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Centrifuge modelling of remediation of liquefaction-induced pipeline uplift using model root systems

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ABSTRACT: Buried pipelines are susceptible to floatation within liquefiable soil after earthquakes. When soil liquefies, its shear strength is significantly reduced due to generation of excess pore pressure. A buried pipeline within such soil can then uplift due to a combination of (i) an upwards pore pressure gradient across the pipe and (ii) the resisting force contributed from soil shear strength being significantly reduced. Roots have been confirmed to increase the shear resistance of soil, so they can potentially be used as a new countermeasure against pipeline uplift, in locations where there is no above-ground infrastructure (i.e. where uplift is most likely). Three centrifuge tests have been conducted in this study to evaluate this potential. One was performed as a benchmark and the other two included one of two overlying model shallow root systems (either fibrous roots only, or fibrous and large structural roots) respectively. The results show that roots can be used as a remediation method against pipeline uplift induced by soil liquefaction. Model fibrous roots were shown to reduce uplift displacements by 15% while the model system consisting of both large structural and fibrous roots further reduced uplift to approximately 28%.

1 INTRODUCTION

Pipelines can suffer severe damage from strong earthquakes. One of the possible damage patterns is pipeline uplift within the liquefiable soil. In the field, this phenomenon has been observed in numerous earthquakes including: 1989 earthquake of Loma Prieta (O'Rourke et al., 1991), 1995 earthquake of Kobe (Shinozuka, 1999), 2004 earthquake of Chuetsu (Yasuda & Kiku, 2006), and recent 2011 earthquake of Tohoku (Chian & Tokimatsu, 2012).

One of the possible remediation methods, in locations without overlying infrastructure (e.g. roads or buildings) is to increase the strength of overlying soil above the pipeline. The reinforcing effect of roots on soil has been recognized by its ability to increase slope stability (Gray & Leiser, 1982, Coppin & Richards, 1990, Gray & Sotir, 1996) and many studies have been conducted for quantifying the contribution of roots (Wu, 2013), including using geotechnical centrifuge modelling with real live plants (Sonnenberg et al., 2010) and 3D printed analogue root models (Liang et al., 2016). To the best of the authors' knowledge, there has been no previous study about effects of roots on remediation of soil liquefaction. Nevertheless, research on fibre reinforcement, which has been used to simulate root reinforcement in laboratory tests, could assist our understanding of how this might work. Fibres were first found to increase soil liquefaction resistance by Noorany & Uzdavines (1989) using cyclic triaxial tests and this result has been verified by other researchers through similar element tests (Krishnaswamy & Isaac, 1994, Boominathan & Hari, 2002, Noorzad & Fardad Amini, 2014, Manafi Khajeh Pasha et al., 2016). Based on the geotechnical centrifuge modelling conducted by Wang & Brennan (2014, 2015), fibres can increase soil stiffness and limit significant deformation caused by soil liquefaction.

As a pioneering study, three centrifuge tests were conducted to investigate the potential of shallow root systems to remediate the pipeline uplift caused by soil liquefaction. A benchmark test was performed first to demonstrate the uplift of the pipeline within liquefiable soil during and after a sequence of ground motions. Synthetic fibres were then introduced into the overlying soil above the pipeline in the subsequent test to mimic the mechanic effects of a purely fibrous root system on limiting the uplift of the pipeline. Three-dimensional models of larger structural roots were placed together with fibres in the final test to investigate an alternative shrub-type root system on reducing the uplift of the pipeline.

2 CENTRIFUGE MODELLING

2.1 *Apparatus and instruments*

All tests were performed using the Actidyn C67-2 geotechnical centrifuge at the University of Dundee on 1:30 scale models at 30-g. Input ground motions were simulated using the Actidyn Q67-2 earthquake simulator mounted on the centrifuge. More details about the centrifuge and the earthquake simulator can be found in Bertalot (2013) and Brennan et al. (2014). Models were prepared in an equivalent shear beam (ESB) container with internal dimensions of 674 × 312 × 280 mm, which was described by Bertalot (2013) in detail. Accelerometers (ACCs), pore pressure transducers (PPTs), linear variable transducers (LVDTs) and draw wire transducers (DWs) were used for relevant measurements.

