Effect of Fine Content on Lateral Wall Movement of Bearing Reinforcement Earth (BRE) Walls

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Abstract

This paper presents a numerical parametric study on lateral movement of bearing reinforcement earth (BRE) walls with different backfill properties using the finite element method software PLAXIS 2D. The backfill materials consisted of four types of soils, which were mixtures of silty clay and sand at different fine contents of 2, 20, 40, and 80% by dry weight. The model parameters for the numerical simulation were obtained from the conventional laboratory tests and back-calculated from the laboratory pullout tests of the bearing reinforcement. The geotextile elements were used to model the bearing reinforcements by converting the contribution of friction and bearing resistances to the equivalent friction resistance, which was represented by the soil-bearing reinforcement interaction ratio, R_{inter}. The relationship between the maximum horizontal wall movement and the fine content can be expressed by a polynomial function. The maximum horizontal wall movement significantly increased as the fine content increased. The excessive movement was realized when the fine content was greater than 45%. The increase of the fine content moved the location of the maximum wall movement higher up from the mid to the top of the wall.

Keywords: Bearing reinforcement, Fine content, Lateral movement, Bearing reinforcement earth wall.

1. INTRODUCTION

The bearing reinforcement system was initially developed as an inextensible reinforcement in Thailand by Horpibulsuk and Niramitkornburee (2010) [1]. It is a relatively cost-effective reinforcement system whose advantages include: availability of raw materials, simple and fast installation, convenient transportation, and high pullout and rupture resistances with a less required steel volume. The configuration of the bearing reinforcement is shown in Figure 1. It is composed of a combination of a longitudinal member and several transverse (bearing) members. The longitudinal member comprises a deformed steel bar while the transverse members are a set of equal steel angles, which produce high pullout bearing resistance. This reinforcement has been introduced into industry practice in Thailand since 2008. Several BRE walls have been constructed in several different regions of Thailand; namely in the north, northeast, and south of the country. The BRE wall design method with coarse-grained fill materials (<15% fine content) has been developed based on laboratory and full-scale tests [2,3,4,5].

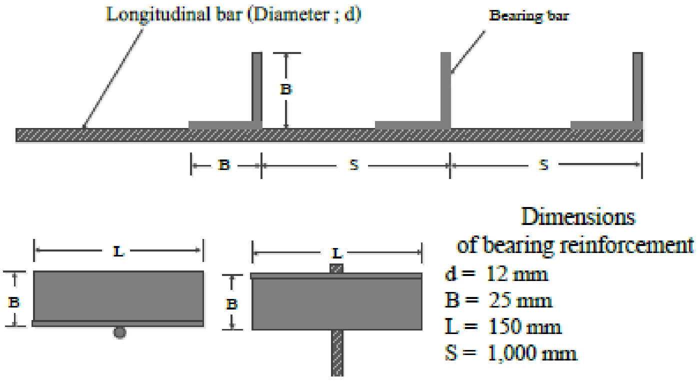


Figure 1 (a) Typical configuration of the bearing reinforcement

Coarse-grained soil is often required as a backfill material. When coarse-grained soils are not locally available within a construction site, the construction cost is largely dependent on haulage cost. The haulage cost between a borrow source and the construction site is often exorbitant. A potential means to reduce the construction cost is to use locally available soils as backfill materials. The use of locally available marginal soils (e.g. low-quality soils with more than 15% fine content) as a backfill could reduce the cost of fill material by as much as 60% compared to the use of high-quality offside soils and reduce the air pollution from the transportation [6,7]. However, due to the low shear strength of fine-grained soil, internal stability against pullout failure is questionable. To ensure the use of fine-grained soil as a backfill material, [8,9] investigated the pullout mechanisms of the bearing reinforcements embedded in cohesive-frictional soils at various fine and water contents. The bearing pullout mechanism was found to be dominant by the fine content.

