Buoyancy of Buried Pipes in Liquefiable Soil under Rooting

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ABSTRACT

A total of sixteen shaking tests were conducted to determine the effectiveness of polypropylene fibre reinforcement in hindering the vertical displacement of a buoyant object in liquefied sand. By comparing the measured ascension velocity of the buoyant object in different tests the sample yielding the most desirable results was identified. While completely restraining the buoyant object proved impossible, ascension velocities of up to eighteen times lower were recorded in reinforced sand layers compared to that in average clean sand. Analysis of test results shows that, when initially coming into contact with the fibre-reinforced sand layer, the buoyant object’s ascension velocity is only mildly affected, but begins to decrease significantly after the layer has been penetrated to a certain degree. It has been found that this is due to the fact that a driving shear force is needed to activate the strain-hardening response of the fibre reinforced sand layer. Fibre reinforcement may thus become a mitigation method to minimize liquefaction-caused damage to infrastructural lifeline networks.

Keywords  Liquefaction, Buoyant Pipes, Fibre Reinforcement, Shaking Experiment
CONTENTS

1 INTRODUCTION ........................................................................................................................................... 1

2 LITERATURE REVIEW ................................................................................................................................. 6
   2.1 Liquefaction ........................................................................................................................................ 6
   2.2 Effects of Liquefaction ......................................................................................................................... 6
   2.3 The Matter of Surfacing Pipes ........................................................................................................... 8
   2.4 Fibre reinforcement ............................................................................................................................ 11

3 TEST SETUP AND METHODOLOGY ........................................................................................................... 14
   3.1 Test Sample Elements ....................................................................................................................... 14
   3.2 Testing Procedure ............................................................................................................................. 17
   3.3 Test Arrangements ............................................................................................................................ 19
   3.4 Information Recorded ....................................................................................................................... 21

4 RESULT ANALYSIS AND DISCUSSION ..................................................................................................... 30
   4.1 Relevant Observations Regarding Tests ............................................................................................ 30
      4.1.1 Displacement of Fibres within the Sand Matrix ........................................................................ 30
      4.1.2 Thickness of Reinforced Layer .................................................................................................. 32
      4.1.3 Fibre Distribution in the Test Samples ....................................................................................... 33
      4.1.4 Varying Ascension Velocity Segments ..................................................................................... 34
   4.2 Effects of Fibre Content .................................................................................................................... 36
      4.2.1 Fibre Content Comparison ......................................................................................................... 36
      4.2.2 Arrangement Comparison .......................................................................................................... 38
   4.3 Further Research ................................................................................................................................ 40

CONCLUSION ............................................................................................................................................... 42

REFERENCES ............................................................................................................................................... 43
1 INTRODUCTION

According to the theory of plate tectonics the crust of the earth is formed of thicker continental and thinner oceanic plates that float on its mantle. It is the movement and interaction of the plates, whether it be divergent (away from each other), convergent (towards each other) or transform (parallel to each other), that cause sudden releases of energy which are believed to be the source of earthquakes on the surface (Brennan, 2015).

Figure 1 Movement of tectonic plates (Maggie’s science connection)

The occurrence of earthquakes has been mapped determining what are generally believed to be the boundaries of the greater tectonic plates which can be seen in Figure 2 below.

Figure 2 Tectonic plates (7 Continents of the World)

Earthquakes of higher magnitude can cause great devastation by horizontally shaking the ground. Results of shaking range from slope, bridge and building foundation failure to cracks in roads and lateral buckling of rail tracks. Because of their destructive power, earthquakes must be studied and understood, so that necessary precautions can be taken when designing structures where they are expected to occur.
One phenomenon, that is usually caused by earthquakes, but can be caused by other actions on the soil such as driven piles, explosions or drilling, that often contributes to the damage done is liquefaction. Generally associated with soils composed primarily of sand that may on occasions contain silt, liquefaction is a term originally coined by Mogami and Kubo in 1953 as reported by Kramer (1996).

Soils are a multi-phase material containing solids, liquids usually in the form of water, and gasses. Especially if the soil is cohesionless, loose and saturated with water, when shaken the particles rearrange themselves into a denser structure forcing some of the water out of the voids. This results in an immediate increase of pore pressure, due to the fact that water is incompressible, causing effective stress to decrease and momentarily reducing the strength of the soil drastically. As can be seen in Figure 3 it is the short period of time portrayed by the middle image, in which the particles lose contact with each other, the soil liquefies and allows objects to move inside the matrix almost unrestrained. Cyclic loading, such as periodical horizontal actions from an earthquake, enable this phenomenon to occur several times. This can cause damage to the infrastructure by allowing heavier objects such as concrete foundations to sink into, and lighter objects like pipes to escape from, the soil.

Figure 3 Sand liquefaction (Brennan 2007)

Not all soils are in danger of liquefying. Liquefaction susceptibility is governed by three properties the soil must have. First, there needs to be a sufficient amount of water present for the soil to be saturated. Second, the soil must be loose enough for it to be compressible, if the soil particles aren’t rearranged in a denser matrix, pore pressure will not increase and effective stress will not be reduced. Finally, the soil in question must have a low enough permeability so that water cannot simply dissipate or drain away. If any of the listed characteristics is not met, it is unlikely for liquefaction to occur. Soils made up of loose sand, occasionally silty sand, have been known to liquefy, a diagram specifying a range of such soils composed of certain particle sizes can be seen in Figure 4.
Some of the most notable earthquakes where liquefaction was also present were the “Good Friday” earthquake in Alaska, and Niigata earthquakes in 1964, the Kobe earthquake in 1995, and the Christchurch and Tohoku earthquakes in 2011. Images of their effects can be seen in Figures 5-8 below.
Among the several types of damage that can be caused by earthquakes that induce liquefaction in soils is the surfacing of buoyant pipes that carry gas or water below pavements or roads. Due to the liquefied soil losing strength and its ability to confine them the pipes which are lighter than the soil are pushed upwards by the surrounding pressure. Due to the displacement the integrity of the pipes may be compromised leading to leakage or the surface above them can be damaged as can be seen below in figures 9-12.

This work explores the effectiveness of fibre reinforcement as a possible solution that could prevent damage being sustained by such pipes in the event of liquefaction. By conducting simple shaking experiments on a miniature buried pipe model composed of medium density saturated fibre-reinforced sand and a small buoyant cylinder, it is the goal of this paper to find the optimal arrangement and sand-reinforcement ratio to restrain the buoyant object.

![Figure 9: Pipes damaged during 2011 Christchurch earthquake (Giovinazzi et al 2011)](image1)

![Figure 10: Pipes damaged due to liquefaction in Christchurch 2011 (Garland, 2015)](image2)

![Figure 11: Uplifted pipeline (Pierepiekarz 2011 as reported by Taeseri 2015)](image3)

![Figure 12: Pipe displacement attributed to liquefaction Tohoku 2011 (Yossy Yossy 2011)](image4)
Fibre reinforcement is commercially used to increase the durability and ensure the integrity of the surface layers of sports turfs and sand banks, however testing has been carried out to determine whether it can be used to solve geotechnical problems. Research shows that the addition of fibres to medium density sands makes them less prone to liquefaction and increases their shear strength (Ibraim et al, 2010; Diambra et al, 2010; Jin Liu et al among others). Knowing this, observing the effects fibre reinforcement might have on a buoyant object draws interest as it might lead to innovative geotechnical solutions in earthquake caused damage control.

