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Influence of grille spacing on the uplift behaviour of steel grillages for OHLs

Influence de l'espacement des grilles sur le comportement à l'élévation des grilles en acier pour les lignes aériennes électriques

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ABSTRACT: The increasing development of renewable energy (e.g. on and offshore wind) has increased the demand on existing electricity transmission networks in the UK. However, the remoteness of the transmission network, particularly in Scotland, makes upgrade and renewal, both economically and environmentally challenging, with often highly restrictive access constraints. Steel grillages are an alternative non-concrete foundation that can be loaded immediately post-backfill and transported to remote locations using low-ground pressure vehicles or helicopters. This paper investigates the optimisation of steel grillages for overhead line foundations such that the uplift load-displacement response is comparable to solid foundations (i.e. a concrete pad). Initial 1g uplift tests have shown that the optimal grille-spacing-to-width ratio (s/w) for a comparable ultimate uplift capacity to a solid plate lies within $1 < s/w < 2$.

RÉSUMÉ: Le développement croissant des énergies renouvelables (par exemple, les éoliennes terrestres et en mer) a augmenté la demande sur les réseaux de transmission d'électricité existants au Royaume-Uni. Cependant, l'éloignement du réseau de transmission, en particulier en Écosse, rend les travaux de modernisation et de renouvellement à la fois économiquement et environnementalement difficiles, avec des contraintes d'accès souvent très restrictives. Les grillages en acier sont une alternative aux fondations en béton qui peuvent être chargées immédiatement après le remblai et transportées vers des lieux reculés en utilisant des véhicules à basse pression au sol ou des hélicoptères. Cet article examine l'optimisation des grillages en acier pour les fondations de lignes aériennes de manière à ce que la réponse au déplacement sous charge de soulèvement soit comparable à celle des fondations solides (c'est-à-dire une dalle en béton). Les premiers tests de soulèvement à 1g ont montré que le rapport optimal entre l'espacement des grilles et la largeur (s/w) pour une capacité ultime de soulèvement comparable à une plaque solide se situe dans l'intervalle $1 < s/w < 2$.

Keywords: Grillage foundations; uplift; physical modelling; transmission infrastructure.

1 INTRODUCTION

The widespread and increasing development of both on- and offshore renewable energy in Scotland requires connection to the electrical transmission network. However, the existing network has insufficient capacity to meet future developments and new localised transmission infrastructure or upgrades are required. The current foundation design practice for new (or upgraded) overhead lines (OHLs) adopts material-heavy concrete spread foundations (e.g. concrete pads or pyramids). While these solutions have shown to be effective, they are not always practical when employed in remote and challenging terrain where limited or no access exists and often require the economically and environmentally costly operation of haul roads. Thus, recent interest in non-concrete alternatives has grown, such as those that can be heliborne or transported and installed using low-ground pressure vehicles, speeding up construction time and negating concrete's 28-day curing time before backfilling and loading. One alternative non-concrete solution is steel grillages, consisting of multiple standard steel sections (e.g. I-beams and angle sections) bolted together (Papailiou, 2017). Steel grillage foundations have been utilised extensively for steel lattice towers but fell out of fashion in the 1980s, coinciding with the development of drilled concrete cast in-situ piles (Kulhawy *et al.*, 1983). Unfortunately, this led to a loss of knowledge and experience of these foundation types in the UK, specifically concerning their required configurations for resisting uplift forces. This paper investigates the optimum grille spacing of grillages subjected to uplift in granular soils through a series of scaled 1g uplift tests to address this knowledge gap.

1.1 Current UK design approach

The frustum method is a commonly adopted approach for determining the uplift capacity of shallow foundations for OHLs (National Grid, 2018). However, it is unclear whether the frustum method applies to grillages. Further guidance exists in BS EN 50341-1 (2012), stating that the net area of the grillage may be assumed, given that the spacing between grilles (s) does not exceed ⅓ the width (w) of the grilles and thorough backfill compaction is achieved. In addition to the uplift capacity, National Grid (2018) sets a serviceability criteria of 25 mm maximum vertical displacement.