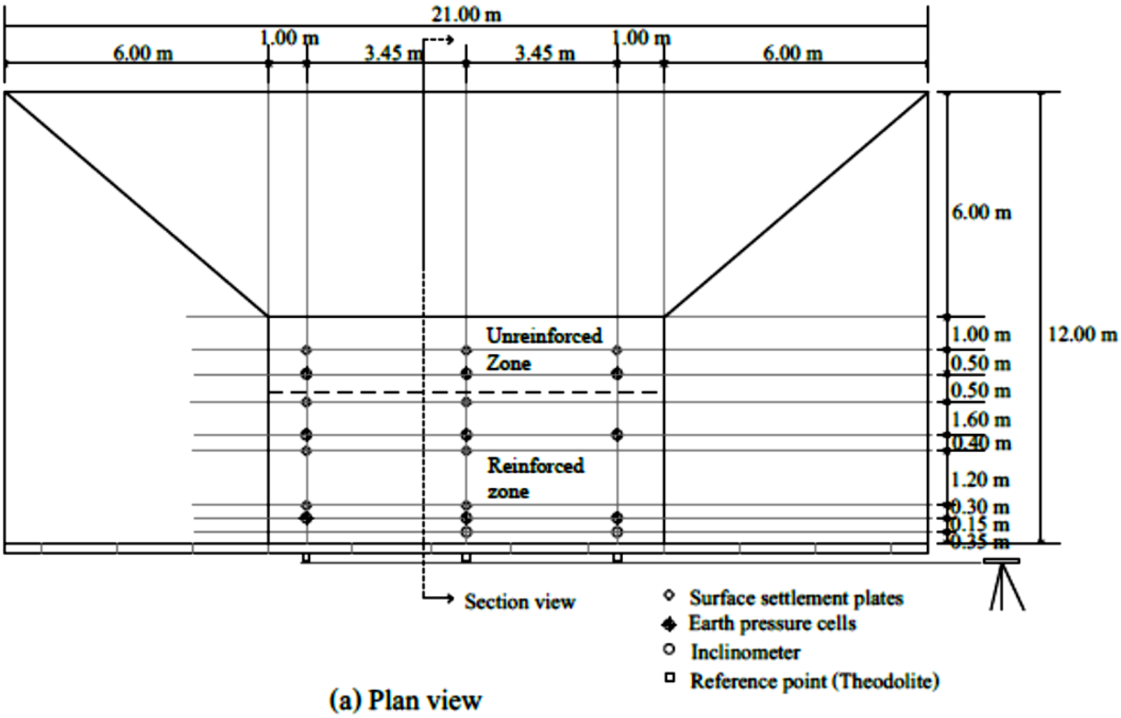
According to many researchers [10,11,12,13,14], numerical methods (i.e. finite difference and finite element methods) have been widely used for design and analysis of MSE structures. Numerical methods can model structural components, material properties, construction sequence and compute deformations, forces, strains, and stress distribution at any location of interest in a reinforced soil structure [15]. In addition, they can be used for design, parametric studies, and simulation of the behavior of the earth structures [16]. However, the suitability of a numerical method for modeling MSE structures requires calibration and validation between calculated and observed behavior of laboratory and full-scale tests in order to produce convincing results. The PLAXIS program has been proved as a powerful and accurate tool to predict the performance of the MSE wall and pullout test results [3,17,18].

The finite element code incorporated in PLAXIS 2D was used in this study. The finite element models with material properties were first calibrated according to laboratory large-scale pullout test reported by Horpibulsuk and Niramitkornburee (2010) [1] and Sukmak et al. (2015) [8] and the full-scale bearing reinforced earth wall reported by Horpibulsuk et al. (2011) [2]. The objective of this paper was to evaluate the effect of fine content on the lateral wall movement of BRE wall. The knowledge gained from this study provides useful information for further analysis and design of other BRE walls with different types of backfills, ground conditions, and features of bearing reinforcement.