The best possible outcome would be the complete restriction of the buoyant object with no displacement during shaking. In case this proves to be impossible, as liquefaction cannot be completely prevented, rather only liquefaction susceptibility reduced (Noorzad & Amini, 2014) the effect of the reinforcement will be commented on and samples containing reinforced soil will be compared to samples made up of clean soil.

A second goal of this paper is to determine the likelihood of fibres being a viable solution to civil engineering problems. Based on the outcome of the conducted tests, observations will be made and speculation will be done on whether natural plant roots could replace the polypropylene fibres used in the test setup. By presenting the results of these simple tests, this work is intended to encourage or discourage further, more precise testing that could determine the reliability and cost effectiveness of fibre reinforcement in the question of protecting pipes from earthquake-caused damage.

To summarise, natural disasters occur on our planet claiming lives and causing damage amounting to huge sums of money, earthquakes are one of the most prominent. Among others it is the duty of engineers to attempt to combat this issue. Geotechnical engineers are the engineers that deal with the problem of earthquakes most extensively. A phenomenon named “Liquefaction” was observed during two great earthquakes in 1964 that partly motivated extensive studies to be conducted on the subject (Kramer, 1996). Many types of damage sustained by infrastructure have been attributed to liquefaction, among which is the subset of damage sustained by pipes. Pipes can be damaged in several ways, which will be discussed in more detail in further chapters. One of the types of damage sustained is caused by the pipes surfacing in the soil due to their buoyancy. There are several ways to design against this issue. This paper aims to determine whether reinforcing the soil above the pipes with polypropylene fibres can be listed among the viable solutions.
2 LITERATURE REVIEW

2.1 Liquefaction

“When cohesionless soils are saturated, rapid loading occurs under undrained conditions, so the tendency for densification causes excess pore pressure to increase and effective stress to decrease.” (Kramer, 1996)

Several types of liquefaction phenomena have been identified that differ mostly in the way they are triggered.

“In one respect static and cyclic liquefaction are cause by the same thing - there is a plastic volumetric strain that arises sufficiently quickly that the pore fluid cannot escape as fast as the plastic strain accumulates. Excess pore pressure results from the impended drainage, reducing the mean effective stress and with corresponding reductions is shear stress and strength. The difference between static and cyclic liquefaction is the way plastic volumetric strains are generated. [...] In the case of cyclic induced liquefaction, the plastic volumetric strains arise through densification bought on by the cyclic stress changes which tend to pack the soil particles closer together. Cyclic induced densification affects soil, including dense sands and overconsolidated clays – it is only a question of to what extent.” (Jeffries & Been, 2006)

Static liquefaction is more common and by far the more damaging. Static liquefaction can be further categorised into two subsets depending on their modes of triggering. In the case of monotonic shear the stress ratio governs. If it increases either due to an increase in deviatory stress or decrease in mean effective stress static liquefaction can be triggered, provided the soil is loose enough. The other triggering method is in a post-earthquake scenario. There can be cyclically induced excess pore pressure originating from the earthquake. This may be enough to cause soil failure under any imposed loading that the soil might be subjected to. Such was the case with the Lower San Fernando dam in 1971. (Jeffries & Been, 2006)

2.2 Effects of Liquefaction

Settlement of foundations

Possibly the most visually terrifying effect of liquefaction is when the soil the foundation of a building is resting on loses its strength and stiffness. The soil is thus deformed and allows foundations to sink, however not always in a uniform fashion. At times it happens that not all the soil liquefies under a building but only a patch of it, thus only part of the building will sink causing it to tilt instead, as can be seen in Figure 13.
Bridges are another structure that can be affected by this since the foundations carrying it will be permanently submerged and therefore saturated. Several bridges have been observed to fail in this way due to earthquakes, some of the more notable ones being in Niigata 1964 and Taiwan 1999.

**Buoyancy of buried structures**

Similar to pipes, other buried objects that are hollow and therefore lighter than the soil they are submerged in can be forced to the surface due to liquefaction. Manholes and even swimming pools have been damaged in this way.

**Figure 13:** Foundation failure due to liquefaction

**Figure 14:** Bridge pier foundation due to liquefaction

**Figure 15:** Damage in Brooklands from the 2010 Canterbury earthquake, where buoyancy caused by soil liquefaction pushed up an underground service including this manhole (CES CIVIL ENGG. Seminar, 2015)

**Figure 16:** Buoyant manhole (Matsumiya, 2010)
**Boiling**

Occurring with stratified soils, boiling may be an issue when coming to affect under paved roads or streets. The surfacing water and soil can potentially block circulation and affect traffic. Fortunately, lives are unlikely to be threatened by this effect of liquefaction.

![Figure 17: Sand boiling cause by liquefaction (heaven awaits, After Sims and Garvin 1999)](image)

2.3 **The Matter of Surfacing Pipes**

Measures can be taken in order to protect lifeline networks in the event of earthquake induced liquefaction. Most include either reducing the liquefaction susceptibility of the soil surrounding the buoyant objects or using heavier objects to counteract the buoyant forces. Some examples are: compacting the soil, mixing cement in with the soil or continuous structural measures (Taeseri et al, 2015). Although these measures are being applied in some cases, they are believed to be too expensive and time consuming to be used in all instances.

Saddle bags made out of geotextiles such as the ones commercialized by Allan Edwards Inc. (ECOBAG- Geotextile Pipeline Weight) could also serve this purpose as they are used to combat buoyancy. However, it is unclear how the saddle bags would behave in the event of an earthquake.
“After the Great East Japan Earthquake in March 11, 2011, the Japanese government started to show interest in effective and inexpensive mitigation methods that could prevent damage to existing lifelines in the future. A mitigation method called the “Horn Type Structure (HTS)” (Figure 21) was subsequently developed at the University of Tokyo (Otsubo 2012 as reported by Taeseri et al, 2015). […] Small scale experiments were conducted at the University of Tokyo and centrifuge tests were conducted at ETH-Zurich, aiming to understand the mechanism better and to develop a calculation method.” (Taeseri et al, 2015)

The HTS mitigation method is said to be different and more cost effective due to the fact that it is only installed “at strategic points along the pipeline network” (Taeseri et al, 2015). The HTS does not prevent the soil from liquefying, rather it is “a system that increases the uplift resistance of the pipeline” (Taeseri et al, 2015). Uplift resistance is ensured by equipping the pipe with a horn shaped steel object with a plate at the top that is in
contact with non-liquefiable soil. The resistance force of the HTS was directly correlated with a given plate size $B \text{[m]}$, a depth of embedment $H \text{[m]}$ and the density $\rho \text{[kg/m}^3\text{]}$ of the non-liquefiable layer. (Taeseri et al, 2015)

Although the HTS mitigation method truly appears to be an overall good solution to the problem of buoyant lifeline networks an observation must be made regarding its effectiveness. Due to the fact that the horn structure is made out of steel, though installation costs will be lowered, manufacturing prices will be relatively high. While this could be countered with the argument that the HTS will only be installed in strategic points along the pipeline network, it is difficult to assess how many will be needed per unit length of lifeline. If this number were too small, the pipes might be in danger of bending due to the HTS, because during an earthquake the uplift force will be a uniform pressure counteracted by point supports (Figure 22). If this is to be avoided, more HTS’s will be needed and this will raise the price.

![Figure 22: Possible bending failure mode of HTS](image)

While steel pipes might be strong enough to resist bending moments even in the case of long spans, PVC and concrete pipes will not. A factor that will further add to the price is the fact that two soil types are needed for the HTS to be effective, complicating logistical matters with the need to supply the non-liquefiable soil.

