An Evaluation of Soil-Geogrid Interaction Models

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ABSTRACT

Analytical models from literature for geogrid pullout resistance were reviewed in this study. The models were characterized as either grid-like or planar, rigid or non-rigid, and based on whether they predict the load displacement curve or only the ultimate pullout resistance. Seven of the models were reviewed in terms of their adequacy to capture soil-geogrid interaction. Three of these models are related to the FHWA model and four to the mechanistic model by Jewell et al. (1984). The sensitivity of these seven models to normal stress, embedded length, friction angle and transverse rib thickness is compared to experimental observations. For the mechanistic models, the plasticity solution for bearing resistance that best captured the sensitivity differed depending on the variable under consideration. The FHWA model with $F^*\alpha$ a function of normal stress best represented the experimentally observed sensitivity of pullout resistance to the four variables considered. When using the default $F^*\alpha$ values, the FHWA model was less sensitive to the input variables than the experimental results, i.e., the model was conservative.

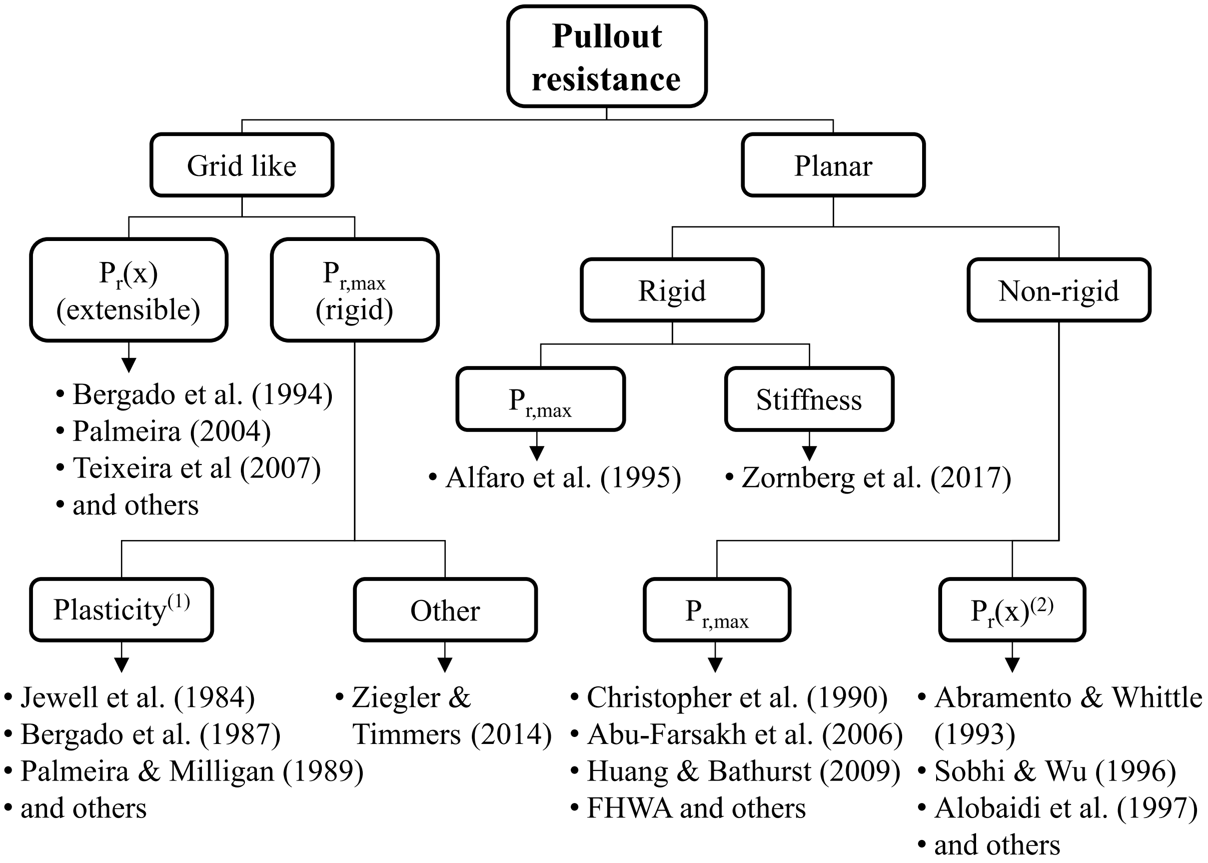
INTRODUCTION

Characterization of soil-geogrid interaction lies at the heart of designing with geogrids, whether for reinforcement or stabilization applications. Conventional geotechnical design procedures typically do not consider the interaction of individual geogrid ribs with particles of soil. Rather, the behaviour of the soil-geogrid composite is considered, e.g., the interface shear strength, the pull-out strength, or the coefficient of soil-geosynthetic interaction. However, modelling the contribution and behaviour of the individual ribs is useful when investigating the difference in performance of several geogrids in a soil type, or the difference in performance of a given geogrid in different soil types.

