Pullout Force/Displacement Relationship of Extensible Grid Reinforcements

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ABSTRACT

A model for predicting the pullout resistance of polymer-grid reinforcement has been proposed. The influence of bearing member rigidity and spacing ratio (S/D) are explicitly expressed in the hyperbolic model. A new bearing capacity equation is incorporated for calculating the maximum pullout force. The displacement along the reinforcement is calculated by using the proposed pullout bearing resistance model together with the elongation of the grid longitudinal member. The validity of the method is confirmed by good agreement between calculated values and actual test data. The analytically determined effective reinforcement embedment lengths (i.e. the length of the reinforcement in tension) and pullout displacement to mobilize the desired pullout resistance of polymeric grids under different backfill conditions and under different applied normal pressures, provide useful information for the design of reinforced earth structures against pullout failure.

NOTATION

\[ \begin{align*}
  c & \quad \text{Cohesion} \\
  c_a & \quad \text{Adhesion} \\
  d & \quad \text{Unit length} \\
  d_{ct} & \quad \text{Displacement for mobilizing maximum skin friction resistance}
\end{align*} \]
d_n  Normalized pullout displacement
D  Thickness of grid reinforcement transverse member
E_t  Initial tangent modulus of backfill soil in triaxial test
E_{ip}  Initial slope of pullout bearing resistance/normalized displacement curve
f_b  Pullout bond coefficient
F_s  Friction resistance of starting reinforcement segment
F_{al}  Average axial force in reinforcement longitudinal member
I  Moment of inertia
I_d  Bearing member deflection rigidity index
I_s  Soil stiffness index
J  Stiffness of reinforcement (kN/m)
k_s  Linear shear stiffness of soil/reinforcement interface (kN/m)
K  Horizontal earth pressure coefficient
L  Length of reinforcement providing bond
L_s  Span of the two ends fixed beam
L_{1}  Length of reinforcement segment
n  Number of grid bearing members
n_e  Exponent in bearing resistance ratio and space ratio relationship
N_c  Bearing capacity factor for cohesion resistance
N_o  Bearing capacity factor for overburden resistance
p_a  Atmospheric pressure
P_n  Maximum pullout force (kN/m) for a grid with n bearing members
PR  Pullout rate
R  Bearing resistance ratio
R_{ip}  Failure ratio for pullout bearing resistance
R_{l}  Initial slope ratio between pullout and triaxial test
R_{io}  Initial slope ratio for rigid bearing member
R_{r}  Stiffness ratio
R_{cr}  Critical stiffness ratio
s  Space between two neighbouring transverse members
s/D  Bearing member space ratio
T_{l}  Bearing force/width of starting reinforcement bearing member (kN/m)
W  Width of reinforcement providing bond
β  Angle of rotational failure zone
δ  Angle of skin friction
(δ_{21})_{m}  Midpoint movement of starting reinforcement segment
Δ_{21}  Elongation of starting reinforcement segment
\dot{\epsilon}  Average strain rate of its reinforcement segment
Grid reinforcement pullout resistance

σ_b  Bearing resistance on grid reinforcement bearing member
σ_bm  Maximum pullout bearing stress
σ_bul  Ultimate pullout bearing stress
σ_n  Normal stress
φ  Friction angle of soil

1 INTRODUCTION

For designing reinforced earth structures, especially reinforced walls, the reinforcement length is determined by checking the pullout resistance of the reinforcement. For grid reinforcement, the pullout resistance consists of two components, namely the friction resistance from the grid frictional area and passive bearing resistance from grid bearing area. The friction resistance is relatively small and just needs a small relative displacement to be fully mobilized. Reinforced earth is a composite material, and the deformations in the backfill soil and in the reinforcement must be compatible. To design a reinforced wall or steep slope using extensible grid reinforcements, two things need to be known, namely the pullout resistance mobilization process of an individual bearing member of the grid and the pullout force transfer mechanism along the longitudinal member of the grid.

Two failure mechanisms for pullout passive bearing resistance have been proposed to estimate the maximum pullout resistance, namely the general shear failure mode (Peterson & Anderson, 1980) and the punching failure mode (Jewell et al., 1984), which provide apparent upper and lower bounds of actual pullout test results (Jewell et al., 1984).

