# Physical modelling of geosynthetic-reinforced soils spanning voids

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ABSTRACT: Geosynthetic-reinforcement is used to mitigate the effects of sinkholes and other voids on geotechnical and other civil structures under which they form. The reinforcement is placed to create a load-transfer mechanism that transfers the load of the overburden soil to the surrounding ground. Physical model tests of the behaviour of unreinforced and basally-reinforced granular fills over voids were conducted in a geotechnical centrifuge using a trapdoor model where soil arching and mechanisms of deformation were investigated. A comparison of the reinforced and unreinforced soil behaviour is presented, with a discussion on the load-displacement behaviour (arching), soil deformation, and geosynthetic deflection.

*Keywords: geotechnical centrifuge, trapdoor, void spanning, geosynthetic-reinforcement, arching*

## 1 INTRODUCTION

Geosynthetics are commonly used as a preventative measure to reinforce soil structures where there is potential for the formation of voids, localised subsidence or differential settlement below the structure. Examples include the construction of embankments for roads and railways over areas where there is the potential for sinkholes, collapse of mines or underground infrastructure such as tunnels. The role of the reinforcement is to span the void that may form and support the imposed vertical load above it, thereby preventing total collapse and limiting settlement.

The study of geosynthetic-reinforced soils over voids is important in order to quantify the benefit of the reinforcement and hence provide for an appropriate design. In this research, physical model tests were conducted in a geotechnical centrifuge to investigate soil arching and mechanisms of deformation of granular soils over a void both with and without geosynthetic reinforcement.

A comparison of unreinforced and reinforced soil behaviour is shown in this paper to investigate how the presence of the geosynthetic alters the soil arching behavior, and to give insight into the required load carrying capacity of the geosynthetic as it spans the void formed.

## 2 BACKGROUND

When a void forms or subsidence develops below soil structures reinforced with a geosynthetic, this reinforcement layer deflects into the space created. The deflection of the geosynthetic into the void has the effect of bending of the soil layer and stretching of the geosynthetic. As a result, the load transfer across the void is achieved by two mechanisms (see Figure 1): bending generates active arching in the soil and a reduction of load acting on the geosynthetic, and stretching mobilises a portion of the geosynthetic strength according to tensioned membrane theory (Giroud et al., 1990).

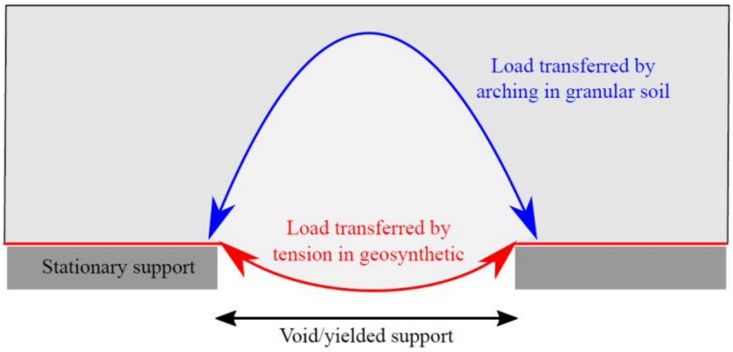


Figure 1: Schematic representation of load transfer mechanism in geosynthetic-reinforced soil.

## 2.1 *Arching theory*

Arching is a phenomenon that occurs in granular soils when there is a relative movement in the soil that is opposed by a shearing resistance between the yielding and stationary parts of the soil. There is a resultant increase in pressure on the stationary part and decrease in pressure on the yielding portion. This is called the arching effect as the soil is said to 'arch' over the yielding part of the support (Terzaghi, 1936).

Arching therefore involves the redistribution of stress around a yielding portion of the soil mass, and would occur for example when there are inclusions in the soils that are softer than the surrounding soil and yield and shed load, termed active arching, as would be the case with a geosynthetic deflecting into a void.

The vertical stress on the trapdoor, $\sigma_v$ (kPa), is calculated for a trapdoor of width $B$ (m) according to Equation 1 below as presented by Terzaghi (1943):

$$\sigma_v = \frac{\gamma B}{2K\tan\phi}\left(1 - e^{\frac{-2K\tan\phi H}{B}}\right) \qquad (1)$$

Where $\gamma$ (kN/m$^3$) is the soil density, $H$ (m) is the soil height, $\phi$ (°) is the angle of friction of the soil, and K is the coefficient of lateral stress. This equation is based on vertical sliding surfaces, a uniform stress distribution on the trapdoor, and a uniform coefficient of lateral stress between the yielding and stationary soil. Terzaghi (1943) assumed this to be empirical and equal to 1.

