Pullout mechanism of the bearing reinforcement embedded in claystone soil of Mae Moh mine

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ABSTRACT

Bearing reinforcement, which is composed of a longitudinal member (steel deformed bar) and transverse (bearing) members (a set of equal angle steel), has been established as an effective earth reinforcement material. The equation for estimating the pullout resistance of this reinforcement in coarse-grained soils has been previously developed but not for fine-grained soil. Claystone soil, abundant in Mae Moh mine, is a fine-grained material when crushed and compacted. It was proposed to be a backfill material in the Bearing Reinforcement Earth (BRE) wall for mining activities. The pullout resistance mechanism of the bearing reinforcement embedded in the claystone soil is presented in this paper. The total pullout resistance is the sum of the pullout friction and bearing resistances. The pullout friction resistance is approximated from soil shear strength and interaction factor $\alpha$. The bearing pullout resistance of a single isolated transverse member can be approximated from the punching shear mechanism. The transverse member interference is classified into three zones, depending upon spacing and dimension of transverse member, $S/B$ ratio. Based on a critical analysis of the test results, the pullout resistance equations for bearing reinforcement with different normal stresses, dimensions and spacing of transverse members embedded in claystone soils compacted at optimum point (optimum water content and maximum dry unit weight) are developed in term of total strength parameters.

Keywords: bearing reinforcement, Mae Moh mine, claystone, pullout resistance

1 INTRODUCTION

Mechanically stabilized earth (MSE) with different types of earth reinforcement can be used as retaining structures for mining applications. Strip steel reinforcement has been widely used in Thailand for highway bridge abutment and slope protection because this reinforcement is conveniently transported to a factory for galvanization and subsequently to the construction site, and furthermore is simple and fast to install due to its strip shape. However, it is primarily imported from Africa, leading to high construction costs. Steel grid is the other reinforcement, which has been widely researched (Bergado et al., 1993, 1996; Chai, 1992; and Tin et al., 2011) and applied to many MSE projects in Thailand. Even though the grid reinforcement exhibits higher pullout resistance, its installation is more difficult than that of the strip reinforcement.

Horpibulsuk and Niramitkornburee (2010) have recently developed a new cost-effective inextensible reinforcement type, termed as “Bearing reinforcement”. Figure 1 shows the typical feature of the bearing reinforcement, which is composed of a longitudinal member and transverse (bearing) member. The longitudinal member is a deformed steel bar and the transverse members are a set of steel equal angles. This reinforcement has the advantages of both strip and grid reinforcements, i.e., simple and fast installation to the panel wall facing and high pullout resistance with less steel quantity. The transverse members are only installed in the passive zone (behind the maximum tension plane) as determined by the coherent gravity structure hypothesis for engineering and economic purposes. The earth stabilized by this reinforcement is designated as “Bearing Reinforcement Earth (BRE) wall” (Horpibulsuk et al., 2011). The BRE wall system has been accepted as one of the standard MSE walls for the Department of Highways in Thailand.

To date, studies on bearing reinforcement are limited to high-quality coarse-grained soils (<15% fine
content), as specified by the Department of Highways in Thailand. In the Mae Moh mine however, the abundant soils are claystone and red-beds, which are the fine-grained soil. The investigation of the pullout resistance mechanism of bearing reinforcement embedded in claystone is the focus of this paper. The laboratory pullout tests on the bearing reinforcement embedded in various cohesive-frictional soils were performed by using a large-scale pullout apparatus (Horpibulsuk and Niramitkornburee, 2010; Suksiripattanapong et al., 2013) to simulate the short-term situation as previously undertaken by Chai (1992); Bergado et al. (1993 and 1996) and Sukmak et al. (2015). The pullout resistance equation for the bearing reinforcement in term of normal stress, dimension and spacing of transverse members is proposed. The outcome of this study is fundamental and useful for the BRE wall design for mining activities.

Fig. 1. Typical schematic view of the bearing reinforcement (Horpibulsuk and Niramitkornburee, 2010)

2 MATERIALS AND METHODS

The soil used in this investigation is the claystone from Mae Moh mine. This soil is classified as high plasticity silt (MH), according to the Unified Soil Classification System (USCS). Its specific gravity is 2.67. The liquid limit and plastic limit are 54% and 36%, respectively. The compaction characteristics under standard Proctor energy are optimum water content (OWC) = 29.6% and maximum dry unit weight, $\gamma_{\text{max}} = 13.6$ kN/m$^3$. Total strength parameters of this claystone at the optimum point obtained from a large direct shear apparatus with the diameter of 35 cm are $c = 57$, and $\phi = 12$ degrees.