The test results of Palmeira & Milligan (1989) show that the pullout resistance is strongly influenced by the bearing member space ratio, S/D, in which S is the bearing member spacing and D is the bearing thickness (see Fig. 3, later). The larger the S/D ratio, the higher the bearing resistance from an individual bearing member. Furthermore, the pullout resistance mobilization process, i.e. pullout resistance/displacement relationship, is rarely investigated. However, understanding the pullout resistance mobilization process is important because the reinforced earth structure does not always work at a limit equilibrium condition. Thus, the designed pullout resistance should be compatible with the deformation condition of the structure.

For extensible polymer grid reinforcements under the influence of pullout force, considerable elongation of grid longitudinal members will occur. In this case, along the pullout direction, the magnitude of the mobilized resistance of each bearing member varies, with the largest value
occurring at the front bearing member. In addition, under an applied pullout force and a certain confining pressure, only a certain portion of the grid has a relative displacement with the surrounding soil. In designing reinforced earth structures with extensible grid reinforcement, to determine the effective embedment length or pullout displacement for mobilizing a designed pullout resistance, it is necessary to know the load transfer mechanism from the grid to the soil.

In this paper, a hyperbolic pullout resistance/pullout displacement model of an individual grid bearing member is first presented. Then, the method for analytically determining the pullout force/pullout displacement curve for polymeric grid reinforcement is given. Finally, the pullout displacement and the effective embedment length necessary to mobilize the desired strengths of the Tensar grids, SS2 and SR80, for certain assumed backfill soil conditions are given in graphical form which can serve as a reference for the designer. Henceforth, Tensar grids SS2 and SR80 will be referred to as geogrid A and geogrid B, respectively.

2 PULLOUT FRICTION RESISTANCE

The mobilization process of pullout friction resistance is similar to the friction resistance of an axially loaded pile, which just needs a small relative displacement to be mobilized. The friction resistance/displacement relationship can be simply modelled by a linear elastic-perfectly plastic model. The linear shear stiffness, $k_s$, can be calculated as follows:

$$k_s = \frac{c_n + \sigma_s \tan \delta}{d_{cr}}$$

(1)

in which, $c_n$ is the adhesion, $\delta$ is the skin friction angle between the soil and the grid reinforcement friction surface, $\sigma_s$ is the applied normal pressure and $d_{cr}$ is the displacement for mobilizing the maximum friction resistance. Equation (1) also demonstrates that the maximum friction resistance is determined by the Mohr–Coulomb failure criteria.

3 PULLOUT PASSIVE BEARING RESISTANCE

For the inextensible steel grid used in laboratory tests, the mobilized pullout resistance on each reinforcement segment can be practically treated as equal. Therefore, the pullout test results of steel grids are directly
used to investigate the pullout bearing resistance/pullout displacement relationship of an individual bearing member.

The pullout friction resistance of a steel grid can be subtracted from the total pullout resistance to obtain the pullout bearing resistance. For analysing the pullout test results, the pullout displacement is normalized by the bearing member (transverse member) thickness. Using the normalized displacement, the pullout bearing resistance mobilization process for different transverse member thicknesses can be compared. The laboratory test results show that the relationship of pullout bearing stress, \( \sigma_b \), and normalized displacement, \( d_n \), of an individual bearing member can be modelled by a hyperbolic function (Chai, 1992). The model takes the following form:

\[
\sigma_b = \frac{d_n}{\frac{1}{E_{ip}} + \frac{d_n}{\sigma_{ult}}}
\]  

(2)

where \( E_{ip} \) is the initial slope of the bearing resistance/normalized displacement curve and \( \sigma_{ult} \) is the ultimate value of the bearing stress.