## 2.2 *Tensioned membrane theory*

The tensioned membrane theory refers to the ability of a geosynthetic sheet to deflect and absorb forces initially perpendicular to its surface through tension. Stretching of the geosynthetic mobilises a portion of the geosynthetics strength; as such, a differential movement (deflection) is required across the reinforcement layer.

The pressure distribution on the geosynthetic as the soil arches and the orientation of that pressure relative to the geosynthetic reinforcement influences the deformed shape that it will take and thus the tension across the width of the void. In order to estimate the tension in the geosynthetic, various assumptions have been presented in the literature are shown in Table 1. Gourc and Villard (2000) showed how the assumption of vertical pressure results in a tensile force approximately 7% greater than for a normal pressure distribution on the geosynthetic. van Eekelen and Bezuijen (2012) showed that the inverse triangular distribution with high pressure at the edges of the void, and no pressure at the centre, results in less tensile force being carried by the geosynthetic than the assumption of a uniform pressure distribution.

The assumptions made by the different researchers above highlight the importance of understanding the deflected geosynthetic profile in order to appropriately determine the required strength of this reinforcement layer.

Table 1. Geosynthetic pressure and deflected profile alternatives

| Pressure distribution | Pressure orientation relative to geosynthetic | Deformed profile shape | Reference |
|---|---|---|---|
| Uniform | Normal | Circular | Gourc and Villard (2000) |
| Uniform | Vertical | Parabolic | Gourc and Villard (2000) |
| Inverse triangular | Vertical | Cubic | van Eekelen and Bezuijen (2012) |

### 2.3 *Existing design procedures*

In practice, when designing geosynthetic-reinforced soils above voids, the two load transfer effects of arching and tension in the geosynthetic are decoupled and considered individually. The interaction and compatibility between these two components is not considered (Giroud et al., 1990). Design codes (Blivet et al., 2002; BS 8006, 2010; EBGEO, 2010; Villard and Briançon, 2008) use Terzaghi's methodology to calculate a uniform vertical pressure on the geosynthetic, with the assumption of $K$ being $K_a$, the active earth coefficient. Problem geometry, soil properties and settlement criteria are used to determine the maximum deflection of the geosynthetic assuming a parabolic deflection. Once these parameters are known, the geosynthetic properties required for reinforcement are determined.

Huckert et al. (2014) showed that Terzaghi's vertical stress is higher than was observed in physical and numerical experiments. Huckert et al. (2014) and van Eekelen and Bezuijen (2012) showed experimentally that an inverse triangular pressure distribution is observed in tests of geosynthetic reinforced embankments over voids and piled embankments respectively. As highlighted by Bezuijen and van Eekelen (2014), the presence of the geosynthetic influences arching, and using theories from unreinforced soil arching should not be directly applied to reinforced soils.

Without an understanding of the most appropriate pressure values and distribution, and interaction of the tensioned membrane and soil arching load transfer mechanism, the design of the geosynthetic is going to be conservative and potentially unviable for construction in application cases.

### 2.4 *Experiment objectives*

This series of testing was conducted in order to measure and observe the arching and deformation that occurs in a granular soil fill when a void is formed below it in both a reinforced and unreinforced case. This allows an understanding of arching in the soil, and how the presence of the geosynthetic impacts this. The aim of the tests was to observe if any interaction effects are evident, and measure the deflected shape of the geosynthetic and compare this to theoretical assumptions that have been made.

## 3 CENTRIFUGE MODELLING

Soil behavior is highly non-linear and dependent on the stress level applied by the self-weight of the soil. Centrifuge modelling is a physical modelling technique used to test small-scale physical models at an appropriate stress level in order for the model to reflect representative behaviour of the soil by applying an increased gravitational acceleration through the rotation of the centrifuge.

Centrifuge modelling was conducted in the 10m balanced beam centrifuge at the University of Cambridge at a gravitational acceleration of N = 40. A model consisting of a 50 mm wide rectangular trapdoor was used to simulate the formation of a small void (2 m prototype width). Plane-strain testing with the inclusion of a transparent boundary was chosen for the ability to obtain optical measurement of soil and geosynthetic displacements using Particle Image Velocimetry (PIV) (Stanier et al. 2015).