In this work, analytical models for soil-geogrid interaction during pull-out are discussed. A subset of these models is also compared to experimental results in terms of their sensitivity to a series of key variables.

FOUR GROUPS OF MODELS IN LITERATURE

The prediction of geogrid pullout capacity has been thoroughly studied in literature. The models were developed either by considering the interaction of individual ribs with the soil or by calculating an average interaction factor across the geogrid. Thus, the models can be broadly categorized as either considering the geogrid as a grid-like inclusion or a planar inclusion. One can further distinguish between models that predict the full load-displacement curve ($P_r(x)$) and those only concerned with the ultimate pullout capacity ($P_{r,max}$). Finally, some models simplifies the geogrid to be a rigid body. A summary of the different types of analytical models is shown in Figure 1. This diagram is by no means exhaustive. Four of these groups of models are discussed in the following sections.



Notes

1) Can be simplified to a planar model
2) Mostly for geotextiles

Figure 1. Classification of analytical models for pullout resistance.

Grid-like, ultimate strength (rigid), plasticity

One of the first analytical models for geogrid pullout resistance was presented by Jewell et al. in 1984. The pullout resistance (P_r) is modelled as the sum of the frictional resistance along the surface of the geogrid ($P_{R,F}$) and the bearing resistance of the individual transverse ribs ($P_{R,B}$):

$$\begin{aligned} P_R &= P_{R,F} + P_{R,B} \\ &= 2 \cdot \alpha_f L_e \sigma_\mathrm{n} \tan\delta + A_b \cdot \frac{L_e}{S} \cdot \sigma_b \end{aligned} \tag{1}$$

where a_f is the fraction solid area of the geogrid, L_e is the embedded length, σ_n is the normal stress acting on the geogrid, δ is the soil-geogrid interface friction angle, A_b is the average area of a transverse rib, S is the spacing of the transverse ribs and σ_b is the bearing resistance of an individual transverse rib.

Jewell et al. (1994) combined the contribution of the frictional resistance and bearing resistance into a single interaction f_b as shown in Equation 2. A similar model that considered the frictional resistance of the transverse separate from that of the longitudinal ribs was presented by Koerner et al. in 1989.

$$P_r = 2L_e \sigma_n \tan\phi \, f_b \tag{2}$$

$$\text{where } f_b = \alpha_f \left(\frac{\tan\delta}{\tan\phi}\right) + \frac{\sigma_b}{\sigma_n} A_b \cdot \frac{1}{S} \cdot \frac{1}{2\tan\phi} \tag{3}$$

The bearing resistance (σ_b) for an individual transverse rib can be calculated from plasticity theory. Two solutions were presented by Jewell et al. (1984) for granular materials. The first ($\sigma_{b,upper}$, Equation 4) assumed the ribs to be a rotated horizontal footing and formed an upper bound to the experimental results. The second ($\sigma_{b,lower}$, Equation 5) assumed a punching failure, and was a lower bound to the experimental results. An alternative solution by Matsui et al. (1996), shown in Equation 6, falls between the two. For cohesive backfill, Bergado et al. (1987) assumed the ribs to be a deeply embedded strip footing when calculating the bearing resistance.

$$\sigma_{b,lower} = e^{\left(\frac{\pi}{2}+\phi\right)\tan\phi} \cdot \tan\left(\frac{\pi}{4}+\frac{\phi}{2}\right) \cdot \sigma_n \tag{4}$$

$$\sigma_{b,upper} = e^{\pi\tan\phi} \cdot \tan^2\left(\frac{\pi}{4}+\frac{\phi}{2}\right) \cdot \sigma_n \tag{5}$$

$$\sigma_{b,Matsui} = \sigma_n e^{\pi\tan\phi} \tan\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\left[\cos\left(\frac{\pi}{4}-\frac{\phi}{2}\right) + (1-\sin\phi)\sin\left(\frac{\pi}{4}-\frac{\phi}{2}\right)\right] \tag{6}$$

The models in Equations 1 to 6 are the only purely mechanistic models considered in this paper, that is only the results of unit cell tests are required to predict pullout capacity. All subsequent models include one or more coefficients calibrated in various forms of pullout tests.

Some authors (Palmeira and Milligan, 1989; Jewell, 1990; Bergado & Chai, 1994; Moraci & Gioffre, 2006; Cardille et al., 2017; and others), recommended minor adjustments to the model in Eq. 1 to better capture the effect of interference between transverse ribs. These adjustments are based on the experimental observation that interference occurs when S/t is less than 50 (Palmeira & Milligan, 1989).

