A METHOD OF EXAMINING INTERNAL STABILITY OF BEARING REINFORCEMENT EARTH (BRE) WALL

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Abstract

The bearing reinforcement has been in practice in Thailand since 2007 as a cost-effective earth reinforcement for a mechanically stabilized earth wall. The reinforcement 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. Based on the full-scale test results on the performance of the bearing reinforcement (BRE) wall, it is found that the possible failure plane of the BRE wall can be approximated using the coherent gravity structure hypothesis. The horizontal stress on the reinforcement can be computed by multiplying the vertical stress by the lateral earth pressure coefficient, K. At the top of the BRE wall, the K value is close to the at-rest earth pressure coefficient, K_0. This K value decreases linearly with depth and is equal to the active earth pressure coefficient, K_a, at 6 m depth. Both the possible failure plane and the relationship between K and wall depth investigated are typical of walls with inextensible reinforcements. From this full-scale observation, a limit equilibrium method for examination of the internal stability of the BRE wall is proposed.

Keywords: Bearing reinforcement earth wall, internal stability, possible failure plane, lateral earth pressure coefficient

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. Consequently, the reinforcement becomes the key factor. The lower the steel volume used

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and the faster the installation, the lower the construction cost.

Besides the metal strip and steel grid reinforcements, Horpibulsuk and Neramitkornburee (2010) have introduced a cost-effective earth reinforcement designated as “Bearing reinforcement”. It is simply installed, conveniently transported, and possesses high pullout and rupture resistances with less steel volume. Figure 1 shows the typical configuration of the bearing reinforcement, which is composed of a longitudinal member and transverse (bearing) members. The longitudinal member is a steel deformed bar and the transverse members are a set of steel equal angles. The longitudinal and transverse members are very strongly welded. The welding strength is designed to sustain a load not less than the tensile strength of the longitudinal member, according to the American Institute of Steel Construction (AISC). The reinforcement is connected to the wall facing (1.5 x 1.5 m) at the tie point (2 U-shaped steel) by a locking bar (a deformed bar) (*vide* Figure 2). The vertical spacing between tie points is usually 0.75 m and the horizontal spacing is 0.75 and 0.375 m, depending upon the loading level.

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. Since the external stability of the BRE wall can be examined by the conventional method (McGown *et al*., 1998), the examination of the internal stability is the main issue of this paper. An attempt to develop a simple and rational method for examining the internal stability of the BRE wall has been made in this paper. The developed method is a limit equilibrium analysis that the pullout resistance of the bearing reinforcement, the lateral earth pressure coefficient, and the possible failure plane must be known. The pullout resistance mechanism of the bearing reinforcement in coarse grained soil has been successfully investigated by Horpibulsuk and Niramitkornburee (2010). The method of predicting the pullout resistance of the bearing reinforcement will be briefly presented in the next section.

Since the failure plane and lateral earth pressure coefficient of a MSE wall are mainly dependent upon the reinforcement stiffness, soil-reinforcement interaction, and friction angle

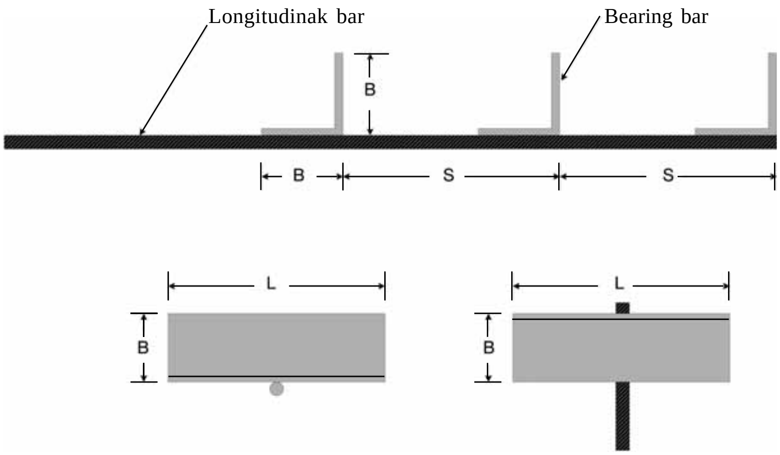

Figure 1. Configuration of the bearing reinforcement (Horpibulsuk and Niramitkornburee, 2010)

of the backfill (Bathurst *et al*., 2005; Park and Tan, 2005; Skinner and Rowe, 2005b; Al Hattamleh and Muhunthan, 2006; Hufenus *et al*., 2006; Nouri *et al*., 2006; Chen and Chiu, 2008), the performance of the BRE wall must be investigated in the light of the development of a simple and rational design procedure. The full-scale test on a BRE wall on a hard stratum was performed and the possible failure plane and the lateral earth pressure coefficient for the BRE wall are reported in this paper. Finally, the method of examining the internal stability of the BRE wall is introduced.