The load on the trapdoor was measured with a load cell in the centre whilst two Linear Variable Differential Transformers (LVDTs), one on either end of the door, are used to measure the displacements. An annotated photograph of the centrifuge package and trapdoor model used in the centrifuge is shown in Figure 2.

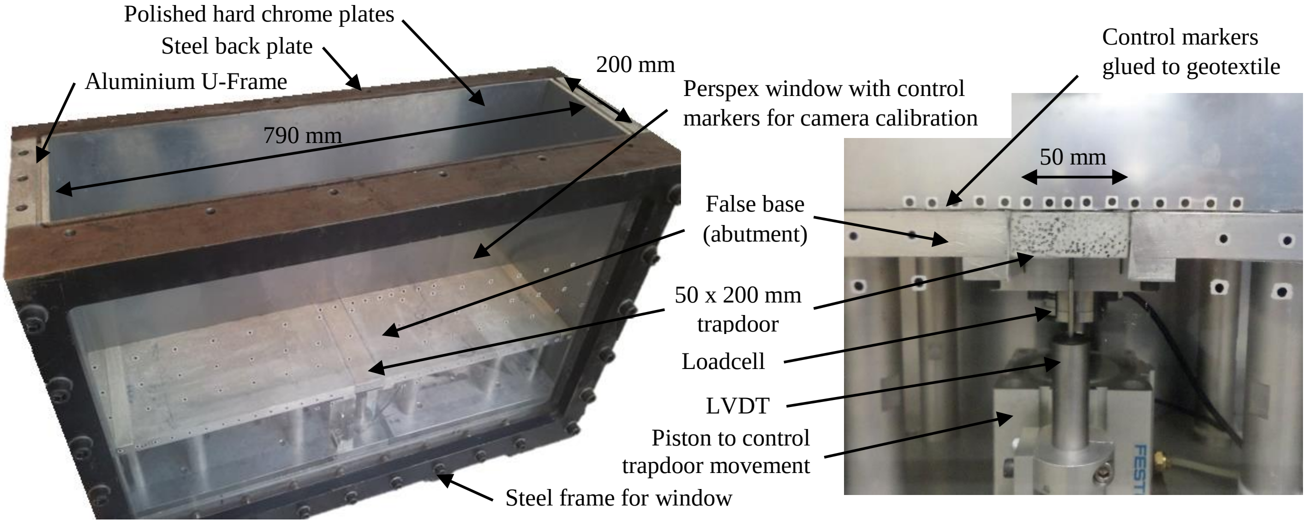


Figure 2: Centrifuge package and trapdoor model

## 3.1 *Setup*

Tests in both reinforced and unreinforced soils were conducted at a soil overburden height (H) to void width (B) ratio, H/B, of 1 (low overburden) and 3 (high overburden). These limits were chosen as the EBGEO German design guidelines for design of reinforced soil (EBGEO, 2010) define these points as the boundary between different structural behaviours of reinforced soil.

## 3.2 *Granular material*

Dry Hostun sand was used for the soil in the model; the sand used included a mix of approximately 5 % dyed blue sand to create more contrast and soil texture and allows better tracking of soil deformation in the image analysis. The soil has a $d_{50}$ of 0.480 mm, $\Phi_{crit}$ of 35.4°, and $e_{min}$ and $e_{max}$ of 0.555 and 1.01 respectively (Heron, 2014). The sand model was prepared at a target relative density (RD) of 85 % by using air pluviation with an automatic sand pourer as described by (Zhao et al., 2006). This achieves a consistent and uniform relative density of the soil. The soil properties achieved in the models tested are shown in Table 2; the soil height was measured to the nearest millimeter and in the tests with 50 mm soil height, this difference results in estimates of RD > 100% using the previously stated $e_{min}$ and $e_{max}$ parameters. The $e_{min}$ was adjusted to ensure that the maximum recorded density was 100%; the adjusted value was 0.51.