The method assumes the resistance (Q_{FM}) is the sum of the weight of the foundation (W_f) and the weight of soil above the foundation confined within an inverted frustum (W_s) extending upwards at angle θ from the base of the foundation (Eq. 1-3):

$$Q_{FM} = W_f + W_s \tag{1}$$

$$W_s = \tfrac{1}{3}H\gamma(B^2 + B \cdot B_s + B_s^2) \tag{2}$$

$$B_s = \mathrm{B} + 2\mathrm{H}\tan\theta \tag{3}$$

where H is the embedment depth (m), B is the foundation width (m), and γ is the soil unit weight (kN/m^3). The frustum angle θ is dependent on the raw SPT N-value for granular soils, of, typically 15° for $10 \leq N < 20$ and 25° for $20 < N$.

1.2 Alternative uplift design approach

Alternative approaches for determining the uplift capacity of shallow OHL foundations have been investigated by Davidson and Brown (2021), showing that Giampa et al. (2019) best estimated the uplift capacity in granular soils. The method assumes the failure mechanism develops as an uplifted wedge at the dilation angle (ψ), mobilising shear resistance along the failure surface at the four triangular wedges along the perimeter (F_2) and conical wedges at the corners (F_3), and resistance from the weight of confined soil directly above the foundation (W_1), four triangular wedges along the perimeter (W_2), and conical wedges at the corners (W_3) (Eq. 4-9):

$$Q_G = F_2 + F_3 + W_1 + W_2 + W_3 \tag{4}$$

$$F_2 = \tfrac{1}{2}\gamma H^2 p\left(\tan\phi_{pk} - \tan\psi\right)\left[\left(\frac{1+k_0}{2}\right) - \frac{(1-k_0)\cos 2\psi}{2}\right] \tag{5}$$

$$F_3 = \tfrac{1}{3}\pi\gamma H^3\left(\tan\phi_{pk} - \tan\psi\right)\cos\left(\phi_{pk} - \psi\right) \tag{6}$$

$$W_1 = \gamma H A \tag{7}$$

$$W_2 = \tfrac{1}{2}\gamma H^2 p \tan\psi \tag{8}$$

$$W_3 = \tfrac{1}{3}\pi\gamma H^3 \tan\psi \tag{9}$$

where A and p are the foundation's area (m^3) and perimeter (m^2), ϕ_{pk} is the peak friction angle, and K_0 is the lateral earth pressure coefficient (at rest).

2 PHYSICAL TESTING

The 1-g testing regime consisted of developing a reduced (1:10) plane-strain model grillage to investigate the influence of the grille-to-grille spacing ratio (s/w) where s is the spacing between grilles and w is the grille width, as illustrated in Figure 1.

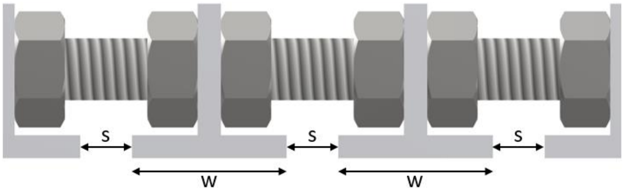

Figure 1. Illustration of grille-to-grille spacing ratio of (1:10) model grillage (s/w = ⅓ for the model shown).

2.1 Model setup

The grillage models developed allowed for multiple grille spacing (s/w = 1/2, 1/3, 1, 2, 5, and solid) while keeping the overall width of the foundation constant. The grilles were modelled using T-sections to allow for consistent compaction of sand between the grilles during sand bed preparation. The grilles were connected via three M8 threaded bars running perpendicular to an attached vertical shaft (stub connection). The positioning and spacing of individual grilles were controlled using M8 nuts placed on either side of the web. The dimensions and schematic of the model grillage are given in Table 1 and Figure 2, respectively.

The scale of the T-section, and thus the grillage, was chosen based upon the D_{50} particle size (0.14

mm (Lauder, 2010)) so that the particle scaling law requiring an opening between two embedded grilles to have a spacing ≤ 50 x D_{50}, (Garnier *et al.*, 2007), matching the smallest grille spacing (7mm). The grille length matched the box width to create plane-strain conditions for further investigation into the mechanistic behaviour.

Table 1. Grillage dimensions at model and prototype scale.