The models discussed above all approximate the transverse ribs of the geogrid as footings that increases the pullout resistance by providing bearing resistance. In contrast, Ziegler & Timmers (2004) assumed that the transverse ribs cuts into the soil like a plough. The volume of soil mobilized by these transverse "ploughs" provides frictional resistance against the adjacent soil body, and this increases the pullout resistance of the composite.

Planar, ultimate strength (non-rigid)

In 1990 Christopher et al. presented a model for ultimate pullout resistance of planar reinforcement:

$$P_r = F^* \cdot \alpha \cdot \sigma_v \cdot L_e \cdot C \tag{7}$$

where F^* is the pullout resistance factor, α a scale correction factor and C a constant equal to 2 for geogrids.

The model in Equation 7 is in the same general form as that of Jewell et al. (1984) (see Equation 2). That is, pullout resistance is a function of normal stress, friction angle, length, and a factor representing soil-geogrid interaction. Furthermore, in the absence of experimental data F^* can be calculated from contribution of the individual ribs as in the case of Jewell et al. (1984). However, in current practice $F^*\alpha$ is either considered to be a single variable calculated from experimental data (Huang & Bathurst, 2009), or the default values in the FHWA design guide (Berg et al. 2009) is used:

$$F^* = \frac{2}{3}\tan\phi \text{ and } \alpha = 0.8 \text{ for geogrids} \tag{8}$$

In the original model by Christopher et al. (1990), the α factor represented the extensibility of the geosynthetic and the strain softening behaviour of the backfill. Thus, the model is classified as non-rigid for this study.

Several authors have refined this model for specific use cases. Alfaro et al. (1995) separated the contribution of the purely frictional resistance to pullout ("2D interaction") from the restrained dilatancy at the edges of the geogrid ("3D interaction"). The so-called "3D interaction" at the edge of the geogrid was back calculated from experimental data for each configuration. Abu-Farsakh et al. (2006) proposed a modification to calculate the scaling factors for cohesive soils.

Huang & Bathurst (2009) investigated the accuracy of the FHWA model for a database of 478 pullout tests. They proposed a non-linear model following earlier experimental studies that showed the non-linear relationship between normal stress and pullout resistance:

$$P_r = \beta(2\sigma_v L_e F^* \alpha)^{1+\kappa} \tag{9}$$

where $\beta = 5.51$, $1 + \kappa = 0.629$ and $F^*\alpha$ is the default FHWA factors.

Similarly, Miyata & Bathurst (2012) proposed non-linear modifications to the Japanese model for pullout resistance.

Grid-like, load-displacement (non-rigid)

The mechanistic models based on plasticity theory (Eq. 1 to 6) are limited in that it does not consider the extension of a geogrid during pullout. Furthermore, these models cannot predict the development of the pullout resistance with displacement. As an alternative, several authors developed incremental models (Palmeira, 2009) for pullout-displacement. These models have the following general form:

1) Assume a displacement and force at the front of the geogrid.
2) Calculate the bearing resistance mobilized at the first transverse rib due to the displacement, the extension of the first segment due to the applied force, and the frictional resistance of the first segment.
3) Calculate the bearing resistance, extension and frictional resistance for subsequent ribs based on the extension of the prior segments.
4) Iterate by adjusting the applied force until the force at $L_e = 0$ is 0.

The models differ in their assumption regarding the development of rib bearing resistance with displacement, as well as the constitutive relationship assumed for the shear stress along the interface. For example, Bergado & Chai (1994) modelled the bearing resistance to increase hyperbolically with displacement. The relationship between shear stress and displacement was assumed to be elastic-perfectly plastic. Sieira et al. (2009) modelled the bearing resistance to increase linearly with geogrid strain and the shear-stress to be hyperbolically related to displacement.

Alternatively, Palmeira (2004) and Teixeira et al. (2007) used the results of single transverse rib pull-out tests as input to the model. In addition, the model by Teixeira et al. (2007) requires experimentally measured frictional resistance of isolated longitudinal ribs. Thus, a significant limitation of this group of models is that they often require involved calibration coefficients.

Planar, load-displacement and stiffness (non-rigid)

The interaction mechanism between geotextiles and soil is typically simpler than that between a geogrid and soil. Consequently, the development of tensile stress along a length of geotextile can be accurately modelled by considering the local equilibrium along the interface:

$$\frac{dT}{dx} = -2\tau \tag{10}$$

where dT is the change in unit tension over a length dx and τ the interface shear stress between the geosynthetic and the soil.