Pullout Resistance of the Bearing Reinforcement

The pullout resistance of the bearing reinforcement is the summation of the pullout friction and bearing resistance. Maximum pullout friction resistance, P_f, of the longitudinal member can be calculated from

$$P_f = \pi DL\sigma_n \tan\delta \qquad (1)$$

where D and L are the diameter and length of the longitudinal member, respectively, σ_n is the normal stress, and δ is the skin friction angle. The δ/ϕ ratio of 1.0 was recommended for design (Horpibulsuk and Niramitkornburee, 2010). The high δ/ϕ ratio is because of the contribution of the skin roughness of the deformed bar.

Laboratory test results showed that the maximum bearing stress of a single isolated transverse member, $\sigma_{b\max}$, in coarse-grained soil can be approximated by the modified punching shear mechanism proposed by Bergado *et al*. (1996). The stress characteristic field is shown in Figure 3. 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, σ_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. The pullout bearing resistance can be approximated from:

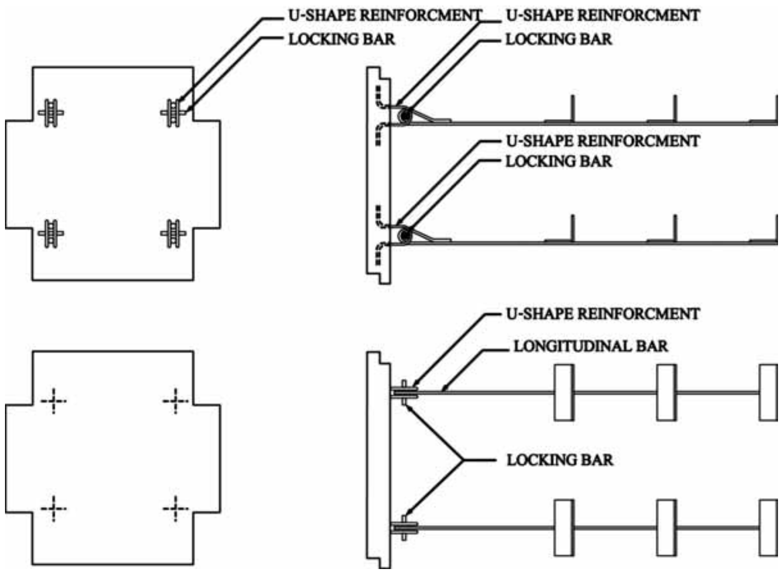

Figure2. Connection of the bearing reinforcement to wall facing (Horpibulsuk and Niramitkornburee, 2010)

$$\sigma_{b\max} = N_q \sigma_n \tag{2}$$

$$N_q = \frac{1}{\cos\phi}\exp\left[\pi \tan\phi\right]\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \tag{3}$$

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 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.

The pullout test results on the bearing reinforcement (Figure 4) shows that when the S/B is larger than 25, there would be no more transverse member interference. Thus, this ratio is referred to as the free interference spacing ratio. When the 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 3 zones, depending upon the S/B ratio. Zone 1 is referred to as block failure when the $S/B \leq 3.75$. 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.

$$F = \frac{P_{bn}}{nP_{b1}} \tag{4}$$

where P_{b1} is the pullout bearing force of a single isolated transverse member ($n = 1$), and P_{bn} is the