Grillage Property	**Dimension**	
	Model (mm)	**Prototype (m)**
Width, $\boldsymbol{B}$	260	2.6
Length, $\boldsymbol{L}$	440	4.4
Embedment, $\boldsymbol{H}$	260	2.6
Grille width, $\boldsymbol{w}$	20	0.2
Grille height, $\boldsymbol{h_g}$	20	0.2
Grille thickness, $\boldsymbol{t_g}$	3	0.03

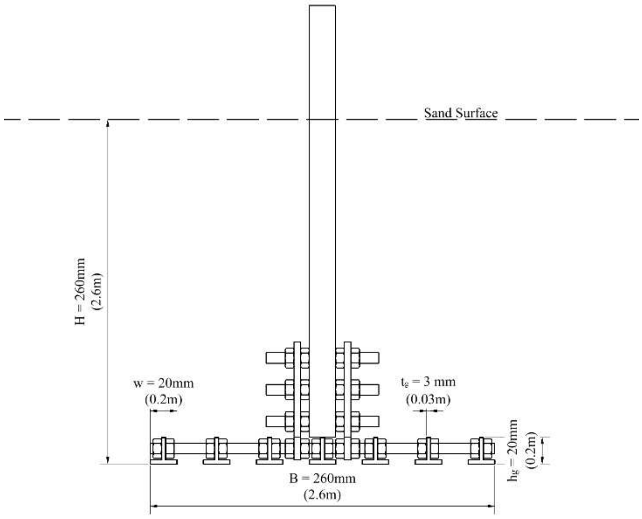

Figure 2. Dimension of assembled model grillage (assumed prototype dimensions shown in brackets).

2.2 Testing programme

The sand used for testing was dry HST95, which has been extensively characterised (Lauder, 2010). The relative densities investigated in this research are medium-dense (D_r = 42%) and dense (D_r = 82%). The properties relevant to determining the analytical capacity are given in Table 2.

Table 2. HST95 sand properties required for analytical comparison (Lauder, 2010).

Property	**Relative Density, $\boldsymbol{D_r}$**	
	42%	**82%**
Dry unit weight, $\boldsymbol{\gamma}$ (kN/m^3)	15.8	17
Peak friction angle, $\boldsymbol{\phi_{pk}}$ (°)	37.4	45.4
Dilation angle, $\boldsymbol{\psi}$ (°)	6.5	16.9
Earth-pressure coefficient, $\mathbf{K_0}$	0.47	

The soil boxes (internal dimensions 900 x 448 x 448 mm) were prepared through pluviating sand to a bed thickness of h = 140 mm, the grillage placed at the centre of the box and sand pluviated above (i.e. wished in place) to a depth H = 260 mm (H/B = 1).

The uplift tests were conducted using an Instron-5985 UTM (Redhill 3 software) attached with a 10 kN load cell fitted with ¾ inch (19.05 mm) wedge action tensile grips fastened to the grillage stub. Uplift was tested under displacement-controlled loading at 10 mm/min, terminating after 50 mm of displacement at a logging rate of 0.1 Hz.

3 RESULTS AND DISCUSSION

3.1 Load-displacement response

Load-displacement responses at prototype scale (scale factor N = 10) are presented in Figure 3 and Figure 4, for D_r = 42% and 82%, respectively. The uplift resistances are the resistance mobilised from the soil shear and weight (i.e., excluding the grillage self-weight). At the prototype scale (i.e. Force x N^3 and displacement x N), the ultimate uplift resistance mobilised from a solid plate for D_r = 42% and 82% is 828 kN and 951 kN, respectively. Comparable uplift resistances are observed for s/w ratios of ⅓-to-1 (medium-dense) and ⅓-to-2 (dense).

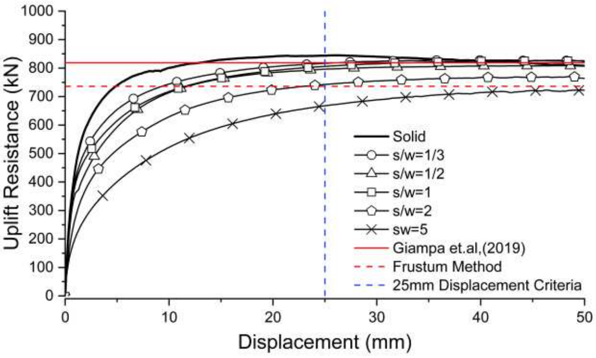

Figure 3. Uplift load-displacement response of grillages in medium-dense sand D_r = 42% at prototype scale.

