Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © 1996 Balkema, Rotterdam. ISBN 90 5410 833 9

Some insights into reinforced wall behaviour based on finite element analysis

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ABSTRACT: Based on the results of finite element analyses, issues such as the effects of intermediate reinforcing layers, the effect of interface shear, the effect of panel continuity and location of panel connections, facing rigidity, backfill soil stiffness and foundation stiffness are discussed.

1 INTRODUCTION

The literature now contains numerous examples demonstrating the use of the finite element method (FEM) for predicting the performance of specific laboratory model tests or field prototypes. In this paper, the results of FEM are used as the basis for improving the understanding of the effects of intermediate reinforcing layers, interface shear, panel continuity and location of panel connections, facing rigidity, backfill soil stiffness and foundation stiffness on the behaviour of reinforced soil walls.

2 EFFECT OF INTERMEDIATE LAYERS

Conventional analytical and design methods for reinforced soil walls with wrap-back type facing do not consider any reinforcing contribution from the intermediate layers that are wrapped back to form the facing. Rather, the function of the wrap back is generally considered to be for protecting the soil at the face from ravelling and for providing a convenient means of wall construction.

The reinforcing effect of intermediate layers was examined by Ho and Rowe (1994) in the context of predicting the performance of a centrifugal reinforced soil model wall reported by Jaber (1989). The wall was constructed with eight main layers of geotextile serving as reinforcement and shorter intermediate wrap-back layers serving as facing elements. Ho and Rowe (1994) showed that the intermediate layers do exhibit some reinforcing effect, but the effect appears to diminish toward the top of the wall where curtailment of these layers occurs farther away from the Rankine failure plane. Close to the bottom of the wall, the main and intermediate layers which are at the same elevation experience similar magnitudes of force. At the top, the force in the intermediate layers was insignificant when compared to that in the main layers.

The reinforcing effect of intermediate layers is further substantiated in the situation where the reinforcing effect of the intermediate layers was excluded in the analysis and this was found to induce a significant increase in the force in the main layers as shown in Figure 1. Associated with the increase in the maximum reinforcement forces there was also a substantial increase in the predicted horizontal displacement of the reinforced soil model wall when the reinforcing of the intermediate (wrap-back) layer was neglected.

These findings may partly explain the conservatism of current analytical and design methods for this type of reinforced soil wall since these methods do not consider the reinforcing contribution provided by the intermediate layers.

3 PANEL CONTINUITY

Segment type facings provide a convenient means of wall construction. However, in the analysis of reinforced soil walls involving these types of

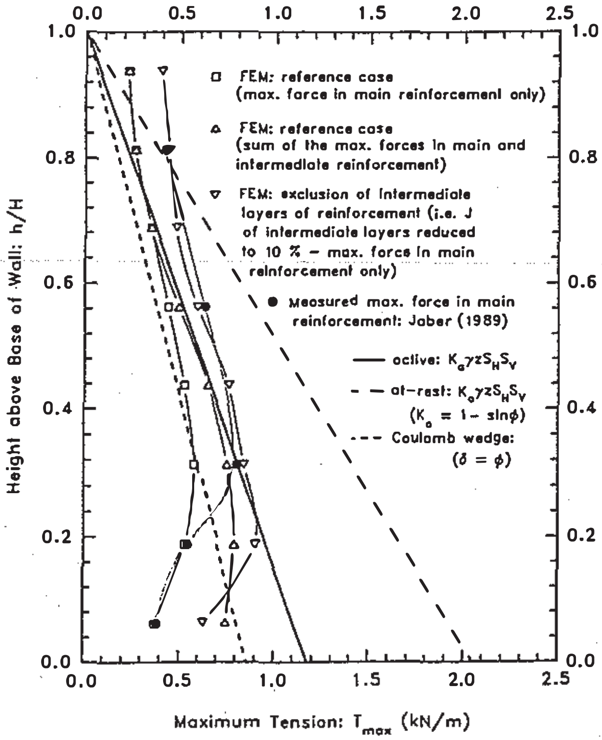

Figure 1 Predicted and observed maximum tensile force distribution (geotextile model) (after Ho and Rowe, 1994).

facing, there are uncertainties regarding the effective locations of connection of adjoining panels and their continuity (i.e. the connection behaves somewhere between a pure hinge and a rigid connection).

Numerical results examining the effects of the location of panel connection and facing panel continuity on the behaviour of reinforced soil walls have been discussed by Ho and Rowe (1994) who compared the predicted and observed performance of a centrifugal reinforced soil wall constructed with segment facings and found that varying the effective locations of facing panel connections which were modelled as pure hinge did not appear to have a significant effect on the predicted behaviour of the model wall. For reasonable uncertainty regarding the modelling of the segmented facing, the predicted displacement and forces were all in good agreement with the observed values.

In the same study, the effect of panel continuity on the behaviour of reinforced soil wall model was also examined. It was found that only in the case where the facing was modelled as a continuous beam was there a slight reduction in the horizontal displacement at the lower part of the wall and a slight redistribution of maximum force among the lower layers of reinforcement relative to the results for a segmented facing.