Different assumptions have been made in the literature to solve the partial differential equation. Abramento & Whittle (1993) used shear lag analysis from the field of fibre reinforced composites. Other authors assumed the shear stress-displacement relationship to be elastic-perfectly plastic (Sobhi & Wu, 1996), bi-linear (Madhav et al., 1998), hyperbolic (Gurung et al., 1999; Perkins & Cuelho, 1999) or strain softening (Alobaidi et al., 1997). Furthermore, the stress-strain response of the geosynthetic can be modelled as linear elastic (e.g. Sobhi & Wu, 1996) or hyperbolic (e.g. Perkins & Cuelho, 1999).

Weerasekara & Wijewickreme (2010) considered the resistance contributed by the section of the soil that has strained post-peak separate from resistance where the shear stress is still developing. Pullout tests for design projects are typically done in unsaturated soils, consequently, Ghazavi & Bavandpouri (2022) explicitly considered the effect of matric suction when modelling the pullout resistance.

Even though these models are developed for geotextiles they can be used to analyse the distribution of stress and strain in a geogrid during pullout (e.g. Sugimoto & Alagiyawanna, 2003). In addition, Zornberg et al. (2017) solved Equation 10 to derive the stiffness of the soil-geosynthetic composite at small strain.

Summary of the available models

Multiple analytical models have been developed to predict geogrid pullout capacity. These models range from simple empirical models to complex, iterative models that require calibration coefficients from non-conventional tests. The accuracy of the models typically increases with complexity. However, the complex models are not necessarily practical for conventional design or for use in sensitivity studies where multiple calibration coefficients would be required.

The mechanistic model by Jewell et al. (1984) and the semi-empirical FHWA models are simpler to implement but may not capture the complex mechanisms of soil-geogrid interaction. To investigate the validity of these simpler models, the sensitivity of the predicted pullout capacity to a series of key variables will be compared to experimentally measured sensitivity.

SENSITIVTY ANALYSIS OF GEOGRID PULLOUT RESISTANCE

Several factors affect the ultimate resistance of a geogrids in a pullout test. Some of these relate to the experimental setup such as the length of the sleeve at the opening, the method of applying normal stress and the flexibility of the face (Farag & Acar, 1993; Sugimoto et al, 2001; Wang et al, 2017). Others relate to the boundary conditions imposed during the test, such as the magnitude of the normal stress and the displacement rate. Finally, the soil properties, geogrid properties and soil-geogrid interaction all contributed to the measured resistance.

To study the relevance of some of the analytical models discussed above, the sensitivity of these models to the tests variables was compared to pullout results reported in literature. Only the ultimate pullout resistance was considered for the analysis, and only two sets of models will be analysed: 1) the purely mechanistic model by Jewell et al. (1984) for a rigid geogrid and 2) the mostly empirical model by Christopher et al. (1990) that considers geogrid extensibility.

For the mechanistic model, the bearing resistance of the transverse ribs was calculated using the solution that forms a lower bound (Eq. 4), the one that forms an upper bound (Eq. 5) as well as the solution by Matsui et al. (1996) (Eq. 6) as recommended by Moraci & Gioffre (2006). For the empirical models the FHWA model with default values (Eq. 7), the FHWA model with an average $F^*\alpha$, the FWHA model with normal stress dependent $F^*\alpha$ (Huang & Bathurst, 2009) and the non-linear model by Huang & Bathurst (2009) (Eq. 9) was considered. The second and third variations of the FHWA models were only implemented when tests were repeated at three or more different confining stresses.

The models and the experimental results were compared in terms of their sensitivity to normal stress (σ_n), embedded length (L_e), soil friction angle ($\tan\phi$) and the average thickness of the transverse ribs (t_{avg}). The sensitivity to t_{avg} was only calculated if the geometry of the different geogrids were otherwise the same. Only unitized, uniaxial geogrids were considered for this study. As such, the average thickness was also correlated to the ultimate strength of the geogrids.

Four sets of data from literature were selected for the sensitivity analysis for a total of 59 tests. A summary of the datasets is shown in Table 1. These datasets were selected as they all considered at least two of the variables of significance to this study in each test. The tests were all conducted at a displacement rate of 1 mm/min. The soil-geosynthetic interface friction angle was assumed to be $\frac{1}{3}\phi$ (Cardille et al. 2017). For the tests by Lopes & Lopes (1999) only the residual friction angle was reported. The tests by Lopes & Lopes (1999) are also the only ones that cannot be considered dense.

The sensitivity (m) of the models and the experimental results to the four variables was defined as the change in pullout resistance (predicted: P_r^* or measured: P_r) for a change in the variable under consideration (ΔX):

$$m = \frac{\Delta P_r}{\Delta X} \text{ or } m^* = \frac{\Delta P_r^*}{\Delta X}$$

All variables were normalized using its minimum and maximum value in this dataset before calculating the sensitivity. Thus, if an increase in length from 0.4 m to 0.9 m results in an increase in P_r of 6 kN/m the sensitivity will be equivalent to when an increase in thickness of 0.005 m also results in an increase P_r of 6 kN/m.