Thus a different mitigation method is proposed that can be used on most types of liquefiable soil, will avoid the problem of pipe bending and that could likely be even less expensive.
2.4 Fibre reinforcement

“It is well known that the roots of surface vegetation contribute to the stability of slopes by adding strength to the near-surface soils in which the effective stress is low.” (Ibraim et al, 2010). The same can be applied to deeper soil layers by using polypropylene fibres as reinforcement. Research has shown that adding fibres to liquefiable soil can significantly improve several qualities needed for civil engineering and infrastructural purposes such as liquefaction susceptibility, lateral spreading, and strength.

**Liquefaction susceptibility:**

By conducting triaxial tests on fibre reinforced sand researchers have found that “the reinforcement inclusions reduce the potential for the occurrence of liquefaction in both compression and extension triaxial loadings and convert a strain softening response (typical for a loose unreinforced sand) into a strain hardening response.” (Ibraim et al, 2010)

The same team from the University of Bristol, United Kingdom state in a different publication that “Mixing a loose clean sand with random discrete flexible fibres has been found beneficial in decreasing the susceptibility to the phenomenon of liquefaction under monotonic loading. The addition of fibres can convert the strain softening response, typical of a loose unreinforced sand, into a strain hardening response by affecting the pore pressure generation and the effective stress path response.” (Diambra et al 2011).

Stress-controlled cyclic triaxial tests conducted at Babol University of Technology, Iran have shown that “fiber inclusions significantly increased liquefaction resistance of sand specimens.” (Noorzad & Amini, 2014)

**Lateral spreading:**

Results from triaxial testing have revealed further beneficial properties of fibre-reinforced sand, it has been claimed that “one of the consequences of liquefaction is the lateral spreading of the soil, it seems that the presence of fibres can limit or even prevent the occurrence of this phenomenon.” (Ibraim et al, 2010)
Undrained ring shear test have been carried out “in order to understand the effect of the fiber content and sand density on the static liquefaction behavior of fiber-reinforced sand.” (Liu et al. 2011) It has been found that “The presence of fibers may limit or even prevent the occurrence of lateral spreading that is often observed in unreinforced sand.” (Liu et al. 2011)

Centrifuge tests have been conducted at the University of Dundee to test the effect of fibre reinforcement on backfill behind a caisson type quay wall in the event of liquefaction. “The presence of fibres in backfill effectively reduced lateral displacement of quay wall and backfill settlement. Quay wall outward displacement induced an excess pore pressure drop in the clean sand backfill adjacent to the back of quay wall, while this phenomenon did not occur in fibre-reinforced backfill. Increase of shear strength and self-supporting behaviour at large shear strain may be the beneficial effects of fibre-reinforcement.” (Wang & Brennan, 2015)
Fibre content

It has also been shown that the amount of fibre content is relevant to the effect observed regarding liquefaction susceptibility and shear modulus. “Upon increasing the fiber content and fiber length, the number of loading cycles leading to liquefaction increased.” (Noorzad & Amini, 2014) Results also revealed that the shear modulus increases with increasing fibre content. (Noorzad & Amini, 2014)

Soil density

Furthermore by comparing tested samples of different densities “the reinforcement effect in medium dense samples was found to be more significant than that of looser samples.” (Noorzad & Amini, 2014)

Undrained ring shear testing confirms this, as the outcome was similar: “The results indicate that the undrained shear behavior of fiber-reinforced loose samples is not greatly influenced by the presence of fiber, but for medium dense and dense samples, the presence of fiber clearly affects their undrained behavior. Untreated specimens showed a continuous decrease in shear resistance after failure, while the specimens treated with fiber showed fluctuations even after shear failure, and these fluctuations become stronger with increasing fiber content. The peak shear strength increases with the fiber content, especially in dense specimens.” (Jin Liu et al 2011)

Conclusion

Although it has been observed that fibre reinforcement has the effect on sand to convert the strain softening response, into a strain hardening response it has been found that this does not happen immediately as the sand requires to be disturbed beforehand. “It is proposed that the fibre-reinforced sand requires a driving shear stress to mobilize the full effectiveness of the fibre reinforcement.” (Wang & Brennan, 2014)

Thus it has been shown that researchers agree on the positive effects of fibre reinforcement regarding liquefaction susceptibility and lateral spreading of sand. It has also been found that increased fibre content and soil density will have a more noticeable effect. Supported by the work of these researchers and others, a suggestion is made to test the use of fibre reinforcement in civil engineering problems where liquefaction is a governing threat. The use of randomly distributed polypropylene fibre reinforcement as a mitigation method for pipelines under the effect of buoyant forces is therefore a reasonable proposal.
3 TEST SETUP AND METHODOLOGY

The main objective of this project was to test whether a buried buoyant pipe can be kept from surfacing by reinforcing the soil above it with polymer fibres. For this purpose a miniature buried pipe model was created which could be used to repeatedly conduct the same shaking experiment so that alternative reinforcement models could be tested and compared. Sixteen samples were tested in total.

Some concepts have been used in order to simplify the text. These are listed and defined for the extent of this paper, below.

**Sample:** each time a test is being carried out the box is filled with sand, water, fibre reinforcement and the buoyant object which are arranged in a certain way, this will from here on be referred to as a “sample”.

**Layer:** This refers to a layer of sand in the box which has a depth equal to the diameter of the pipe being used as the buoyant object which is 45mm in this set of tests, thus we can also refer to a half layer, which is 22.5mm deep.

This section presents the components used for testing, how test samples are assembled, what the alternative structures of the test samples are, what information was gathered from the tests and how this was done.

3.1 Test Sample Elements

Necessary elements for performing the test are: sand, a standard soil shaker, a steel box, a buoyant object, fibre reinforcement and water. These objects will now be described in detail:

**Sand**
The sand used to conduct the tests was a siliceous sand of medium density. The following Table contains the physical properties of HST50.
Table 1: Physical properties of used sand

Summary of physical properties of HST50

<table>
<thead>
<tr>
<th>Property</th>
<th>HST50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading description</td>
<td>Medium sand</td>
</tr>
<tr>
<td>Permeability, $k^a$ (m/s)</td>
<td>$4.95 \times 10^{-4}$ (25%)</td>
</tr>
<tr>
<td>One-dimensional Young’s modulus, $E'_0$</td>
<td>824 (61%)</td>
</tr>
<tr>
<td>(kN/m²)</td>
<td></td>
</tr>
<tr>
<td>$D_{10}$ (mm)</td>
<td>0.19</td>
</tr>
<tr>
<td>$D_{50}$ (mm)</td>
<td>0.25</td>
</tr>
<tr>
<td>Critical state friction angle $\phi'_{\text{crit}}$</td>
<td>34</td>
</tr>
<tr>
<td>Critical state interface friction angle $\delta'_{\text{crit}}$</td>
<td>27</td>
</tr>
<tr>
<td>Maximum dry density, $\rho_{\text{max}}$ (kg/m³)</td>
<td>1765</td>
</tr>
<tr>
<td>Minimum dry density, $\rho_{\text{min}}$ (kg/m³)</td>
<td>1535</td>
</tr>
</tbody>
</table>

* Permeability and $E'_0$ shown with relative density of sample in parenthesis.
* $E'_0$ determined at effective stresses relevant to model testing (0.2-0.3 kN/m²).
* Particle size at 10% passing from particle size distribution determination.
* Friction angles determined at normal stresses from 0.2 to 70 kPa.