2.2 *Model materials*

The sand used in the models was HST 95 Congleton sand. It is a uniform fine silica sand with a mean particle size D_{50} = 0.13 mm, an effective size D_{10} = 0.1 mm, a coefficient of uniformity C_u = 2.25, a coefficient of curvature C_c = 1.36 and a specific gravity G_s=2.63. The maximum and minimum void ratios are e_{max} = 0.795 and e_{min} = 0.463 respectively. The fine fibrous roots were modelled by synthetic fibres with the commercial name Loksand^{TM} (Figure 1). Their nominal length and diameter are 35 mm and 0.1 mm respectively. The specific gravity of this synthetic material is 0.91 and the tensile strength is 200 MPa. All property data for Loksand^{TM} was provided by the manufacturer.

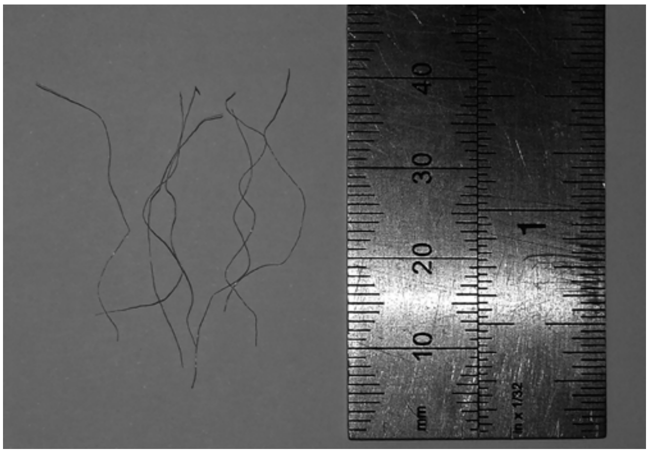

Figure 1 Loksand^{TM} fibres

The pipe model was made from a hollow Polyvinyl Chloride (PVC) plastic tube with closed ends on both sides. The length of the pipe model was 255 mm, the outer diameter was 40 mm and the mass was 231.95 g.

The *uPrint SE* Acrylonitrile Butadiene Styrene (ABS) prototyper (known as a 3D printer) at the University of Dundee was used to construct the scaled model of the large structural roots with representative complex architecture. The tensile strength of the ABS is around 17MPa. More details about the ABS can be found in the work of Liang et al. (2014).

The procedures of 3D printing root models were as described by Liang et al. (2014).

The prototype of the root architecture used was from the coarse roots of *Arctostaphylos pungens* (a chaparral shrub) for which detailed root architecture was available from Wu et al. (2014). When scaling the prototype down by 1:30 for centrifuge modelling according to the scaling law, diameters of the model are comparable to those of the Loksand^{TM}. The model 3D printed models hence would lose their functionality as larger structural roots in the centrifuge tests. The prototype was therefore reasonably modified by increasing diameter six times while maintaining length as the original. The architecture adopted, reconstructed by AutoCAD, is shown in Figure 2 and the 3D printed model is shown in Figure 3.The maximum depth of model of the large structure roots was 20mm.

Methylcellulose solution with 30 times viscosity of water was used as the pore fluid instead of water. This is to resolve the disparity between the scaling laws for the time of diffusion processes and a dynamic event (Madabhushi, 2014).

