERGEFORMAT }) was designed and constructed which was based on a pair of counter-rotating eccentric masses (ERM) to provide balanced, vertical sinusoidal vibration. The rotational speed, eccentricity and mass of the rotating masses were included as variables in the testing programme. To simplify the design, two identical Como Drills 719RE380 DC motors were used to drive the ERMs, controlled by a single speed regulator. The equipment as used is shown in { REF _Ref472587337 \h * MERGEFORMAT }. The rotational speed of the ERMs was verified at various current/voltage levels with a stroboscope and proven to be consistent between the two motors. The rotational speeds which could be achieved with the described apparatus and calculated dynamic force amplitude at each speed are shown in { REF _Ref458166297 \h * MERGEFORMAT }.

Figure { SEQ Figure * ARABIC }. Schematic drawings of the vibrator: a) with the outer casing; b) without the outer casing. ERM = eccentric rotating mass.

Figure { SEQ Figure * ARABIC }. Experimental setup showing pile suspended from the Instron loadcell, with vibrator attached, after a vibro-extraction test.

Table { SEQ Table * ARABIC }. Paired eccentric rotational mass (ERM) properties. Average values for one ERM. Offset is measured from the centre of the ERM to the centre of the 2.3mm diameter motor mounting hole. Thickness and radius are the dimensions of the ERM cylinder.

ERM Set	Thickness [mm]	Radius [mm]	Offset [mm]	Mass [g]
a	12.4	12.6	5.4	50.1
b	6.0	12.6	5.3	25.8
c	5.9	12.5	2.8	24.8
d	6.0	6.0	2.0	5.5
e	12.1	12.5	2.1	51.6

Figure { SEQ Figure * ARABIC \\s 1 }. Correlation of rotational speed and centrifugal force generated for each eccentric mass set (a to e) – see { REF _Ref472072329 \\h * MERGEFORMAT } for ERM properties.

The model pile used throughout all tests was a 400mm length (*L*) of austenitic stainless steel open-ended pipe, with an outer diameter (*D*) of 60.33mm and wall thickness of 2.77mm. The stated dimensions equate to a slenderness ratio (*L/D*) of 6.63. A bar with a threaded hole was welded across the top of the pile for the rigid attachment of the vibrator. A gap on either side of the bar allowed the distance to the top of the sand to be measured after installation (internally, to assess plugging). The average external surface roughness of the pile was measured at 2.90μm. The internal roughness was assumed to be the same.

HST95 sand was used for all tests. This fine grained sand has been extensively characterised in previous studies at the University of Dundee (e.g. { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Jeffrey</Author><Year>2016</Year><RecNum>476</RecNum><DisplayText>Jeffrey et al. (2016)</DisplayText><record><rec-number>476</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469292075">476</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Jeffrey, John Ross</author><author>Brown, Michael John</author><author>Knappett, Jonathan Adam</author><author>Ball, Jonathan David</author><author>Caucis, Karlis</author></authors></contributors><titles><title>CHD pile performance: part I–physical modelling</title><secondary-title>Proceedings of the Institution of Civil Engineers-Geotechnical Engineering</secondary-title></titles><periodical><full-title>Proceedings of the Institution of Civil Engineers-Geotechnical Engineering</full-title></periodical><pages>1-15</pages><dates><year>2016</year></dates><isbn>1353-2618</isbn><urls></urls></record></Cite></EndNote>}), with the principal properties provided in { REF _Ref471464606 \\h * MERGEFORMAT }. The grain size of the sand has not been scaled in line with the other geometric aspects of the model, to preserve the material properties of the sand. { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Garnier</Author><Year>1998</Year><RecNum>480</RecNum><DisplayText>Garnier and Konig (1998)</DisplayText><record><rec-number>480</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469883950">480</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Garnier, J</author><author>Konig, D</author></authors></contributors><titles><title>Scale effects in piles and nails loading tests in sand</title><secondary-title>Centrifuge</secondary-title></titles><pages>205-210</pages><volume>98</volume><dates><year>1998</year></dates><urls></urls></record></Cite></EndNote>} and { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Fioravante</Author><Year>2002</Year><RecNum>268</RecNum><DisplayText>Fioravante (2002)</DisplayText><record><rec-number>268</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455631092">268</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Fioravante, V</author></authors></contributors><titles><title>On the shaft friction modelling of non-displacement piles in sand</title><secondary-title>Soils and Foundations</secondary-title></titles><periodical><full-title>Soils and Foundations</full-title></periodical><pages>23-33</pages><volume>42</volume><number>2</number><dates><year>2002</year></dates><isbn>1341-7452</isbn><urls></urls></record></Cite></EndNote>} note that where *D/D₅₀* is >50 (where D_{50} is the sieve size passing 50% of the sample by mass), grain size scaling effects can be neglected. It is therefore assumed that for all tests, there are no issues (in terms of pile-soil interaction) caused by the grain size of the sand since D/D_{50} is equal to 431.

Testing of the model scale vibro-extractor and pile at 1g results in significantly reduced confining stresses compared to those experienced in the field. Consequently, since the peak soil friction angles have been shown to relate to the degree of dilation and thus, the relative density and mean effective stress conditions (Bolton 1986), it is necessary to allow for a change in peak friction angle at low confining stress. Derivation of the peak friction angle (ϕ_p) from shear box tests by { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Lauder</Author><Year>2010</Year><RecNum>479</RecNum><DisplayText>Lauder (2010)</DisplayText><record><rec-number>479</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469690823">479</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Lauder, Keith</author></authors></contributors><titles><title>The performance of pipeline ploughs</title></titles><dates><year>2010</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>} and { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Jeffrey</Author><Year>2012</Year><RecNum>477</RecNum><DisplayText>Jeffrey (2012)</DisplayText><record><rec-number>477</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469363974">477</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Jeffrey, John</author></authors></contributors><titles><title>Investigating the performance of continuous helical displacement piles</title></titles><dates><year>2012</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>}, using secant values from the origin (zero apparent cohesion), as advocated by { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Bolton</Author><Year>1986</Year><RecNum>376</RecNum><DisplayText>Bolton (1986)</DisplayText><record><rec-number>376</rec-

