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Effects of reinforcement rigidity on the behavior of reinforced soil wall-embankment system on soft ground

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ABSTRACT: A study was undertaken to investigate the behavior of reinforced soil wall-embankment system on soft ground through a series of parametric studies using a finite-element method of analysis. The emphasis of the parametric studies was placed on the effect of reinforced soil system rigidity to the deformation patterns and other associated behavior. System rigidity (S_r) is reflected by both rigidity or extensibility and amount of reinforcement in the reinforced soil mass. As demonstrated by the results of finite-element analyses, there was an interaction between the reinforced soil mass and the soft ground. The response of soft ground under the embankment loading was influenced by the system rigidity of reinforced soil. Higher system rigidity led to smaller lateral movements of the soft ground than those with lower system rigidity, but had the tendency to settle more at the toe due to the rigid body rotation of the potential active zone within the reinforced soil mass. Consequently, the pattern of soft ground movements affected the outward facing movement of the reinforced soil wall. While the maximum outward facing movement decreased with increasing system rigidity for the case of reinforced soil wall on rigid ground, the same structure but on soft ground exhibited a complex pattern of deformation due to two operating mechanisms that were identified in the study. It was found that the increase in system rigidity does not necessarily result to the reduction of maximum outward facing movement when such structure is constructed on soft ground.

1 INTRODUCTION

Reinforced soil structures are essentially flexible structures that can generally accommodate large lateral and vertical movements without excessive structural distress. Owing to their flexibility, however, reinforced soil structures exhibit complex deformation patterns especially if these are constructed over soft and compressible grounds. It was demonstrated in Alfaro et al. (1995a) from two field test facilities using inextensible and extensible grid reinforcements that construction of reinforced soil walls on soft ground is feasible. Special attention has to be paid however to the chosen type of facing units because these will put limitations on the amount of vertical and lateral movements the wall can tolerate.

This study investigates the behavior of reinforced soil wall-embankment system on soft ground with inextensible and extensible grid reinforcements. Its main purpose is to identify the operating mechanisms to which inextensibly and extensibly reinforced soil mass behave on soft ground. A well-validated finite-element method of analysis that incorporated the relevant simulation considerations of reinforced embankment on soft ground was employed in the study.

2 MODELLED STRUCTURE AND FEM DETAILS

Two fully-instrumented 6.0 m high reinforced soil test facilities were constructed on soft Bangkok clay. One test facility used inextensible grid reinforcements (refer Bergado et al. 1991) and the other used extensible polymer grid reinforcements (see Bergado 1993), both utilizing common cohesive backfill soils. These were the reinforced soil structures on soft ground where the finite-element modelling employed in this study have been validated against their actual field measurements. Hence, it was found appropriate in the parametric studies to consider these test facilities as modelled structure.

The parametric studies included four different reinforced soil system rigidities. Reinforced soil system rigidity, S_r is expressed in the following equation:

$$S_r = \frac{E \cdot A}{S_v \cdot S_h} \qquad (1)$$

where E = Young's modulus of reinforcement; A = cross-sectional area of reinforcement; S_v = vertical reinforcement spacing; and S_h = horizontal reinforcement spacing. The range of reinforced soil system rigidity covered both inextensible steel grid reinforce-