Table 2. Soil properties achieved in the centrifuge models

| **Test name** | **H/B** | **Soil height (mm)** | **Relative Density (%)** | **Unit weight (kN/m³)** |
|---|---|---|---|---|
| UNRNF 3 | 3 | 150 | 73.59 | 15.81 |
| UNRNF 1 | 1 | 50 | 92.24 | 16.76 |
| RNF A-3 | 3 | 150 | 79.11 | 16.08 |
| RNF A-1 | 1 | 50 | 100.00 | 17.19 |

## 3.3 *Geosynthetic material*

A model geosynthetic was selected for use in the tests based on scaling of the tensile strength-strain behavior as presented by Springman et al. (1992) and Viswanadham and Konig (2004). This scaling required that the tensile strength mobilized per unit width at any given strain is reduced by a factor of N from the prototype (full-scale) to the model material. The model tensile strength, $T_m$, is therefore equal to 1/N times the prototype tensile strength, $T_p$. Assuming a linear elastic behaviour of $T = J\varepsilon$, where $J$ is the secant stiffness and $\varepsilon$ is the strain, the model secant stiffness, $J_{m,}$ is 1/N times the prototype secant stiffness, $J_p$.

A woven polyester pollen mesh was used as a model geosynthetic reinforcement; a photograph of the model material is shown in Figure 3. Cyclic testing was conducted to determine the material stiffness. It was found that pre-straining the material to approximately 13% strain and then unloading and reloading gave a repeatable stiffness in the expected deformation range of the application of 10% strain. A minor amount of plastic strain was observed in each loading and unloading cycle, the average loading stiffness was 27.04 kN/m. This is equivalent to a prototype material stiffness of 1082 kN/m. The stress-strain curve is shown in Figure 4.

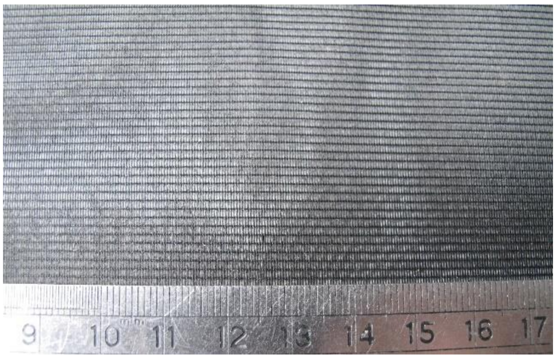


Figure 3: Model geosynthetic material

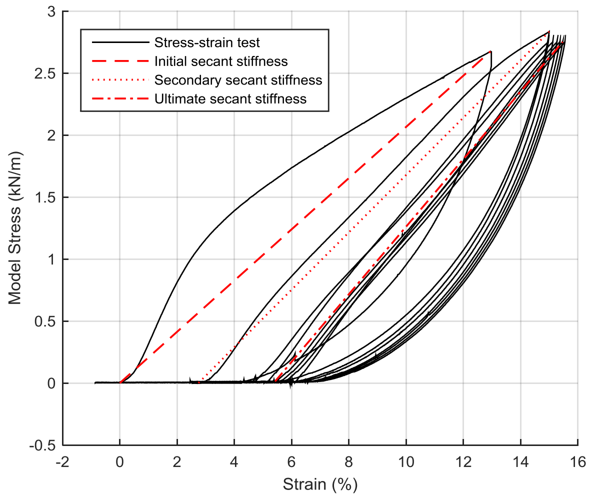


Figure 4: Cyclic stress-strain results of Pollen Mesh model geosynthetic material

## 4 RESULTS AND IMAGE ANALYSIS

### 4.1 *Soil deformation*

The deformation in the soil was assessed through PIV analysis of images captured during the lowering of the trapdoor.

The soil displacement profile for each test reported in this study is shown in Figure 5. In the reinforced tests, the displacement is shown for when the geosynthetic completely spans the void and carries the soil load without support from the trapdoor. The clearance between the trapdoor and deflected geosynthetic can be seen in the figures. In the unreinforced tests, the soil displacement profile at the equivalent displacement as when the geosynthetic spans the void in the reinforced tests.

The following observations can be made regarding the soil deformation:

- The unreinforced tests, Figure 5 (a) and (c), show an apparent rigid body motion of the soil directly above the trapdoor; the displacement contours are closely spaced indicating zones of high deformation and have steep sides approaching a triangular deformation profile
- In the reinforced tests, Figure 5 (b) and (d), there is expansion in the soil; the contours are distributed through the deformed soil, with deformation approaching a parabolic shape.
- Comparing the unreinforced and reinforced displacement profiles, the inclusion of the geosynthetic reinforcement appears to engage a greater volume of soil in the arching mechanism. This is evident by comparing the height and width of the smallest displacement contour shown, i.e. 0.5 mm. The reinforced tests limit the displacement to the profile shown; in the unreinforced tests further displacement would occur as the door is lowered further and no further movement would occur in the reinforced test.
- A visual comparison between the two reinforced tests shows that the soil displacement profile is approximately the same shape and size up until the point where the soil surface is intersected in the low overburden test. This implies that the arching in the soil is at an equivalent state in these tests, despite the difference in the overburden height. The application of Equation 1 with the modifications used in design discussed in Section 2.3 gives that in the deep

overburden test the soil load on the geosynthetic is more than double the load when the low overburden is used.

