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Comparative assessment of 1g and centrifuge uplift tests on steel grillage foundations

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ABSTRACT: Steel grillages, as an alternative to concrete foundations for overhead lines, offer construction advantages in remote and challenging terrains, such as those present in Scotland. Their non-concrete nature allows for transportation to the site and pre-fabrication using low-ground pressure vehicles or helicopters, eliminating the need for haul roads and removing concrete curing times, thereby accelerating construction. This paper compares the response of 1g and centrifuge uplift tests on steel grillage foundations, demonstrating ultimate uplift capacity comparable to a solid plate. However, they are subject to reduced stiffness with increasing grille-to-grille spacing, which is critical when assessing against displacement design criteria. The paper also explores the scaling of uplift displacement and the influence of particle size on stiffness by comparing two different particle sizes in both 1g and centrifuge testing. In 1g testing, two particle sizes were used: D_{50} of 0.13 mm (sand) and 4 mm (gravel). Centrifuge testing at 28g employed D_{50} sizes of 0.13 mm and 0.19 mm (sands/gravel substitute).

1 INTRODUCTION

The increasing deployment of renewable energy (predominantly on and off-shore wind) in Scotland (UK) has increased demand on the existing transmission infrastructure. With this demand set to rise, outstripping existing capacity, new localised or upgraded transmission infrastructure is required to meet future demand. However, much of the proposed line routes are in remote and challenging terrain, with limited or no access, posing significant challenges for currently adopted approaches that utilise concrete spread foundations (e.g. concrete pads or pyramids).

Grillage foundations are an alternative non-concrete solution for overhead line (OHL) foundations that are well suited to difficult terrain (Papailiou, 2017), behaving similarly to other shallow foundations (Stewart and Kulhawy, 1990). The concrete-free nature of these foundations allows for transportation to site pre-fabrication using low-ground pressure vehicles or helicopters. This eliminates the need for haul road construction and concrete curing time (28 days), thereby accelerating construction and reducing cost and environmental impact.

Steel grillages have a history of use for OHL foundations in the UK, falling out of fashion in the 1980s, despite having been shown to provide a comparable uplift resistance to solid plates for an s/w ratio, where s is the space separating grilles and w is the width of the grille, between $1 \leq s/w < 2$, though shown to have a less stiff response with increasing s/w ratios. (Martin, 1975; Danziger et al. 1989; Shepherd et al. 2024). The reduction in stiffness (i.e. greater mobilised displacement) is crucial when considering the serviceability of OHLs with a permissible vertical displacement of < 25 mm (National Grid, 2018).

Barata et al. (1985) attributed the loss of stiffness to the flow through between the grilles post-peak, with grillages backfilled with coarser sand and gravel exhibiting significantly reduced displacements.

This paper investigates the influence of particle size on the uplift load-displacement behaviour of scaled model grillages (and solid plate equivalent) in dense granular soils at 1g and increased g in the geotechnical centrifuge. The study also allows for the scaling of mobilised displacement in the centrifuge to be further investigated. Palmer et al. (2003) reported that the normal assumptions that displacements measured in the centrifuge scaled at the model scale factor significantly overpredicted the mobilised displacement experienced at prototype scale, despite accurately representing the scaled uplift capacity. It is, therefore, recommended that mobilised uplift displacements for pipeline uplift remain unscaled in centrifuge testing (Garnier *et al.* 2007), but it remains unclear whether this applies to all shallow foundations.

2 PHYSICAL TESTING

The testing process involves two distinct physical model setups, comprising a 1g plane-strain model at a 1:10 scale and a 1:28 centrifuge model. Both models use two different dry soils (different particle size distributions) at a relative density (D_r) = 82% (Dense), with one of the soils used for both setups. To further investigate the impact of particle size on the stiffness of the load-displacement response of grillage foundations, two grillages (as well as a solid plate) were tested for each setup and soil.

2.1 Model setup

The grillages discussed here have grille-to-grille spacing ratios of 1 and 5, where s is the space separating grilles and w is the width of the grille, as illustrated in Figure 1. To ensure consistent soil bed preparation, the grilles were modelled as T-sections (i.e. no upper flange blocking the pluviation path). These particular s/w ratios have been selected to provide a case in which the grillage has a comparable peak uplift resistance to a solid plate (s/w = 1) (albeit with reduced stiffness) and a grillage with a reduced peak-uplift resistance (s/w = 5).

