PULLOUT RESISTANCE OF BEARING REINFORCEMENT EMBEDDED IN SAND

SUKSUN HOPPIBULSUK and ANEK NIRAMITKORNBUREE

ABSTRACT

Mechanically stabilized earth (MSE) structure has been widely accepted as a retaining structure. Its construction cost is mainly controlled by backfill materials, which are generally coarse-grained soils, and reinforcement type (steel volume). The present paper introduces a new cost-effective reinforcement, designated as “Bearing Reinforcement”. It is composed of a longitudinal member and transverse (bearing) members. The longitudinal member is made of a deformed bar, which exhibits a high pullout friction resistance. The transverse members are a set of equal angles, which provide high pullout bearing resistance. The maximum pullout bearing resistance of a single isolated transverse member, \( \sigma_{\text{max}} \), can be determined by using the plasticity solution based on the modified punching shear failure mechanism. Influential factors governing the mobilization of pullout bearing resistance are spacing, \( S \), leg length, \( B \), and numbers, \( n \) of transverse members. The larger the \( S/B \), the lower the transverse member interference. The \( S/B \) ratios of <3.75 and >25 are referred to as full and free interference, respectively. The relationship between normalized average pullout bearing stress, \( \sigma_{\text{av}}/n\sigma_s \), and pullout displacement, \( d \), where \( \sigma_{\text{av}}/n \) is average pullout bearing stress of the bearing reinforcement with \( n \) transverse members and \( \sigma_s \) is applied normal stress, is practically identical for the same level of transverse member interference. This relationship can be modelled by hyperbolic function. From this finding, a suggested procedure for estimating pullout characteristics (maximum pullout resistance and pullout force versus displacement relationship) of the bearing reinforcement for any level of transverse member interference (any \( S, B, \) and \( n \)) based on a one point test on the bearing reinforcement with a single isolated transverse member is proposed. Good agreement has been obtained between the predicted and the measured pullout characteristics. This suggested method is useful for the internal stability analysis of MSE wall in terms of engineering and economic viewpoints.

Key words: bearing member interference, bearing reinforcement, mechanically stabilized earth walls, pullout resistance (JGC: H2/K11)

INTRODUCTION

The use of inextensible reinforcements to stabilize earth structures has grown rapidly in the past two decades. When used for retaining walls or steep slopes, they can be laid continuously along the width of the reinforced soil system (grid type) or laid at intervals (strip type). Both grid and strip reinforcements are widely used around the world including Thailand. The construction cost of the mechanically stabilized earth (MSE) wall is mainly dependent upon the transportation of backfill from a suitable borrow pit and the reinforcement type. The backfill is generally granular materials, according to a specification of the Department of Highways, Thailand. The transportation of the backfill is thus a fixed cost for a particular construction site. As such, the reinforcement becomes the key factor. The lower the steel volume used and the faster the installation, the lower the construction cost.

In Thailand, a widely used strip reinforcement is the ribbed steel reinforcing strip. It is 50 mm in width and 4.2 mm in thickness with yield strength of 520 MPa. This reinforcement is conveniently transported to a factory for galvanization and to a construction site as well as simple and fast to install due to its strip shape. Since it is not produced in Thailand and is imported from Africa, the construction cost is relatively high due to the high import charges. The steel grid reinforcement can be locally manufactured. This reinforcement has been extensively studied at the Asian Institute of Technology by Prof. D. T. Bergado and his co-workers (Bergado et al., 1988, 1996; Shivashankar, 1991; Chai, 1992). The advantage of the grid reinforcement is that the pullout bearing resistance in the resistant zone is high. However, the total volume (weight) of steel grid required is still high due to wasted transverse (bearing) bars in the active (unstable) zone. The transportation and installation of the grid reinforcement are less convenient than those of the strip rein-

\[ S/B \] 

\[ \sigma_{\text{av}}/n\sigma_s \] 

\[ \sigma_{\text{max}} \] 