The factors controlling the initial slope of the normalized pullout bearing resistance curve mainly consists of the backfill soil stiffness and bearing member (deflection) rigidity. The dimensionless bearing member deflection rigidity index, \( I_d \), is defined as follows:

\[
I_d = \frac{E \cdot I \cdot d}{L^2 \cdot D \cdot p_s}
\]  

(3)

where \( L \) is the span of a fixed beam, \( E \) is the elastic modulus of reinforcement, \( D \) is the bearing member thickness, \( I \) is the moment of inertia of the bearing member cross-sectional area, and \( d \) and \( p_s \) are the unit length and atmospheric pressure to make \( I_d \) dimensionless. The bearing member thickness (or bar diameter), \( D \), enters into the expression of the bearing member deflection rigidity index because at the same pullout bearing resistance level, the loading on the bearing member is proportional to the bearing member thickness. Placing the bearing member thickness in the denominator of the \( I_d \) expression enables the deflection rigidity index of the different bearing members to be compared at the same bearing resistance level which is convenient for analysing the pullout test data.

The influence of the deflection rigidity index on the initial slope of the normalized pullout bearing resistance curve is related to the backfill soil stiffness by the stiffness ratio, \( R_s \), defined in eqn (4) as:
\[ R_s = \frac{I_s}{I_t} \times 100 \text{ (\%)} \]

where \( I_s \) is the soil stiffness index which has been defined by Vesic (1972) as the shear modulus divided by the shear strength of the soil.

Based on the test data and considering the main influence factors, the initial slope of the pullout bearing resistance curve is empirically expressed as follows:

\[ E_{ip} = \frac{\ln R_s}{\ln R_{re}} R_{ro} E_i \]

where \( E_i \) is the initial slope of the triaxial compression test stress/strain curve of the backfill soil, \( R_{ro} \) is the initial slope ratio \( (E_{ip}/E_i) \) for the case of a rigid bearing member, and \( R_{re} \) is the limit stiffness ratio. When \( R_s \) is larger than \( R_{re} \), the \( R_{ip} \) will be equal to \( R_{ro} E_i \). From the pullout test results of grids embedded in weathered Bangkok clay, it is determined that \( R_{ro} \) is equal to 0.7 and \( R_s \) is equal to 250\%.

The maximum pullout bearing resistance of grid reinforcement is influenced by several factors. Under the condition that the backfill soil particle size is very small compared with the bearing member thickness, \( D \), the most significant influence factors are backfill soil strength and grid geometry.

As discussed in the previous section, the existing general shear failure mode and punching shear failure mode only provide apparent upper and lower bounds for the actual pullout test failure mechanism (Jewell et al., 1984). A new bearing capacity equation is proposed for calculating the maximum pullout bearing resistance of a single isolated bearing member. Since for a deeply embedded foundation, the failure model is dominated by punching failure (Vesic, 1963), the new equation is derived from the stress characteristic field as shown in Fig. 1. The bearing capacity factors, \( N_q \) and \( N_c \), can be expressed as follows:

\[ N_q = \left[ \frac{1 + K}{2} + \frac{1 - K}{2} \sin(2\beta - \phi) \right] \frac{1}{\cos \phi} \exp \left(2\beta \tan \phi \right) \tan \left(\frac{\pi}{4} + \frac{\phi}{2}\right) \]

\[ N_c = \frac{1}{\sin \phi} \exp \left(2\beta \tan \phi \right) \tan \left(\frac{\pi}{4} + \frac{\phi}{2}\right) - \cot \phi \]

and the maximum pullout bearing resistance, \( \sigma_{bm} \), can be calculated as follows:

\[ \sigma_{bm} = cN_c + \sigma_r N_q \]
where $K$ is the horizontal earth pressure coefficient, $\beta$ is the angle of rotational failure zone that varies according to soil compressibility, i.e. if the soil is more compressible, the $\beta$ angle is smaller (Vesic, 1963), $c$ is the cohesion and $\phi$ is the friction angle of the backfill soil. For $\beta$ equals to $\pi/2$ and $K$ equal to 1.0, the proposed formula predicts the laboratory pullout test data well (Chai, 1992).

The bearing member spacing ratio has a strong influence on pullout resistance. Generally, the larger the bearing member spacing ratio, the higher the pullout passive bearing resistance for an individual bearing member. By considering this factor, a parameter of bearing resistance ratio, $R$, is introduced, which is defined as the ratio between the maximum pullout bearing stress of an inextensible grid and that of a single isolated bearing member. The bearing resistance ratio, $R$, is a function of $S/D$ as follows:

$$R = a + b \left( \frac{S}{D} \right)^n$$

(9)

in which $a$ and $b$ are constants, and $n$ is between 0.5 and 1.0. The $S/D$ ratio is varied from 1 to 45. When $S/D$ is larger than 45, the value of $R$ is 1.0.