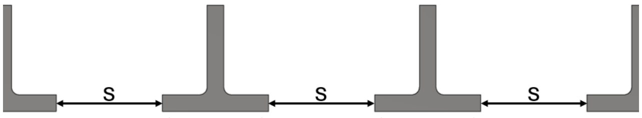

Figure 1 Illustration of grille-to-grille spacing ratio (s/w = 1 for the model shown)

The 1g plane-stain model discussed in Shepherd et al. (2024) was developed using standard 20 x 20 x 3 mm stainless steel T-sections fastened to three M8 threaded bars with a nut on either side of the web, which allowed for multiple s/w ratios to be investigated. The connection of the grillage to the stub (vertical shaft) was via two triangular plates fastened to the threaded bars, similar to the grilles. A schematic of the assembled 1g model is shown in Figure 2.

The centrifuge models were fabricated (3D printed) from stainless steel (316L) using direct metal laser sintering. The models were divided into two components, the grillage and the stub, connected with an M6 countersunk screw with the grillages featuring a countersunk clearance hole at their base and stub threaded at its base. Splitting the model in such a way allowed for the adjustment of stub heights to accommodate various embedment ratios for each s/w ratio fabricated. The scale (1:28) was predicated on the spacing (s) for the grillage with the smallest s/w ratio (s/w = 1) and mean particle sizes of HST95 sand (D_{50} = 0.14 mm (Lauder, 2010); for the recommended spacing between two embedded grilles ≥ 50xD_{50} (i.e. 7 mm) (Garnier *et al.* 2007) see Table 3 for s/D_{50} ratios for each model grillage and soil. The assembled centrifuge model is shown in Figure 3.

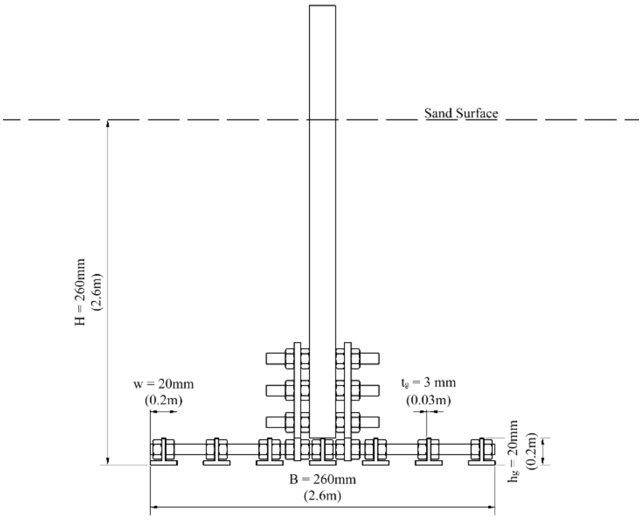

Figure 2 Dimension of assembled 1:10 1g model grillage (prototype dimensions shown in brackets)

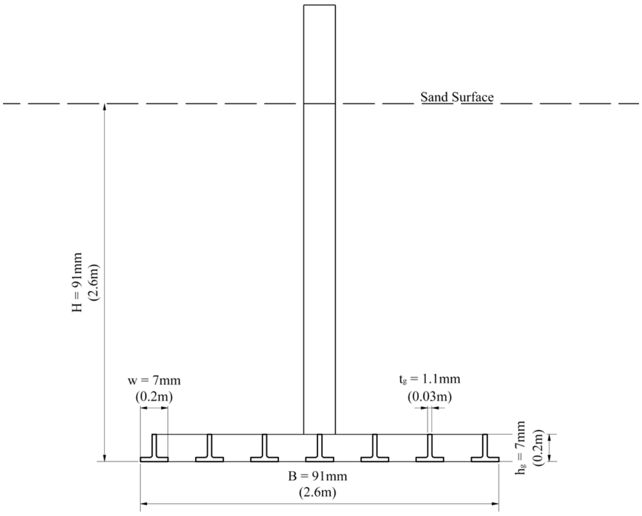

Figure 3 Dimension of 1:28 centrifuge model grillage (prototype dimensions shown in brackets

The dimensions of the 1g and centrifuge grillage models are summarised in Table 1, along with dimensions at the prototype scale, with a comparison of the two models shown in Figure 4.