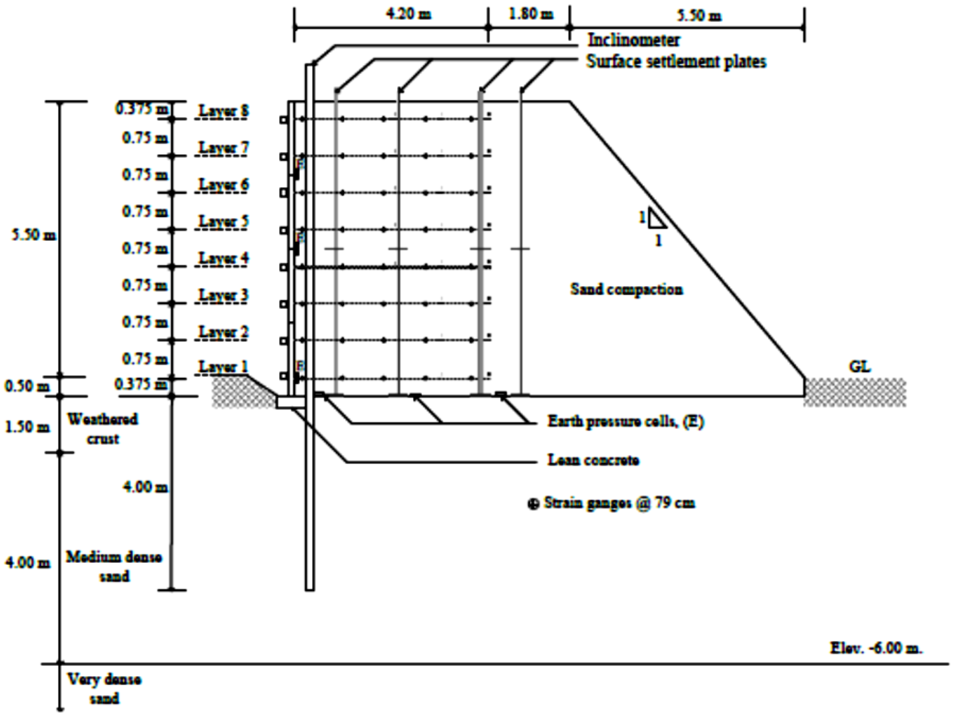
2. FULL-SCALE TEST OF BRE WALL FOR REFERENCE NUMERICAL MODEL

The construction of a bearing reinforcement earth (BRE) wall was completed on the campus of the Suranaree University of Technology (SUT) in Thailand on 20 July 2009. The foundation consisted of a 1.5-m thick weathered crust layer of silty sand, which was underlain by a medium dense silty sand layer down to about 6 m deep and then a very dense silty sand layer. Soil samples were obtained from a borehole at the construction site down to 8 m deep. The ground water was not detected during boring. The backfill for the earth wall was clean sand, which is classified as poorly-graded sand (SP), according to the Unified Soil Classification System (USCS). The details of the foundation and the backfill can be found in Horpibulsuk et al. (2011) [2]. The backfill was compacted in layers of about 0.15 m lift thickness to a density of higher than 90% the standard Proctor maximum density. The total time spent for the construction of the wall was 20 days. The details of the staged construction the test can be referenced to Horpibulsuk et al. (2011) [2].

The test wall was 6 m high, 9 m wide, 6 m long at the top, and 21 m wide at the base, as illustrated in Figure 2. The side and back slopes were 1:1. The wall facing panels made of segmental concrete panels (1.50 x 1.50 x 0.14) were placed on a lean concrete leveling pad (0.15 m wide and 0.15 thick) at two days after curing. During the construction, four facing panels were installed in the middle portion of the wall width (9 x 6 x 6) with eight reinforcement levels. The details of the bearing reinforcement for each layer are summarized in Table 1.



(a) Plan view



(b) Section view

Figure 2. Schematic diagram of the test wall instrumentation

Table 1-Reinforcement details for the test wall (Horpibulsuk and Niramitkornburee, 2010)

Facing panel	Reinforcement layer	Spacing between longitudinal members (mm)	Number
1	1 (bottom)	500	2
	2	500	2
2	3	500	2
	4	750	3
3	5	750	3
	6	750	3
4	7	750	3
	8 (Top)	750	3

3. CALIBRATION OF BRE WALL FOR REFERENCE NUMERICAL MODEL

The 2D Plaxis Finite Element (FE) program was used to simulate the construction of the wall. The BRE wall was molded as a plane strain problem. The FE mesh and boundary condition are shown in Figure 3. The nodal points at the bottom boundary were fixed in both directions and those on the side boundaries were fixed only in the horizontal direction. The simulation was performed under a drained condition because the ground water was not detected during the test. Properties of the compacted soil were determined from conventional laboratory tests that did not consider the time-dependent behavior, such as creep of soil. The creep model is beyond the scope of this study because it aimed to simulate the wall behavior with simple and well-known soil models for practical design.