number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1459322344">376</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Bolton, MD</author></authors></contributors><titles><title>The strength and dilatancy of sands</title><secondary-title>Geotechnique</secondary-title></titles><periodical><full-title>Géotechnique</full-title></periodical><pages>65-78</pages><volume>36</volume><number>1</number><dates><year>1986</year></dates><urls></urls></record></Cite></EndNote>}, demonstrates in { REF _Ref458251113 \h * MERGEFORMAT } that an increase in the peak friction angle is observed under decreasing normal effective stress as a result of increased dilation during shearing. At the base of the model pile, the largest effective stress (σ'_v) expected is approximately 6 to 7kPa, resulting in peak friction angles (ϕ_p) of 38 to 53º for loose and dense sand respectively. At the mid-pile depth, ϕ_p increases to 48º for loose sand and 59º for dense sand. { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Lauder</Author><Year>2010</Year><RecNum>479</RecNum><DisplayText>Lauder (2010)</DisplayText><record><rec-number>479</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469690823">479</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Lauder, Keith</author></authors></contributors><titles><title>The performance of pipeline ploughs</title></titles><dates><year>2010</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>} also conducted experiments to determine the interface friction angle (δ) between dense HST95 and a typical steel surface, reporting an angle of 27º.
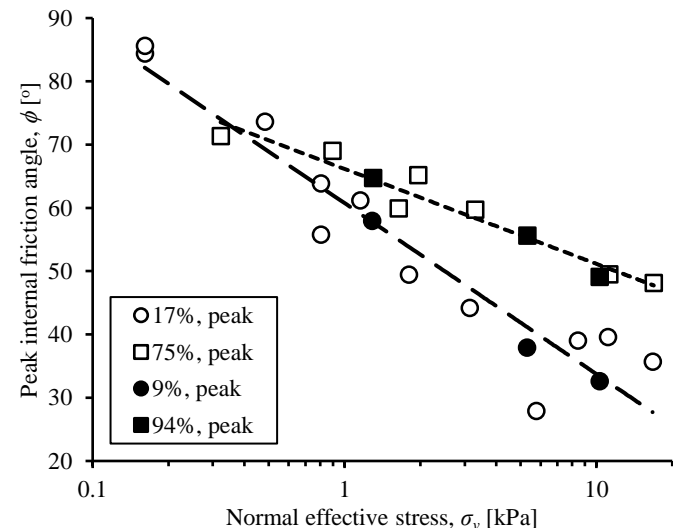

Figure { SEQ Figure * ARABIC \s 1 }. Peak friction angle of HST95 sand at low effective stresses, derived from shear box. Open and filled symbols show data from { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Lauder</Author><Year>2010</Year><RecNum>479</RecNum><DisplayText>Lauder (2010)</DisplayText><record><rec-number>479</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469690823">479</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Lauder, Keith</author></authors></contributors><titles><title>The performance of pipeline ploughs</title></titles><dates><year>2010</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-

type><urls></urls></record></Cite></EndNote>} and { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Jeffrey</Author><Year>2012</Year><RecNum>477</RecNum><DisplayText>Jeffrey (2012)</DisplayText><record><rec-number>477</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469363974">477</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Jeffrey, John</author></authors></contributors><titles><title>Investigating the performance of continuous helical displacement piles</title></titles><dates><year>2012</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>} respectively.

Table { SEQ Table * ARABIC }. Summary of HST95 sand properties. ϕ = friction angle, δ = interface friction angle, CS = critical state, σ'_v = vertical effective stress.

Property	Value
Sieve size passing 10 per cent of sample by mass, D_{10} [mm]	0.10
Sieve size passing 50 per cent of sample by mass, D_{50} [mm]	0.14
Specific gravity, G_s [g/cc]	2.63
ϕ_{peak} – loose sand, σ'_v = 0-3kPa [º]	53
ϕ_{peak} – loose sand, σ'_v = 3-7kPa [º]	40
ϕ_{peak} – dense sand, σ'_v = 0-3kPa [º]	55
ϕ_{peak} – dense sand, σ'_v = 3-7kPa [º]	48
δ_{cs} – dense sand, 0-3kPa [º]	35
δ_{cs} – dense sand, 3-7kPa [º]	30
Minimum dry density, ρ_{min} [kg/m³]	1487
Maximum dry density, ρ_{max} [kg/m³]	1792

The sand was tested dry, such that there were no excess pore pressures generated due to the vibration. As a result, the tests represent an upper-bound on the extraction forces that would be required in a 1-g model of an offshore pile where the soil is fully saturated.

A box with internal dimensions of 500 x 468mm and 668mm depth was used for all tests. Three sides and the base were made from 16mm thick aluminium, while the remaining side was 14mm thick transparent acrylic. The dimensions of the model pile, installed to 400mm penetration depth, results in a pile to box wall diameter ratio of 7.76 and separation of 4.44 pile diameters between the pile tip and base of the box, which are in line with previous studies which suggested boundary effects would be negligible ({ ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Robinsky</Author><Year>1964</Year><RecNum>437</RecNum><DisplayText>Robinsky and Morrison (1964)</DisplayText><record><rec-number>437</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1467019912">437</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Robinsky, EI</author><author>Morrison, CF</author></authors></contributors><titles><title>Sand displacement and compaction around model friction piles</title><secondary-title>Canadian Geotechnical Journal</secondary-title></titles><periodical><full-title>Canadian Geotechnical Journal</full-title></periodical><pages>81-93</pages><volume>1</volume><number>2</number><dates><year>1964</year></dates><isbn>0008-3674</isbn><urls></urls></record></Cite></EndNote>}, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Phillips</Author><Year>1987</Year><RecNum>481</RecNum><DisplayText>Phillips and Valsangkar (1987)</DisplayText><record><rec-number>481</rec-

number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469949772">481</key></foreign-keys><ref-type name="Book">6</ref-type><contributors><authors><author>Phillips, R</author><author>Valsangkar, AJ</author></authors></contributors><titles><title>An experimental investigation of factors affecting penetration resistance in granular soils in centrifuge modelling</title></titles><dates><year>1987</year></dates><publisher>University of Cambridge Department of Engineering</publisher><isbn>0309-7439</isbn><urls></urls></record></Cite></EndNote>}, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Vipulanandan</Author><Year>1990</Year><RecNum>213</RecNum><DisplayText>Vipulanandan et al. (1990)</DisplayText><record><rec-number>213</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455620018">213</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Vipulanandan, Cumaraswamy</author><author>Wong, Daniel</author><author>O'Neill, Michael W</author></authors></contributors><titles><title>Behavior of vibro-driven piles in sand</title><secondary-title>Journal of Geotechnical Engineering</secondary-title></titles><periodical><full-title>Journal of Geotechnical Engineering</full-title></periodical><pages>1211-1230</pages><volume>116</volume><number>8</number><dates><year>1990</year></dates><isbn>0733-9410</isbn><urls></urls></record></Cite></EndNote>}, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Foray</Author><Year>1991</Year><RecNum>483</RecNum><DisplayText>Foray (1991)</DisplayText><record><rec-number>483</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469955140">483</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Foray, P</author></authors><secondary-authors><author>An-Bin Huang</author></secondary-authors><subsidiary-authors><author>The National Science Foundation (in part)</author></subsidiary-authors></contributors><titles><title>Scale and boundary effects on calibration chamber pile tests</title><secondary-title>First International Symposium on Calibration Chamber Testing/ISOCCTl</secondary-title></titles><pages>147-160</pages><dates><year>1991</year><pub-dates><date>28-29 June 1991</date></pub-dates></dates><pub-location>Potsdam, New York</pub-location><publisher>Elsevier</publisher><urls></urls></record></Cite></EndNote>}, and { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Jeffrey</Author><Year>2012</Year><RecNum>477</RecNum><DisplayText>Jeffrey (2012)</DisplayText><record><rec-number>477</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469363974">477</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Jeffrey, John</author></authors></contributors><titles><title>Investigating the performance of continuous helical displacement piles</title></titles><dates><year>2012</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>}).