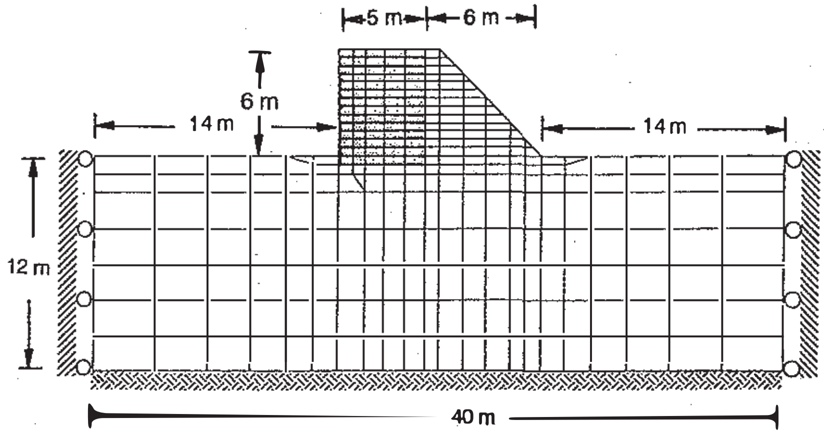


Fig. 1 Finite-element discretization of the modelled structure

ment (S_r = 4.0 x 10^5 and 7.6 x 10^4 kPa) and extensible polymer grid reinforcements (S_r = 2.4 x 10^2 and 4.0 kPa). Two foundation rigidities were also included to compare the behavior of reinforced soil structures on soft ground with those on rigid ground. An elasto-plastic soil model (modified Cam clay) was used to simulate the soft ground while an elastic soil model was employed for rigid ground, both of which considered the consolidation process.

Figure 1 shows the finite-element discretization together with the boundary conditions used in the analysis. The mesh size was considered a good compromise between accuracy and computer time. The bar elements representing the reinforcements are shown in bold lines while the interface elements are not shown in the mesh to minimize congestion of drawing lines. A linear elastic model with limiting yield stress was used to characterize the behavior of the reinforcement which was idealized as continuous sheet and modelled as bar (truss) element with axial stiffness but negligible flexural rigidity. The facing unit was modelled as beam element with axial, shear and bending stiffness. At facing junctions, the connection was modelled as a hinge. The interaction between backfill soil and grid reinforcement was modelled by introducing Goodman type soil-reinforcement interface element. For grid reinforcement, the interface resistance mobilization process in pullout and direct shear mechanisms are different (Alfaro et al. 1995b). The simulation should therefore include a modelling technique wherein it can detect whether it is in a direct shear or pullout mechanism and then select the appropriate interface properties to be used corresponding to the acting interaction mechanism. The technique employed here was similar to that which was used by Hird and Kwok (1989). It considered the interface elements above and below the reinforcement as pair elements, and the signs of shear stresses of these pair elements are compared to determine whether the direct shear (same sign) or the pullout (different sign) is the acting interaction mechanism. Interface shear resistance determined by direct shear tests was simulated by a hyperbolic shear stress-displacement model. Pullout interface shear resistance from grid longitudinal members and bearing resistance from grid transverse members were also simulated by a hyperbolic model. For both direct shear and pullout mechanisms, the normal stiffness of the interface was prescribed with a value of 10^7 kN/m^3 for compression case and 10^2 kN/m^3 for tension case.

The finite-element analysis also included the simulation considerations for embankments on soft ground as outlined in Chai and Bergado (1993), particularly the large deformation phenomenon associated with the construction of earth structures on soft ground. This was considered by updating the nodal coordinates in the soft ground and varying the clay permeability during the consolidation process. Also, the actual construction was simulated by updating the coordinates of the node above the current construction top surface, ensuring that the applied embankment thickness would be the same as the field value. In the simulations, the embankment was constructed in layers 0.45 m high consisting of 3 lifts. The gravitational force of each layer was applied in increments and each lift was assumed to be constructed in one day. The simulation of the compaction induced lateral pressure, which was considered by most researchers as an important factor, was not implemented in this particular investigation. Preliminary finite-element analysis that was carried out indicated that the compaction induced lateral pressure appears to have insignificant effect for the two test facilities where the numerical simulation was validated, probably because of construction procedure and flexibility of facing units.

The finite-element analysis was carried out using a computer program CRISP-AIT (Chai 1992) which is a modified version of CRISP (Britto and Gunn 1987) and which has incorporated some important features for the simulation of the behavior of reinforced soil embankment on soft ground. The model parameters used in the analysis are summarized in Tables 1 to 4.