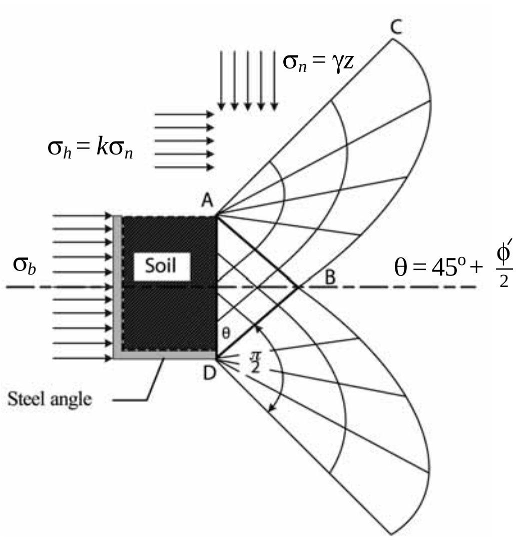

Figure 3. Possible failure mechanism of a single isolated transverse member (Horpibulsuk and Niramitkornburee, 2010)

pullout bearing force of the bearing reinforcement with *n* transverse members. From the experimental study, it has been found that

$$F = a + b\ln\left(\frac{S}{B}\right) \tag{5}$$

where *a* and *b* are constant, depending upon *n*. The constants *a* and *b* can be determined by the following equations:

$$b = 0.527\left[1 - \frac{1}{n}\right] \tag{6}$$

$$a = 1 - 3.219b \tag{7}$$

Full-scale Test on a BRE Wall

Subsoil Investigation

A test bearing reinforcement earth wall was constructed on the campus of the Suranaree University of Technology on 20 July 2009. The general soil profile consists of weathered crust layer of silty sand over the top 1.5 m. This layer is underlain by medium dense silty sand down to about 6 m depth. Below this layer is the very dense silty sand. Figure 5 summarizes the subsoil profile and the relevant parameters. Soil samples were obtained from the borehole at the construction site down to 8 m depth. Index tests were performed on the subsoil samples. The in-situ strength of the subsoil was measured by

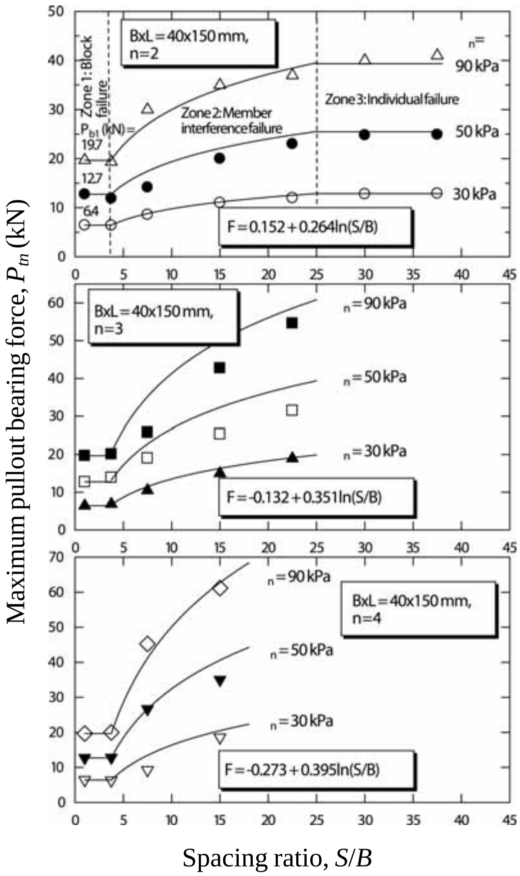

Figure 4. Effect of spacing ratio on pullout bearing resistance of the bearing reinforcement (Horpibulsuk and Niramitkornburee, 2010)

the standard penetration test.

Construction of the Bearing Reinforcement Earth Wall

The backfill material used in the earth wall was uniform sand. It consists of 0.3% gravel, 97% sand, and 2.7% silt. The particle size distribution is as follows: average grain size, D_{50} = 0.31 mm; uniformity coefficient, C_u = 2.4; and coefficient of curvature, C_c = 1.2. This sand is classified as poorly graded sand (SP), according to the Unified Soil Classification System (USCS). Its specific gravity is 2.77. The compaction characteristics under standard Proctor energy are optimum water content (OWC) = 6.3% and maximum dry unit weight, $\gamma_{d,max}$ = 16.8 kN/m^3. Strength parameters of this sand at the optimum point obtained from a large direct shear apparatus with the diameter of 35 cm are c' = 0, and ϕ' = 40 degrees.