Loose sand beds were prepared by stirring the sand to promote high levels of shear deformation, thus achieving critical state and a relative density (D_r) averaging 17%. An air pluviation system, with a slot pluviator, was employed to generate beds of dense sand between 77 and 81% D_r.

Jacked pile installation and extraction was achieved using an Instron 5980 universal mechanical testing system set at a continuous displacement velocity of 50mm/min with a 30kN load cell. Displacement and load data were captured at a rate of 20Hz. The pile was fully embedded into the sand from a starting position ~1mm above the sand surface.

The force required to extract the model pile was investigated under three different conditions for both loose and dense sand. Initial pull-out tests with no vibration established a benchmark against which the subsequent vibro-extraction tests were compared. The vibration was applied in two different ways depending on the particular test (Table 2), for example, with both low and high frequencies, as well as being switched off for a short period during the extraction. Tests were conducted for each of the situations described ({ REF _Ref471464803 \h * MERGEFORMAT }) to prove repeatability and account for variations in sand density. Details of the sub-set of results presented in this paper are given in { REF _Ref471468794 \h * MERGEFORMAT }.

Installation tests are prefixed with the letter I and extraction tests with E and VE for monotonic and vibro-extraction methods respectively. The sand density is identified in the test number by either L or D for loose and dense states respectively.

Table { SEQ Table * ARABIC }. Summary of the experimental programme.

Type of test	Number of tests performed	Aim
Installation	38	Embed the pile for extraction while recreating installation effects which may influence tensile tests. Establish the axial compressive pile capacity.
Monotonic extraction	12	Measure the benchmark tensile capacity of the pile.
Constant vibro-extraction	16	Measure the influence of various levels of vibration on the tensile capacity of the pile.
Intermittent vibro-extraction	10	Investigate the influence of vibration on the soil properties.

Table { SEQ Table * ARABIC }. Extract of record of experiments. D_r = relative density, ρ = bulk density, ω_{cyc} = ERM rotation speed, F_c = ERM dynamic force.

Test	D_r [%]	ρ [kg/m³]	Extraction type	ERM set	ω_{cyc} [Hz]	F_c [N]
E-D-03	77.07	1714.74	Mono	-	-	-
E-D-04	77.32	1712.57	Mono	-	-	-
E-L-05	17.03	1531.38	Mono	-	-	-
E-L-06	17.03	1531.38	Mono	-	-	-
E-L-07	17.03	1531.38	Mono	-	-	-
E-L-08	17.03	1531.38	Mono	-	-	-
VE-D-01	77.95	1714.46	Vibro	b	81.62	72.79
VE-D-02	81.49	1725.03	Vibro	c	44.70	11.11
VE-D-03	78.88	1712.69	Vibro	a	55.40	66.49
VE-D-04	77.92	1719.9	Vibro	e	80.27	56.01
VE-L-02	17.03	1531.38	Vibro	b	82.83	74.98
VE-L-03	17.03	1531.38	Vibro	b	81.62	72.79
VE-L-04	17.03	1531.38	Vibro	b	64.32	45.20
VE-L-16	17.03	1531.38	Vibro	c	34.97	6.80
VE-L-18	17.03	1531.38	Vibro	d	53.75	2.62

LABORATORY TEST RESULTS: ANALYSIS AND DISCUSSION

Pile Installation

In all tests, the pile was observed to plug during installation approximately 220mm displacement, with no discernible difference in the average incremental filling ratio (IFR) between tests in loose and dense sand (final plug height above pile tip ranged from 220-249mm with average IFR of 58 and 60% for loose and dense sand respectively). This result contrasts with scale model experiments, using a 42.7mm outside diameter pile, by { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Paik</Author><Year>2003</Year><RecNum>536</RecNum><DisplayText>Paik and Salgado (2003)</DisplayText><record><rec-number>536</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1471104900">536</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Paik, K.</author><author>Salgado, R.</author></authors></contributors><titles><title>Determination of Bearing Capacity of Open-Ended Piles in Sand</title><secondary-title>Journal of Geotechnical and Geoenvironmental Engineering</secondary-title></titles><periodical><full-title>Journal of geotechnical and geoenvironmental engineering</full-title></periodical><pages>46-57</pages><volume>129</volume><number>1</number><dates><year>2003</year></dates><urls></urls></record></Cite></EndNote>} who determined that IFR increased from 55 to 75% as the relative density was increased from 21 to 90% when installing the model pile by means of impact from a hammer. Similarly, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Lehane</Author><Year>2001</Year><RecNum>212</RecNum><DisplayText>Lehane and Gavin (2001)</DisplayText><record><rec-number>212</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455616463">212</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Lehane, BM</author><author>Gavin, KG</author></authors></contributors><titles><title>Base resistance of jacked pipe piles in sand</title><secondary-title>Journal of Geotechnical and Geoenvironmental Engineering</secondary-title></titles><periodical><full-title>Journal of geotechnical and geoenvironmental engineering</full-title></periodical><pages>473-480</pages><volume>127</volume><number>6</number><dates><year>2001</year></dates><isbn>1090-0241</isbn><urls></urls></record></Cite></EndNote>} found that the initial relative density of dry sand was a controlling factor in the plug length of 40-114mm diameter piles which were jacked into sand using 40-80mm length strokes. It is therefore suggested that the continuous jacking method employed herein is a more dominant factor than relative density in the development of the observed final plug length.

Installation of the pile into loose sand resulted in the head of the pile being level with the surface of the sand. However, installation of the pile into dense sand resulted in significant dilation, such that, by the end of driving, soil dilation had radiated outwards to the edge of the model container to such a point that the top of the sand surface, measured at the edge of the box, was approximately 4-5mm above the starting position, rising to around 10mm at the pile. The observation of sand dilation occurring at the boundary of the box implies that the boundary conditions may not be suitable near surface.