\[ \sigma_{\text{av}}/n \]
To develop a new cost-effective inextensible reinforcement type, four factors that need to be considered are, available raw material, simple and fast installation, convenient transportation, and high pullout and rupture resistances with less steel volume. At Geoform Co., Ltd. and the School of Civil Engineering, Suranaree University of Technology, the first author have developed a new type of reinforcement, designated as "Bearing Reinforcement". It combines the advantage of the strip and the grid reinforcements together, which meets these four essential factors. Figure 1 shows the typical feature of the bearing reinforcement, which is composed of a longitudinal member and transverse (bearing) members. The longitudinal member is a deformed steel bar and the transverse members are a set of equal steel angles. The longitudinal and transverse members are very strongly welded. The welding strength is designed to sustain the load not less than the tensile strength of the longitudinal member, according to the American Institute of Steel Construction (AISC). Since the transverse members produce high pullout bearing resistance, only few transverse members are needed in the resistant zone (none in the active zone) and hence the cost effectiveness. The reinforcement
is connected to the wall facing (1.5 × 1.5 m) at the tie point (2 U shape steel) by a locking bar (a deformed bar) (vide Fig. 2). The vertical spacing between the tie points is usually 0.75 m and the horizontal spacing is 0.75 and 0.375 m, depending upon the loading level. The laboratory and full-scale investigations on the pullout resistance of this reinforcement have been commenced since 2007 in Suranaree University of Technology. This reinforcement has been introduced into practice in Thailand since 2008 by the first author and Geoform Co., Ltd. Several bearing reinforcement stabilized earth walls have been constructed by Geoform Co., Ltd. in different areas; namely north, northeast, and south of Thailand.

For a MSE wall design, an examination of external and internal stability is a routine design procedure. The examination of external stability is generally performed using the conventional method (limit equilibrium analysis) assuming that the composite backfill-reinforcement mass behaves as a rigid body (McGown et al., 1998). The internal stability deals with rupture and pullout resistances of the reinforcement. The potential failure plane for the inextensible reinforcement stabilized earth structure is practically assumed by the bilinear failure mechanism (coherent gravity structure hypothesis) (Anderson et al., 1987). The internal stability against rupture failure is governed by the area and the strength of the reinforcement. The pullout resistance of any type of reinforcement generally consists of two parts: friction and bearing resistances. The friction pullout resistance results from soil shearing on the reinforcement surface. The bearing pullout resistance results from soil bearing on bearing areas, which are normal to the pullout direction. For the ribbed steel reinforcing strip, the main contribution on the pullout resistance is the friction resistance. The soil-reinforcement interaction for the strip reinforcement is a combined 2-D and 3-D interaction mechanism (Hayashi et al., 1999). As the strip reinforcement is pulled out and shear displacement occurs along the interface, the zone of soil surrounding the reinforcement tends to dilate. However, the volume change is restrained by the surrounding nondilating soil, resulting in an increase in normal stress on the soil-reinforcement interface. The result of restrained dilatancy has been designated as the 3-D interaction mechanism. The methods to predict and determine the pullout resistance of the ribbed steel reinforcing strip (Alforo et al., 1995; Hayashi et al., 1999; Alforo and Pathak, 2005; AASHTO, 2002) are available.

For grid reinforcement, the pullout resistance is mainly attributed from the bearing resistance. Due to the wide width of the reinforcement, the soil-reinforcement interaction mechanism is plane strain condition. The existing pullout bearing failure mechanisms for the plane strain condition are general shear failure (Peterson and Anderson, 1980), punching shear failure (Jewell et al., 1984), and modified punching shear failure (Chai, 1992; Bergado et al., 1996). The general shear failure mode assumes a characteristic field as shown in Fig. 3(a). The bearing capacity equation given is the Prandtl's solution (Prandtl, 1921) of the failure stress for shallow smooth strip foundation. The horizontal effective stress is considered to be equal to applied vertical stress, \( \sigma_v \). However, during pullout test, the bearing member is more or less like deep strip foundation so the characteristic field may not be the same as that for shallow foundation.

Punching shear failure mode is based on the stress characteristic field as shown in Fig. 3(b). It is assumed that the stress acting on the inclined rupture line is the vertical stress, \( \sigma_v \). Thus, the normal stress on the rupture line AC is \( \sigma_v \cos \phi \). The angle of rotational failure zone was assumed as \( \theta = (45 + \phi/2) \) degrees. The general shear failure and punching shear failure mechanisms provide apparent upper and lower bounds, respectively and cannot predict the actual pullout bearing resistance very well (Jewell et al., 1984; Palmerira and Milligan, 1989). Modified punching shear failure mechanism has been proved as suitable for approximating the pullout bearing resistance of steel grid reinforcement.