The backfill materials used in this study consisted of four types of soils, which were mixtures of silty clay and sand at different fine contents. The four backfill materials were poorly-graded sand (F:S=2:98), clayey sand (F:S=20:80), clayey sand (F:S=40:60), and high-plasticity clay (F:S=80:20), in which F stands for percentage of fines and S stands for percentage of sand. The material properties used for simulation were determined according to the laboratory large-scale direct shear tests reported by Horpibulsuk and Niramitkornburee (2010) [1] and Sukmak et al. (2015) [8]. As such, all backfill materials and all foundation soils were modeled as linearly elastic-perfectly plastic materials with the Mohr-Coulomb (MC) failure criteria, which had five input parameters: elasticity modulus (E), Poisson's ratio (), cohesion (c), internal friction angle (), and dilatency angle (). The material properties of the backfill used for the FE simulation are shown in Table 2.

The facing panel was modeled as beam (plate) elements. The input parameters for strength and modulus of elasticity are shown in Table 3. Linearly elastic material was used to simulate behavior of wall facing. AASHTO (1992) recommended that the soil-facing panel interface coefficient, R should be 0.75-1.0, which has been used in the numerical studies by Suksiripattanapong et al. (2012) [3]. Since the variation of this interface coefficient is not large, the effect of interface coefficient was not investigated in this research and it was assumed to be 0.90 for all simulations.

The bearing reinforcement (3-D material) was modeled as 2-D continuous sheet elements (called geotextile elements) in the Plaxis manual with a linear elastic material. The required equivalent parameters for 2-D geotextile elements were soil-reinforcement interaction ratio, Rinter and axial stiffness per meter, EA, which is the product of the elastic modulus (E) of reinforcement (= 20 GPa) and its cross-sectional area per unit width (A). The linearly elastic-perfectly plastic model was used to simulate the interaction between soil and bearing reinforcement. The input parameters of reinforcement are shown in Table 3, where EA = 4.5x10$_4$ kN/m.

The soil-reinforcement interaction ratio, R_{inter} is defined as the ratio of the shear strength of soil-reinforcement interface to the shear strength of the surrounding soil [19]. R_{inter} in the numerical model was determined by simulating large-scale laboratory pullout test results. The equivalent frictional resistance is represented by the soil-structure interaction ratio, R_{inter}. The linearly elastic-perfectly plastic model was used to simulate the interaction between soil and bearing reinforcement.

25.00 m 12.00 m 28.00 m Weathered crust Medium dense sand Very dense sand 1.5 m 4.5 m 1