Although none of the conditions regarding the location of panel connection and facing continuity that were examined by Ho and Rowe (1994) correctly depict the actual situation, based on the results of these sensitivity studies it appears that the related uncertainty may not be a significant factor since the effect on the predictions was relatively small.

4 EFFECT OF FACING RIGIDITY

Tatsuoka (1993) discussed the role of facing rigidity in the context of observations made in laboratory model tests and field tests, and has shown that facing rigidity is an important parameter to be considered. However, there has been little discussion of the mechanism whereby facing rigidity affects the behaviour of reinforced soil walls.

Numerical findings by Ho and Rowe (1996) also indicate that facing rigidity is an important factor to consider. Figure 2 shows the effect of facing rigidity (EI) on the force interaction of a numerical model wall constructed with a full panel facing (hinged toe) and on a rigid foundation. Reducing in the facing rigidity was found to slightly increase the total force required for internal equilibrium of the reinforced soil block but to decrease the force (both vertical and horizontal) being transferred to the bottom of the facing. This is because a more flexible facing is more susceptible to local deformation and is less effective in transmitting force to the bottom of the wall, thereby limiting the force being transferred to the bottom of the facing. As a consequence, part of the force required for external equilibrium is redistributed to the reinforcement resulting in larger reinforcement forces near the bottom of the wall but lower forces near the top. This redistribution of force is necessary to maintain static equilibrium conditions.

In addition, a reduction in facing rigidity was also found to decrease the force required for external equilibrium of the facing due to the consequence of a reduction in the lateral soil pressure immediately behind the wall face (Figure 3). The decrease in lateral soil pressure with reduced facing rigidity is due to the fact that a more flexible facing is less effective in confining the backfill at the wall face.

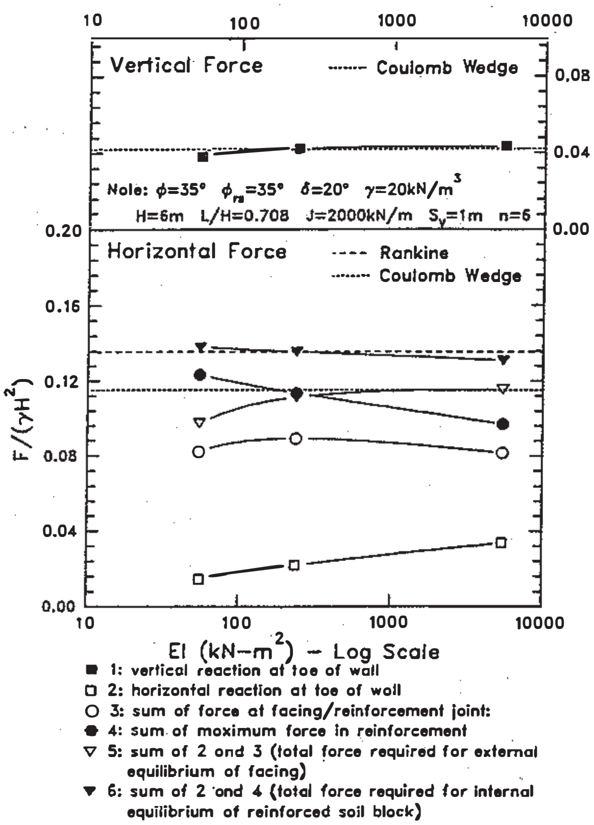

Figure 2 Interaction diagram for the effect of facing rigidity (EI)

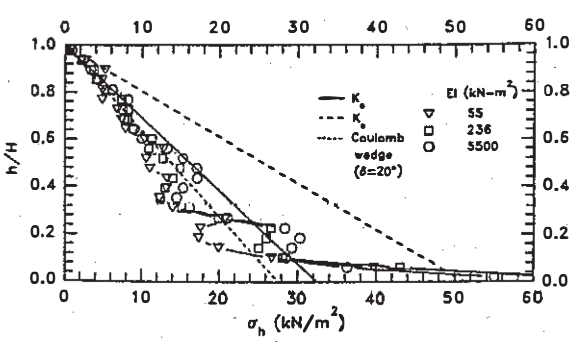

Figure 3 Horizontal soil pressure σ_h behind facing for the effect of facing rigidity (EI).

A change in facing rigidity was found to affect both the magnitude of horizontal displacement at the wall face and the location at which the maximum horizontal displacement occurs. It has been shown that reducing the facing rigidity has a general effect of inducing a larger total force in the reinforcement layers, inducing a larger force in the lower reinforcement layers and smaller force in the top layers relative to the case with a more rigid facing. As a consequence, the reinforcement strain and hence the soil strain will also be smaller at the top and larger at the bottom for the lower facing rigidity and hence there is a downward shift of the location of maximum horizontal displacement at the wall face. The increase in the horizontal displacement at the wall face for the case of a reduced facing rigidity is due to an increase in soil strain in both the reinforced zone and unreinforced zone but the latter appears to be less significant in this case.