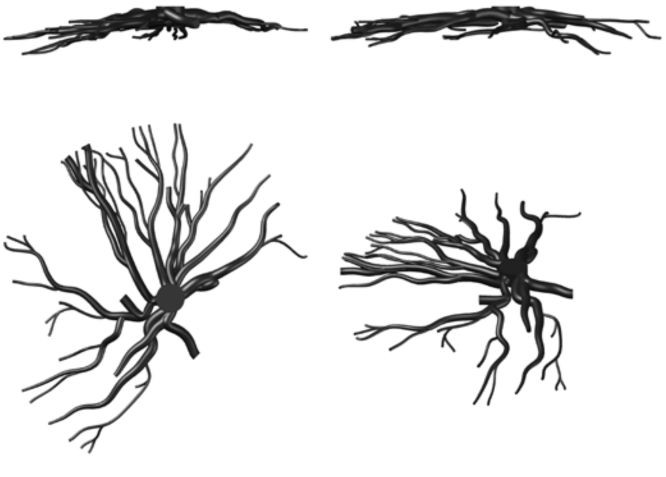

Figure 2 Modified design of architecture of large structural roots

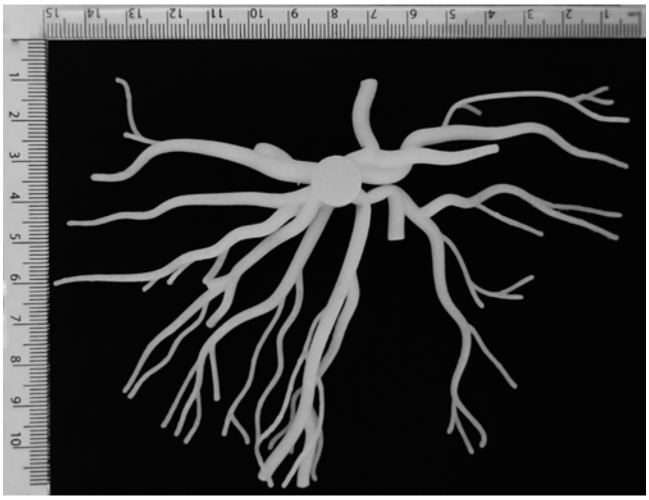

Figure 3 ABS model of large structural roots from 3D printer

2.3 *Model preparation*

There are three centrifuge models presented in this study. Their schematic profiles are shown in Figure 4 and Figure 5. The first model (PU1) represents the bench mark condition in which there was no remediation method applied to limit the uplift of pipe induced by soil liquefaction (Figure 4). The second and third models (PU2 and PU3) represent the conditions in which fibrous roots and fibrous with large structural roots were applied in the 40 mm (1.2 m in prototype) soil layer above the pipeline (Figure 5). In each case the normalized cover-depth of the pipe was one diameter (1.2 m). Units used in this subsection are at model scale while those in other sections are at prototype scale (unless otherwise stated).