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 details of the pullout apparatus is found by Horpibulsuk and Niramitkornburee (2010). 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. The spacing between transverse members, $S$, varies from 150 to 1500 mm, depending upon the number of transverse members. In this study, the number of transverse members, $n$, are 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.

3 TEST RESULTS

Figure 2 shows a pullout test result of a longitudinal member with a diameter of 16 mm and length of 2.6 m. Maximum pullout friction resistance, $P_{f\text{max}}$ of the longitudinal member can be calculated from:

$$P_{f\text{max}} = \pi DL(\alpha c + \sigma_n \tan \delta)$$

(1)

where $D$ and $L$ are diameter and length of the longitudinal member, respectively, $\sigma_n$ is normal stress, $\alpha$ is the adhesion factor and $\delta$ is the skin friction angle. The test results show that the displacement at failure is insignificantly affected by normal stress and is about 3.0 mm for all the applied normal stresses.

Fig. 2. Pullout test results of a longitudinal member under different normal stresses.

Fig. 3. Pullout test results of a longitudinal member under different normal stresses.
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 3 shows the typical total pullout force and displacement relationship of the bearing reinforcement with a 1.0 m longitudinal member and a 40x150 \((B \times L)\) 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.

The maximum pullout bearing resistance can be determined from the plasticity solutions. 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). The maximum bearing stress, \(\sigma_{\text{max}}\), of a single transverse member is generally presented in the form:

\[
\sigma_{\text{max}} = N_q \sigma_n
\]

where \(N_q\) is bearing capacity factor depending upon the mode of failure, and \(\sigma_n\) is normal stress. \(N_q\) for general shear failure, punching shear failure, and modified punching shear failure, respectively, is presented as follows:

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

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

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

Using their proposed equations (Eqs.3 to 5), the comparison between the measured and predicted maximum bearing stress is shown in Figure 4. The measured \(\sigma_{\text{max}}\) is obtained from the assumption that the soil in the angle leg acts as a rigid block. Thus, the \(\sigma_{\text{max}}\) is the ratio of maximum pullout force to bearing area \((B \times L)\). It is found that the predicted values by punching shear failure mechanism (Jewell et al. 1984) agree well with the measured ones. This is different from the previous studies by Horpibulsuk and Niramitkornburee (2010) and Suksiripattanapong et al., (2013) on the coarse-grained soils in that modified punching shear failure mechanism (Jewell et al. 1984) provides the best estimation of pullout resistance.

Figure 5 shows the typical relationship between maximum pullout bearing force, \(P_{\text{bm}}\) and transverse member spacing ratio, \(S/B\) for 40x150 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 \((n = 1)\), \(P_b\). It is found that when \(S/B\) is larger than 15, there would be...
no more transverse member interference. Thus, this ratio is referred to as free interference spacing ratio. This value is lower than that found by Horpibulsuk and Nirmakornburee (2010) and Sukspiripattanapong et al., (2013) for various coarse-grained soils, which was reported to be 25. 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 Figure 5. Zone 1 is referred to as block failure when S/B ≤ 3.75. Zone 2 is regarded as member interference failure when 3.75 < S/B < 15. Zone 3 (S/B ≥ 15) 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.

\[
F = \frac{P}{nP_i}
\]  

(6)

The higher the level of transverse member interference (the lower the S/B), the lower the \(P_{in}\), 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. The following equation for interference factor is hence:

\[
F = a + b \ln \left( \frac{S}{B} \right)
\]  

(7)

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 \(P_{in}\) and \(P_{i}\) are the same, and 2) when S/B equals 15, 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 15, respectively. From these two conditions, the constants a and b can be determined from the following equations:

\[
a = 1 - 2.708b
\]  

(8)

\[
b = 0.722 \left[ 1 - \frac{1}{n} \right]
\]  

(9)

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 shown by the solid lines in Figure 6. Equations (1), (2) and (5)-(9) have been successfully used for designing a BRE wall in Mae Moh mine of Electrical Generating Authority of Thailand.

4 CONCLUSIONS

This paper deals with the development of a rational method of predicting pullout resistance of the bearing reinforcement embedded in claystone of Mae Moh mine. The developed equations were successfully adopted to design a BRE wall as a crusher plant support. The conclusions can be drawn as follows:

1. The predictive pullout resistance equations are proposed in term of total strength parameters, which is applicable for short-term design. 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 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 < 15) 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, F, in term of S/B and two constants, a and b, depending upon n. The higher the S/B, the lower the F, 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.

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