A study of the soil arching in unreinforced soils was conducted by da Silva et al. (2016). This study showed that the ultimate load reached in the yielding portion of the soil, .i.e. the load on the trapdoor, was approximately equivalent for the overburden heights tested of H/B = 1, 2 and 3. This is comparable to the result from the tests reported in this study showing that the soil arching state at the end of the test is equivalent in two reinforced tests conducted.

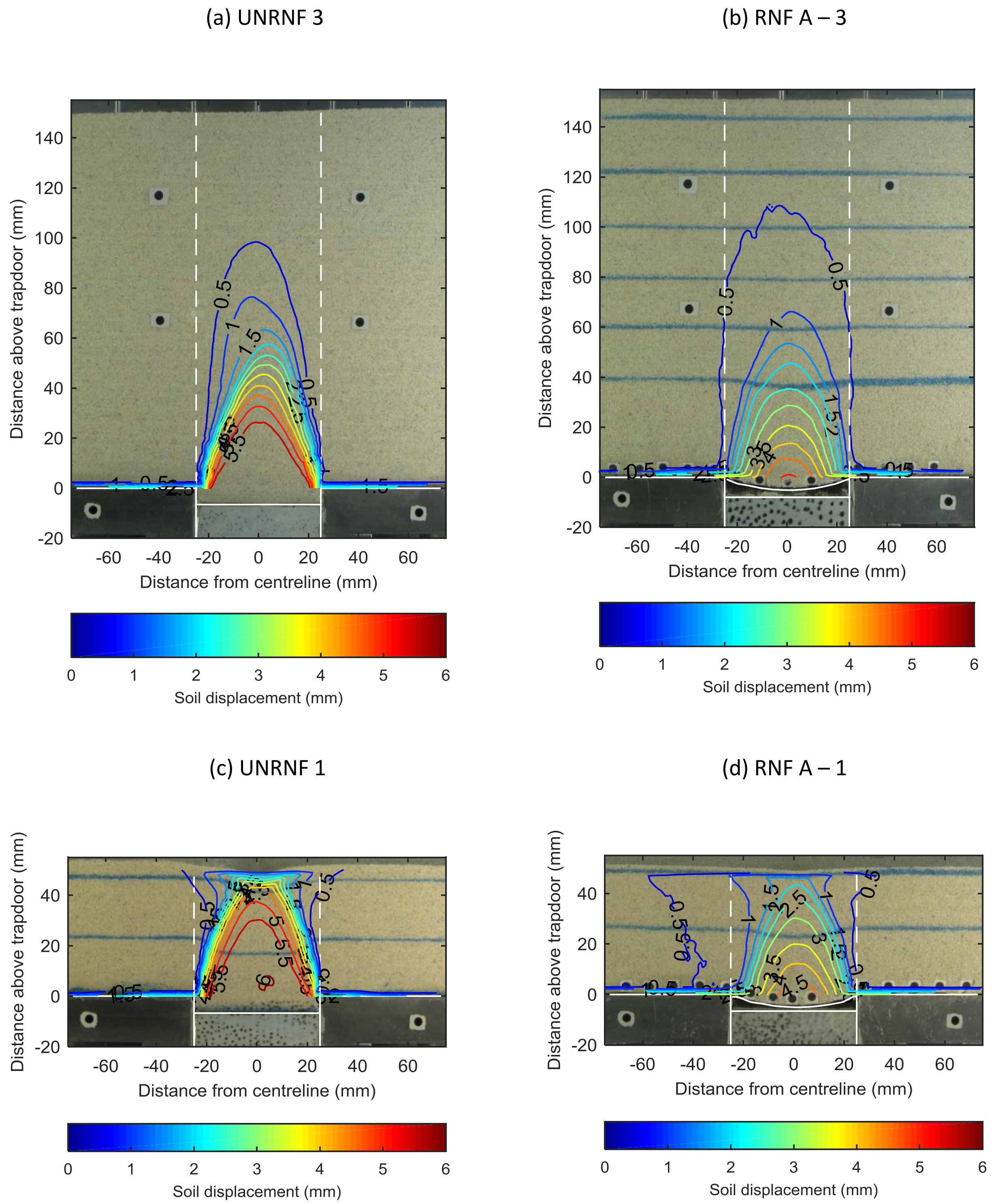


Figure 5: Soil displacement profiles for final arching state (a) Unreinforced soil, H/B = 3; (b) Reinforced soil, H/B = 3; (c) Unreinforced soil, H/B = 1; and (d) Reinforced soil, H/B = 1.