Table 1 Soil parameters for the soft ground

Parameter	Symbol	Value
Kappa	κ	0.11
Lambda	λ	0.51
C.S.L. slope	M	0.90
Gamma	Γ	5.12
Poisson's ratio	ν	0.30
Modulus (kPa)	E	4000
Friction angle (degrees)	ϕ'	29.0
Cohesion (kPa)	c'	29.0
Unit weight (kN/m^3)	γ	15.0
Horizontal permeability (m/sec), (x10^{-8})	k_h	5.2
Vertical permeability (m/sec), (x10^{-8})	k_v	2.6

Table 2 Hyperbolic soil parameters for backfill soil

Parameter	Symbol	Value
Cohesion (kPa)	c	110.0
Friction angle (degrees)	ϕ	28.7
Modulus number	k	1015
Modulus exponent	n	0.20
Failure ratio	R_f	0.84
Bulk modulus number	k_b	1050
Bulk modulus exponent	m	0.24
Unit weight (kN/m^3)	γ	16.3

Table 3 Reinforcement parameters

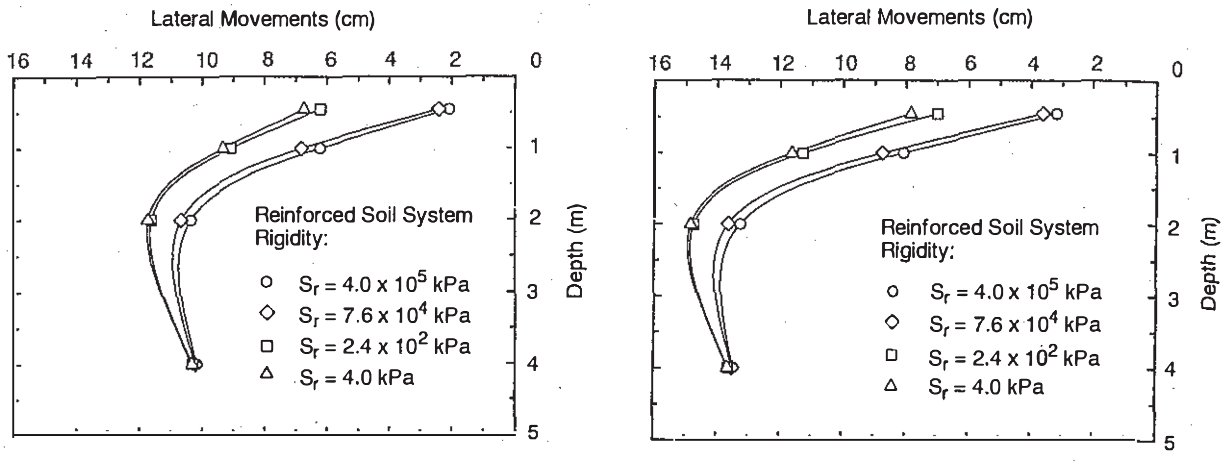
Parameter	Symbol	Value
Young's modulus (kPa)	E	varies
Shear modulus (kPa)	G	varies
Moment of inertia (m^4)	I	4.5 x 10^{-10}
Cross-sectional area (m^2)	A	1.8 x 10^{-4}
Yield stress (kPa)	σ_y	varies

Note: Given values are for a meter strip width

Table 4 Interface parameters for direct shear and pullout interaction mechanisms

Mechanism	Parameter	Symbol	Value
Direct Shear Interaction Mechanism	Cohesion (kPa)	c	110.0
	Friction angle (degrees)	ϕ	32.5
	Shear stiffness number	k_I	11980
	Shear stiffness exponent	n_I	0.34
	Failure ratio	R_{fI}	0.87
	Shear stiffness number for reloading	k_{rI}	1300
Additional Parameters for Pullout Interaction Mechanism	Adhesion (kPa)	c_a	50.0
	Skin friction angle (degrees)	δ	9.0
	Initial slope ratio for rigid bearing member	R_{io}	0.10
	Critical rigidity index ratio (%)	R_{rc}	250.0
	Resistance ratio exponent	nr	0.75
	Free transverse member interaction space ratio	$(S/D)_2$	45
	Rigidity index of transverse member	I_d	28
	Transverse member spacing (mm)	S	225.0
	Transverse member thickness (mm)	D	5.4
	Displacement for mobilizing max. skin friction (mm)	d_{cr}	2.0
	Fractional area of reinforcement for skin friction	A_r	0.06

Note: Refer to Chai (1992) for definition of parameters



(a) end of construction

(b) 1 year after construction

Fig. 2 Lateral movements of the soft ground beneath the toe of reinforced embankment

3 EFFECT OF REINFORCEMENT RIGIDITY ON THE RESPONSE OF SOFT GROUND

3.1 *Deformation Patterns*

The finite-element analysis reveals that higher reinforced soil system rigidity reduced the lateral movements of the soft ground (Fig. 2). It appears however that the reduction is confined only at the proximity of 2 m depth, beyond which there is no significant difference.