Considering the pullout bond coefficient, $f_b$ (Jewell et al., 1984), it was found that the index $n$ is a function of the backfill soil friction angle. The general form of $f_b$ is defined as follows:

$$f_b = \frac{P_n}{2LW(c + \sigma_n \tan \phi)}$$

(10)
where \( L \) and \( W \) are the length and width of the reinforcement providing bond, respectively. It is suggested that when the backfill soil friction angle, \( \phi \), is larger than 45°, take \( n_1 \) as 0.5; when \( \phi \) is between 35 and 45°, take \( n_1 \) as 2/3; when \( \phi \) is in the range of 25–35°, take \( n_1 \) as 3/4; and when \( \phi \) is smaller than 25°, take \( n_1 \) as 1.0. Then the constants \( a \) and \( b \) in eqn (9) can be determined by using two conditions: (a) when \( S/D \) equals a specific value, \( S_1/D \), corresponding to a rough sheet bearing member space ratio, the pullout bond coefficient, \( f_b \), is 1.0, and (b) when \( S/D \) is larger than a certain value, \( S_2/D \), the pullout bearing resistance ratio, \( R \), is 1.0 (Chai, 1992).

The ratio \( S_1/D \) is specified as 1, i.e. the bearing members are joined close together forming a rough sheet. From the test results of Chai (1992) and that of Palmeira & Milligan (1989), it has been found that the \( S_2/D \) value is in the range of 40–50. Using 45 as representative value does not cause a significant error.

The maximum pullout bearing resistance of a grid reinforcement is expressed as the maximum pullout bearing resistance of an isolated single bearing member, \( \sigma_{um} \), multiplied by bearing resistance ratio, \( R \). The ultimate pullout bearing resistance, \( \sigma_{ult} \), is related to the maximum value by the pullout bearing failure ratio, \( R_{fb} \) (\( \sigma_{ult} = \sigma_{um}/R_{fb} \)). \( R_{fb} \) is approximately the same as that of the triaxial test failure ratio of backfill material (Chai, 1992).

Figure 2 shows a comparison of the measured and calculated maximum pullout bearing resistances (stresses) of steel grid embedded in weathered Bangkok clay. It shows that agreement between measured and predicted values is quite good.

Under the conditions of low applied normal pressure and small \( S/D \) ratio, the pullout test curves showed softening behaviour. The pullout softening behaviour can be incorporated into the proposed hyperbolic pullout bearing resistance model by varying the backfill soil strength parameters from peak to critical state values during the pullout process (Chai, 1992).

4 ANALYTICAL DETERMINATION OF PULLOUT CURVE OF EXTENSIBLE GRID REINFORCEMENT

4.1 General procedure

During pulling out of the grid reinforcement, the pullout force transfers to the bearing members and friction surface through the longitudinal members. Due to the elongation of the longitudinal members, especially
for extensible grid reinforcement, the mobilization of the resistance for different bearing members along the reinforcement varies and in most cases, during the pullout process, only a certain part of the reinforcement has movement relative to the backfill soil. The maximum pullout force is controlled by the strength of the reinforcement itself and not the soil/grid reinforcement interface strength.

The procedure for calculating the pullout curve of an extensible grid reinforcement is first to divide the reinforcement into segments as shown in Fig. 3. The next step is to assume a small displacement in front of the first bearing member. Then, calculate the corresponding bearing resistance and friction resistance. This displacement must be small enough, and practically, when applied to a starting bearing member, it should not cause displacement at the bearing member just behind the starting member. Therefore, the average relative displacement for mobilizing the friction resistance of the longitudinal member behind the first bearing member is assumed to be half of the displacement applied to the first bearing member. Then, assume a small pullout displacement at the next reinforcement segment just behind the previous one, and calculate the pullout friction and passive bearing resistance for each reinforcement segment.

Fig. 2. Comparison of predicted and measured pullout bearing resistances.