Table 1 Grillage dimensions at model and prototype scale

Grillage Property	1g (mm)	Centrifuge (mm)	Prototype (m)
Scale	1:10	1:28	1:1
Width, B	260	91	2.6
Length, L	440	91	2.6 (4.4)*
Embedment, H	260	91	2.6
Grille width, w	20	7	0.2
Grille height, h_g	20	7	0.2
Grille thickness, t_g	3	1.1	0.03

** Prototype dimensions from plane-strain model in brackets*

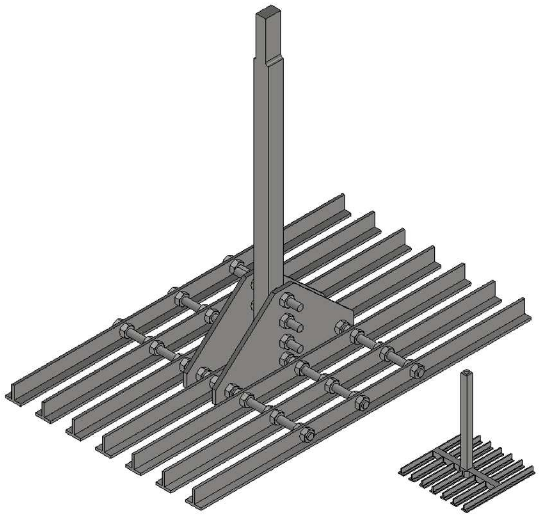

Figure 4 Size comparison between 1:10 1g plane-strain grillage and 1:28 centrifuge grillage at s/w=1

2.2 Test setup

2.2.1 Soil properties

Three different soils have been used in this study: two sands (HST50 & HST95) and one pea gravel (2-6 mm), with the HST50 sand used only for centrifuge setup and pea gravel exclusively for the 1g setup, with the HST95 sand being used for both test setups, with the sands being an analogue for a fine sand (HST95) and medium gravel (HST50) when scaled to prototype scale of the centrifuge model. The sands have been extensively tested to acquire and confirm their characteristics and behavioural properties (Lauder, 2010). The pea gravel properties were characterised using methods outlined in BS 1377-2, (2022) to determine the maximum and minimum dry density, PSD, and particle density. The shear behaviour properties of the pea gravel (at D_r = 82%) were determined through direct shear tests using the GDS large automated direct shear system (GDSLADS) (300 mm square) at a shearing rate of 1 mm/min with a total displacement range of 50 mm at a logging rate of 60 Hz. The soil properties are given in Table 2.

Table 2. Soil properties

Soil Property	Pea Gravel	HST50	HST95
Effective particle size, D_{10} (mm)	2.40	0.19	0.10
Average particle size, D_{50} (mm)	3.94	0.26	0.14
Critical state friction angle φ'_{crit} (°)	41.8	34.0	32.1
Dilation angle* at D_r=82%, ψ (°)	17.5	11.5	12.9
Peak friction angle* at D_r=82%, ϕ_{pk} (°)	55.9	43.2	42.3
Min dry density, ρ_{max} (kN/m^3)	14.4	15.1	14.6
Max dry density, ρ_{min} (kN/m^3)	15.6	17.2	17.6

**Inferred from best-fit peak strength relationship from direct shear tests for data at effective stresses between 5-80 kPa, at D_r=82%*

2.2.2 Soil bed preparation

The model foundations were wished in place (WIP) at a H/B = 1 for all tests. The soils were prepared to a D_r = 82%; the sands were via slot pluviation, and the gravel was hand-tamped in controlled layers. The foundations were WIP by preparing the soil bed to the required depth for H/B = 1, with subsequent soil placed (or pluviated) above. The 1g tests had one foundation per box (internal dims 900 x 448 x 448 mm) set at the centre of the box under plane-strain condition. The centrifuge tests were placed to allow two foundations per box (internal dims 800 x 500 x 434 mm) spaced evenly from each other (309 mm) and the edges of the box (155 mm). A summary of the test setups is given in Table 3.