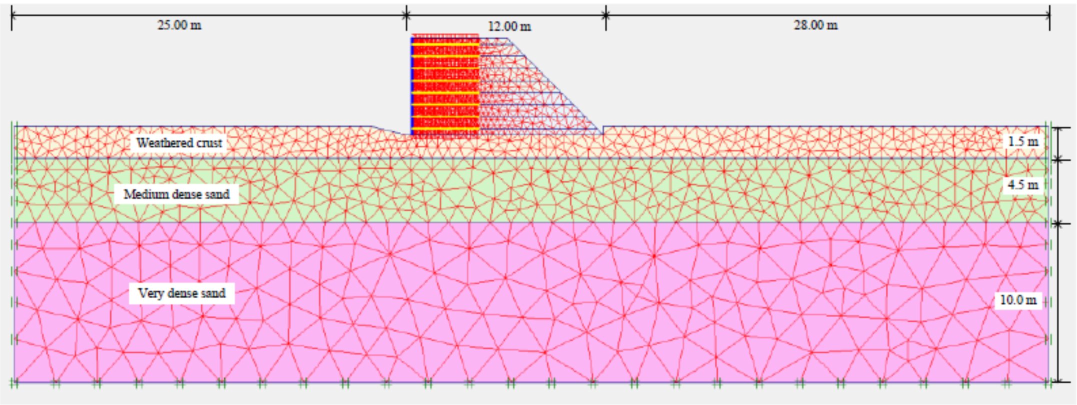


Figure 3 Numerical model and mesh details for 2D FE model simulation of BRE wall

4. FINITE ELEMENT ANALYSIS

4.1. SOIL-STRUCTURE INTERACTION RATIO, RINTER

Several laboratory pullout tests were carried out in a metallic box of 2.6 m x 0.6 m x 0.6 m high. The details and sketch of the pullout apparatus are referenced to Horpibulsuk and Niramitkronburee (2010) [1]. The longitudinal member of the reinforcement was 12 mm in diameter and 2.6 m long. The width of the transverse member was 150 mm. The number of transverse members, n used in this study were n = 2 and 3. The laboratory pullout test was modeled as a plane strain problem. The nodal points at the bottom boundary were fixed in both directions and those on the side boundaries were only fixed in the horizontal direction. The detail of simulated pullout apparatus model can be reference to Sukmak et al. (2016) [20]. The soil-bearing reinforcement interaction ratio for a specific number of transverse members was back-calculated from the laboratory pullout tests by Horpibulsuk and Niramitkornburee (2010) [1] for poorly-graded sand (F:S = 2:98) and by Sukmak et al. (2015) [8] for clayey sands (F:S = 20:80), clayey sand (F:S = 40:60), and high-plasticity clay (F:S = 80:20). The R_{inter} value is dependent on the number of transverse members and soil properties.

Several pullout tests at different applied normal stresses were modeled (σ_n = 30, 50, and 90 kPa) in order to simulate the reinforcement at different depths in the wall. In the back-calculation, the input parameter for the geogrid element is the equivalent axial stiffness. The input parameters for soils and reinforcement were provided in Tables 2 and 3.

Table 2-Model parameters for backfills and foundations

	Backfill				Foundation		
Types of soil	Poorly-graded sand	Clayey sand (F:S =20:80)	Clayey sand (F:S =40:60)	High plasticity clay (F:S =80:20)	Weathered crust	Medium dense sand	Very dense sand
Material model	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb
□□□ (kN/m^3) dry	17.0	20.1	18.9	16.1	17.0	17.15	18
□sat (kN/m^3)	18.15	22.0	20.8	18	18.0	18.15	19.0
$E\ (kN/m^2)$	35,000	10,000	5,000	1,500	6,250	40,000	50,000
v	0.33	0.40	0.40	0.40	0.30	0.25	0.25
c (kPa)	3	20	25	38	20	1	1
□□ (degrees)	40	35	32	14	26	35	38
□□ (degrees)	8	0	0	0	0	3	8

Table 3-Model parameters for reinforcement and concrete facing

	Bearing reinforcement (Geotextile)			Concrete facing (Plate element)	
Material model	Elastic			Elastic	
EA (kN/m)			4.5 E+4		3.556 E+6
Longitudinal member (SD40)	Tensile strength		560	EI $(kN.m^2/m)$	5,808
	Elongation (%)		15		
Transverse member (Fe24)	Tensile strength		402		
	Elongation (%)		21	w $(kN/m/m)$	3.36
Rinter	Poorly-graded sand	n=2	0.65		
		n=3	0.75		
	Clayey sand (F:S =20:80)	n=2	0.60	v	0.15
		n=3	0.70		
	Clayey sand (F:S =40:60)	n=2	0.55		
		n=3	0.65		
	High plasticity clay (F:S =80:20)	n=2	0.38		
		n=3	0.40		

4.2. LATERAL WALL MOVEMENT

The simulated and measured horizontal wall movements with different backfills are compared and shown in Figure 4. The simulated result of the wall with the fill of F:S = 80:20 is not included because of its excessive horizontal wall movement. The comparison between the measured and simulated horizontal wall movements with the backfill of F:S = 2:98 is considered to be reasonable. The horizontal wall movements were the sum of the horizontal movement during construction (caused by the lateral movement of reinforced and unreinforced soil zones) and the foundation wall movement and settlement. The horizontal wall movements increased as the fine content increased due to the decrease in shear strengths of the backfills. The increase of the fine content changed the location of the maximum wall movement higher up from 2.0 m for F:S = 2:98 to 6.0 m (the top of the wall) for F:S = 80:20. In addition, the maximum horizontal movement occurred at the top of the wall (6 m high). This characteristic implies that the BRE wall tends to rotate around the toe