Modified punching shear failure mode is based on the
stress characteristic field as shown in Fig. 3(c). It is assumed that (a) there are only two failure zones: active (ABD) and rotational zone (ABC); (b) the stress state beyond the rupture line AC can be expressed by normal stress, $\sigma_n$, and horizontal stress, $K\sigma_n$, which are all the principle stresses and $k$ is the horizontal earth pressure coefficient; and (c) the strength on AC is fully mobilized. Bergado et al. (1996) have suggested to take $\beta = \pi/2$ and $k = 1.0$. The $\beta = \pi/2$ is the same value used for deriving the bearing capacity equation for a strip footing.

The maximum bearing stress of a single isolated transverse member, $\sigma_{bmax}$, in coarse-grained soil is presented in the form:

$$\sigma_{bmax} = N_q \sigma_n$$

where $N_q$ is bearing capacity factor, depending upon the mode of failure, and $\sigma_n$ is normal stress. $N_q$ for the three failure mechanisms is presented in terms of soil friction angle, $\phi$, as follows:

$$N_q = \exp \left[ \pi \tan \phi \tan \left( \frac{\pi}{4} + \phi \right) \right]$$

for general shear failure

$$N_q = \exp \left[ \left( \frac{\pi}{2} + \phi \right) \tan \phi \right] \tan \left( \frac{\pi}{4} + \phi \right)$$

for punching shear failure

$$N_q = \frac{1}{\cos \phi} \exp \left[ \pi \tan \phi \tan \left( \frac{\pi}{4} + \phi \right) \right]$$

for modified punching shear failure

$$N_q = \exp \left[ \pi \tan \phi \tan \left( \frac{\pi}{4} + \phi \right) \right]$$

(\beta = \pi/2 \text{ and } k = 1.0)

For the bearing reinforcement, the pullout resistance is also the summation of pullout friction and bearing resistances. Besides the maximum pullout resistance, the pullout force and displacement mobilization process must be investigated since most of the MSE walls do not reach the limit equilibrium state. For analyzing and predicting the behaviour of MSE walls, therefore, an understanding of the pullout resistance mobilization mechanism is necessary.

The present paper attempts to investigate the pullout characteristics (pullout force versus pullout displacement relationship and maximum pullout resistance) of a single isolated transverse member and the role of influential factors (dimension, spacing and numbers of transverse members, and normal stress) on the transverse member interference and pullout characteristics of the bearing reinforcement. Finally, a rational and practical method of predicting the pullout characteristics of the bearing reinforcement for different levels of transverse member interference is proposed. Comparisons of the predicted and the measured pullout test results are presented to reinforce the applicability of the proposed method.

LABORATORY INVESTIGATION

Soil Sample

The soil used in this investigation is a clean sand. It consists of 0.3% gravel, 97% sand, and 2.7% silt. The gradation of the sand is presented in Table 1 together with a specification of the Department of Highways, Thailand.

<table>
<thead>
<tr>
<th>Particle size</th>
<th>%Finer of the tested sand</th>
<th>%Finer according to the specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 mm</td>
<td>100.0</td>
<td>100</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>99.1</td>
<td>30–100</td>
</tr>
<tr>
<td>0.425 mm</td>
<td>76.4</td>
<td>15–100</td>
</tr>
<tr>
<td>0.150 mm</td>
<td>10.7</td>
<td>5–65</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>0.0</td>
<td>0–15</td>
</tr>
</tbody>
</table>

For analyzing and predicting the behaviour of MSE walls, therefore, an understanding of the pullout resistance mobilization mechanism is necessary.

Bearing Reinforcement

To understand the role of the influential factors (dimension, spacing, and numbers of transverse members and normal stress) on the pullout characteristics, the pullout tests on the bearing reinforcements with different dimensions, numbers, and spacing of transverse members have been conducted under different applied normal stresses. The leg length, $B$, and the length, $L$, of the tested transverse members (steel equal angles) are 25, 40, and 50 mm and 100, 150, and 200 mm, respectively, which are generally used for MSE walls. As such, $B/L$ ratio varies between 0.13 and 0.5, higher the $B/L$ ratio is possibly associated with a high geometry effect. This geometry effect is the same as that for the strip shallow foundation. Generally, the geometry effect plays a significant role for shallow foundation that the failure mechanism is governed by the general shear failure. The spacing between transverse members, $S$, varies from 15 to 150 centimeters, depending upon the number of transverse members. In this study, the number of transverse members, $n$, is 1 to 4, which is generally the case in practice. The pullout friction resistance of a longitudinal member is investigated from the pullout test on a single longitudinal member with a diameter of 16.0 mm and length of 2.6 m.
Table 2. Mechanical properties of longitudinal and transverse members

<table>
<thead>
<tr>
<th>Member</th>
<th>Material name</th>
<th>Tensile strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>SD40</td>
<td>560</td>
<td>390</td>
<td>15</td>
</tr>
<tr>
<td>Transverse</td>
<td>Fe24</td>
<td>402</td>
<td>235</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 2 presents mechanical properties of the longitudinal and transverse members. Physical properties of the transverse members are presented in Table 3. These physical and mechanical properties are determined by the Thailand Industrial Standard (TIS).