The surface settlement profiles of the soft ground at the end of construction are shown in Fig. 3. The post construction settlement profiles follow similar pattern. An interesting feature of the settlement profile is that there is a localized pattern within about 1.5 m distance behind the wall face. It is within this distance that the potential active zone of reinforced soil mass may be situated. In this vicinity, it can be seen that higher reinforced soil system rigidity provided higher settlement at the toe with its maximum value also located near the toe. On the other hand, lower system rigidity had lower settlement at the toe with its maximum value located away from the toe to the interior portion. This behavior suggests that higher system rigidity inherent for inextensibly reinforced soil mass produced higher settlement at the toe because a more rigid reinforced soil mass tend to rotate more about the toe compared to that of extensibly reinforced soil mass which has lower system rigidity.

3.2 *Base Pressures*

The reinforced soil mass can also be considered analogous to that of either a rigid or a flexible surfacial loading on soft ground. Any factor tending to increase the rigidity of the reinforced soil mass will result in larger settlement and higher vertical base pressure at the toe as depicted in Fig. 4.

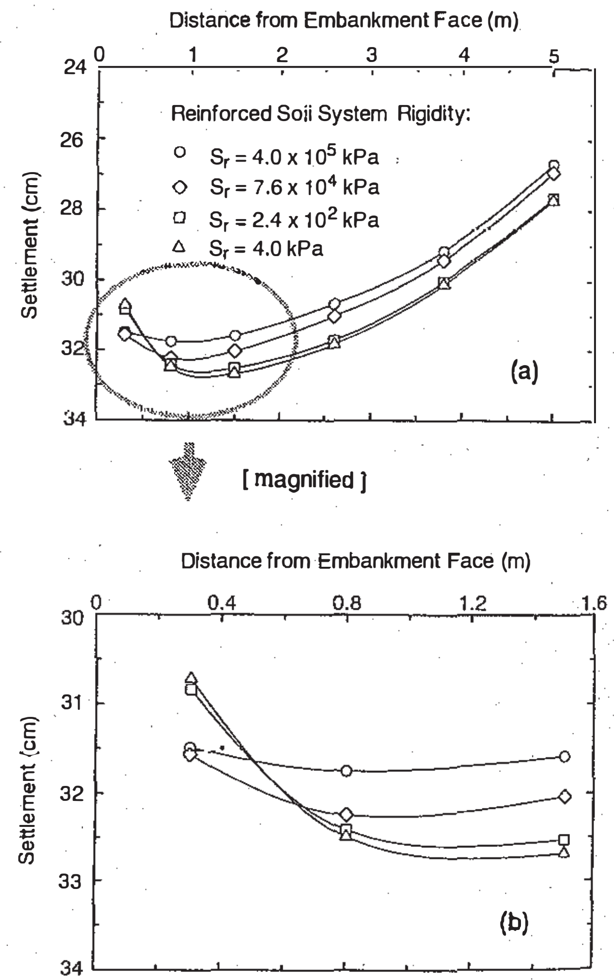


Fig. 3 Ground surface settlement profiles

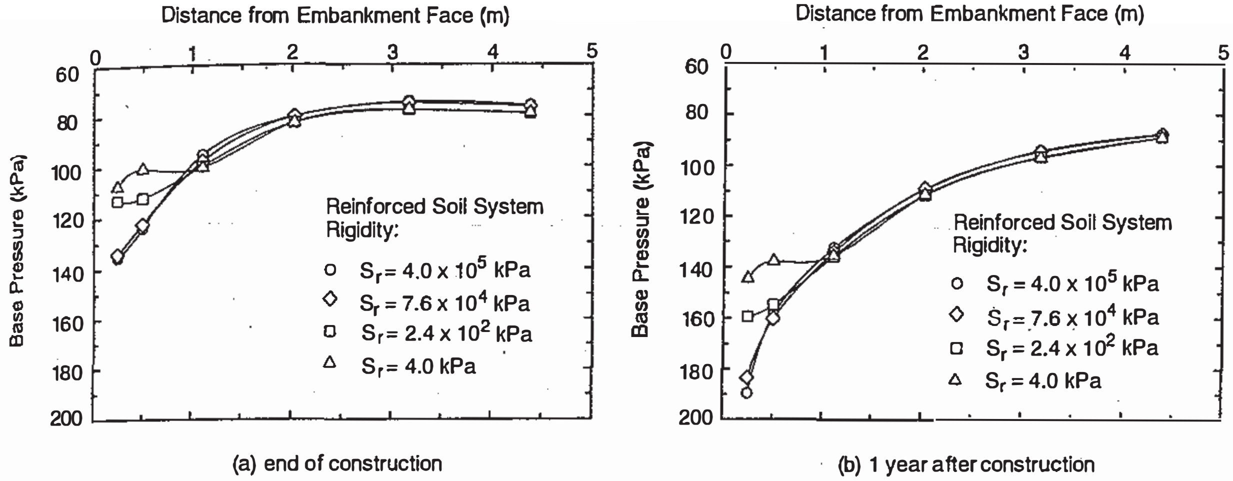


Fig. 4 Vertical base pressure distributions

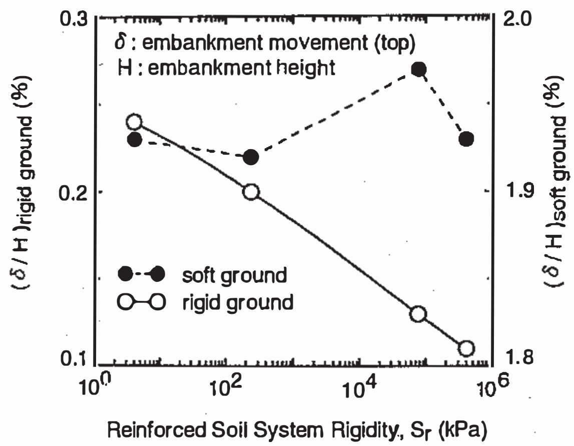


Fig. 5 Variation of (δ / H) with system rigidity

4 EFFECT OF FOUNDATION RIGIDITY ON THE RESPONSE OF REINFORCED EMBANKMENT

4.1 *Deformation Patterns*