Fig. 3. Cross-section of grid reinforcement.
towards the front where the pullout force is applied. This process is continued until the reinforcement breaks or pulls out of the backfill soil. The series of pullout displacements and corresponding resistances can be used to plot the pullout curve. The steps involved in this procedure are as follows:

(a) Assume a small pullout movement at the starting bearing member, such as the front bearing member for first iteration, \( \delta_1 \).
(b) Compute the corresponding bearing load, \( T_1 \), on the starting bearing member, according to the hyperbolic bearing resistance/normalized displacement relationship as discussed previously.
(c) Compute the friction force, \( F_1 \), of the reinforcement segment behind the starting bearing member by using an average shear displacement of \( \delta_1/2 \) and an elastic-perfectly plastic shear stress-displacement relationship.
(d) Compute the elongation \( \Delta_{11} \) of the starting segment using \( T_1 + F'_1 \) as axial force by the following expression:

\[
\Delta_{11} = \frac{(T_1 + F'_1) L_1}{J}
\]

in which \( J \) is the reinforcement stiffness (kN/m), \( L_1 \) is the length of the reinforcement segment.
(e) Estimate a midpoint movement of the starting segment:

\[
(\delta_{11})_m = \delta_1 + \frac{\Delta_{11}}{2}
\]

(f) Compute the friction force, \( F_1 \), of the first segment by using shear displacement, \( (\delta_{11})_m \).
(g) Compute the average axial force of the first segment \( F_{a1} \):

\[
F_{a1} = \frac{T_1 + F_1}{2}
\]

(h) Repeat the steps (d)–(g) by using \( F_{a1} \) as the axial force instead of \( T_1 + F'_1 \), until the convergence between the average axial force and friction resistance is achieved. Then, go to the next segment, and gradually work along the grid reinforcement to get the total pullout force, \( P_m \), and displacement, \( \delta_m \), at the front of the reinforcement.

The procedure is then repeated starting from the next reinforcement segment just behind the previous one until a series of values, \( P_m \) and \( \delta_m \), are obtained. These values can then be used to plot a computed pullout displacement curve.
4.2 Considering the load–strain–time behaviour of polymer grids

For extensible grid reinforcement, such as polymer grids, the modulus is a function of the strain rate, temperature, and stress level. In order to compute the pullout force/displacement curve properly, these factors must be taken into account. The nonlinear, strain rate, and temperature dependent behaviour of the load/displacement relationship can be considered by a successive iteration technique, i.e. using a secant modulus for the corresponding load level, strain rate, and temperature. The test results by McGown et al. (1984) have been used to represent the nonlinear, strain rate, and temperature dependent load/displacement relationships of geogrid A and geogrid B. The modulus of geogrid A and geogrid B at different stress levels, strain rates and temperatures can be obtained by the modulus of the index test curve (temperature of 20°C and strain rate of 2%/min) at a given stress level multiplied by the strain rate and temperature correction factors. The strain rate and temperature correction curves given by McGown et al. (1984) are for peak loads. It is assumed that the degree of influence of temperature and strain rate on secant modulus is the same as on the peak load. It is also assumed that the strain rate correction factor and the temperature correction factor are independent of each other. The test strain rate and temperature ranges are: strain rate from 10^{-1}%/min to 10^0%/min and temperature from 0°C to 40°C.

The index curves, strain rate correction curves, and temperature correction curves (McGown et al., 1984) are simulated by polynomial functions. The base point for strain rate correction is 2%/min. At this strain rate, the correction factor is equal to one. The base point for the temperature correction factor is 20°C. At this temperature, the temperature correction factor is also equal to one.

The polynomial function takes the following form:

\[ y = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n \]  

(14)

where \( y \) is the function, \( x \) is the variable, and \( a_1, \ldots, a_n \) are constants. The polynomial functions for index test curves for geogrid A and geogrid B strain rate correction factors, and temperature correction factors for geogrid A and geogrid B series are given in Table 1.