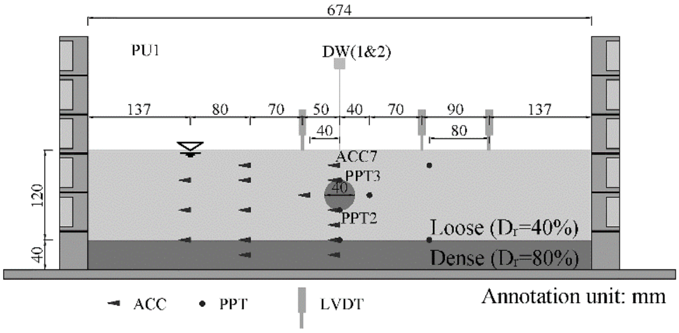

Figure 4 Centrifuge model and instrument distribution of PU1

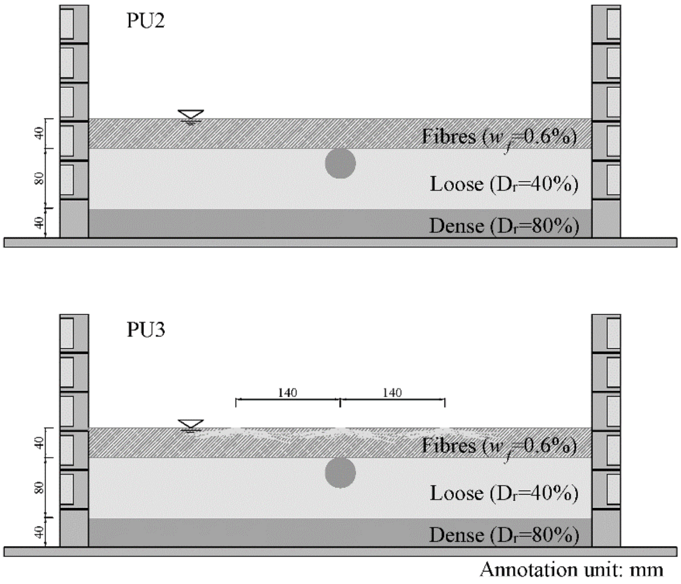

Figure 5 Schematic profiles of PU2 and PU3

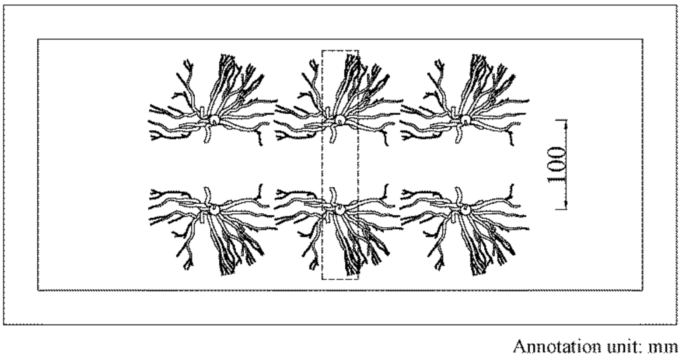

Figure 6 Plan distribution of models coarse roots in PU3

Layered sand models with relative densities (D_r) of 40% overlying a lower layer of 80% were prepared by dry pluvation using a spot pluviator and slot pluviator respectively. The reinforced layers with fibrous roots in model PU2 and combined root system in model PU3 were also prepared by dry pluviation using the slot pluviator. Fibre content (w_f) was 0.6% by mass relative to that of sand in the corresponding layer. The equivalent fibre content in volume is 1%, which is within the range of root content in volume found in the field (Bengough, 2012) Further details about the dry pluviation method used in this study can be found in the work of Wang & Brennan (2014). ACCs, PPTs and the pipe model and the coarse roots model were placed at the pre-determined locations during the dry pluviation, and LVDTs and DWs were installed after completion of dry pluvaition. Instrument distribution was identical in all models – this is shown using model PU1 as an example in Figure 4. The plan distribution of large structural root models and pipeline model is shown in Figure 6. The roots were placed in this way to ensure symmetrical behaviour at either end of the pipe, so as to avoid twisting out of plane and jamming the pipe between the walls. Securing supports were then placed to avoid the accidental movement of pipe model before centrifuge testing. After completion of these procedures, models were saturated with viscous methylcellulose solution.

2.4 *Test programme*

After completing the preparation, the model was loaded onto the earthquake simulator. The centrifuge was then spun up at intervals of 10-g until reaching the desired g-level (30-g in this study). A succession of three input motions (EQ1, EQ2 and EQ3) were then simulated. There was an adequate time interval between each motion to allow the completion of excess pore pressure dissipation within the model. This was confirmed by observations of the PPTs. The three input ground motions were ramped sinusoidal motions having the same properties (frequency content and duration) except for the maximum amplitude of acceleration (Figure 7). The time histories of the input motions can be described by the following equations and parameters of three input motions are summarised in Table 1.

$$A(t) = \begin{cases} \dfrac{t}{nT} A_0 \sin(\omega t) & 0 \le t < nT \\ A_0 \sin(\omega t) & nT \le t < (N-n)T \\ \dfrac{NT-t}{nT} A_0 \sin(\omega t) & (N-n)T \le t \le NT \end{cases} \qquad (1a)$$

$$\omega = \frac{2\pi}{T} \qquad (2b)$$

where A = amplitude of acceleration; A_0 = maximum amplitude; t = time; T = period of motion; n = number of ramped motion cycles; and N = total number of motion cycles.

Table 1 Properties of input motions (prototype scale)