Figure 5 shows the pattern of maximum outward face movements occurring at the end of construction for varying system rigidity on both soft and rigid grounds. The post construction movements follow similar pattern. While the outward face movements decreased with increasing system rigidity for the case of embankment on rigid ground, the same structure but on soft ground exhibited complex deformation pattern. This complex pattern is attributed to the interaction between the reinforced embankment and the soft ground associated with reinforced soil system rigidity.

The potential increase of outward face movement with decreasing system rigidity, as generally understood for such structure on rigid ground, is apparently compensated by the decrease in outward face movement of the same structure but on soft ground due to two operating mechanisms that were identified. One mechanism is that the decrease in system rigidity is associated with increasing lateral ground movement particularly beneath the center of the reinforced embankment. This tends to reduce the top movement because of the bending effect of reinforced embankment, such that concave upward. Another mechanism is that the decrease in system rigidity tends to decrease the settlement and base pressure at the toe, which could reduce the potential outward rotation of the wall face. The occurrence of one or both of these operating mechanisms could result to just a slight or even to a decrease of overall outward face movement with decreasing system rigidity.

The practical implication of this numerical finding is that the preference of the designer in attempting to reduce the possible outward movement of reinforced soil wall by intuitively increasing the system rigidity could be misleading when such structure is to be constructed on soft grounds.