During the pullout test, the strain rate along the reinforcement is not constant. For simplicity, it is assumed that the strain rate along the reinforcement length which has been in tension by the pullout force is varied linearly from zero to maximum, and the average strain rate is controlled by the pullout rate. The average strain rate for any reinforcement segment can be expressed as follows:
Table 1
Polynomial Functions

<table>
<thead>
<tr>
<th>Function Variable</th>
<th>Constants</th>
<th>Region of the variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS2 TF $\varepsilon$</td>
<td>$a_0 = 0.1664$, $a_1 = 7.1823$, $a_2 = -0.0711$, $a_3 = 0.0388$, $a_4 = -0.0010$</td>
<td>0–12%</td>
</tr>
<tr>
<td>SS $F_t$ log $\dot{e}$</td>
<td>$a_1 = 0.9649$, $a_2 = 0.1406$, $a_3 = 0$, $a_4 = 0$</td>
<td>$10^{-3}$–$10^2$%/min</td>
</tr>
<tr>
<td>SR80 series $F_t$ $T$</td>
<td>$a_1 = 1.1385$, $a_2 = -0.0115$, $a_3 = 0$, $a_4 = 0$</td>
<td>0–40°C</td>
</tr>
<tr>
<td>SR80 series $F_t$ log $\dot{e}$</td>
<td>$a_1 = 0.9506$, $a_2 = 0.1683$, $a_3 = 0.0320$, $a_4 = 0.0013$</td>
<td>$10^{-1}$–$10^2$%/min</td>
</tr>
</tbody>
</table>

TF = axial force (kN/m).
$\varepsilon$ = axial strain.
$F_t$ = strain rate correction factor.
$\dot{e}$ = strain rate (%/min).
$T$ = temperature (°C).

$$b_i = \frac{PR}{nL_1} \frac{2i - 1}{n}$$  \hspace{1cm} \text{(15)}

where $b_i$ is the average strain rate of the $i$th reinforcement segment, PR is the pullout rate, (mm/min), $L_1$ is the length of a reinforcement segment (mm), $n$ is the number of reinforcement segments which have been placed in tension by the pullout force, and $i$ is varied from 1 to $n$ where the first reinforcement segment at the face in which the pullout force is applied is $n$ and the last segment in tension is 1.

The aforementioned procedure for calculating the pullout force/displacement curve of extensible grid reinforcement is incorporated in a microcomputer program named PULLOUT.

5 COMPARISON OF CALCULATED AND LABORATORY PULLOUT TEST RESULTS

The laboratory pullout test results (Chai, 1992) using polymer grids as reinforcements with compacted weathered Bangkok clay as backfill materials are compared with the calculated values. The comparisons are given in the form of total pullout force/displacement curves as well as the displacements along the reinforcement at different total pullout forces.
The backfill soil and reinforcement parameters are given in Table 2. The parameters of the backfill soil are determined from triaxial unconsolidated undrained test results which is close to pullout test condition, and the skin friction angle is from direct shear test results (Chai, 1992). The parameters of adhesion and displacement to mobilize the maximum friction resistance between the weathered Bangkok clay and polymer grids plane surface are assumed by referring the pullout test results of a steel bar from the compacted weathered Bangkok clay (Shivashankar, 1991). The reinforcement properties are shown in Table 3. The projection area of the apertures to the pullout direction is added to the bearing area of the bearing member. The frictional areas of the grids were calculated by using the average width of a grid longitudinal member. The test temperature was 25°C and the pullout rate was 1 mm/min.

Figures 4 and 5 show a comparison of pullout force/displacement curves for geogrid A and geogrid B, respectively. In general, the calculated pullout force/displacement curves agree well with the test data. However, it seems that the calculated displacements are a little bit larger than the

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Modulus number $\left( k \right)$</th>
<th>Modulus exponent $(n)$</th>
<th>Failure ratio $(R_f)$</th>
<th>Cohesion $(kPa)$</th>
<th>Friction angle $(^\circ)$</th>
<th>Adhesion $(kPa)$</th>
<th>Skin coefficient $(kPa)$</th>
<th>$d$ $(mm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathered clay</td>
<td>1 198</td>
<td>0.34</td>
<td>0.87</td>
<td>132.6</td>
<td>30.5</td>
<td>20.0</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Sand $(\phi = 35^\circ)$</td>
<td>900</td>
<td>0.65</td>
<td>0.9</td>
<td>0</td>
<td>35.0</td>
<td>0</td>
<td>15.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Sand $(\phi = 40^\circ)$</td>
<td>1 000</td>
<td>0.6</td>
<td>0.9</td>
<td>0</td>
<td>40.0</td>
<td>0</td>
<td>15.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Friction resistance between soil and polymer grids plane surface.