Methodology

The pullout test apparatus used in this investigation is made of rolled steel plates, angles, channels, and H-sections welded or bolted together to give the inside dimension of 2.6 m in length by 0.6 m in width by 0.8 m in height as shown in Fig. 4. The front wall contains the upper and lower parts with a slot in between for the reinforcement specimen. Friction between the tested sand and the side walls of the apparatus was minimized by the use of a lubricated rubber member as recommended by Alfaro et al. (1995). During the pullout of the reinforcement, due to an arching effect of the front wall, the normal stress on the reinforcement near the front wall may increase (dilate) or decrease (contract). In order to reduce this effect, a sleeve was installed inside the slot opening, which was 150 mm in horizontal width and 100 mm in height to isolate the bearing reinforcement near the front wall. The compacted sand thickness of 300 mm was maintained above and below the reinforcement.

Normal stress was applied with a pressurized air bag positioned between the compacted sand and the top cover of the apparatus. Before installing the air bag, a 30 mm thick layer of fine sand was placed on the top of the com-
The purpose of this procedure was to try to produce a uniformly distributed normal stress on the top of the backfill soil (Fig. 4). The pullout force was applied by 200 kN capacity electro-hydraulic controlled jack. The pullout displacement at the front of the pullout apparatus was monitored by a linear variation differential transformer (LVDT). The maximum applied pullout displacement (end of test) is 40 mm, which is about 10% leg length \( B \) of the transverse member. For deep foundation, the full mobilization of the bearing stress is about 10% of the pile diameter (Whitaker, 1976). Similarly, this end of pullout test can be regarded as the full mobilization of pullout resistance. The displacement along the longitudinal member could be measured using strain gauge and hence an indirect measurement of force along the longitudinal member. For inextensible reinforcements, measuring the displacement along the longitudinal member did not yield much useful information (Bergado et al., 1996). This measurement is thus not the goal of this study. The applied normal stress was 30, 50, and 90 kPa. These different applied normal stresses were considered to simulate total vertical stress (due to dead and live loads) on the bearing reinforcement at different depths. The live load of 20 kPa is generally used for MSE wall design in Thailand. The pullout tests on the bearing reinforcements were conducted in the compacted dry sand (at optimum point) since the drainage is generally provided to prevent a presence of permanent and temporary water table in the MSE wall. The pullout rate of 1 mm/min was adopted throughout the tests.

**TEST RESULTS**

**Pullout Friction Resistance of a Longitudinal Member**

Figure 5 shows a pullout test result of a longitudinal member with a diameter of 16 mm and a length of 2.6 m. Maximum pullout friction resistance, \( P_f \), of the longitudinal member can be calculated from:

\[
P_f = \pi DL \sigma_n \tan \delta
\]  

where \( D \) and \( L \) are diameter and length of the longitudinal member, respectively, \( \sigma_n \) is normal stress, and \( \delta \) is the skin friction angle. It is of interest to mention that \( \delta \) is quite high with its value of 58.7 degrees. Consequently, \( \delta/\phi \) ratio is greater than unity and is about 1.47. This high ratio is due to the contribution of the skin roughness of the deformed bar. This shows more advantage of the use of a deformed bar as a longitudinal member than that of a round bar for the same diameter, length, and strength. It is also found that the displacement at failure is insignificantly affected by normal stress. It is about 3.0 mm for all the applied normal stresses.

The difference between peak and residual strengths is insignificant. It is thus suggested that practically, the pullout friction force and displacement relationship can be modelled by a linear-perfect plastic model in terms of two parameters: skin friction angle, \( \delta \), and initial linear skin friction stiffness, \( k_s \). This \( k_s \) can be determined by the following equation.

\[
k_s = \frac{\sigma_n \pi DL \tan \delta}{d_f}
\]  

where \( d_f \) is the displacement at maximum pullout friction force and taken as 3.0 mm.