(Launder et al, 2012)

**Shaker**

A standard soil shaker which is usually used for the sieving of soils was used to generate motion which was necessary to liquefy the soil. The shaker is suitable for this task as it always moves at the same frequency, which was measured to be 16.5 Hz. Having the same motion for all samples was important for the comparison of the alternative reinforcement arrangements. A picture of the shaker can be seen in Figure 25. The bars are used to fix the sample to the shaker.

Figure 25: Standard soil shaker

Figure 26: Strongbox
Strongbox

The Strongbox has two important features. Screwed on the sides there are two joints which make it possible to attach it to the shaker and on one side it has a transparent PVC wall, through which the movement of the buoyant object can be tracked. The internal dimensions of the box are 105mm *220mm*250mm (depth; width; height). This will become important when measuring the amount of reinforcement that should be used for each sample as it will be directly proportional to the weight of soil used.

Buoyant object

A steel pipe of diameter 45mm was used. The ends of the pipe were sealed up with two small, 5mm thick PVC disks and insulated against water and air with silicon. The steel pipe was 90 mm long, together with the disks and a glued-on sponge membrane the total length of the pipe was 105mm. A ballast of 60 g (small metal disks) was also placed inside the pipe. For the object to be buoyant it needed to have a lower unit weight than the sand used in the test, while being heavier than water. This ensured that the pipe would stay submerged while assembling the sample, but would rise when the soil was to be liquefied. The unit weight of the buoyant object was 13.4kN/m³.

Reinforcement

Polypropylene fibre reinforcement was used to strengthen different parts of the soil used in tests with the purpose of preventing the buoyant object from surfacing. The randomly distributed fibres, interlock themselves with sand particles restricting their motion when being subjected to shaking or shearing, thus making it more difficult for the buoyant object to pass through.
The material is commercially named Loksand™ (shown in Figure 28). The nominal length of the fibres is 35mm their diameter is 0.1mm. Specific gravity and tensile strength are 0.91 and 200MPa, respectively. All these parameters were provided by the manufacturer. As the aspect ratio (the ratio of length to diameter) of the fibres is large, the length of the fibres is much larger than the particle size of the soil, yet the diameter is comparable, these fibres may interact well with sand particles and contribute more to composite strength according to the work of Michalowski and Čermák (2003) (Wang & Brennan, 2014)

**Water**

Potable water was used to fully saturate the soil for all tests in order to ensure that it would liquefy in all cases. If the soil were not fully saturated test results would differ and would be difficult to compare. Liquefaction was desired in all tests so that a full effect could be resisted by the reinforced soil.

### 3.2 Testing Procedure

Each test sample has two important variables that characterize it. These are Arrangement (0; 1; 1.2; 2 and 3); and Reinforcement-sand ratio (0.6-0.8-1.0). These will be described and discussed in section 3.3 ”Test Arrangements”.

The general steps taken to prepare a sample are presented below, broken down into the following steps:

**Lubrication of the box and buoyant object**

Before every test the sliding surfaces of the buoyant object and the box were coated with petroleum jelly to ensure that friction between the buoyant object and the box does not affect the outcome and does not assist the reinforcement in restraining the buoyant object.

**Addition of water**

Following lubrication, the necessary amount of water for saturation was poured into the box. It was necessary to add water first, otherwise bubbles would be created and the soil would not be entirely saturated as was the case with test no. 7, which can be seen in Figure 29, where water was added only after the placing of the sand and reinforcement in an attempt to distribute the fibres more homogeneously. Having more water than necessary is preferable to the alternative of having too little.
Addition of base sand layer

Sand was placed via pluviation with the use of a cup. A half layer of sand was placed on the bottom of the box. It was noticed that if the buoyant object was placed directly on the bottom of the box it would be obstructed and surfacing velocity would be reduced in the beginning, making the recording longer and therefore larger in size.

Placing of buoyant object

The buoyant object was placed on the base layer approximately in the middle. Following this the samples would be prepared differently depending on the respective arrangement and reinforcement-sand ratio of each instance.

Calculation of reinforcement mass

It was observed that in research papers regarding fibre reinforcement the reinforcement-sand ratio of mass was below 1%. This was done similarly using ratios of 0.6%, 0.8% and 1% to mass in the tests. The necessary amount of reinforcement was calculated based on the volume of the layer which would usually be 105*220*45mm³ (depth, width, height). The weight of the sand was calculated with the average density of the used sand which could be determined from minimum and maximum values presented in Table 1. Information will be presented regarding the specifications of all individual tests including the exact mass of the reinforcement used in each instance.

Placement of reinforcement

The appointed mass of reinforcement was placed by hand, attempting to orient the fibres randomly while dividing them homogeneously in the designated layer. As it was difficult to control the distribution of the fibres which were clumped together randomly it would be imprecise to say that
an exact layer of sand was reinforced. It would be more accurate to describe it as the designated mass of fibres being placed on the level where the reinforced layer was to begin. On occasion it did happen that the fibres exceeded the designated layer as can be seen in Figure 30 taken from test 14. Conveniently the reinforcement could be placed into the water at the height that was needed and did not rise to the surface. The tests would have been made more difficult if the reinforcement had floated.

![Figure 30: Test 14 before shaking circle representing strayed fibres during placement](image)

**Addition of covering sand layer**

Finally sand was added by pluviation to achieve the reinforced layer by using a cup. Pluviation was chosen in favour of other means of mixing the fibres with the sand as this was the method used by Wang and Brennan (2014).

### 3.3 Test Arrangements

**Arrangement 0**

Tests 1-5 and test 13 were conducted with clean sand. The purpose of the first five tests was to make sure that the buoyant object would behave as expected, would not become wedged, would not be hindered by friction and would rise to the surface in a short amount of time. The latter was necessary because of the limited filming time for each video, which was 36 seconds.

Test 13 was conducted to act as a reference, along with all the unreinforced layers of other tests. Thus the impact of different
arrangements and reinforcement-sand ratios could more easily be understood.

**Arrangement 1**

Most tests were conducted with arrangement 1 with the intention of observing the ascension of the buoyant object through both clean and reinforced soil. After conducting a number of tests different arrangements were also tested to explore the possibility of using fibre reinforcement as a solution to civil engineering problems. Coincidentally this was the arrangement where the reinforced layer was in the same position roots would normally be, on the surface-most layer. It would be very advantageous to solve the issue of buoyant pipes in an environmentally friendly way, without the addition of polypropylene fibres to act as reinforcement, but instead by employing plant roots to act as a safety barrier.

![Figure 31: Arrangement 1](image1)

**Arrangement 1.2**

To determine whether the buoyant object would behave the same way if only the exact patch of soil that is covering it would be reinforced, arrangement 1.2 was tested. As can be seen in Figure 32 arrangement 1.2 is an exact copy of arrangement 1 containing reinforcement only in the middle of layer 3. It had been anticipated that due to the lack of reinforcement in the sides of the layer the buoyant object might displace laterally.

![Figure 32: Arrangement 1.2](image2)

**Arrangement 2**

If used to solve civil engineering problems the reinforcement would be expected to prevent the buoyant objects from moving entirely as this would assure that no damage is sustained. In this case the reinforcement should be placed directly above the pipe with another layer above it to account for the additional depth that the pipes might be buried. Arrangement 2 was tested to assess this scenario.
Arrangement 3

It had been thought that if arrangements 2 and 1.2 were combined less material would be used and the pipe would be prevented from moving entirely. To account for the matter of lateral displacement the buoyant object was wrapped with a reinforced layer instead of just being covered. This would have proven difficult to model if it had not been for the addition of two slim steel plates that acted as temporary walls and kept the fibres in place while sand was added. The steel plates were removed before shaking.