4.2 *Reinforcement Tensile Forces*

The effect of reinforcement rigidity or extensibility on the maximum tensile forces occurring at one year after construction is depicted in Fig. 6 for structure both on soft and rigid grounds. Also shown are the at-rest and active earth pressure lines which are respectively associated with the design of inextensibly and extensibly reinforced soil wall on rigid ground. The role of reinforcement rigidity seemed clear in that rigid reinforcement attracted greater tension under working conditions.

For the case of inextensibly reinforced embankment on rigid ground, the calculated maximum tensile forces are close to the K_0-line except at the bottom because of the influence of friction between the reinforced soil

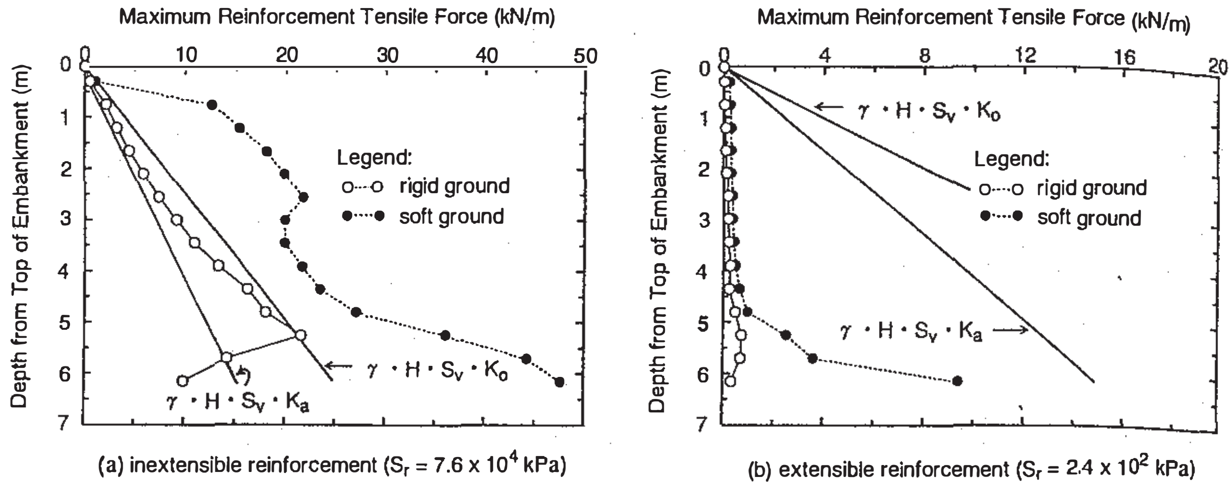


Fig. 6 Distribution of maximum reinforcement tensile forces along the embankment height

mass and the underlying rigid ground which reduces the amount of tension in the bottom layer. This justifies the common design practice wherein the maximum tensile forces are assumed to vary from at-rest condition at the top to active condition at 6 m depth below the top. Higher maximum tensile force than the K_o-line were obtained for inextensibly reinforced soil wall on soft ground particularly near the top and bottom of the embankment. It should be noted that the compaction effect, which was considered by most investigators to induce high tensile forces near the top, was not included in the simulation. The large outward face movement due to the rotation of the potential active zone inherent for inextensibly reinforced soil wall on soft ground has been regarded to have generated higher than expected tension near the top. Higher tensile forces were obtained at the bottom because of the uneven settlement and lateral extrusion of soft ground.

For the case of extensibly reinforced soil wall, the calculated maximum tensile forces were found to be much smaller than those calculated from K_a-line, except at the bottom of the structure on soft ground where it straddle the active pressure line. This finding indicates that extensibly reinforced soil wall under working condition endures significant movements and shearing deformations before bringing extensible reinforcement into play.

5 CONCLUSIONS

The results from finite-element analysis have enabled an improved understanding of the effect of reinforced soil system rigidity on the overall deformation of reinforced soil wall-embankment system on soft ground.

The increase in system rigidity of the reinforced soil mass led to lower lateral movements in the soft ground but had the tendency to settle more below the toe due to its rigid body rotation. Outward face movement of the wall is influenced by the interaction between the reinforced soil mass and the soft ground associated with system rigidity. It was found that the increase in system rigidity does not necessarily result to the reduction of outward face movement.

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