The wall was 6 m high, 9 m long at the top, 6 m wide at the top, and 12 m long, 21 m wide at the base, as illustrated in Figure 6. The side and back slopes were 1:1. The ground was dug to 0.65 m depth below the original ground to make a lean leveling pad of 0.15 m thickness. The wall facing panel was placed on the leveling pad after 2 days of curing. The facing panels were made of segmental concrete block which measured 1.50 x 1.50 x 0.14 m in dimension. In this construction, 4 facing panels were installed in the middle zone of the wall width (9 x 6 x 6 m) with 8 reinforcement levels. The vertical spacing between each reinforcement level is 0.75 m. The horizontal spacing is 0.75 m for levels 4 to 8 and 0.375 for levels 1 to 3. The transverse member spacing is 750 mm for all transverse members. This spacing is larger than 25*B* where *B* is the leg length of the transverse member. As such, there is no transverse member interference. Table 1 shows the details of the bearing reinforcement for each reinforced layer.

The backfill was compacted in layers of about 0.15 m thickness to a density of about 95% the standard Proctor density. The compaction was carried out with a hand compactor. The degree of compaction and water content were checked regularly at several points for all the compaction layers by the sand cone method. Wherever the degree of compaction was found to be inadequate, additional compaction was done until the desired standards were met. The total time spent for the construction was 20 days.

Instrumentation Program

The strains and tensile forces along the longitudinal members were measured by outdoor waterproof type strain gauges. The initial readings on the strain gauges were taken corresponding to zero tension (strain) in the reinforcements at the time of its installation before being subjected to any load. Subsequent readings were taken as the wall was constructed and after completion of the construction at regular intervals of time. The measurement points were located at 0.23, 1.02, 1.81, 2.60, and 3.39 m

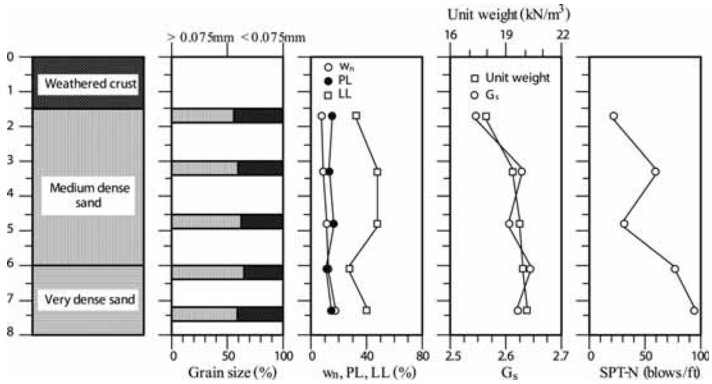

Figure 5. Soil profile of the construction site

distance from the wall. The strain gauges were installed at all eight layers of the bearing reinforcement in the middle zone of the wall (9 x 6 x 6 m).

Field Test Results

Maximum Tension Plane

Figure 7 illustrates the reinforcement tension measured at 14 days after the end of construction. The measured reinforcement tensions at the bottom of the earth wall show high tension at the point near the wall facing panel while the middle and top layers show high tension at the points about 1.8 m distance from the wall face. Overall, the maximum tension line (possible failure plane) of the bearing reinforcement corresponds to the bilinear type of maximum tension line (coherent gravity structure hypothesis) as expected for metal strip and grid reinforcements (Anderson *et al.*, 1987; ASHTO, 1996).

Lateral Earth Pressure

Figure 8 shows the relationship between the wall depth (1/wall height) and the coefficients of lateral earth pressure, K, at the maximum tension in reinforcements at 14 days after the end of construction. The coefficients of earth