**Pullout Bearing Resistance of a Single Isolated Transverse Member (n = 1)**

The pullout bearing force at any displacement is the difference between the total pullout force and the pullout friction force. The total pullout force is directly obtained from the pullout test on the bearing reinforcement with a single transverse member (\( n = 1 \)). Figure 6 shows the typical total pullout force and displacement relationship of the bearing reinforcement with a 1.0 m longitudinal member and a 40 x 150 \((B \times L)\) mm transverse member. It is notable that initially, the pullout resistance sharply increases with displacement and then gradually increases until failure at a large displacement of about 40 mm, which is the end of test. The initial sharp increase is caused by the pullout friction resistance, which fully mobilizes at small displacement (about 3 mm) while the soil-bearing capacity fully mobilizes at large displacement.

Figure 7 shows the relationship between the normalized pullout bearing stress, \( \sigma_b/\sigma_n \) and the pullout dis-
placement, \( d \), of the single isolated transverse member (\( n = 1 \)) for \( B \times L \) of 25 \( \times \) 100, 25 \( \times \) 150, 40 \( \times \) 150, 40 \( \times \) 200, and 50 \( \times \) 150 mm. The pullout bearing stress, \( \sigma_b \), is determined by assuming that the transverse member and soil in the transverse member act as a rigid block penetrating into the front soil during pullout. As such, the pullout bearing stress is calculated from the ratio of pullout bearing to bearing area (\( B \times L \)). This assumption was verified by the identical pullout test results of a transverse member and a thick plate having the same \( B \) and \( L \) under different normal stresses. The bearing stress at the pullout displacement of 40 mm (end of test) is defined as the maximum bearing stress. It is of interest to mention that \( \sigma_b/\sigma_n \) and \( d \) relationship is practically the same for all values of \( \sigma_n \), \( B \), and \( L \). In other words, the pullout bearing stress, \( \sigma_b \), is dependent only upon the applied normal stress, irrespective of \( B/L \) ratio. This implies that the geometry effect is minimal for the range of applied normal stress and \( B/L \) ratio considered. The \( \sigma_b/\sigma_n \) and \( d \) relationship can be modelled by a hyperbolic function and presented in the form:

\[
\frac{\sigma_b}{\sigma_n} = \frac{1}{\frac{E_i/\sigma_n}{\sigma_{b_{\text{max}}}/\sigma_n} + d}
\]  

where \( E_i \) is the initial slope of pullout bearing stress—displacement curve and \( \sigma_{b_{\text{max}}} \) is the maximum pullout bearing stress of a single isolated transverse member. The \( E_i \) is the same as the initial modulus used in a non-linear hyperbolic soil model (Duncan et al., 1980). It increases with the applied normal stress. If the \( E_i/\sigma_n \) and \( \sigma_{b_{\text{max}}}/\sigma_n \) are known, the \( \sigma_b/\sigma_n \) versus \( d \) relationship for any \( \sigma_n \), \( B \), and \( L \) can be drawn.

Three pullout bearing failure mechanisms have been proposed; namely, general shear failure (Peterson and Anderson, 1980), punching shear failure (Jewell et al., 1984), and modified punching shear failure (Bergado et al., 1996). Using the three proposed solutions (Eqs. (1) to (4)), the comparison between the measured and the predicted maximum bearing resistance of the single isolated transverse member for various dimensions (\( B \) and \( L \)) is shown in Fig. 8. It is found that the predicted values by the modified punching shear failure mechanism (Bergado et al., 1996) agree well with the measured ones. As such, the possible failure mechanism for a single isolated transverse member is illustrated in Fig. 9 based on the modified punching shear failure mechanism.

For a particular sand, the parameter \( \sigma_{b_{\text{max}}}/\sigma_n \) in the hyperbolic solution (Eq. (7)) for any \( B \) and \( L \) can be approximated using the plasticity solution. This parameter is constant and equal to \( N_g \), which is dependent only upon soil friction angle. With the known \( N_g \) of 39.01, the \( E_i/\sigma_n \) is approximated from curve-fitting and equal to 5.56 mm\(^{-1}\).
Pullout Resistance of the Bearing Reinforcement \((n > 1)\)

In practice, the bearing reinforcement consists of several transverse members placed at regular intervals. During the pullout of the bearing reinforcement, the transverse members interfere with each other. A dimensionless parameter, transverse member spacing ratio, \(S/B\) is introduced herein to investigate the influence of spacing, \(S\), and dimension \((B \text{ and } L)\) of transverse members on the pullout bearing characteristics. Generally, the larger the \(S/B\), the higher the pullout bearing resistance up to a certain maximum value, due to less interference among transverse members.