Monotonic Extraction

Monotonic pull-out tests were conducted in both loose and dense sand to determine the baseline pile capacity and extraction behaviour without the application of vibration at any stage. The self-weight of the pile and vibrator was subtracted from the measured extraction load to give the net tensile load, Q_t. In a comparison of the load-displacement curves of each of the monotonic extractions, shown in { REF _Ref471465124 \h * MERGEFORMAT }, it is apparent that the density of the sand plays an important role in the tensile capacity of the pile, with a ~350% increase observed in the peak capacity of dense over loose sand. The post-peak decay in capacity can be seen to follow the same trend for both densities as the extraction progresses, with curves from all tests converging at a load of approximately 18N by a displacement of 270mm ({ REF _Ref471465124 \h }). At around 250mm displacement, each curve reduces at a faster rate over a distance of around 20mm. For each test, as the pile is extracted the starting point of this behaviour occurs as the pile tip reaches the depth of the top of the internal sand plug as measured after installation. This observation indicates that: 1) the weight of the plug is such that the plug remains stationary relative to the model container/sand during extraction; 2) the internal shaft friction must contribute to the overall shaft friction; 3) the shaft friction after this point is solely comprised of the external friction component.

Vibro-extraction

In measuring the efficacy of the vibro-extraction method, a number of metrics can be considered in the qualification of the results including the maximum tensile capacity, as defined by the peak measured load, and the total energy required, quantified by the work done in extracting the pile.

In loose sand, a total of five tests were conducted with vibration applied immediately before extraction started and for the total duration of the extraction test. The dynamic force applied by the pile head vibrator was varied by changing either the rotational speed or the eccentric mass properties ({ REF _Ref472072329 \h } & { REF _Ref458166297 \h * MERGEFORMAT }) to achieve the results as presented in the load-displacement curves of { REF _Ref472332516 \h } In terms of the tensile capacity of the pile, as indicated by the peak load, it can be seen that with the application of sufficient vibration, the capacity can be reduced to little more than the self-weight of the pile shown by test VE-L-02, which has a net peak load of only 1.45N, some 0.8% of the net pile capacity seen in test E-L-06 (benchmark pull-out data with no vibration). This significant reduction in extraction force occurs even in the absence of positive excess pore pressures which might be induced by the vibration (sand is dry). By reducing the vibrational energy imparted to the pile (lowering the rotational speeds and varying the ERM properties) it can be seen in { REF _Ref472332379 \h } that there is an increase in tensile pile capacity with the lowest possible applied vibration resulting in a peak in the load-displacement curve only 10% lower than the baseline monotonic extraction.

Six continuous vibro-extraction tests were conducted in dense sand, with the load-displacement curves for three of the tests shown in { REF _Ref472332465 \h } along with a reference curve from monotonic test E-D-03 for comparison. Peak tensile capacity under the influence of vibration can be seen to reduce by approximately 30-40% in all but one test when compared to E-D-03. As above, this reduction occurs even in the absence of any positive excess pore pressures which may develop in a fully saturated soil due to the vibrations, which may further reduce the extraction force. Each of the tests employed different levels of dynamic force as in the loose tests. To allow comparison of the results the tensile capacity for loose and dense tests were normalised by the corresponding monotonic tensile capacity, as shown in { REF _Ref471465775 \h * MERGEFORMAT }.
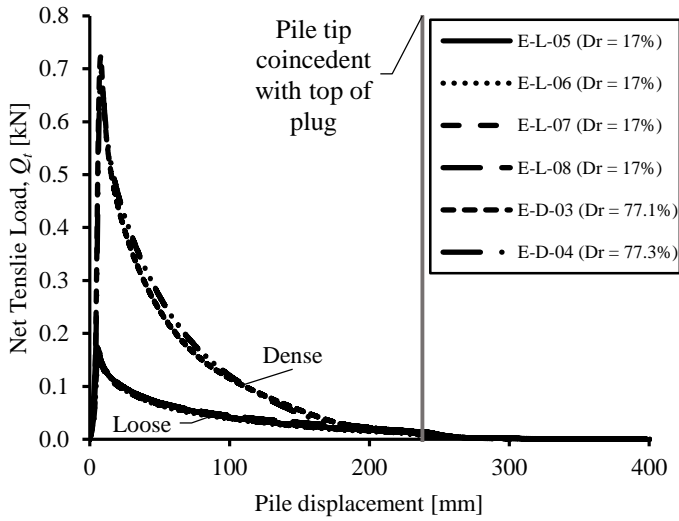
Figure { SEQ Figure * ARABIC }. Load-displacement response for monotonic pull-out tests in loose and dense sand. Vertical line indicates average position of internal soil plug after full installation of the pile.
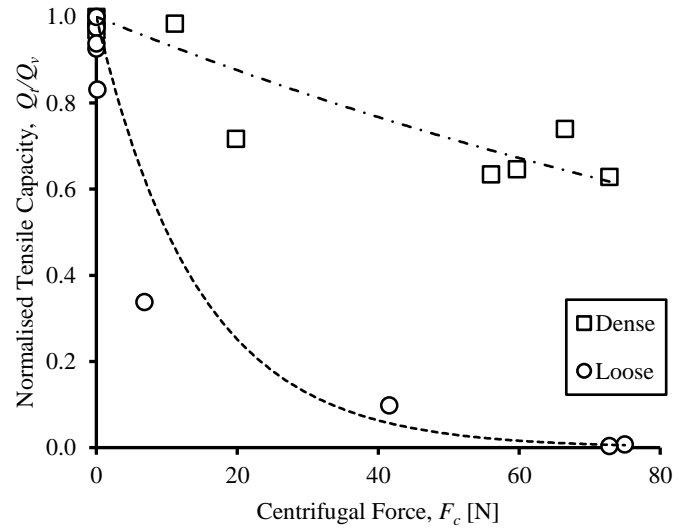

Figure { SEQ Figure * ARABIC }. Load-displacement curves for initial series of vibro-extraction tests in loose soil. A reference curve from monotonic extraction test E-L-06 is included for comparison.

Figure { SEQ Figure * ARABIC }. Load-displacement curves for a subset of the initial series of vibro-extraction tests in dense soil. A reference curve from monotonic extraction test E-D-03 is included for comparison.

Figure { SEQ Figure * ARABIC }. Normalised reduction in tensile pile capacity with increasing centrifugal force from the vibrator in loose and dense sand. Points with zero centrifugal force are from tests with no vibration (monotonic).