*Displacement to mobilize peak skin friction resistance.

<table>
<thead>
<tr>
<th>Type of reinforcement</th>
<th>T. member thickness $(mm)$</th>
<th>T. member width $(mm)$</th>
<th>T. member space $(mm)$</th>
<th>L. member thickness $(mm)$</th>
<th>L. member width $(mm)$</th>
<th>L. member space $(mm)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS52</td>
<td>1.5</td>
<td>4.0</td>
<td>40.0</td>
<td>1.5</td>
<td>4.0</td>
<td>28.0</td>
</tr>
<tr>
<td>SR80</td>
<td>3.6</td>
<td>16.0</td>
<td>160.0</td>
<td>1.4</td>
<td>10.0</td>
<td>22.5</td>
</tr>
</tbody>
</table>

T. transverse; L. longitudinal.
measured ones in the small displacement region. The reasons are: (a) the low accuracy of displacement measurement; (b) the limitation of the calculation method. The displacements along the extensible reinforcements were measured by using inextensible piano wires connected to a spring loaded extensometer fixed on the outside face of back wall of the pullout box and attached to desired position on the reinforcement through pre-drilled holes at the back of the pullout box. The wires were encased in stiff tubing to enable free movement during the test. The calculation method mimed the strain rates and temperature histories. However, strain rate dependency, actually, they may be related. The input data in the calculations a
Grid reinforcement pullout resistance

Fig. 6. Typical comparison of pullout displacement along the geogrid B.

ment length which is in tension is assumed to vary linearly. In reality, the strain rate is nonlinear.

Figure 6 shows a typical comparison of pullout displacements along the reinforcement at given pullout stress levels under an applied normal pressure of 50 kPa for geogrid B. It can be seen that the calculated values agree very well with the test data. As mentioned previously, for polymer grids, the total pullout force is controlled by the tension strength of the grids. It also shows that before the grids were broken, the length of reinforcement in tension was 0.8 m.

From a comparison between the calculated and laboratory pullout test results, it can be observed that the method developed in this study can predict both the pullout force/displacement curves and the displacements along the reinforcement at a given pullout force. In most cases, the difference between the calculated and measured value is within 20%.

6 PULLOUT STRENGTH/EMBEDMENT LENGTH DISPLACEMENT RELATIONSHIP

The effective embedment length and pullout displacement for mobilizing the given strength are functions of backfill soil and reinforcement properties, applied normal pressures as well as working conditions. In actual applications, the backfill soil condition is varied from place to place, and the reinforcement strain rate is difficult to assess. Furthermore, the ageing effect on reinforcement is also difficult to estimate. In order to provide some reference information regarding the effective embedment length and
pullout displacement to mobilize the given strength of extensible reinforcement the following assumptions are made first.

1. Temperatures: 0°C for cold area and 30°C for tropic area.
2. Strain rate: 10^-2%/min.
3. Reinforcement: geogrid A and geogrid B with parameters as shown in Table 3.
4. Backfill material: compacted weathered Bangkok clay with the strength and deformation parameters as given in Table 2, and two assumed granular backfills with friction angles of 35° and 40° and the other selected parameters are also tabulated in Table 2.
5. Applied normal pressure is varied from 10 kPa to 300 kPa to simulate a reinforced wall up to 15 m in height.

Then, the effective embedment length and necessary pullout displacement for mobilizing the given strength are analytically calculated by the method described previously and presented in graphical form.

Figures 7(a,b) and 8(a,b) show the plots of applied normal pressure versus pullout displacement and reinforcement length in tension under a given pullout force for geogrid A and geogrid B embedded in compacted weathered Bangkok clay, respectively. Figures 7(a) and 8(a) show that when the temperature is increased from 0°C to 30°C, the pullout displacement for mobilizing the certain pullout resistance is increased due to the lower modulus of the reinforcement at the higher temperature. It can also be noted that increasing the temperature leads to a reduction in reinforcement strength. However, the length of the reinforcement in tension for a given pullout force is not influenced by the temperature very much. The analytical results show that the reinforcement length in tension is slightly reduced when the temperature increases because the larger elongation of the reinforcement at higher temperature can mobilize higher bearing resistance. Nevertheless, the difference is less than for a reinforcement segment (containing one bearing member). Therefore, for normal pressure versus reinforcement length in tension plots, the temperature influences are not included.