Input motion ID	A_0 (g)	T (s)	N	n
EQ1	0.045			
EQ2	0.100	0.5	28	9
EQ3	0.210			

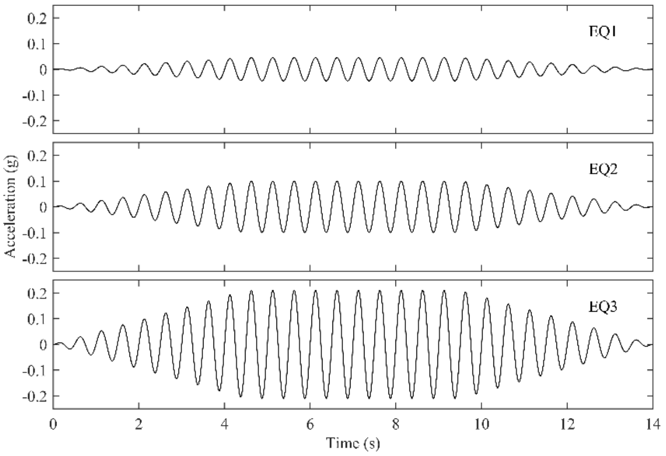

Figure 7 Time histories of input ground motions

3 TEST RESULTS

3.1 *Uplift response of pipeline*

Based on the time histories of pipeline uplifts shown in Figure 8 (derived from the average of direct measurements of DW1 and DW2), the uplift predominantly occurred co-seismically. Ultimate accumulative uplift displacements increase with the intensity of the ground motions. Around 70% of the total accumulative uplift was attributed to that in the final ground motion event regardless of the reinforcement condition. Uplift displacements were effectively reduced by introducing root systems in model PU2 and model PU3. The relative uplift displacements, which are the measured uplift displacements of pipeline relative to the settled ground surface, in each ground motion event are shown in Figure 9. The total relative 525mm pipeline uplift in model PU1 was limited to 443mm in model PU2 and 380mm in model PU3 (around 15% and 28% of pipeline uplift were inhibited by the two root systems, respectively). Thus, the large structural roots contributed around 13% to limiting pipeline uplift when acting with the fibrous roots. More specifically, 33% and 52% of relative pipeline uplift displacements were reduced in EQ1, 16% and 29% in EQ2, and 14% and 25% in EQ3 in model PU2 and model PU3 respectively. Reduction of the relative pipeline uplift attributed to root systems increases with the pipeline uplift potential (ground motion intensity) when considering value rather than the percentage. In EQ1 event, the relative pipeline uplift in model PU1 was 27mm, and 9mm and 14mm of uplift displacements were reduced in model PU2 and model PU3 respectively. In EQ3 event, such reduction increased to 51mm and 91mm in model PU2 and model PU3 while the relative uplift displacement in model PU1 was 362mm.

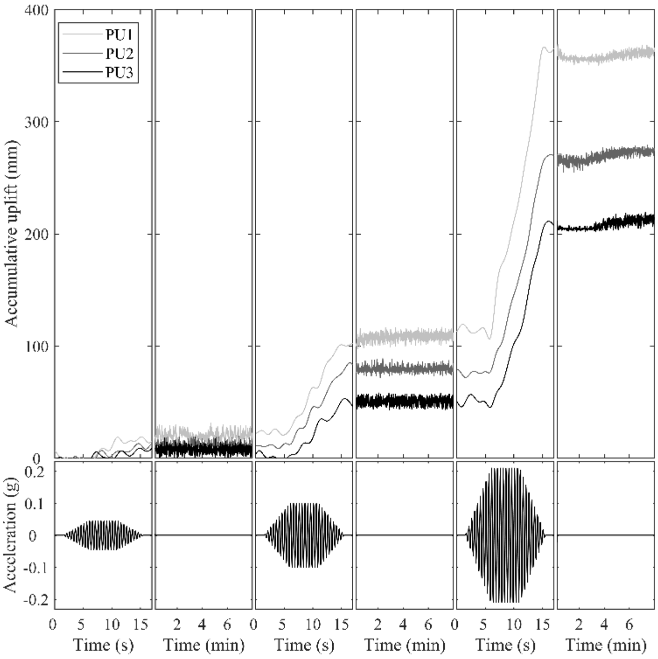

Figure 8 Time histories of accumulative uplift of pipeline

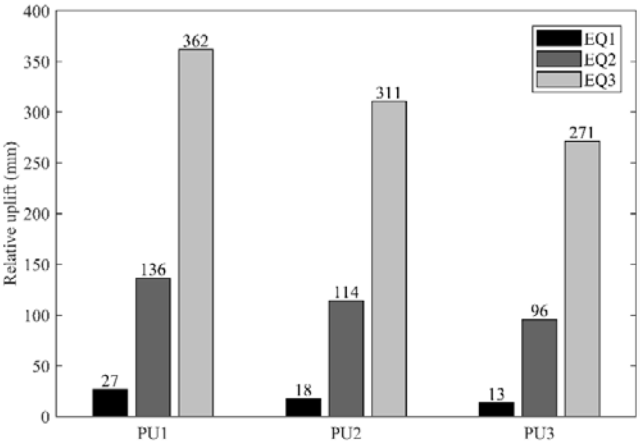

Figure 9 Relative uplift of pipeline to the ground

3.2 *Dynamic response of soil above pipeline*

Displacements in the EQ3 event played a dominant role in all models and due to limitations of paper length, results only in the EQ3 event are shown in this and the following subsections.

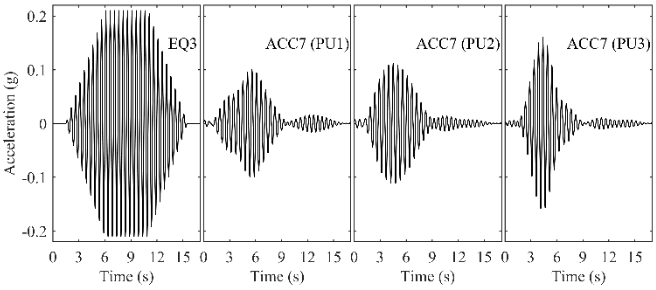

Figure 10 Acceleration responses of cover soil in EQ3 event

As shown in Figure 10, the accelerations recorded by ACC7 within the cover soil above the pipeline were significantly de-amplified compared with the original EQ3 input motion. The peak acceleration was reduced to around 0.1g in model PU1 and model PU2, and to around 0.15g in model PU3. It indicates soil softening caused by liquefaction, even though the soil was reinforced with root systems. The overlying soil in model PU3 was less softened than those in the other tests. It is also suggested that soil in model PU2 was less softened than that of model PU1. The dynamic responses of overlying soil in the three tests support the conclusion that the root systems increase the shear strength of soil, which is beneficial to limit the uplift of the pipeline.