Table 3 Summary of the test setups

Test ID	s/w ratio	s	s/D_{50}	Soil	g-level
1	0 (solid)	-	-	HST95	1
2	1	20	142.9		
3	5	100	714.3		
4	0 (solid)	-	-	Pea Gravel	
5	1	20	5.1		
6	5	100	25.4		
7	0 (solid)	-	-	HST50	28
8	1	7	50		
9	5	35	178.6		
10	0 (solid)	-	-	HST95	
11	1	7	26.9		
12	5	35	134.6		

2.2.3 Loading condition

The loading conditions of both test setups were conducted under monotonic displacement-controlled uplift. The 1g tests were carried out using an Instron-5985 UTM (Bluehill 3 control and logging software) attached with a 10 kN load cell, attached to the grillage stub via 3/4-inch (19.05 mm) wedge action tensile grips, uplifted at 10mm/min with a total displacement range of 30 mm, logging at 10 Hz.

Figure 5 University of Dundee Geotechnical Centrifuge

The centrifuge tests were carried out using a dual-axis actuator (rig) fitted with a Novatech F310-Z load cell with a limit of 20 kN, Figure 5, with the CompactRIO paired with Kollmorgen AKD servo-drives logging at 125 Hz. This rig is described as the "screw pile actuator" and has previously been described by Al-Baghdadi (2018); and Davidson et al. (2022). The centrifuge foundation models were attached via a coupler, illustrated in Figure 6, which allowed the foundation to remain free from the actuator while raising the g-level until displacement began.

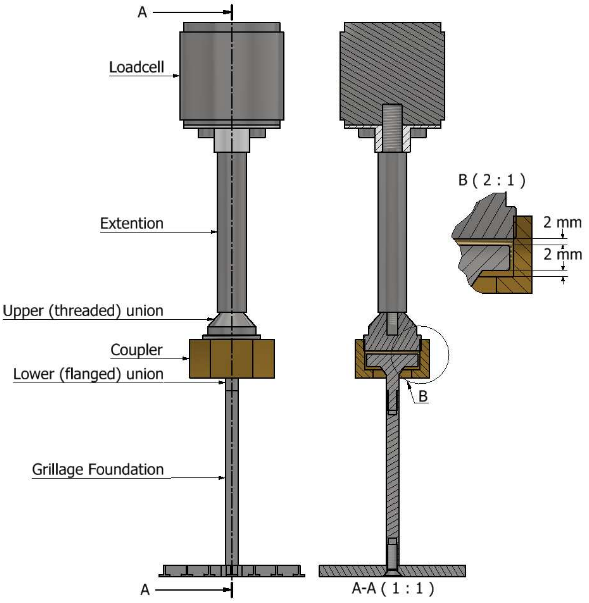

Figure 6 Schematic of centrifuge foundation loadcell connection (Davidson and Brown, 2021)

3 RESULTS AND DISCUSSION

3.1 Load-displacement response

The load-displacement response of grillage uplift tests at unit gravity and increased g are presented in Figure 7 and Figure 8, respectively. The resistance shown is the shear and weight mobilised from the soil (i.e., excluding self-weight). Both responses have been scaled up to prototype scale, with Force x N^3 for the 1g set-up and N^2 for the centrifuge, with displacement x N for both setups, where N is the scale factor of 10 and 28 for the 1g and centrifuge models, respectively.

The load-displacement results of the 1g plane-strain tests indicate that a comparable uplift resistance is achieved for an s/w ratio of 1 for the 2-6 mm pea gravel and HST95 sand, with a reduced capacity for an increased s/w = 5. It is also evident that stiffness decreases with increasing s/w relative to the solid plate equivalent, in agreement with the observations of Martin, (1975); and Danziger et al. (1989).

Comparing the response between the pea-gravel and HST95, the load-displacement response is similar regarding the initial development of capacity and stiffness despite the difference in s/D_{50} (see Table 3;) with the response between the two soils for an s/w = 5 almost identical (with s/D_{50} values of 25.4 and 714.3 for the gravel and sand, respectively). The differences emerge in the continual development of capacity post-yield in the gravel for the solid plate and s/w = 1 (s/D_{50} = 5.1); such a response is likely due to the interlocking of particles at very low effective stress, with the continual development and collapse of new shear bands at the edges of the foundation, where the failure wedge develops. The influence of particle interlocking was also evident with void formation beneath the base of these two foundations (solid and s/w = 1), observed through the Perspex end of the box, indicating plugging between the grilles of the grillage.