Table 1. Datasets analysed for the sensitivity analysis

Source	Number of tests	Variables			
		Normal stress	Length	Soil type	Geogrid geometry
Lopes & Lopes (1999)	4	Yes	No	Two granular	Yes (2)
Abu-Farsakh et al. (2006)	10	Yes	No	One cohesive	Yes (3)
Moraci & Recalcati (2006)	36	Yes	Yes	One granular	Yes (3)
Abdi & Mirzaeifar (2017)	9	Yes	No	Three granular	No

Soil-geogrid interaction is a complex, non-linear problem. A such, the sensitivity to variable depends on the magnitude of change of the dependent variable. For example, increasing the length from 0.8 m to 1 m will not result in the same increase in P_r as increasing the length from 0.2 m to 0.4 m. Thus, the sensitivity was calculated for each available permutation in the experimental data, e.g. ΔP_r^* for $\sigma_n = 25$ to 50 kPa, $\sigma_n = 25$ to 100 kPa, and $\sigma_n = 50$ to 100 kPa.

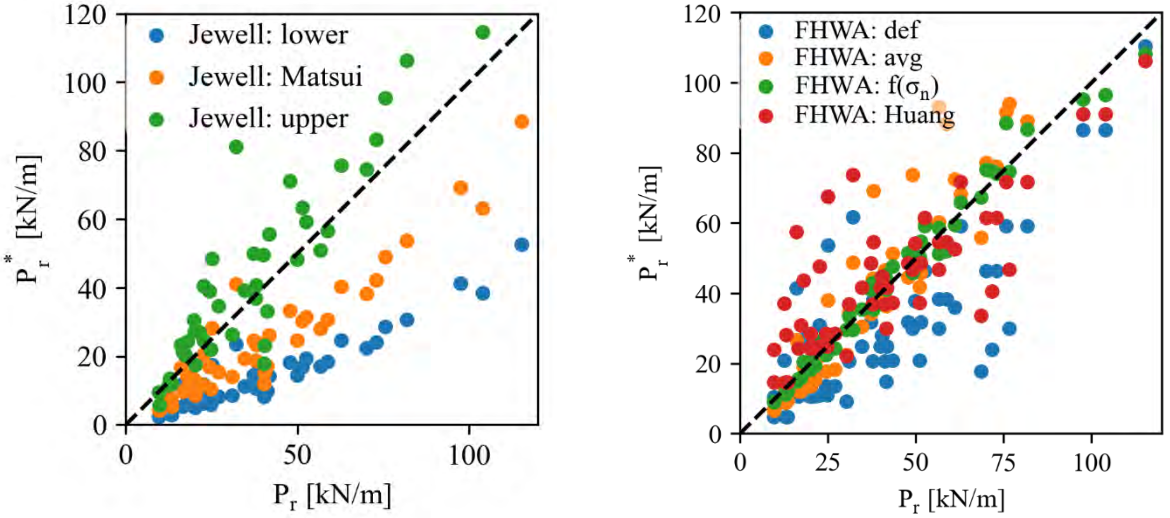
RESULTS OF THE SENSITIVITY ANALYSIS

The objective of this work was not to evaluate the accuracy of the different models. However, the predicted values (P_r^*) are compared to the measured values (P_r) in Figure 2 as a reference. For this dataset, the upper bound solution for transverse rib bearing resistance (Eq. 5) best correlated with the measured pullout resistance. For the FWHA models, the most accurate model considered $F^*\alpha$ as a variable of normal stress.

The sensitivity of the analytical models ($\Delta P_r^*/\Delta X$) is shown as a function of the experimentally measured sensitivity ($\Delta P_r/\Delta X$) in Figure 3 to Figure 6 for length, normal stress, friction angle and average rib thickness respectively. Values above the 1:1 line indicates that the models are more sensitive to the variables than measured experimentally, values below the 1:1 line indicates the inverse.

Figure 3b shows that all four of the FHWA models were for the most part as sensitive to a change in the embedded geogrid length (L_e) as the experimental results. Similarly, the sensitivity of the mechanistic model with the Matsui et al. (1996) solution for bearing capacity agreed with the experimental results. However, the lower bound solution for rib bearing resistance results in a model that was less sensitive to L_e than the experimental results (see Figure 3a). In contrast, the upper bound solution for bearing resistance results in a model that is overly sensitive to L_e. The under- and oversensitivity of these two models is due to the non-linear effect of L_e in the models – by increasing L_e the frictional resistance increases, however, the number of bearing members also reduces.