A clear trend is apparent in both loose and dense conditions – that increased vibration leads to a reduction in the tensile capacity of the pile (even in the absence of any vibration-induced excess pore water pressures). Furthermore, it is evident that the amount of reduction in pull-out load is heavily dependent on the density of the sand. The dramatic reduction in pile capacity to the self-weight of the combined pile and vibrator seen in loose sand is not replicated in dense sand under the same applied vibration. This observation is consistent with the experience of vibro-piling activities where the rate of penetration increases as the relative density decreases (Holeyman and Michiels, 2006).

Of note in tests VE-L-02, VE-L-03 and VE-L-04 in { REF _Ref472332379 \h } is the reduction of the net tensile load (measured load minus the combined pile & vibrator self-weight) to below zero. It is suggested that the level of vibration of the pile in these tests was sufficient to generate a buoyancy force as described by { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Bernhard</Author><Year>1967</Year><RecNum>464</RecNum><DisplayText>Bernhard (1967)</DisplayText><record><rec-number>464</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1467372479">464</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>Bernhard, Rudolf Karl</author></authors></contributors><titles><title>Fluidization phenomena in soils during vibro-compaction and vibro-pile-driving and-pulling</title><secondary-title>Special Report 106</secondary-title></titles><dates><year>1967</year></dates><pub-location>Hanover, New Hampshire</pub-location><publisher>US Army Material Command</publisher><urls></urls></record></Cite></EndNote>}.

{ ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Youd</Author><Year>1967</Year><RecNum>367</RecNum><DisplayText>Youd (1967)</DisplayText><record><rec-number>367</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1459165946">367</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Youd, Thomas Leslie</author></authors></contributors><titles><title>The engineering properties of cohesionless material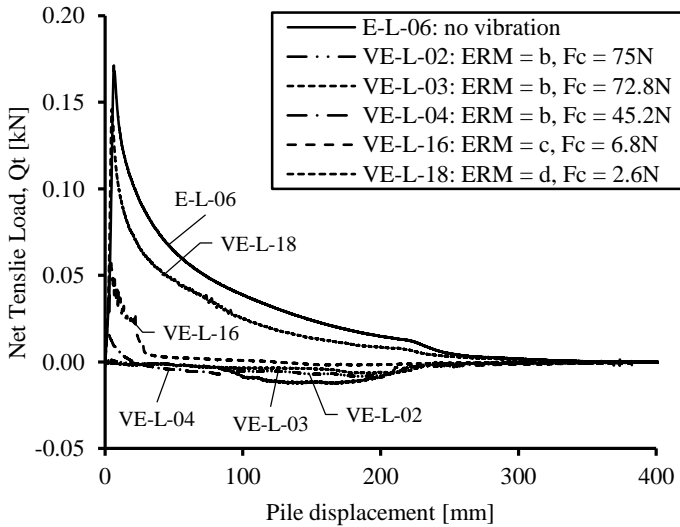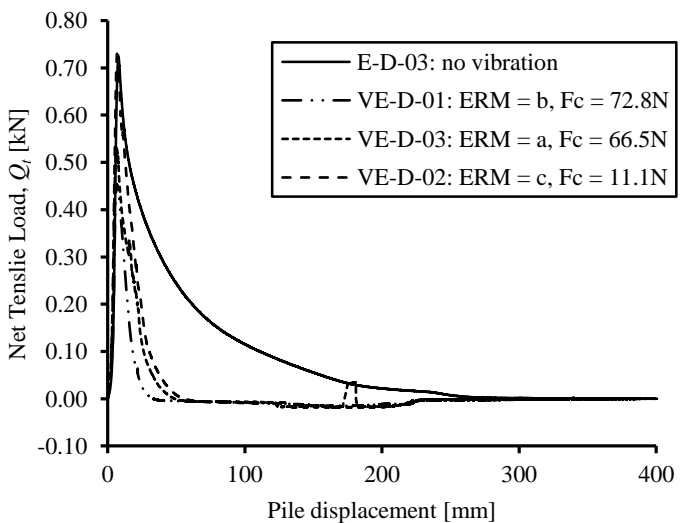s during vibration</title><secondary-title>Civil, Construction, and Environmental Engineering</secondary-title></titles><volume>Doctor

of Philosophy</volume><number>Paper 3225</number><dates><year>1967</year></dates><publisher>Iowa State University</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>} related the increase of acceleration required to densify sands of higher relative density to the amount of potential energy in the soil system, with the upper and lower bounds of the magnitude of this energy corresponding to the minimum and maximum soil densities respectively. For a particular particle to reach a lower energy state (i.e. densify) it must overcome the friction of grain-to-grain contacts and the interlocking of particles. It is, therefore, apparent that a greater energy barrier to particle rearrangement will be present in granular materials with greater interlocking of particles and higher friction. In sand, this equates to the friction and dilation angles, which are directly influenced by the relative density. More energy must be applied to reduce these components and overcome the much larger energy barrier caused by dilation in dense sands. This requirement is compounded further in small scale model tests as a result of the increase of dilation angles at low effective stresses, as demonstrated by { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Lauder</Author><Year>2010</Year><RecNum>479</RecNum><DisplayText>Lauder (2010)</DisplayText><record><rec-number>479</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469690823">479</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Lauder, Keith</author></authors></contributors><titles><title>The performance of pipeline ploughs</title></titles><dates><year>2010</year></dates><publisher>University of Dundee</publisher><work-type>PhD</work-type><urls></urls></record></Cite></EndNote>}.

This concept is visible in the results presented in { REF _Ref472332379 \h } and { REF _Ref472332465 \h } where a marked contrast is evident in the influence of the same levels of vibration on the pull-out capacity of the model pile between loose and dense sand. The maximum available vibration from the model vibrator was not sufficient to overcome the effects of dilation and significantly decrease the friction angle in dense sands. Consequently, the pull-out capacity was only lowered slightly.