Figure 10 shows the typical relationship between maximum pullout bearing force, \(P_{bn}\) and transverse member spacing ratio, \(S/B\) for 40 \(\times\) 150 mm transverse members \((n = 2 \text{ to } 4)\) under different applied normal stresses compared with maximum pullout bearing force of a single isolated transverse member \((n = 1)\), \(P_{b1}\). It is found that when \(S/B\) is larger than 25, there would be no more transverse member interference. Thus, this ratio is referred to as free interference spacing ratio. When \(S/B\) is less than 3.75, the shear surface caused by each transverse member joins together to form a rough shear surface and only the first transverse member causes bearing resistance. In this case, all the transverse members would act like a rough block. As such, the maximum pullout bearing resistance is determined from the summation of the friction on the block sides and the bearing capacity of the first transverse member. Since the bearing capacity is more dominant, the pullout bearing resistance is close to that of a single isolated transverse member. This \(S/B\) ratio is thus defined as a rough block spacing ratio. From this finding, the failure mechanism of the bearing reinforcement is classified into three zones, depending upon \(S/B\) ratio as shown in Fig. 10. Zone 1 is referred to as block failure when \(S/B \geq 3.75\). Zone 2 is regarded as member interference failure when \(3.75 < S/B < 25\). Zone 3 \((S/B \geq 25)\) is individual failure where soil in front of each transverse member fails individually.

The level of transverse member interference can be expressed by the interference factor, \(F\). It is defined as the ratio of the average maximum pullout bearing force of the bearing reinforcement with \(n\) transverse members to that of a single isolated transverse member.

\[
F = \frac{P_{bn}}{nP_{b1}} \tag{8}
\]
(the lower the $S/B$), the lower the $P_{bn}$, and hence the lower the $F$. Based on the analysis of the test data, it is found that the interference factor is mainly dependent upon $S/B$, and $n$, irrespective of $L$ and applied normal stress. Since the geometry effect is minimal (the soil-reinforcement interaction is likely plane strain condition), the length of transverse member, $L$, does not play any significant role on the interference factor. The following equation for interference factor is hence:

$$F = a + b \ln \left( \frac{S}{B} \right)$$  \hspace{1cm} (9)

where $a$ and $b$ are constants, depending upon $n$. These two constants can be obtained with the two physical conditions: 1) when $S/B$ equals 3.75, the interference factor equals $1/n$ since $P_{bn}$ and $P_{b1}$ are the same, and 2) when $S/B$ equals 25, the interference factor equals unity. These two conditions establish the lower and upper values of $F$ at corresponding values of $S/B=3.75$ and 25, respectively. From these two conditions, the constants $a$ and $b$ can be determined by the following equations:

$$b = 0.527 \left[ 1 - \frac{1}{n} \right]$$  \hspace{1cm} (10)

$$a = 1 - 3.219b$$  \hspace{1cm} (11)

As such, $a$ and $b$ values are 0.152 and 0.264, -0.132 and 0.351, and -0.273 and 0.395 for $n=2$, 3, and 4, respectively. Using these $a$ and $b$ values for different $n$, the maximum pullout bearing resistance can be predicted as

**Table 4.** Predicted and measured pullout resistance of bearing reinforcement with $25 \times 150$ mm transverse members for $n=2$ to 4