Similar is seen for the centrifuge load-displacement response for both HST50 and HST95 (with s/D_{50} values of 26.9 and 50 for s/w = 1 and 134.6 and 178.6 for s/w = 5, for HST50 and HST95 respectively; a comparable ultimate uplift resistance to a solid plate is mobilised for a grillage with an s/w ratio of 1, with a reduced capacity for the wider spacing ratio (s/w = 5). It is also noted that as the s/w ratio increases, the stiffness of the response decreases. The results support the findings of the 1g uplift tests and literature on the influence of the s/w ratio on the mobilised capacity. However, relative to the 1g test, the reduction in stiffness with increasing s/w is significantly greater for the centrifuge tests; this may be a result of increased dilation as a result of low effective stress in the 1g tests, limiting the flow through potential; or from an over-estimation of the mobilised displacement at prototype scale from the usual assumptions that displacements measured in the centrifuge scales with the model scale factor, as observed by Palmer et al. (2003) for the uplift of buried pipelines, despite accurately representing the scaled uplift capacity.

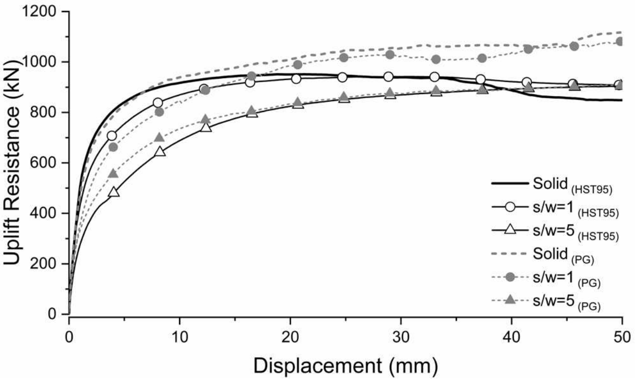

Figure 7 Uplift load-displacement response at prototype scale of 1g tests in 2-6mm Gravel & HST95 sand at D_r=82%

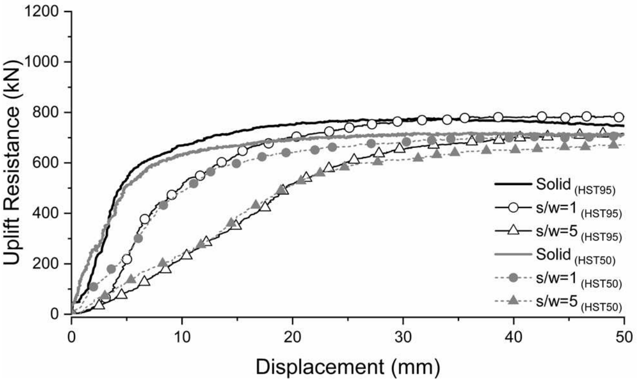

Figure 8 Uplift load-displacement response at prototype scale of centrifuge tests in HST50 & HST95 sand at D_r=82%

The uplift behaviour exhibited by the two soils is very similar in terms of the mobilised stiffness for all s/w ratios, with a reduced uplift resistance measured between HST95 and HST50 for the solid plate and s/w = 1 of around 65 kN, with a similar disparity between the two soils at an s/w ratio of 5; such a difference in capacity is anticipated due to the differences in soil unit weight and dilation angle accounting for 29.9 kN when determining capacity analytically (Giampa *et al.* 2019), and a slightly higher relative density for HST95 of $+ D_r = 4\%$ when back calculating.

For purposes of comparison between 1g and centrifuge test and comparing any influences of particle size on capacity, the design capacities, Q_D, derived using the tangent intercept method (BS EN 61773, 1997) are presented in Figure 9 as normalised as a breakout factor plotted against s/w ratio. The breakout factor F_q^* is derived from dividing the uplift resistance by the weight of the soil directly above the grillage ($Q/\gamma HA$), where Q is the uplift resistance, γ is the soil unit weight, H is the embedment depth, and A is the area of the grillage footprint.

The influence of particle size effects on the breakout factor is minimal for both the 1g and centrifuge setups, as illustrated in Figure 9. The value of F_q^* is most significant at s/w = 0 (i.e. solid plate), ranging from 2.11-2.33 and 1.71-1.88 for the centrifuge and 1g test, respectively, which decreases with increasing spacing ratio. At s/w ratios of 1 and 5, F_q^* ranges from 2.05-2.21 and 1.98-2.20 for the centrifuge tests and 1.69-1.77 and 1.54-1.69, respectively, for the 1g tests. The difference in breakout factor emerges from the difference in mobilised failure mechanism, in that the plane-stain model is restricted to developing a frustum from only two sides (i.e. reduced failure surface and mobilised soil volume), resulting in a reduced capacity. Slight differences are also likely due to influences of shear strength properties, which are not accounted for in the normalised breakout factor.