Ten additional vibro-extraction tests were conducted where the vibration was switched off for a short period during extraction of the pile and either left off for the remainder of the extraction, or switched back on again. A summary of the load-displacement curves for the loose tests are presented in { REF _Ref472001423 \h }, with additional repeat tests omitted for clarity. As before, monotonic test E-L-06 is shown for comparison. In test VE-L-05, the vibration was stopped after 200mm of displacement and left off for the remainder of the test. With vibration applied, the load-displacement curve exhibits the same behaviour as test VE-L-03 ({ REF _Ref472332379 \h }), which had the same properties of vibration, but as soon as the vibration was turned off (instantaneously via a switch), the load immediately increased.
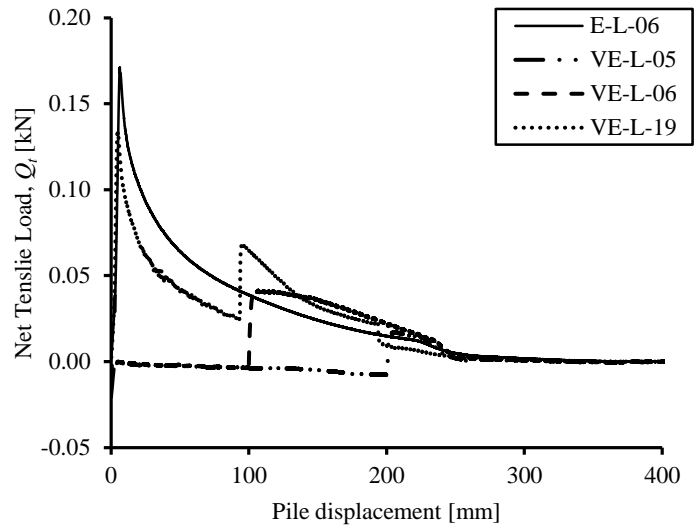

Figure { SEQ Figure * ARABIC }. Load-displacement curves for intermittent vibration tests in loose sand, with monotonic extraction test E-L-06 for comparison.

It was observed that the load increased to a greater level, at the same amount of displacement than if no vibration had been applied (i.e. greater than E-L-06). This behaviour was repeated in test VE-L-06 where the vibration was stopped at 100mm extraction. The decrease in load associated with extraction beyond the top of the plug, as previously discussed, is still apparent at the same position in these tests, indicating that the vibration had little effect on the level of the plug. Finally, in test VE-L-19, the vibration was stopped at 100mm displacement for 100mm of extraction before being resumed. Again, the load increased above the reference case (E-L-06) when the vibration was stopped and decayed at a similar rate to E-L-06 as the pile was extracted. Upon restarting the vibration, the load immediately dropped below the reference line. ERM set d, comprising the smallest mass and eccentricity, was used for this test, hence the greater initial peak load than in the other tests shown in { REF _Ref472001423 \h }.
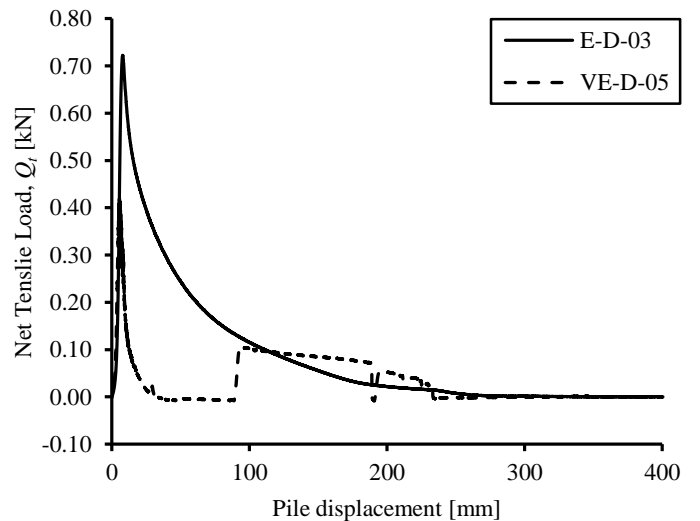

Figure { SEQ Figure * ARABIC }. Load-displacement curves for intermittent vibration tests in dense sand, with monotonic extraction test E-D-03 for comparison.

A single test in dense sand was completed, as shown in { REF _Ref472001705 \h }, with test E-D-03 for comparison. Again, this test exhibited the same behaviour as observed in the loose tests, with the load remaining greater than the benchmark case with no vibration.

The observed increase in pull-out force (shaft resistance) after the application of vibration indicates densification of the sand immediately

adjacent to the pile due to the preceding vibration. It is further suggested that this effect is more pronounced in the internal soil plug than in the sand surrounding the external surface of the pile as it can be seen that in tests VE-L-05 and VE-L-06 in { REF _Ref472001423 \h } that the tensile load converges with the monotonic extraction test (E-L-06) at the point where there is no longer any sand inside the pile (~240mm displacement). Any changes in the sand, assumed to be densification, caused by the initial vibration followed by stopping, are overcome in each case where vibration of the pile was resumed, as in test VE-L-19. Densification is widely described in relation to vibro-compaction methods used in soil improvement procedures and can be related to cyclic shearing of the soil { ADDIN EN.CITE <EndNote><Cite><Author>Massarsch</Author><Year>2002</Year> <RecNum>233</RecNum><DisplayText>(Massarsch, 2002)</DisplayText><record><rec-number>233</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455622617">233</key></foreign-keys><ref-type name="Conference Proceedings">10</ref-type><contributors><authors><author>Massarsch, K Rainer</author></authors></contributors><titles><title>Effects of vibratory compaction</title><secondary-title>TransVib 2002– International Conference on Vibratory Pile Driving and Deep Soil Compaction</secondary-title></titles><pages>33-42</pages><dates><year>2002</year></dates><urls></urls></record></Cite></EndNote>}.

Energy requirements
The energy requirements to extract the pile can easily be obtained by integrating the area beneath the load-displacement curves to determine the work done (W_d).
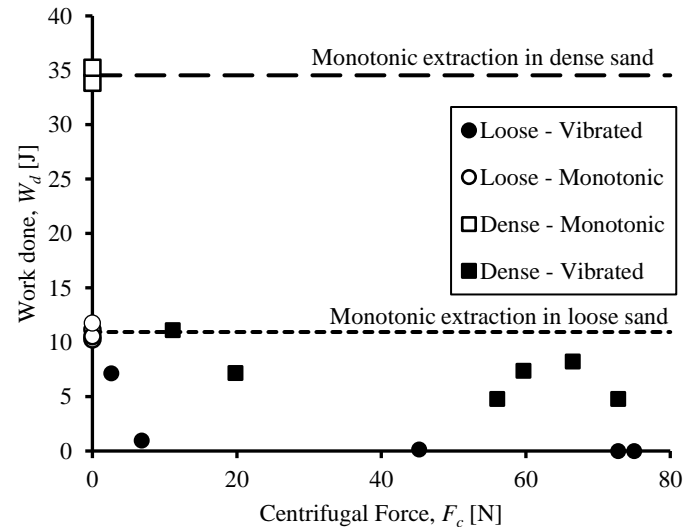

Figure { SEQ Figure * ARABIC }. Work done in extracting the model pile, with and without vibration, in loose and dense sand.