<table>
<thead>
<tr>
<th>$n$</th>
<th>$S/B$</th>
<th>$\sigma_s$ (kPa)</th>
<th>Predicted $P_t$ (kN)</th>
<th>Predicted $P_{b1}$ (kN)</th>
<th>$F$</th>
<th>Predicted $P_{bn}$ (kN)</th>
<th>Predicted $P_{b1}$ (kN)</th>
<th>Measured $P_s$ (kN)</th>
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<tbody>
<tr>
<td>2</td>
<td>5.4</td>
<td>30</td>
<td>6.4</td>
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<td>0.60</td>
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<td>11.6</td>
<td>11.2</td>
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<td>7.3</td>
<td>0.60</td>
<td>8.7</td>
<td>19.4</td>
<td>22.2</td>
<td></td>
</tr>
<tr>
<td>5.4</td>
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<td>19.3</td>
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<td>0.60</td>
<td>15.6</td>
<td>34.9</td>
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<tr>
<td></td>
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<td>6.4</td>
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shown by the solid lines in Fig. 10. The laboratory \( P_{01} \) values (\( P_{01} = 6.4, 12.7, \) and 19.7 kN for \( n = 2, 3, \) and 4, respectively) are used for this prediction. In addition, Table 4 shows an example of a prediction of maximum pullout force, \( P_n \), of the bearing reinforcement with 25 x 150 mm transverse members for \( n = 2 \) to 4 placed at different spacing ratios under the three applied normal stresses. The \( P_n \) is the summation of the maximum pullout friction and bearing forces. In this prediction, \( P_n \) is approximated from Eqs. (1) and (4). By the same way, Fig. 11 shows the comparison between the predicted and the measured pullout force of all the studied bearing reinforcements. It is found that the predicted and the measured values are in very good agreement. This reinforces the applicability of the proposed equations (Eqs. (8) to (11)). These equations have been successfully used for the MSE wall design of the Department of Highways, Thailand by Geoform Co., Ltd.

Now the relationship between pullout bearing force and displacement of the bearing reinforcement for any dimension of transverse members placed at different spacing under different applied normal stresses is investigated. For a particular \( \sigma_n \), the interference factor affects not only the maximum pullout bearing resistance but also the mobilization of the pullout bearing resistance as depicted in Fig. 12. It is found that normalized average pullout bearing stress, \( \sigma_{bn}/n\sigma_n \) versus \( d \) relationship, where \( \sigma_{bn}/n \) is average pullout bearing stress of the bearing reinforcement with \( n \) transverse members, is identical for the same \( F \). The lower the \( F \) (the lower the \( S/B \)), the lower the strength and the initial slope of the pullout force versus pullout displacement relationship. From the analysis of the test data, the relationship between the normalized average pullout bearing stress and displacement for \((1/n) \leq F \leq 1.0\) is proposed in the form:

\[
\frac{\sigma_{bn}}{n\sigma_n} = F \left[ \frac{d}{1 + \frac{d}{E/\sigma_n N_d}} \right] 
\]

(12)

The applicability of this equation is also illustrated in Fig. 12 by comparing the predicted and the measured normalized average pullout bearing stress and displacement relationship. The advantage of this proposed relationship is that the pullout bearing force versus displacement relationship for different normal stresses and interference factors \((S, B, n)\) can be rapidly assessed from a test result of the bearing reinforcement with a single isolated transverse member (one point test) as illustrated in the next section.

SUGGESTED PROCEDURE OF ESTIMATING PULLOUT CHARACTERISTICS

Horpibulsuk (2010) and Horpibulsuk et al. (2010) have performed a full-scale test on a bearing reinforcement stabilized earth (BRE) wall, constructed on a hard soil. They have revealed that the possible failure plane (maximum tensile plane) can be approximated from the coherent gravity structure hypothesis, which is recommended for the inextensible reinforcement stabilized earth walls (Anderson et al., 1987). In practice (effective MSE wall design), for a shallow depth (generally less than 3 meters) where the pullout failure criterion is governed and embedded length in the resistant zone is less, small diameter of a longitudinal member and short leg length, \( B \) (about 25 mm), and long length, \( L \), of transverse members placed at a close spacing (about 500 mm) are recommended. The short \( B \), provides a high \( S/B \) ratio and hence interference factor while the long \( L \) provides large bearing area, and hence high pullout resistance in this limited embedded length. On the other hand, for a deeper depth, where the rupture failure criterion is governed and embedded length is relatively long, large diameter of a longitudinal member and large dimension (large \( B \) and \( L \)) of transverse members placed at a far spacing (about 800 to 1000 mm) are recommended. It is recommended to consider the pullout resistance mobilized only due to axial pullout and ignore the contribution of transverse deformation of the reinforcement. A suggested procedure for estimating pullout characteristics of the bearing reinforcement for any interference factor based on a one point...
test on the bearing reinforcement with a single isolated transverse member \((n = 1)\) is proposed as follows:

1. Perform a large direct shear test on the backfill material to determine shear strength parameters and then determine \(N_q\) using the plasticity solution based on the modified punching shear failure mechanism (Eq. (4)).
2. Determine \(\delta\), which can be directly obtained from a pullout test on a longitudinal member or approximated from \(\delta/\phi = 1.47\).
3. Determine \(\sigma_s\) and \(d\) relationship and \(\sigma_{b\text{max}}\) of a single isolated transverse member, by conducting a pullout test on the bearing reinforcement with a single isolated transverse member under different normal stresses. It should be more or less the same as that calculated from the plasticity solution (Eq. (1)).
4. From \(\sigma_s\) and \(d\) relationship and \(\sigma_{b\text{max}}\) (obtained from step 3), determine \(E_i/\sigma_s\), which is practically the same for any other dimension \((B\) and \(L)\) of transverse member.
5. Determine the interference factor, \(F\), of the required transverse members (required \(n, S, B,\) and \(L\)) using Eqs. (9) to (11).
6. Determine \(P_{b\text{max}}\), and the pullout bearing force versus displacement relationship for the required transverse members using Eq. (12).
7. Assuming that the maximum pullout friction force occurs at \(3.0\) mm and the linear-perfect plastic model is valid for pullout friction characteristics, determine \(k_s\) using Eq. (6) and hence the pullout friction force versus displacement relationship for the required longitudinal member.
8. From the pullout bearing force versus displacement and the pullout friction force versus displacement relationships obtained from steps (6) and (7), respectively, determine the pullout force versus displacement relationship and the maximum pullout force, \(P_n\), of the required bearing reinforcement.

Figures 13 and 14 show the predicted and the measured pullout test results of the bearing reinforcement with four \((n = 4)\) \(40 \times 150\) mm transverse members placed at spacing \((S)\) of 600 mm. In the prediction of pullout bearing force versus displacement relationship \((\text{vide Fig. 13})\), \(N_q\) and \(E_i/\sigma_s\) are taken as \(39.01\) and \(5.56\) mm\(^{-1}\), respectively. Taking \(d_t = 3.0\) mm and \(\delta = 58.7\) degrees, \(k_s\) at different normal stresses can be obtained from Eq. (6). Hence, the pullout force versus displacement relationship can be drawn \((\text{vide Fig. 14})\). These two figures reinforce the applicability of the suggested method. The proposed method is conservative since in reality, the reinforcements are subjected to transverse displacement and oblique pull due to the deformation of the backfill (Shewbridge and Sitar, 1989; Leschisky and Reinschmidt, 1985; Athanasapoulos, 1993; Bergado et al., 2000; Madhav and Umashankar, 2003; Kumar and Madhav, 2009). Consequently, the field pullout resistance is higher than the laboratory one. This suggested method is on sound principles and possibly applied for the other MSE backfills in accordance with the specification of the Department of Highways, Thailand.

CONCLUSIONS

This paper deals with the introduction of a new cost-effective reinforcement, designated as “Bearing Reinforcement” and the development of a rational method of predicting its maximum pullout resistance and pullout force versus displacement relationship. The conclusions can be drawn as follows:

1. From this study, the bearing reinforcement is presented as an alternative reinforcement for MSE wall. In Thailand, it has been used for constructing several MSE walls under the supervision of the Department of Highways. The maximum pullout bearing resistance of the bearing reinforcement with a single isolated transverse member \((n = 1)\) can be approximated by the plasticity solution based on the modified punching shear failure mechanism.
2. The transverse member interference zones are classified into three zones. Zone 1 is block failure where all transverse members act like a rough block. Zone
2 \((3.75 < S/B < 25)\) is member interference failure. Zone 3 is individual failure. In this zone, all transverse members individually mobilize their bearing capacity (free transverse member interference).

3. The transverse member interference can be expressed by the interference factor, \(I\), in terms of \(S/B\) and two constants, \(a\) and \(b\), depending upon \(n\). The higher the \(S/B\), the lower the \(I\), and hence the lower the pullout bearing resistance. The maximum pullout bearing force of the bearing reinforcement can be approximated using \(F\) and the plasticity solution.

4. The transverse member interference affects not only the pullout bearing resistance but also the pullout bearing force mobilization. The lower the \(F\) (the lower the \(S/B\)), the slower the pullout bearing force mobilization (the lower the stiffness of pullout bearing force versus displacement relationship). The proposed normalized pullout bearing stress equation in terms of \(F\) and \(d\) is useful for rapidly assessing the pullout bearing force and displacement relationship for various levels of transverse member interference.

5. The suggested procedure for estimating pullout characteristics (maximum pullout force and pullout force versus displacement relationship) of the bearing resistance for any interference factor based on a one point test is introduced. It is useful for the examination of the internal stability of the MSE walls.

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