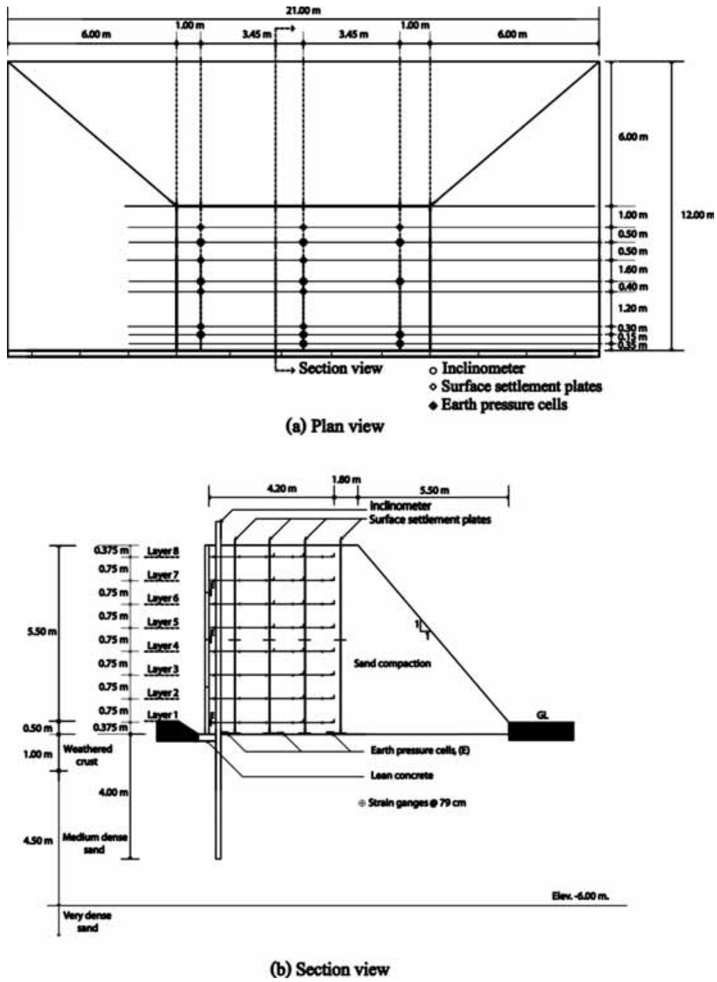

Figure 6. Schematic diagram of the test wall with instrumentation

pressure are calculated from the ratio of the lateral earth pressure, σ_h, to the vertical pressure, σ_v. The lateral earth pressure at the maximum tension in reinforcement was measured from the strain gauges on the reinforcement, while the vertical stress was approximated from overburden pressure where $\gamma = 16.1$ kN/m^3. This K value is used for designing the internal stability of the earth wall (pullout and rupture failure criteria). The measured K was compared to that for inextensible reinforcements recommended by the American Association of State Highway Transportation Officials (AASHTO). ASSHTO (1996) recommends that the horizontal stress, σ_n, at each reinforcement level of an earth wall with inextensible reinforcements shall be calculated using $K = K_0$ at the top of the wall and decreases linearly to $K = K_a$ at 6 m depth where K_a is the coefficient of active earth pressure and K_0 is the is the coefficient of at-rest earth pressure. Below a 6 m depth, $K = K_a$ shall be used. It is found that the measured K is in the same pattern with that recommended by ASSHTO. The K value at the top of the wall is slightly higher than K_0 and the K value at 6 m depth is close to K_a. The change in K with depth is approximately linear.

Suggested Method of Examining Internal Stability of the BRE Wall

The examination of the internal stability deals with the rupture and pullout failure. The pullout resistance mechanism, maximum tension plane (possible failure plane), and coefficient of lateral earth pressure are needed for the examination. A suggested procedure for examining the internal stability of the BRE wall is proposed as follows:

Determine the maximum pullout force in the bearing reinforcement

1. Based on the coherent gravity structure hypothesis, approximate the maximum tension (possible failure) plane of the BRE wall.
2. Determine the maximum pullout force in the bearing reinforcement by multiplying the vertical stress by the coefficient of lateral earth pressure, K, and the vertical and horizontal spacing (S_v and S_h) of the bearing reinforcement.

Determine the rupture strength of the bearing reinforcement

3. Perform a tensile test on the longitudinal member to determine the yield strength.
4. Determine the rupture strength of the longitudinal member by multiplying the yield strength by the cross-sectional area.

Determine the pullout resistance of the bearing reinforcement

5. Perform a large direct shear test on the backfill material to determine shear strength parameters and then determine N_q using Equatuin (3).