3.4 Information Recorded

A total of 16 tests were conducted. In this section the findings and observations made during the tests will be presented and commented on. Next, information will be given regarding the camera used to film the tests, the filming procedure, the data collected and how it was processed.

Tests 1-5 were not filmed, as they were merely meant to ensure that the test components acted as expected. The sand needed to liquefy due to the shaking, no issues occurred with this. The buoyant object however, was difficult to calibrate as it needed to fulfil several expectations. While staying visible, the buoyant object was meant to rise unhindered by friction between the interfaces of the PVC disks at its ends and the box walls, and without becoming wedged or stuck. Both of these problems occurred and needed to be solved.

To address the problem of friction the sliding surfaces were coated with petroleum jelly. Because the buoyant object could not be made exactly the length required to fit into the box sand particles strayed into the space between the buoyant object and box wall. Although the pipe stayed visible
due to the extra fractions of millimetres added by the sand particles the pipe would become stuck, and thus would not rise in spite of the fact that the sand around it was liquefied. The solution to this was to cut off 5 millimetres from the edge of the pipe and add a compressible sponge instead. Following this, even when sand seeped in between surfaces of the buoyant object and the wall, due to it no longer being rigid the object would still surface relatively unhindered.

Test 6 had **10.43g** of reinforcement which was **0.6%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 1**. A bump was formed on the surface of the sand above the buoyant object when the reinforced layer was reached and a clump of fibres rose to the surface escaping the sand matrix.

![Figure 35: Bump forming on soil surface, test 6](image)

![Figure 36: Fibres surfacing, test 14](image)

Test 7 had **18.97g** of reinforcement which was **0.55%** of the mass of the sand in a **90mm** thick layer arranged according to **Arrangement 1**. A bump was formed on the surface of the sand above the buoyant object when the reinforced layer was reached and a clump of fibres rose to the surface escaping the sand matrix.

The reinforcement-sand ratio was meant to be 0.6% but a mistake was made in calculation, the dimension of the box was entered incorrectly into the spread sheet, thus 1.9g less fibres were used in this test.

In an attempt to place the fibres in a more homogeneous manner than could be done in the previous test, water was added to the sample last, after the placing of the fibres and the sand. This resulted in bubbles being formed as can be seen on Figure 29 in section 3.2 “Testing Procedure”. It is unknown whether this factor affected the performance of the reinforcement or influenced the resulting ascension velocity, but for all following tests the assembling of the sample described in section 3.2 was respected.

Test 8 had **17.4g** of reinforcement which was **1.00%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 1**. A bump
was formed on the surface of the sand above the buoyant object when the reinforced layer was reached and a clump of fibres rose to the surface escaping the sand matrix.

After filming was stopped shaking was continued for a time of about 60 seconds (data for this test is based on 22.33 seconds of filmed shaking). The buoyant object would still not rise. Some sand was cleaned away from above the buoyant object and shaking was resumed, however it still did not rise. Thus it was concluded that in this instance the pipe might have gotten wedged thus the test was repeated with the same variables (test no. 9)

**Test 9** had **17.4g** of reinforcement which was **1.00%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 1**. A bump was formed on the surface of the sand above the buoyant object when the reinforced layer was reached and a clump of fibres rose to the surface escaping the sand matrix.

Similarly to test no. 8 after the filming was concluded shaking was continued for another 100 seconds until the pipe surfaced without assistance.

**Test 10** had **13.9g** of reinforcement which was **0.80%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 1**.

This sample was shaken for about four seconds before it was stopped due to the fact that the box was not fixed properly to the shaker. After this was corrected the test was continued but the short period of shaking is thought to have affected the final results. These are discussed in section 4.2 “Effects of Fibre content”.

**Test 11** had **13.9g** of reinforcement which was **0.80%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 1**. A bump was formed on the surface of the sand above the buoyant object when the reinforced layer was reached and a clump of fibres rose to the surface escaping the sand matrix.

The sand in this test is denser than in other tests due to the fact that it has been shaken for 4 seconds prior to the test. The increased density caused the “free velocity” of this sample to be significantly lower than that of other tests and the fibres were also more effective in restraining the buoyant object. This latter claim is supported by the findings of (Ibraim, 2010), affirming that fibre reinforcement has a more significant effect on denser sands.

**Test 12** had **8.7g** of reinforcement which was **1.00%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 1.2**. A bump was formed on the surface of the sand above the buoyant object when the
reinforced layer was reached and a clump of fibres rose to the surface escaping the sand matrix.

As was anticipated the buoyant object displaced laterally avoiding the reinforced area.

![Figure 37: Collision with reinforced area, test 12](image1)

![Figure 38: Contact with reinforced sand, test 12](image2)

![Figure 39: Lateral displacement, test 12](image3)

![Figure 40: Surfacing, test 12](image4)

**Test 13** had no reinforcement and was arranged according to **Arrangement 0**. This test was meant to confirm the ascension velocity of the buoyant object in clean soil and was done to determine whether the clean layers in other arrangements behaved the same way.

**Test 14** had **17.4g** of reinforcement which was **1.00%** of the mass of the sand in a **45mm** thick layer arranged according to **Arrangement 2**. A bump was formed on the surface of the sand above the buoyant object when the buoyant object came to a distance of a layer from the surface of the sand and a clump of fibres rose to the surface escaping the sand matrix. The fibres were not contained in the 45mm thick layer, as can be seen on Figure 30 in section 3.2 “Testing Procedure”.
Test 15 had 15.1g of reinforcement which was 1.00% of the mass of the sand in a 45mm thick circular layer arranged according to Arrangement 3. A bump was not formed on the surface of the sand above the buoyant object and a comparatively small amount of fibres were forced out of the sand matrix.

It is thought that the fibres were not distributed homogeneously on the selected area specified by Arrangement 3 and that too much of the fibres were placed to the side rather than the top of the buoyant object. This is confirmed by test no.16 as the ascension speeds of the two are disproportionate to their quantity of fibres. Figure 41, shows an image which was taken with the intention of presenting the assembly method used for Arrangement 3, also confirms this as the fibres seem denser on the sides than on the top if the buoyant object.

Test 16 had 12.1g of reinforcement which was 0.80% of the mass of the sand in a 45mm thick circular layer arranged according to Arrangement 3. A bump was formed on the surface of the sand above the buoyant object when the buoyant object came to a distance of a layer from the surface of the sand and a clump of fibres rose to the surface escaping the sand matrix.
Table 2: Summary of test results and properties

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Arrangement</th>
<th>Fibre mass (g)</th>
<th>Fibre-sand ratio</th>
<th>Reinforced layer thickness (mm)</th>
<th>Bump</th>
<th>Clump</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1</td>
<td>10.43</td>
<td>0.60%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>18.97</td>
<td>0.55%</td>
<td>90</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>17.40</td>
<td>1.00%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>17.40</td>
<td>1.00%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>13.90</td>
<td>0.80%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>12</td>
<td>1.2</td>
<td>8.70</td>
<td>1.00%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>17.4</td>
<td>1.00%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>15.1</td>
<td>1.00%</td>
<td>45</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>12.1</td>
<td>0.80%</td>
<td>45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Filming and data collection

A Phantom Miro M320S high-speed digital camera was used to film the videos at a frame rate of three hundred frames per second. A video was set to a maximum of 10800 frames or 36 seconds of video. Any longer videos would prove to be unreasonably large in file size, 10.4 gigabytes being the size of a 36 second video. The software which was used to film the videos, the Phantom Camera Control Application, has a user friendly interface which made it easy to jump to certain numbered frames instead of having to use a progress bar.