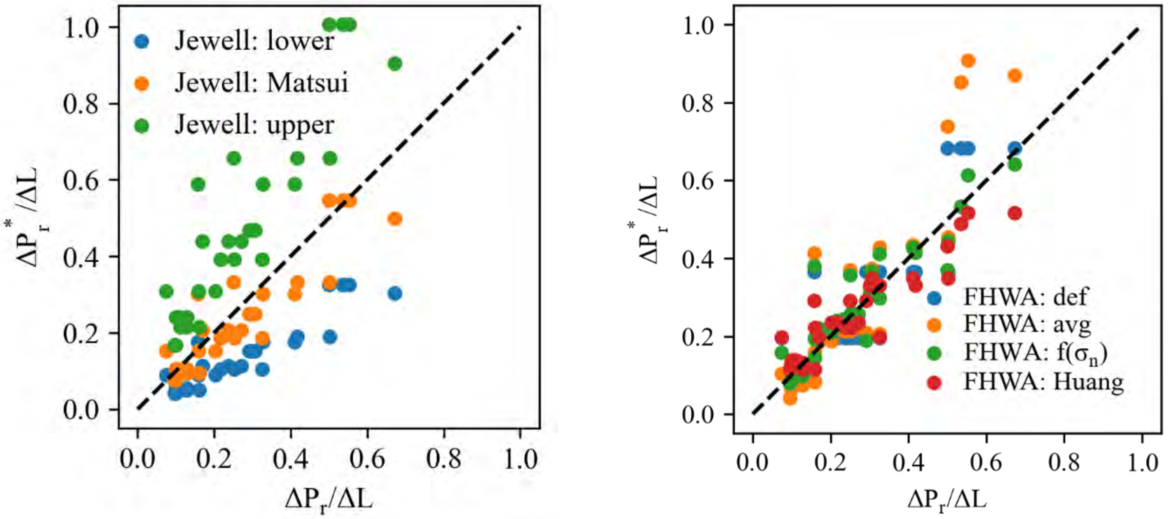
It has been shown that P_r increases non-linearly with confining stress (Huang & Bathurst, 2009). The upper bound mechanistic model captured this trend as shown in Figure 4a. In contrast, the lower bound mechanistic model, and the one based on Matsui's solution, was less sensitive to σ_n than the experimental results. The error was the most significant for tests where a small change in σ_n resulted in a large difference in P_r.



(a) Jewell et al. (1984) and related models

(b) FHWA and related models

Figure 2. Modelled and predicted pullout resistance for two groups of models.

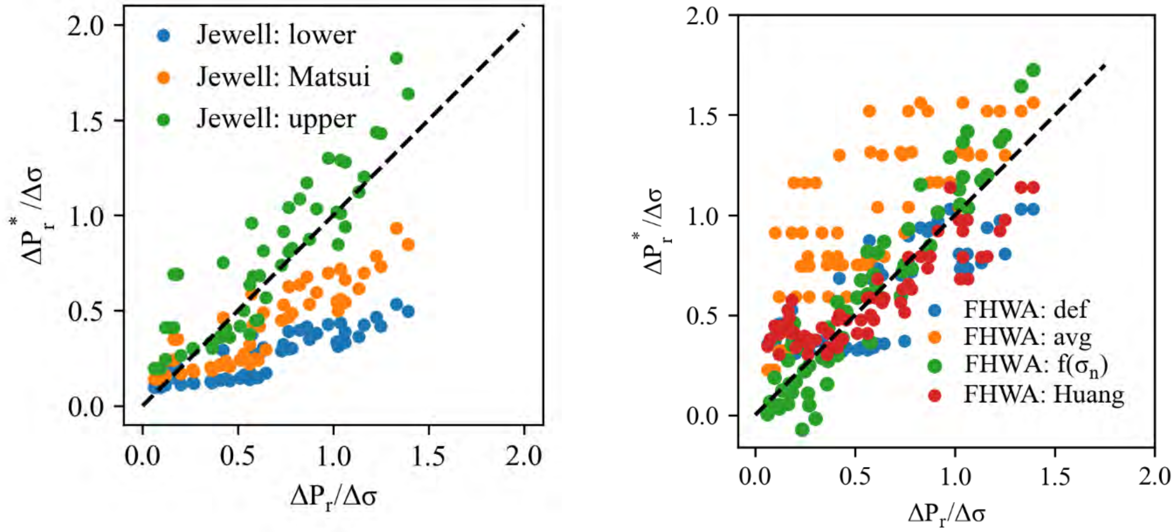


(a) Jewell et al. (1984) and related models

(b) FHWA and related models

Figure 3. Comparison of modelled and measured sensitivity to embedded length for two groups of models. P_r and L_e is normalized between 0 and 1.