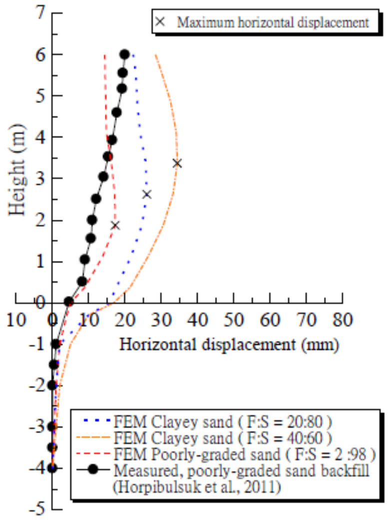


Figure 4. Comparison between the measured and simulated horizontal wall movement for different soil embankments

Figure 5 shows the relationship between the ratios of maximum lateral wall movement to wall height (δ_{max}/H) and the fine content. This relationship can be expressed by a polynomial function. The ratio of maximum lateral wall movement significantly increased with the fine content especially for F > 45%, which δ_{max}/H is higher than the allowable value of 0.40% for inextensible reinforcement suggested by Berg et al. (2009) [21] Thus, based on this specific BRE wall feature and the constitutive models, the selected soil that can minimize horizontal movement should not contain fine contents higher than 45%. The large horizontal displacement for F:S = 80:20 may result from the low shear strength of the backfill and the low bearing resistance due to the failure mode approaching to the punching shear [8].

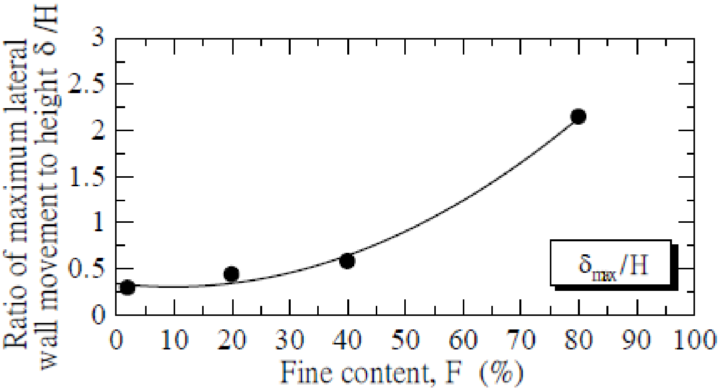


Figure 5. Relationship between maximum horizontal wall movement and fine content

5. CONCLUSIONS

This paper presents a numerical parametric study on behavior of bearing reinforcement earth (BRE) walls with different backfill properties using the numerical software PLAXIS 2D. The backfill materials consisted of four types of soils, which were mixtures of silty clay and sand at different fine contents of 2, 20, 40, and 80% by dry weight. The results from the numerical analysis in this study can provide an understanding of the influence of fine content on the behavior of BRE walls. The following conclusions can be drawn from this study:

1. The geotextile elements were used to model the bearing reinforcements by converting the contribution of friction and bearing resistances to the equivalent friction resistance. The equivalent friction resistance was represented by the soil-bearing reinforcement interaction ratio, R_{inter}, which was back-calculated from the laboratory pullout test. The R_{inter} values decreased following a polynomial function with an increase in the fine content. The soil-structure interactions varied as an increase of the fine content in the ranges of 0.65-0.38 and 0.75-0.40 for n= 2 and 3, respectively.

2. The behavior of lateral wall movement of the BRE wall with different backfill materials during and at the end of construction was simulated. The relationship between the maximum horizontal wall movement and the fine content can be expressed by a polynomial function. The maximum horizontal wall movement significantly increased as the fine content was more than 45% (F>45%). The increase of the fine content changed the location of the maximum wall movement higher up from the mid to top of the wall.

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