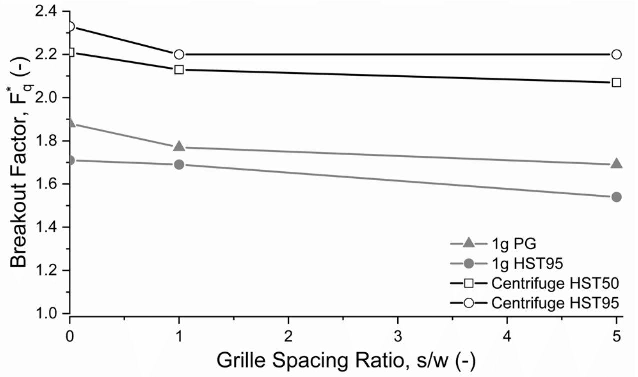

Figure 9 Influence of particle size s/w ratio on breakout factor (F_q^*) for 1g and centrifuge uplift test in dense soil (D_r=82%)

3.2 Mobilised displacements

The influence of the s/w ratio on stiffness may also be shown by presenting the normalised displacement Δ_D/Δ_{25} against s/w for the two test setups (see Figure 10), where Δ_D is the displacement associated with the derived design capacity (Q_D) and Δ_{25} (25 mm) is the permissible vertical displacment of OHL foundations often adopted in industry.

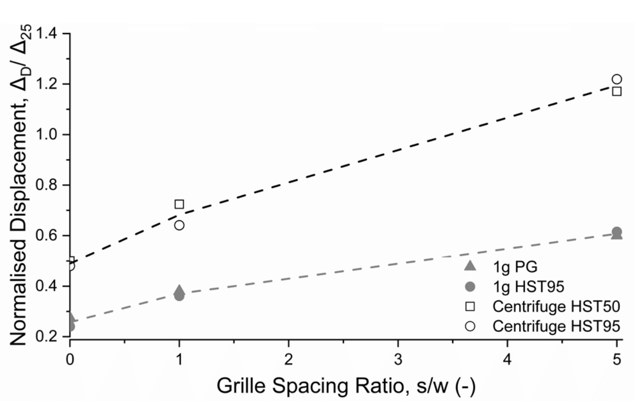

Figure 10 Influence of s/w ratio on normalised displacement Δ_D/Δ_{25} for 1g and centrifuge uplift test in dense soil (D_r=82%)

The normalised displacements of the scaled 1g and centrifuge vary from 0.26, 0.37 and 0.61 and 0.49, 0.68

and 1.19, respectively, for s/w ratios of 0, 1, and 5. It is notable that the normalised displacements of the centrifuge test are almost exactly double that of the 1g tests at each s/w ratio. The difference in scaled displacements indicates that the 1g test setup may be subject to enhanced stiffness response from the plane-strain conditions/low effective stress; at prototype scale, flow through the grilles may be enhanced; otherwise, particle size influences the scaling of displacements. As suggested by Stone et al. (2005). These issues will be the subject of further investigation.

4 CONCLUSION

The study indicates that particle size effects do not influence the capacity or displacements associated with uplifted grillages for a given s/w ratio at 1g or centrifuge model scale. However, the 1g test conducted with the coarser 2-4 mm pea gravel did experience particle interlocking associated with low effective stress levels.

The displacements associated with the derived design capacity at each spacing ratio were uninfluenced by particle size for each test. However, the relative scaled centrifuge displacements were twice the magnitude of the scaled 1g for all s/w ratios. The discrepancy may be associated with the low effective stress or plane-strain nature of the 1g setup. It may further indicate that normal assumptions that measured displacements in the centrifuge scaled with the model scale factor may not be entirely consistent with mobilised displacement experienced at the prototype scale.

Centrifuge and 1g testing in sands and gravels have indicated the grillages with a grille spacing-to-grille width of s/w ≤ 1 provides a comparable uplift resistance to a solid plate, with reduced capacity for wider spacings, with reduced stiffness with increasing s/w. Future testing will, therefore, assess the means of enhancing the stiffness response through geogrid reinforcement and backfilling regimes.

ACKNOWLEDGEMENTS

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