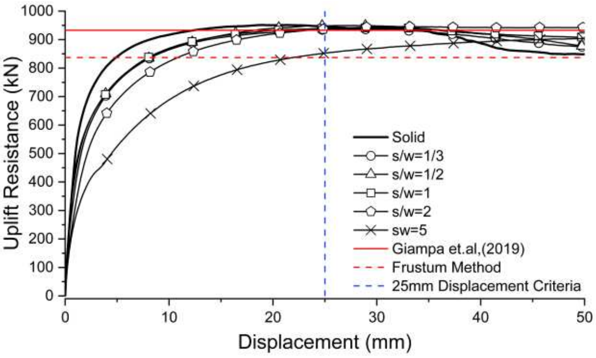

Figure 4. Uplift load-displacement response of grillages in dense sand D_r = 82% at prototype scale.

Whilst the peak uplift resistance is comparable to a solid plate ($s/w = 0$), the load-displacement responses reveal a reduction in stiffness with increasing s/w, as Danziger et al. (1989) observed due to soil flowthrough between the grilles. However, the reduction in stiffness is significant when assessing the design capacity against the permissible displacement of OHL foundations of 25 mm (denoted as the blue dashed line). The reduction in stiffness with increasing spacing ratio of these tests is likely suppressed by increased dilation experienced at 1g and the influence of the plain strain conditions.

The influence of grille spacing is better illustrated in Figure 5, which shows the normalised breakout factor, $F_q^* = (Q/\gamma HA)$, using a design load (Q) derived from the tangent intercept method. However, significant reductions in capacity are noted for larger s/w ratios, with an optimum spacing of $s/w < 1$ for $D_r = 42\%$ and $s/w < 2$ for $D_r = 82\%$, in agreement with the findings of Martin (1975), who observed an optimum $s/w = 1.75$.

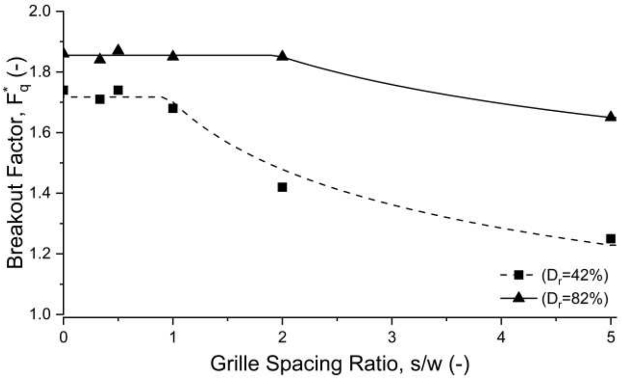

Figure 5. Influence of grille-to-grille spacing ratio (s/w) on breakout factor F_q^* for medium-dense and dense sands.

3.2 Comparison to analytical solutions

Comparing the uplift capacity to the analytical solutions (broken down into the plane-strain components, i.e. not including the wedge components along the Perspex interface), the method proposed by Giampa et al. (2019) (denoted by the solid red line in Figure 3 and Figure 4) provides a good estimate of 819 kN (-3%) and 933 kN (-2%) for $D_r = 42\%$ and 82% respectively, whereas the Frustum method (denoted by the dashed red line) underestimates the capacity, with predicted capacities of 736 kN (-13%) and 837 kN (-12%), respectively. Demonstrating that uplift capacity can be determined using existing analytical solutions assuming the net area of the grillage for spacing ratios of $1 \leq s/w < 2$. This is a significantly wider range of operation than the s/w = ⅓ specified in BS EN 50341-1 (2012), i.e. a potential for significant material savings in grillage adoption.

4 CONCLUSION

The results suggest that the optimum grille-to-width ratio in terms of uplift capacity (acting like a solid) lies between $1 \leq s/w < 2$ (density dependant), which is a wider operational range than the s/w = ⅓ proposed in BS EN 50341-1 (2012). However, an alternative design criterion may be required to consider the reduction of stiffness with increasing s/w. As these tests were undertaken at 1g, further investigation through scaled centrifuge modelling is needed to verify the observed reduction in performance in terms of stiffness.

Further investigation will focus on a series of centrifuge tests that first validate the observations of the influence of grille-to-grille spacing on both capacity and stiffness, scaling of uplift displacement, and influence of particle size before investigating means of enhancing the uplift load-displacement response (in terms of stiffness) through geogrid reinforcement and backfill compaction.

ACKNOWLEDGEMENTS

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