Due to the high strength and high initial modulus of compacted weathered clay backfill, under the given conditions, the reinforcement length in tension is short. Analytical results show that for geogrid A, it was less than 0.5 m, and for geogrid B, it was less than 1.5 m before the reinforcements were broken as shown in Figs 7(b) and 8(b). The pullout displacements before the grids broke were less than 20 mm and 40 mm for geogrid A and geogrid B, respectively, as shown in Figs 7(a) and 8(a).

The calculated results for a sand backfill with a friction angle of 35° are shown in Figs 9(a,b) and 10(a,b) for geogrid A and geogrid B, respec-
Fig. 7. Typical comparison of pullout displacement along the geogrid A.

The tendency of the temperature influence is the same as in the case of the weathered clay backfill. It can be seen that due to the cohesionless sand backfill soil, the pullout displacements and reinforcement lengths in tension at lower applied normal pressure are increased compared with the weathered clay case. For geogrid A under a normal pressure of 20 kPa, analytical results yield a pullout displacement of 60 mm and a reinforcement length in tension of about 20 m for mobilizing 25 kN/m pullout force (Fig. 9(a) and (b)). For geogrid B, they were about 200 mm and 50 m, respectively, for mobilizing a 50 kN/m pullout force (Fig. 10(a) and (b)).
These data are much larger than for the case of weathered clay backfill. However, the pullout displacement and the reinforcement length in tension are reduced with an increase in applied normal pressure more rapidly than that of weathered clay backfill. For instance, for geogrid B, the reinforcement length in tension for mobilizing a 50 kN/m pullout force is reduced from about 5.0 m to less than 1.0 m when the applied normal pressure is increased from 20 kPa at 300 kPa.
The analytical results for a sand backfill with a friction angle of 40° are similar to those of the sand backfill with a 35° friction angle. Figure 11(a,b) shows the pullout displacement and the reinforcement length in tension versus applied normal pressure curves of geogrid B in sand backfill with a 40° friction angle. Comparing with the case of sand with a 35° friction angle, it shows that an increase in friction angle of a backfill material reduces the pullout displacement and reinforcement length in tension under a given pullout force. For example, under an applied
normal pressure of 20 kPa, in order to mobilize 40 kN/m pullout force, the reinforcement lengths in tension were 3.5 m and 4.0 m for backfill sands with 40° and 35° friction angles, respectively.

7 CONCLUSIONS

The pullout resistance of the grid reinforcement consists of two components, friction resistance and passive bearing resistance. The friction
Grid reinforcement pullout resistance

Fig. 11. Pullout displacements and reinforcement lengths in tension for geogrid B in sand with 40° friction angle.

resistance/relative displacement relationship of a reinforcement element can be simulated by a linear elastic-perfectly plastic model. The passive bearing resistance of an individual bearing member can be modelled by a hyperbolic function. The maximum bearing resistance of an isolated single bearing member is determined by the new bearing capacity equation. The bearing member interference and bearing member rigidity are explicitly expressed in the proposed model. For extensible grid reinforcement, the mobilized pullout resistance
along the grid is varied because of the non-linear elongation of the reinforcement longitudinal member. An analytical method for determining the pullout resistance/displacement relationship as well as the displacement along the reinforcement under a given pullout force is proposed. Its validity is confirmed by the reasonable agreement between the calculated and limited actual pullout test results. The method provides a useful tool for reinforced earth design.

The effective embedment length and pullout displacement for mobilizing the desired pullout force of geogrid A and geogrid B are analytically determined for three backfill conditions. The general tendency is that for a given designed pullout resistance, when the applied normal pressure increases, the effective embedment length (i.e. the reinforcement length in tension) and the pullout displacement are reduced. These calculated values can serve as reference for designers of reinforced earth structures when grid pullout is being considered.

REFERENCES