As the relationship between P_r and σ_n is non-linear, an empirical model based on an average value of $F^*\alpha$ will be oversensitive to a change in σ_n. The large scatter in the results for the average $F^*\alpha$ model emphasizes the limitations of this approach. Both the default model and that by Huang & Bathurst (2009) varies from slightly oversensitive to slightly under sensitive. Finally, the stress dependent $F^*\alpha$ model has the best match to the experimental results.



(a) Jewell et al. (1984) and related models

(b) FHWA and related models

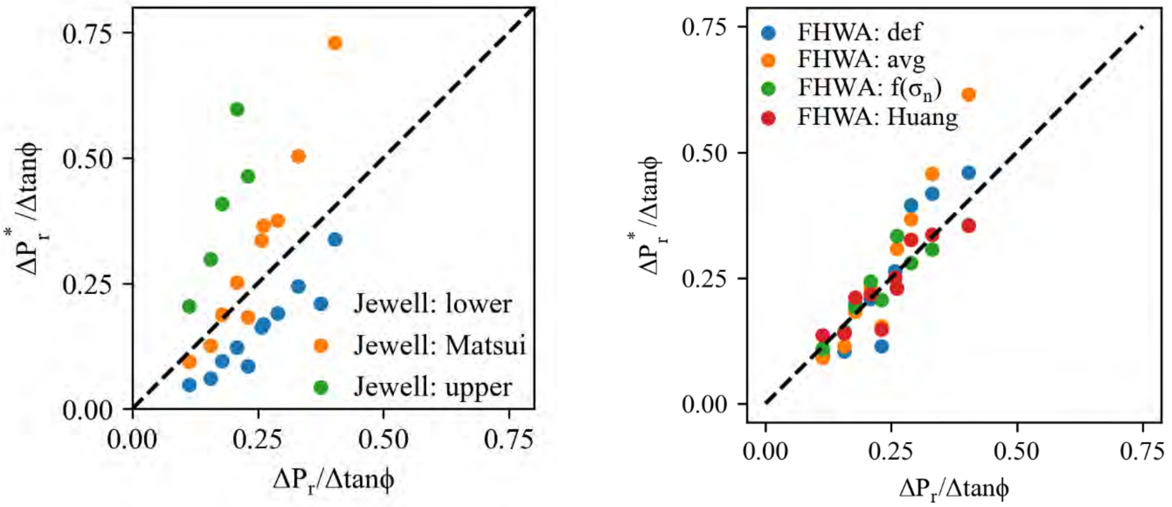
Figure 4. Comparison of modelled and measured sensitivity to normal stress for two groups of models. P_r and σ_n is normalized between 0 and 1.

The datapoints available to investigate the sensitivity to friction angle is limited. However, for the available results both the upper bound mechanistic model and the Matsui's model were overly sensitive to a change in $\tan\phi$ as shown in Figure 5a (some data points for the upper bound solution lies above the range of the y-axis). The difference between these models and the experimental results increased as $\Delta P/\Delta\tan\phi$ increased. The lower bound solution was slightly less sensitive to a change in $\tan\phi$, with a consistent difference across $\Delta P/\Delta\tan\phi$. All the FHWA models shown in Figure 5 were a fair match to experimental data in terms of the sensitivity to $\tan\phi$.

In Figure 6a there is a cluster of points where $\Delta P_r/\Delta t_N < 0$. For these data points, increasing the thickness of the geogrid resulted in a decrease in pullout resistance. The points where $\Delta P_r/\Delta t_{avg} < 0$ were limited to the comparison of two specific geogrids in the dataset. This behaviour may either have been due to experimental scatter, due to a more complex mechanism of interaction related to particle size, or due to a difference in the geogrids not related to t_{avg}.

For the mechanistic models the lower bound model, as well as the one based on Matsui's mechanism, was less sensitive to a change in t_{avg} than the experimental results when $\Delta P_r/\Delta t_N > 0$. However, the upper bound model of Jewell et al. (1984) matched the experimental data's sensitivity to t_{avg} for $\Delta P_r/\Delta t_N > 0$.