The work done in extracting the pile was calculated for all experiments where the pile was vibrated for the full duration of extraction only, as well as for all of the monotonic pull-out tests. A number of salient features are apparent in the results, shown in { REF _Ref471466033 \h * MERGEFORMAT }. Firstly, the amount of work done to extract the pile monotonically is significantly greater, at around 234% more, in dense sand than in loose. Secondly, the mechanical energy required to extract the pile while vibration was applied is not significantly different between the loose and dense cases, with the test at the highest dynamic force in dense sand requiring similar mechanical energy requirements to the tests in loose sand. Finally, beyond an applied centrifugal force of 7N, there is little further to be gained by increasing the centrifugal force in loose sand. This behaviour is repeated in dense sand, where no significant reduction in the work done occurs in tests with vibration

levels greater than 20N centrifugal force, further indicating the effect of dilation.

Calculation and discussion of pile capacity
To determine which of the parameters controlling the tensile capacity of the pile (i.e. the shaft friction) are influenced by the forced vibration of the pile, it is necessary to first establish values of these parameters during monotonic (no vibration) extraction. The shaft friction (Q_s) of a pile in sand is calculated from equations { REF _Ref471903539 \h } and { REF _Ref471908755 \h }. With known values of the interface friction angle and soil density (and hence effective vertical stress), the lateral earth pressure coefficient is assumed to be the only unknown variable in equation { REF _Ref471908755 \h }. By varying K until the calculated pile capacity is equal to the measured capacity, it is possible to determine an average value of earth pressure coefficient for use in calculating the tensile capacity in various densities of sand and furthermore to back-calculate the interface friction angle during the vibro-extraction tests.

$$Q_s = f(z) \cdot A_s \qquad (\{ \text{SEQ Equation} * \text{MERGEFORMAT} \})$$

where;

Q_s = pile shaft capacity [N]

$f(z)$ = unit shaft friction [N/m^2]

A_s = side surface area of the pile [m^2]

$$f(z) = \sigma'_v \cdot K \cdot \tan\delta \qquad (\{ \text{SEQ Equation} * \text{MERGEFORMAT} \})$$

σ'_v = effective stress [N/m^2]

K = lateral earth pressure coefficient

δ = interface friction angle [º]

For each monotonic extraction test, the earth pressure coefficient was back-calculated to match the calculated and measured tensile pile

capacities as shown in { REF _Ref471995516 \h }. These findings are in-line with those of { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Jeffrey</Author><Year>2016</Year><RecNum>476</RecNum><DisplayText>Jeffrey et al. (2016)</DisplayText><record><rec-number>476</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1469292075">476</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Jeffrey, John Ross</author><author>Brown, Michael John</author><author>Knappett, Jonathan Adam</author><author>Ball, Jonathan David</author><author>Caucis, Karlis</author></authors></contributors><titles><title>CHD pile performance: part I–physical modelling</title><secondary-title>Proceedings of the Institution of Civil Engineers-Geotechnical Engineering</secondary-title></titles><periodical><full-title>Proceedings of the Institution of Civil Engineers-Geotechnical Engineering</full-title></periodical><pages>1-15</pages><dates><year>2016</year></dates><isbn>1353-2618</isbn><urls></urls></record></Cite></EndNote>} and { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Meyerhof</Author><Year>1976</Year><RecNum>540</RecNum><DisplayText>Meyerhof (1976)</DisplayText><record><rec-number>540</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1471699195">540</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Meyerhof, GG</author></authors></contributors><titles><title>Bearing capacity and settlement of pile foundations</title><secondary-title>Journal of Geotechnical and Geoenvironmental Engineering</secondary-title></titles><periodical><full-title>Journal of geotechnical and geoenvironmental engineering</full-title></periodical><volume>102</volume><number>ASCE #11962</number><dates><year>1976</year></dates><isbn>1090-0241</isbn><urls></urls></record></Cite></EndNote>} for jacked piles. The average calculated earth pressure coefficients are 1.14 and 4.14 for the loose and dense tests respectively.

With the calculated earth pressure coefficients, the potential reduction in the sand-steel interface friction angles during vibration of the pile was investigated. The procedure described above in calculating K, was repeated, but using the reported average values of K and varying δ until the calculated tensile capacity matched the measured capacity of the vibro-extraction tests. The results of this process in both loose and dense sand are shown in { REF _Ref471996890 \h }. The results demonstrate that the forced vibration of the pile can significantly reduce the interface friction angle, with values approaching zero (0.11^{o}) in the loose tests with over 70N dynamic force. Even at low levels of vibration in loose sand, large reductions in the interface friction angle are apparent with over a 60% ($\delta < 3^{o}$) reduction at 7N centrifugal force. In dense sand, the reduction in interface friction angle is both less pronounced and less immediate than observed in loose sand, requiring over 10N dynamic force to initiate a reduction in the interface friction angle. Above 20N of dynamic force, the reduction in interface friction angle appears to plateau at 30% ($\delta < 20^{o}$) as shown in { REF _Ref471996890 \h }, suggesting that the amount of force imparted by the vibrator is insufficient to overcome dilation of the dense sand.