3.3 *Excess pore pressure generation under pipeline*

The time histories of excess pore pressure difference between the measurement of PPT3 (at the invert of the pipeline and that of PPT2 (at the crown of the pipeline) in the EQ3 event are shown in Figure 11. The differences indicate the uplift force due to excess pore pressure in each model. The excess pore pressure differences in model PU2 and model PU3 were larger than that in PU1. This is mainly caused because pipeline uplift was effectively reduced by introducing root systems in overlying soil above the pipeline. When a pipeline uplifts, a cavity is formed beneath it (Stone & Newson, 2006). The formation of the cavity induces a negative change in pore pressure and therefore reduces the excess pore pressure generated by the cyclic loading. The excess pore pressure at the crown of the pipeline, however, remains much less affected. Therefore, the more the pipeline uplifts, the less excess pore pressure induced uplift force will generate. Model root systems did not reduce excess pore pressure induced uplift force.

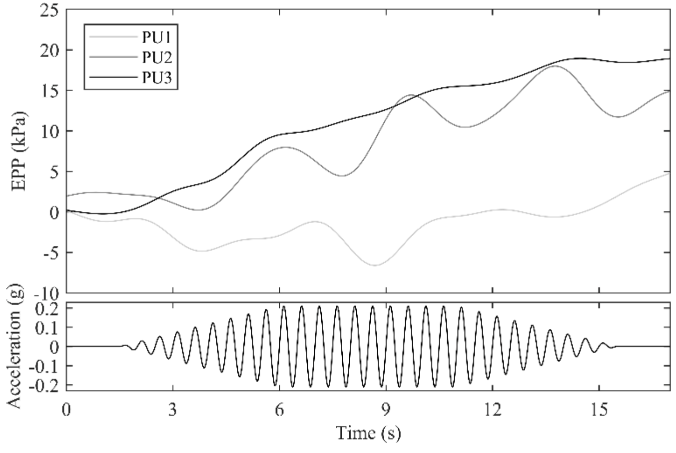

Figure 11 Excess pore pressure difference between PPT2 and PPT3in EQ3 event

4 DISCUSSION

Pipeline uplift in liquefied soil is due to the buoyant force being greater than the resistance against it. This resistance consists of the weight of pipeline, the weight of overlying soil and the shear resistance of soil (Chian & Madabhushi, 2013). In this study, the pipeline model was identical and the weight of overlying soil was not significantly increased by introducing the root systems. The excess pore pressure induced uplift force was also not reduced by introducing root systems. Therefore, improving overlying soil shear strength should be the main contribution to limiting pipeline uplift. The overlying soil was less softened when reinforced with root systems based on their dynamic response. More soil resistance is mobilized the more the pipeline attempts to uplift. This is because the roots only become effective in mobilising soil strength when larger monotonic strains are induced. This interpretation is based on previous research on fibre-reinforced sand suggesting that a certain threshold strain level is required to mobilise the interlocking of soil and fibres to increase the shear strength of soil (Li & Zornberg, 2013, Wang & Brennan, 2015).

5 CONCLUSIONS

This study described centrifuge modelling investigating the use of root systems to remediate soil liquefaction induced uplift of buried pipelines. Introducing root systems in the overlying (cover) soil above the pipeline can reduce the pipeline uplift at various intensity levels of input motions. The fibrous root system reduced uplift by 15% of the total relative uplift after the three ground motion events, and the reduction increased to 28% when the root system also contained larger structural roots. Model root systems did not reduce the uplift force induced by excess pore pressure. The improvements appeared to be provided through the increased shear strength of the cover soil.

Root systems are probably beneficial in reducing pipeline uplift induced by soil liquefaction. The model root system including fibrous with large structure roots appears to be more effective than only includes fibrous roots.

Applying root systems to cover soil above the pipeline is a promising low-cost method for limiting pipeline uplift induced by soil liquefaction in an urban area.

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