### 4.2 *Geosynthetic deflection*

The deflected geosynthetic profile for the reinforced tests was obtained from PIV analysis of the soil directly above the void; this is shown in Figure 6. The maximum central deflection measured was 5.09 and 5.17 mm for the tests with H/B ratios of 1 and 3 respectively.

This maximum central deflection and the deflected shape of the geosynthetic is approximately the same in the two reinforced tests; this is expected if the displacement profile within the soil is the same as seen in Figure 5 (b) and (d). This leads to an interesting observation that the load carried by the geosynthetic appears to be independent of the overburden height of the soil within the range of overburdens tested in this study.

The comparison of the measured profile to an equivalent parabolic and cubic curve estimated from the maximum deflection in the centre and fixed at the edges of the void is shown in the figure. The measured profile fits in between the two curves; from the data in Table 1, the load distribution acting on the geosynthetic appears to be in between a uniformly distributed vertical load, and inverse triangular load distribution.

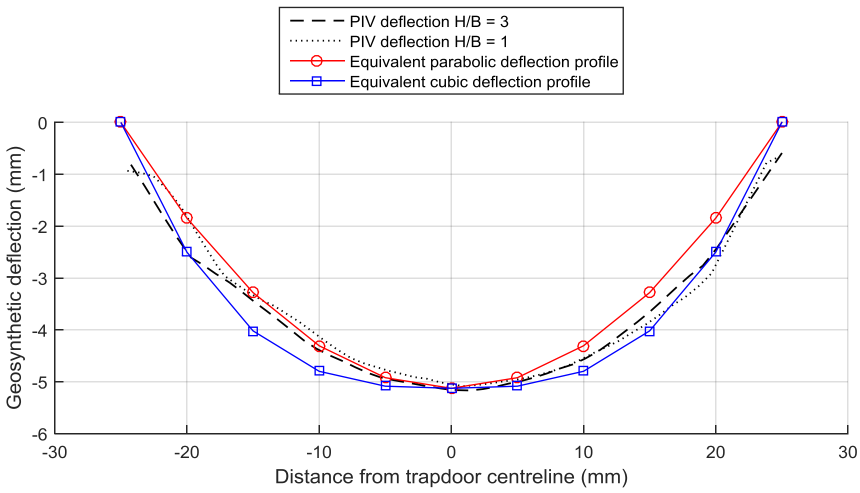


Figure 6: Measured deflected geosynthetic profile from PIV with parabolic curve-fit

## 5 CONCLUSIONS

Geosynthetic-reinforcement is used as a mitigation measure in applications where the potential for void formation or differential settlement exists below geotechnical structures. The differential movement causes arching in the soil, and the geosynthetic is required to span the void, and transfer the overburden soil load onto the stationary supports via tension in the membrane. From the tests conducted in the study, the ability of the reinforcement to limit the soil displacement can be seen.

The soil displacement profiles show that the mechanism of soil arching that occurs when a geosynthetic is present is different to when there is no geosynthetic. A wider and parabolic soil arch is engaged as opposed to a triangular deforming body of soil. Traditional understanding of soil arching may underestimate the arching in the soil, and result in estimates of higher load on the yielding area than are measured experimentally.

The shape of the deflected geosynthetic appear to show that the load carried by the geosynthetic when spanning a void is independent of the soil overburden height, as the shape is the same in the two tests conducted. Based on comparisons to parabolic and cubic deflection profiles, the pressure is not uniformly distributed and is greater closer to the supports than at the centre. A uniform pressure distribution results in a higher required strength of the geosynthetic in design methods.

These observations lead to the conclusion that assumptions used in design may be conservative. From analysis of these tests and further study and investigation, improvement to existing design methods can be made with a more thorough understanding of the behaviour of reinforced soils over voids.

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