The results discussed above are directly comparable to results from other 1g experiments conducted in relation to the handling of granular materials. { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Kaaden</Author><Year>1975</Year><RecNum>538</RecNum><DisplayText>Kaaden (1975)</DisplayText><record><rec-number>538</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1471524169">538</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Kaaden, Alan S</author></authors></contributors><titles><title>Gravity flow of some steelmaking raw materials with particular reference to the effects of vibration</title><secondary-title>Department of Engineering</secondary-title></titles><dates><year>1975</year></dates><publisher>University of Wollongong</publisher><work-type>Master of Engineering</work-type><urls></urls></record></Cite></EndNote>}, demonstrated experimentally the influence of vibration on the interface friction angle (under low confining stresses) between materials used in steel manufacturing and the hoppers used to transfer them. The materials studied included those with internal friction angles of ~60^{o} and interface friction angles of ~30^{o}, which are similar to HST95 sand and the model pile. By applying vibration to the walls of the hopper, { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Kaaden</Author><Year>1975</Year><RecNum>538</RecNum><DisplayText>Kaaden (1975)</DisplayText><record><rec-number>538</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1471524169">538</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Kaaden, Alan S</author></authors></contributors><titles><title>Gravity flow of some steelmaking raw materials with particular reference to the effects of vibration</title><secondary-title>Department of Engineering</secondary-title></titles><dates><year>1975</year></dates><publisher>University of Wollongong</publisher><work-type>Master of Engineering</work-type><urls></urls></record></Cite></EndNote>} found that interface friction angle (δ) could be reduced to as little as 2^{o}, equating to a reduction of 93%.The maximum drop in interface friction angle deduced from the vibro-extraction tests are similar to the findings of { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Kaaden</Author><Year>1975</Year><RecNum>538</RecNum><DisplayText>Kaaden (1975)</DisplayText><record><rec-number>538</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1471524169">538</key></foreign-keys><ref-type name="Thesis">32</ref-type><contributors><authors><author>Kaaden, Alan S</author></authors></contributors><titles><title>Gravity flow of some steelmaking raw materials with particular reference to the effects of vibration</title><secondary-title>Department of Engineering</secondary-title></titles><dates><year>1975</year></dates><publisher>University of Wollongong</publisher><work-type>Master of Engineering</work-type><urls></urls></record></Cite></EndNote>} and are considered to be a close approximation of the values of the interface friction between the pile and sand during the vibrated pull-out tests.
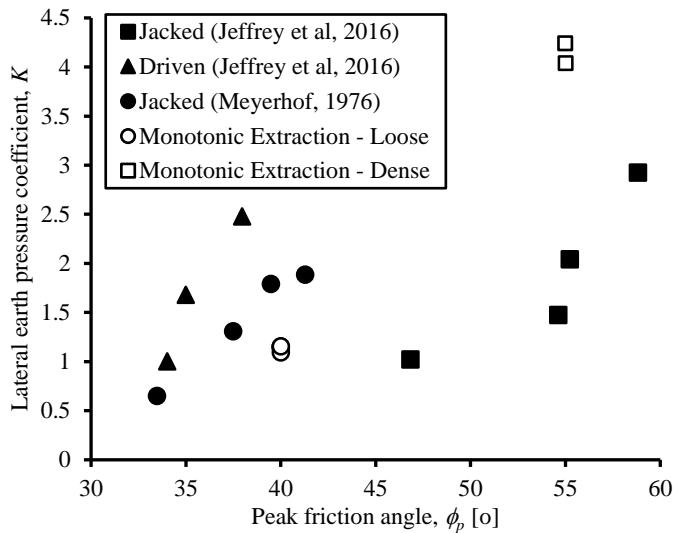
Figure { SEQ Figure * ARABIC }. Earth pressure coefficient (K) relationship with the peak friction angle.
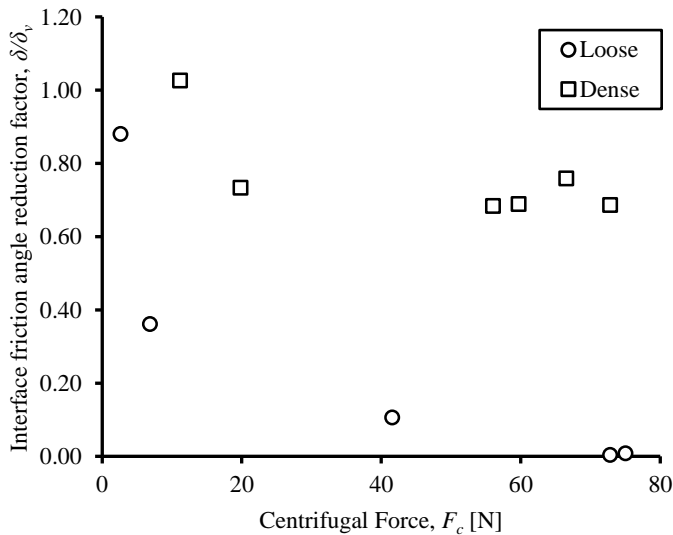

Figure { SEQ Figure * ARABIC }. Relationship between the back-calculated interface friction angles for vibro-extraction tests in loose and dense sands (normalised by the measured interface friction angle with no applied vibration) and the applied centrifugal force.

CONCLUSIONS

The application of high frequency, low amplitude vibration to a 60mm diameter, 400mm long model pile embedded in dry sand was observed to substantially reduce the peak pull-out force. At sufficient levels of vibration (over 70N dynamic force), the tensile capacity of the pile was effectively reduced to zero, leaving only the self-weight of the pile and attached equipment. Under the same vibratory influence, the peak tensile capacity of the pile installed in dense sand was reduced by 31%. These significant reductions in extraction load were observed even in the absence of any positive excess pore water pressures that might be generated in a field case due to the effects of the vibrations.

Through examination of historic and recent research into the effects of vibration on granular media and the back calculation of the lateral earth pressure coefficient and interface friction angle, from test results of this investigation, it was demonstrated that vibration apparently reduces the interface friction angle by an amount which depends on the density of the sand and magnitude of vibration. The reduction was greatest in loose sand, with the apparent interface friction angle decreasing from 27 to <0.5°.

The reduction in peak pile capacity is accompanied by an overall reduction in the mechanical energy required to extract the pile in terms of work done. The drop in energy requirements was significant in both loose and dense sand and it is considered a key metric in the evaluation of the vibro-extraction method from a contractor's perspective. A 72% reduction of the mechanical energy required to extract the pile from dense sand was found to be possible.

Similar to the beneficial results reported by { ADDIN EN.CITE <EndNote><Cite AuthorYear="1"><Author>Zefirova</Author><Year>2012</Year><RecNum>186</RecNum><DisplayText>Zefirova et al. (2012)</DisplayText><record><rec-number>186</rec-number><foreign-keys><key app="EN" db-id="rvws2xtpm90za9ewaxbp2a2vzd5wepaaw9tx" timestamp="1455571686">186</key><key app="ENWeb" db-id="">0</key></foreign-keys><ref-type name="Conference Paper">47</ref-type><contributors><authors><author>Zefirova, A</author><author>Brown, MJ</author><author>Brennan, AJ</author><author>Boyes, S</author></authors></contributors><titles><title>Improving The Performance Of Offshore Pipeline Ploughs Using Vibration</title><secondary-title>7th International Conference on Offshore Site Investigation and Geotechnics: Integrated Technologies - Present and Future</secondary-title></titles><dates><year>2012</year><pub-dates><date>12–14 September 2012</date></pub-dates></dates><pub-location>Royal Geographical Society, London</pub-location><publisher>Society of Underwater Technology</publisher><urls></urls></record></Cite></EndNote>} for vibration-assisted pipeline ploughing, from the results of this investigation it is suggested that there is significant potential in the application of vibration to aid in the efficient decommissioning of offshore piles. Substantially reduced pull-out loads can be achieved, even in the absence of potential positive excess pore water pressures, which may allow for the extraction of piles previously considered too difficult or expensive to remove.

REFRENCES
{ ADDIN EN.REFLIST }