Filming at such a high frame rate made it possible to track minimal movements and to determine the precise frame of important occurrences such as when the buoyant object would come into contact with reinforced layers.

The ascension velocity of the buoyant object was measured by tracking the position of its top-most point with the help of the vertical ruler on the side of the box to the precision of one millimetre at increments of 200 frames and at smaller increments where necessary. By counting the number of frames it took for the object to ascend a certain amount of millimetres, and converting the frames into seconds by dividing by 300, velocities were linearly approximated.
It was expected, in the case of tests in arrangements 1 and 1.2, that when the buoyant object reached the reinforced layer it would slow down considerably, thus resulting in two segments of linear velocities per test. This did happen but by simply observing the videos at normal speed, it became apparent that the object needed to penetrate the reinforced layer to a degree before the reinforcement began significantly hindering its movement, creating a third linear velocity. These are presented in Table 3. The reasons for these phenomena are discussed in section 4.1 “Relevant observations regarding tests”.

Table 3: Ascension velocity of tests in Arrangements 1 & 1.2

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Reinforcement-sand ratio</th>
<th>Free velocity (mm/s)</th>
<th>Transitional velocity (mm/s)</th>
<th>Restrained velocity (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.6 %</td>
<td>10.09</td>
<td>8.50</td>
<td>5.63</td>
</tr>
<tr>
<td>7</td>
<td>0.6 %</td>
<td>11.73</td>
<td>9.30</td>
<td>3.61</td>
</tr>
<tr>
<td>8</td>
<td>1 %</td>
<td>8.46</td>
<td>4.71</td>
<td>0.88</td>
</tr>
<tr>
<td>9</td>
<td>1 %</td>
<td>5.73</td>
<td>2.40</td>
<td>0.54</td>
</tr>
<tr>
<td>11</td>
<td>0.8 %</td>
<td>4.22</td>
<td>3.00</td>
<td>0.71</td>
</tr>
<tr>
<td>12</td>
<td>1 %</td>
<td>12.35</td>
<td>5.00</td>
<td>1.51</td>
</tr>
</tbody>
</table>

1 mass percentage of reinforcement to sand  
2 velocity of buoyant object while in unreinforced layer  
3 velocity of buoyant object while entering reinforced layer but not being slowed to full effect  
4 velocity of buoyant object while in reinforced layer  
5 test no. 12 was in arrangement 1.2

When reading graphs of the type shown on Figure 43 the gradient of the plotted data points represents the velocity of the buoyant object, the closer to horizontal the drawn line is the slower the buoyant object, therefore the more effective the fibres in the sample.

The graphs plot the displacement of the buoyant object in millimetres versus time in seconds as was recorded from the videos made with the high-speed camera. The red lines added symbolize the different ascension speed segments mentioned earlier.

In graphs depicting tests done in arrangements 1 and 1.2 the first segment is fitted to only two data-points. This segment represents the ascension velocity of the buoyant object in clean sand where the ascension velocity is constant as was demonstrated by test 13.
Because transitional velocities were noticed in tests in Arrangements 1 and 1.2, it was thought that the same would occur in tests in Arrangements 2 and 3. However, upon plotting the position of the buoyant object in its ascension versus time only two linear lines could be drawn. The gradient of the first line represents the average ascension velocity of the buoyant object while in the initially reinforced layer while the second represents the same outside the initially reinforced area and is referred to as “post velocity” in Table 4. Although it could be argued that the two segments could have been selected in a way that allowed the straight lines to better fit to the data points, the reason they were chosen this way was to present the average velocity of the buoyant object in the initially reinforced layer and the initially non-reinforced layer. Figure 45 presents images from test 16 with the purpose of clarifying these two regions.

Table 4: Ascension velocity of tests in Arrangements 2 & 3

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Reinforcement-sand ratio</th>
<th>Restrained velocity (mm/s)</th>
<th>Post-velocity (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1 %</td>
<td>2.95</td>
<td>1.03</td>
</tr>
<tr>
<td>15</td>
<td>1 %</td>
<td>5.42</td>
<td>3.24</td>
</tr>
<tr>
<td>16</td>
<td>0.8 %</td>
<td>5.47</td>
<td>1.92</td>
</tr>
</tbody>
</table>

1 mass percentage of reinforcement to sand
2 velocity of buoyant object while in reinforced layer
3 velocity of buoyant object after exiting reinforced layer, displacing along with fibres
Figure 44: Example of how velocity segments were separated for tests done in arrangements 2 and 3.

Figure 45: Ascension of buoyant object in test 16, restrained velocity between position shown on images a and b, port-velocity between positions shown on images b and c.
4 RESULT ANALYSIS AND DISCUSSION

4.1 Relevant Observations Regarding Tests

Before discussing the effects of the different arrangements and reinforcement-sand ratios on the ascension velocity of the buoyant object, a few factors will be discussed that are believed to be relevant. The observed reoccurrences characterise the behaviour of the fibres and may be part of the reason why one arrangement is more effective than another.

4.1.1 Displacement of Fibres within the Sand Matrix

As was presented in Table 2 of section 3.4 that during all the tests clumps of fibres enclosed in bumps of sand rose to the surface of the soil along with, or rather pushed by the buoyant object, clarification can be found in Figures 46-48. As can be seen in Figure 48 in particular fibre reinforcement seems to keep its bushy structure and is pushed upwards by the buoyant object in a clump. The bumps were more prominent in the tests where a higher reinforcement-sand ratio was used. The bumps start appearing around the same time the buoyant object reaches the reinforced layer. It is important to note that the approximate height of these clumps is around 45mm, which is the same as the thickness of the reinforced layer. At a closer inspection of the videos it becomes apparent that the fibres do start to rise as soon as the buoyant object reaches the reinforced layer. This suggests that although the fibres become entangled with the sand matrix and restrain the buoyant object they also have a spring-like nature which prevents any noticeable deformation of the clump. Finally sand clears away due to the shaking, leaving behind only the fibres.

It is suggested that the reason for having a bushy structure is that the fibres were oriented randomly; if the fibres had been oriented horizontally only, this would most likely not have occurred. (Diambra et al, 2010)

It would have been expected that the fibres stay trapped in the sand matrix and smooth out once the buoyant object nears the surface remaining in the sand but it seems they retain their clumpy structure. This raises the question: what would happen if an object were pulled (liquefaction not occurring in this scenario), instead of pushed by buoyant forces, through a fibre reinforced sand layer? Would the same happen, or do the fibres retain their structure only because the sand above them is liquefied? Either way it can be predicted that if the specific gravity of the fibres were higher than 1, their ability to hinder buoyant objects would be increased.
The fact that the fibres have a specific gravity of 0.91 (Wang & Brennan, 2014) clarifies why the fibres float up, however not the whole amount of fibres surfaces but only a portion which is directly above the buoyant object, suggesting that the fibres are in fact properly interlocked with the sand matrix, and rise in clumps due to the action exerted by the buoyant object and to the fact that they preserve their structure.