Table 1. Reinforcement details for the test wall

Facing panel	**Reinforcement layers**	**Number of longitudinal members per facing panel (12 mm deformed bar)**	**Number of transverse members (25 x 25 x 3 mm equal angle)**
1	1 (bottom)	3	2
	2	3	2
2	3	3	2
	4	2	3
3	5	2	3
	6	2	3
4	7	2	3
	8 (Top)	2	3

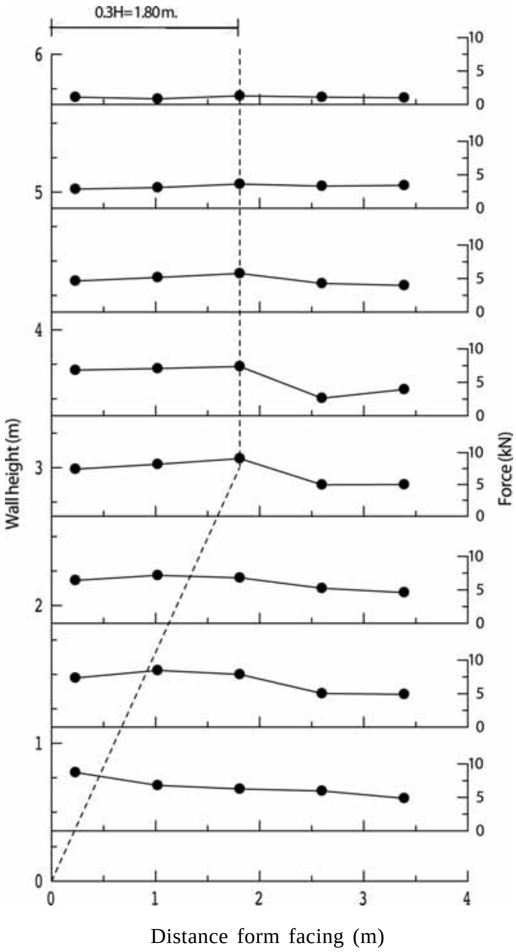

Figure 7. Measured tensions in the bearing reinforcement at 14 days after the end of construction

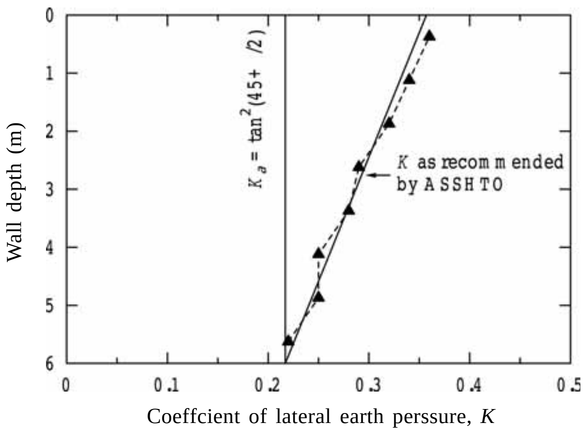

Figure 8. Coefficient of lateral earth pressure at different depths

6. Determine δ, which can be directly obtained from a pullout test on a longitudinal member or approximated from $\delta/\phi = 1.47$.

7. Determine $\sigma_{b\max}$ of a single isolated transverse member from equation (2).

8. Determine the interference factor, F, of the bearing reinforcement with n transverse members behind the failure plane using equations (5) to (7).

9. Determine $P_{b\max}$, which is the summation of the P_f and P_{bn}.

Examine the internal stability

10. Determine the factor of safety against rupture failure. This factor of safety must be greater than 2.0.

11. Determine the factor of safety against pullout failure. This factor of safety must be greater than 1.5.

Conclusions

This paper deals with the review of the pullout resistance mechanism of the bearing reinforcement and the full-scale test results on the BRE wall to investigate the maximum tension plane and the coefficient of lateral earth pressure. Finally, the method of examining the internal stability of the BRE wall is presented. The conclusions can be drawn as follows.

1. The maximum tension plane of the bearing reinforcement earth (BRE) wall follows the coherent gravity structure hypothesis, which is typical of earth walls with inextensible reinforcements.

2. The coefficient of lateral earth pressure at the maximum tension plane of the BRE wall follows that recommended by ASSHTO (2002) for earth walls with inextensible reinforcements.

3. From the method of predicting pullout resistance proposed by Horpibulsuk and Niramitkornburee (2010), the maximum tension plane, and the coefficient of lateral earth pressure investigated from the full-scale test results, the suggested procedure for examination of the internal stability of the BRE wall is introduced.

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