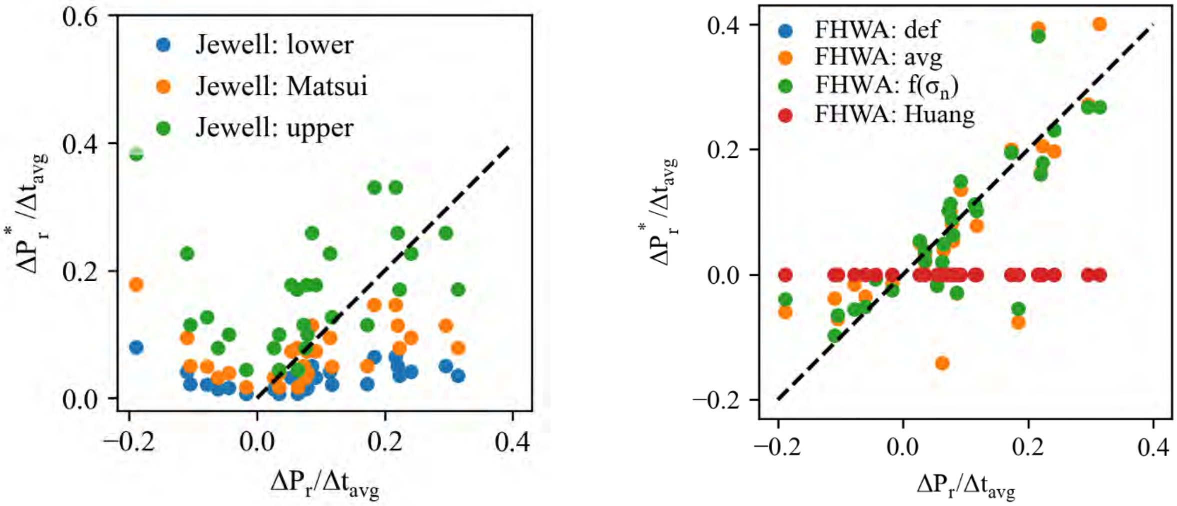
None of the FHWA models explicitly considers the effect of transverse rib height on pullout resistance. Consequently, the default model and the one by Huang & Bathurst (2009) was insensitive to a change in geogrid as shown Figure 6b. By calibrating $F^*\alpha$ to the experimental results, the effect of t_{avg} was implicitly considered in the other FHWA models and thus the models were a fair match to the experimental data where $\Delta P_r/\Delta t_N > 0$.



(a) Jewell et al. (1984) and related models

(b) FHWA and related models

Figure 5. Comparison of modelled and measured sensitivity to friction angle for two groups of models. P_r and $\tan\phi$ is normalized between 0 and 1.



(a) Jewell et al. (1984) and related

(b) FHWA and related

Figure 6. Comparison of modelled and measured sensitivity to average rib thickness for two groups of models. P_r and t_{avg} is normalized between 0 and 1.

SUMMARY

This work presented a summary of some of the analytical models that are available to predict the pullout resistance of geogrids. The models were categorized as grid like or planar, rigid or non-rigid and whether the full load-displacement curve or only the maximum pullout resistance is predicted.

Typically, the models that predict the full load-displacement curve are complex to implement and require non-conventional tests to determine the coefficients. These tests are not always practical for routine design or a sensitivity analysis to develop new products. Consequently, the adequacy of seven of the simpler models to capture the behaviour of the soil-geogrid interaction mechanisms was evaluated using experimental data from literature. The sensitivity of the seven models to four different variables ($L_e, \sigma_n, \tan\phi, t_{avg}$) was compared to the sensitivity of experimental results to those same variables. The study was limited to uniaxial, unitized geogrids.

The findings from the analysis of experimental data can be summarized as:

- The FHWA model with default coefficients, and related models, were all as sensitive to a change in embedded length as the experimental results. For models in the form of Jewell et al. (1984), using Matsui et al.'s (1996) mechanism for rib bearing resistance best captured the measured sensitivity to a change in embedded length.
- The FHWA model with $F^*\alpha$ calibrated as the average of a series of tests at different normal stresses is oversensitive to a change in normal stress. The default FHWA model and the model by Huang & Bathurst (2009) adequately captured the sensitivity to a change in normal stress. So did using a stress-dependent $F^*\alpha$. For the mechanistic models, the upper bound solution for rib bearing resistance by Jewell et al. (1984) was found to be the most accurate.
- For the available data the FHWA models adequately matched the sensitivity of the experimental data to a change in friction angle. Both the upper bound solution for the Jewell et al. (1984) model and Matsui's solution were severely oversensitive to a change in friction angle.
- The relationship between pullout resistance and transverse rib height is complex. For some tests analysed the pullout resistance decreased for an increase in rib thickness. Only the two FWHA models calibrated to the tests data had some resemblance to the experimental sensitivity to transverse rib thickness.
- Of the seven simple models analysed the FWHA models with calibrated, stress dependent $F^*\alpha$ values best captured the sensitivity of the experimental results to the variables considered. However, this model is also highly emprical, which reduces its relevance for investigating the mechanism of soil-geogrid interaction.
- The upper bound solution of Jewell et al. (1984) best predicted the pullout resistance of this dataset. However, the model fell short in terms of the sensitivity to friction angle and average transverse rib thickness.

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