The above mentioned bush-structured reinforcement rises together with an amount of interlocked sand. In case of an earthquake it is unlikely that this phenomenon alone would result in any damage to the pavement. It is more likely that this damage would only be sustained when the buoyant lifeline itself reaches the surface and begins directly interacting with the surface layer, as the fibres would be compressed and the sand would seep out of the way due to the shaking.
It can thus be concluded, that fibres rise in clumps due to the collective effect of the following three: the sand is liquefied, the buoyant object is exerting upward force on the fibres and the clumped fibres are not malleable and mostly retain their form due to their likeness to a spring. Together with the observations that can be made regarding tests 14-16 in Table 4, that ascension velocity increases in higher, initially non-reinforced layers, it is arguable based on the above that the enclosing fibre-reinforcing sand is being sheared by the rising buoyant object (Figure 49) and that a strain-hardening response is evident based on the continuously decreasing ascension velocity. This is in conformity with the findings of both Diambra et al 2011, namely that fibre reinforced sand will harden with strain, and Wang and Brennan, 2014, namely that fibres require a driving shear force to work effectively.

Figure 49: Clump of fibres being sheared upward by buoyant pipe as observed during test 14 done in arrangement 2

It is now clear why layers 2 and 3 of arrangements 2 and 3 were referred to as “initially reinforced” and “initially non-reinforced” in section 3.3, due to the fact that the fibres displace and as a result temporarily reinforce layer 3.

4.1.2 Thickness of Reinforced Layer

Tests done in arrangements 2 and 3 have demonstrated that fibres are carried upward with the buoyant object, will work and become more effective the further the object rises. Based on this and the comparison of the ascension velocities recorded in tests 6 and 7 (Figure 50), the only difference between the two being the thickness of the reinforced layer (45mm and 90 mm), it is suggested that reinforcing a layer thicker than the diameter of the buoyant object is unnecessary as there will not be a significant difference in ascension speed.
Figure 50: Graph emphasising similarity of ascension velocity between samples with reinforcement layers of different thickness but same fibre-sand ratio

4.1.3 Fibre Distribution in the Test Samples

When placing the fibres in preparation of a test it is not possible to distribute them in a truly homogeneous manner. This is the same when removing the reinforced soil from the box after a test has been conducted. The soil comes up in balls of wet sand held together by the fibres. Since the reinforcement in the soil is clearly not homogeneously distributed either before or after the test, the same must be true about the small portion of time in between. The conclusion thus can be drawn that the performance of the reinforcement cannot be accurately estimated based on so few tests, since on such a small scale, with such low amounts of fibres slight errors in placing can impact the outcome. Tests 15-16 are good examples of this, where ascension velocities are disproportionate to fibre content due to errors in placing, also tests 8-9 can be viewed to compare ascension velocities, which are similar to each other, but still differ although fibre content and the arrangement were the same. A more accurate conclusion could be drawn if several more tests were conducted, or if a more accurate method were found to mix the fibres with sand.
4.1.4 Varying Ascension Velocity Segments

Tests have concluded that the further the buoyant object travels upward the more resistance is exerted by the fibres reinforcing the sand matrix. This is true even for tests 14-16 where reinforcement is placed directly above the buoyant object, as the ascension velocity is lowered as the object comes closer to the surface of the sand. Tests done in arrangements 1 and 1.2 significantly differ from those done in arrangements 2 and 3. The possible reasons for their different segments of ascension velocities will be discussed here.

Tests in Arrangements 1 and 1.2 have shown that the buoyant objects’ ascension velocity can be divided into three linear segments which have been named free, transitional and restrained. While the reason behind the different ascension velocities of the former and latter is obvious, the middle one is attributed to the need of shearing the fibre reinforced layer for it to become fully effective. After the reinforced layer has been subjected to sufficient strain it becomes effective and continues to reduce the ascension velocity of the buoyant object. While the restrained velocity was approximated linearly, it is not exactly so, as the velocity continues to decrease while ascending (Figure 51). Similarly, tests done in arrangements 2 and 3 have shown that the ascension velocity of the buoyant object decreases in a non-linear way, but nothing resembling the transitional segment of tests done in arrangement 1 and 1.2 can be seen on the plotted graphs. This is thought to be due to the fact that momentum was not built up as it was in the clean layer of sand in tests done in arrangements 1 and 1.2. However, two segments were determined so that linear velocities could be approximated and test results may be compared.

Figure 51 below presents the movement in several tests, in order to demonstrate, that in all tests the velocity of the buoyant object is reduced the further it has travelled in the fibre-reinforced sand, this is represented by the gradient of the lines that could be drawn between the depicted data points. The different segments can also be observed alongside the different nature of the plotted data-points of tests done in arrangements 1 and 1.2 (tests 7, 9, 11) compared to those done in arrangements 2 and 3 (tests 14 and 16).
Figure 51: Representation of buoyant object movement in several tests
4.2 Effects of Fibre Content

4.2.1 Fibre Content Comparison

Tests in arrangement 1

![Graph showing ascension velocity](image)

Figure 52: Representation of ascension velocities the buoyant object had in test done in arrangement 1

Table 4: Display of ascension velocities the buoyant object had in test done in arrangement 1

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Reinforcement-sand ratio $^1$</th>
<th>Free velocity (mm/s)$^2$</th>
<th>Transitional velocity (mm/s)$^3$</th>
<th>Restrained velocity (mm/s)$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 $^5$</td>
<td>0.0 %</td>
<td>10.05</td>
<td>10.05</td>
<td>10.05</td>
</tr>
<tr>
<td>7</td>
<td>0.6 %</td>
<td>11.73</td>
<td>9.30</td>
<td>3.61</td>
</tr>
<tr>
<td>11</td>
<td>0.8 %</td>
<td>4.22</td>
<td>3.00</td>
<td>0.71</td>
</tr>
<tr>
<td>9</td>
<td>1 %</td>
<td>5.73</td>
<td>2.40</td>
<td>0.54</td>
</tr>
</tbody>
</table>

$^1$ mass percentage of reinforcement to sand

$^2$ velocity of buoyant object while in unreinforced layer

$^3$ velocity of buoyant object while entering reinforced layer but not being slowed to full effect

$^4$ velocity of buoyant object while in reinforced layer

$^5$ test no. 13 had no reinforcement and is acting as reference

For the sake of simplicity the average ascension velocity in clean sand was calculated taking all the cases where the buoyant object travels in clean sand into account. Two results were found: **7.83 mm/s** for all applicable velocities used and **9.74 mm/s** for the case in which the free velocity of test no. 11 was not taken into account, due to the fact that the sand was consolidated prior to recording, as was explained in the reporting about tests nos. 10 and 11 in section 3.4 “Information Recorded”. The lower average will be used when comparing tests done in arrangement 1 to test no 11, the higher will be used when comparing clean soil to reinforced layers of other test samples.
Based on the data gathered from the above mentioned tests, the conclusion can be safely drawn that fibre reinforcement had a considerable effect on the ascension speed of the buoyant object, with test no. 9 showing a velocity in the reinforced layer eighteen times lower than that in the average clean sand. When comparing results obtained from test 9 to that obtained from other tests done in arrangement 1 a favourable non-linear decrease in velocity can be observed with the increase of fibre-sand ratio. While the difference between the velocity recorded in test 9 and 11 seem small it must be taken into consideration that the sand in the latter was denser and thus the fibres more effective (Noorzad & Amini, 2014; Jin Liu et al, 2011). Because of this, it is clear that increasing fibre content to 1% of the mass of the sand layer in question was advantageous in the conducted tests. While it is more than likely that at a certain point the fibre-sand ratio will become inefficient or uneconomical, it is uncertain what the bordering value is.

Tests in arrangements 2 and 3

Because of the fault in test 15 and the lack of other tests done in arrangement 2 it cannot be safely concluded that using a fibre-sand ratio of 1% was advantageous in the case of tests done in arrangements 2 and 3. However it can still be speculated that if more tests were carried out, it is more than likely that the same conclusion would be reached as in case of tests done in arrangements 1 and 1.2, as all other research has found that increasing fibre content is beneficial.

![Figure 53: Representation of ascension velocities the buoyant object had in test done in arrangement 2 and 3](image-url)
Table 5: Display of ascension velocities the buoyant object had in tests done in arrangement 2 and 3

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Reinforcement-sand ratio</th>
<th>Restrained velocity (mm/s)</th>
<th>Post-velocity (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0.0 %</td>
<td>10.05</td>
<td>10.05</td>
</tr>
<tr>
<td>14</td>
<td>1 %</td>
<td>2.95</td>
<td>1.03</td>
</tr>
<tr>
<td>15</td>
<td>1 %</td>
<td>5.42</td>
<td>3.24</td>
</tr>
<tr>
<td>16</td>
<td>0.8 %</td>
<td>5.47</td>
<td>1.92</td>
</tr>
</tbody>
</table>

1 mass percentage of reinforcement to sand  
2 velocity of buoyant object while in reinforced layer  
3 velocity of buoyant object after exiting reinforced layer, displacing along with fibres  
4 test no. 13 had no reinforcement and is acting as reference

4.2.2 Arrangement Comparison

The ascension velocities of the buoyant object measured in tests 14-16 are not as low as they are in tests done in arrangement 1 with the same content of fibres. The most important is the comparison between test no. 9 and no. 14. The main reason behind this is proposed to be the fact that while in tests done in arrangement 1 the buoyant object reaches the reinforcement after a considerable amount of shaking, in the case of tests done in arrangements 2 and 3 the reinforced layer is instantly in contact with the buoyant object. In the case of the former by the time the object reaches the reinforced layer, the sand is compacted to a certain degree and the fibres are now working with high effectiveness. In the case of the latter, fibres come into contact with the buoyant object while the soil is still relatively loose. The result is that the lowest velocity recorded in test 9 is half that of the lowest velocity recorded in test 14. However it is important to observe the entire ascension process of both tests to discuss their effectiveness, as the task of the fibre reinforcement is to protect the buoyant object by restricting its movement in liquefied soil.

If the buoyant object were a lifeline the goal would be to ensure it displaces as little as possible during an earthquake that induces liquefaction. By reinforcing a layer of soil along the lifeline, where liquefaction susceptibility may be an issue, in a way similar to test arrangement 2, the liquefaction susceptibility of the soil would be reduced, and in case of liquefaction the ascension velocity of the lifeline would be expected to be slower than if the lifeline were covered with clean soil. It is difficult to say how much the ascension velocity of a life-sized pipe would be affected, because several variables would be different from the testing conditions. However, when comparing the initial ascension velocity of test 14 to the average ascension velocity of the buoyant object in clean sands, in the case of the former velocity is \( \frac{9.74 \text{mm/s}}{2.95 \text{mm/s}} = 3.33 \) times lower. Thus, although test 9 done in arrangement 1 might produce a lower ascension velocity when the reinforced layer is reached, it would be irrelevant because the lifeline would most likely be damaged by that time. In contrast, fibres in arrangement 2 become effective immediately with the
start of movement and could prevent both minor and major damage from being sustained.

**Figure 54: Graph emphasizing early ascension velocity difference between clean and reinforced**

Samples in Arrangement 1 are similar to the structure of densely rooted surface vegetation, the polypropylene fibre reinforcement could be replaced by naturally grown roots if a suitable plant were found and tested. However pipes are usually placed deeper than the roots of plants could reach and most would be covered by asphalt or some other sort of pavement. Therefore, this solution would only be recommended if the pipes were placed very close to the surface of the ground and no pavement were necessary above them. Examples that fit these criteria are areas with warm climates in case of lifelines crossing a long distance over non-urban areas, lifelines in parks, back yards of houses etc.

Arrangements 1.2 and 3 have also proved to be less effective than arrangement 2 in restraining the buoyant object. In the case of the former lateral displacement was observed, this could cause even more severe damage to a lifeline than the vertical displacement alone. In the latter case it was thought that reinforcing the sand around the buoyant object in a semi-circular shape instead of a layer would solve the problem. While the buoyant object did not displace laterally arrangement 3 proved difficult to assemble, as was demonstrated by test 15. If this issue arose in the laboratory, it can easily occur on a construction site.
4.3 Further Research

It has been found that out of the conducted tests number 14 done in arrangement 2 with 1% fibre-sand ratio was the optimal choice with an initial ascension velocity of 2.95 mm/s and an average 1.03 mm/s ascension velocity after having displaced 67 mm under 36 seconds. Compared to clean sand these results are promising, but cannot be used to project what were to happen outside the laboratory with a life-sized model. Thus several of topics are suggested for further research.

**Scalable shaking tests**

Shaking table or centrifuge tests could be conducted on a sample similar to that of test 14. These could give answers to several questions. How will the fibres and the buoyant object behave if subjected to recorded earthquake shaking frequencies (the frequency of the soil shaker was 16.5 Hz, which is high compared to what was recorded from previous earthquakes).

By conducting such a test it could also be determined whether the fibre reinforcement could have resisted the effects of an earthquake. It could also be determined how much displacement would have occurred, and whether this would have been enough to damage a lifeline network.

If the results of the first test are favourable, a second one could be conducted without disturbing or reassembling the sample to determine whether the fibre reinforced soil will have a similar effect as the first time, after having been stressed.

**Infrastructural application**

It has been observed during the tests that placing fibres homogeneously by hand was difficult. If fibre reinforcement is used as a solution in infrastructural projects a method must be found to homogeneously mix fibres with soil in industrial quantities.

Before recommending the reinforcement of soil with fibres as a solution it is necessary to estimate the material, labour and maintenance costs involved. By comparing them to that of other mitigation methods the cost-effectiveness of the solution may be found.

**Life sized tests**

It is not out of the question that the ascension speeds recorded in the conducted test do not represent only the small buoyant object’s behaviour in fibre reinforced soil. If pipe diameter doesn’t significantly influence the interaction with the reinforced sand, this solution may indeed prove useful. To determine how life-sized lifeline systems would behave in fibre
reinforced soil it is recommended to conduct tests with standard sizes of sewage, gas and electrical lifeline elements.
CONCLUSION

A total of 16 shaking tests were conducted. The soil was liquefied in all tests, the ascension speed of the buoyant object was measured and used as an object of comparison for the effectiveness of different arrangements and fibre-sand ratios. The results suggest that the most practical combination was the one used in test 14 which was done in arrangement 2 with a fibre-sand ratio of 1%.

During neither test was total restriction of the buoyant object achieved, nor was the buoyant object’s ascension velocity reduced to 0 at any point during any test. In varying amounts of time the buoyant object did rise to the surface regardless of the amount of reinforcement used.

During the tests several observations were made upon the nature and behaviour of the polypropylene fibre reinforcement, the most important being that a reinforced layer of soil requires a driving shear force to begin resisting the displacement of a buoyant object. Another was the fact that fibres displace inside the sand matrix in clumps due to the driving force of the buoyant object, continuously decreasing its ascension velocity. Because of this feature, it is suggested that reinforcing a soil layer of thickness equal to the diameter of the buoyant object is sufficient. However, difficulties in distributing the fibres homogenously in the reinforced layer make it necessary for safety factors to be used.

In conclusion, the test results suggest that reinforcing the soil above lifeline networks with polypropylene fibres could be considered as a mitigation method to minimize liquefaction-caused damage. Thus, further research in encouraged to gain a deeper understanding of the capabilities of fibre reinforcement when used to restrain life-sized lifeline networks.
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