The numerical results suggest that for the case of a rigid and non-yielding foundation, the use of a more rigid facing is beneficial (i.e. in terms of smaller reinforcement force and smaller horizontal displacement at the wall face) as compared with a less rigid one. However, if the foundation was less rigid, the effect of facing rigidity may not be as beneficial as in the case examined.

5 EFFECT OF BACKFILL SOIL STIFFNESS

Based on studies reported by Rowe and Ho (1995) and as is evident from Figure 4, the assumed deformation modulus of the backfill E_s does not appear to have a significant effect on the forces required for either external rigid body equilibrium or internal equilibrium of the reinforced soil wall system except for very low values of modulus. The relative insensitivity of the forces to soil modulus is due to the fact that even though the wall is stable the reinforced soil mass (i.e. the area within the anticipated failure zone) is in a general state of plastic failure and hence is not dependent on the elastic (Young's) modulus of the soil.

A more important finding is that the distribution of maximum force in the reinforcement and the connection load between the reinforcement and facing also did not show any significant variation over a wide range of E_s. Similarly, the horizontal soil pressure behind the wall face was found to exhibit only slight variations. These numerical results suggest that the soil deformation modulus E_s is relatively unimportant in controlling the force developed in the reinforcement in this type of wall.

Due to the minor effect of backfill soil deformation modulus E_s on the force

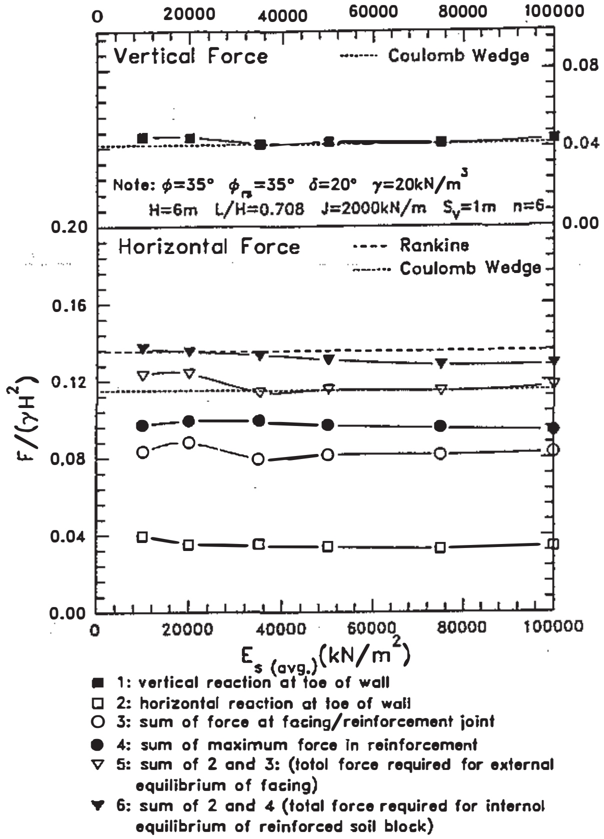

Figure 4 Interaction diagram for the effect of soil deformation modulus (E_s).

development in the reinforced soil wall system, the internal deformation of the reinforced soil block also showed only slight variations (Rowe and Ho, 1996). A change in E_s only affects the horizontal deformation behind the reinforced soil block and consequently the horizontal deformation at the wall face. This situation arises because most of the reinforced soil above the zero force line is in a general plastic state of stress and hence plastic soil strain prevails and the Young's modulus of the soil is largely irrelevant. The strain in the reinforced soil block is controlled by the stiffness of the reinforcement. However, the Young's modulus of the soil does have an effect in the areas where the soil is still largely elastic and these areas are confined to the soil below the zero force line. In these areas, the horizontal soil deformation increases with decreasing E_s and these deformations accumulate toward the top of the wall. As a consequence, the strain in the unreinforced soil above the zero force line also increases with decreasing E_s.

6 EFFECT OF FOUNDATION STIFFNESS

The effect of foundation stiffness is discussed with reference to the results of a numerical study on a centrifugal reinforced soil model wall (Ho and Rowe, 1994). The wall was 508 mm high and was constructed with eight layers of miniature geogrids and on a 76 mm thick foundation of granular materials. In the analysis, the deformation modulus of the foundation materials was modelled using Janbu's equation (i.e. $E_f = K(\sigma_3/P_a)^n$). As shown in Figure 5, a forty fold decrease in the deformation modulus E_f (i.e. that is a change in K in Janbu's equation) only induced a modest increase (i.e. some 30%) in horizontal deformation at the wall face. The increase in the deformation at the wall face arose from both an increase in rigid body movement and in the internal deformation of the reinforced soil block; however, the effect on internal deformation was mainly confined in the lower portion of the wall. Similar to the effect on horizontal deformation, a change in foundation stiffness was not found to significantly affect the maximum force in the reinforcement layers in this case.

In general, the results suggest that

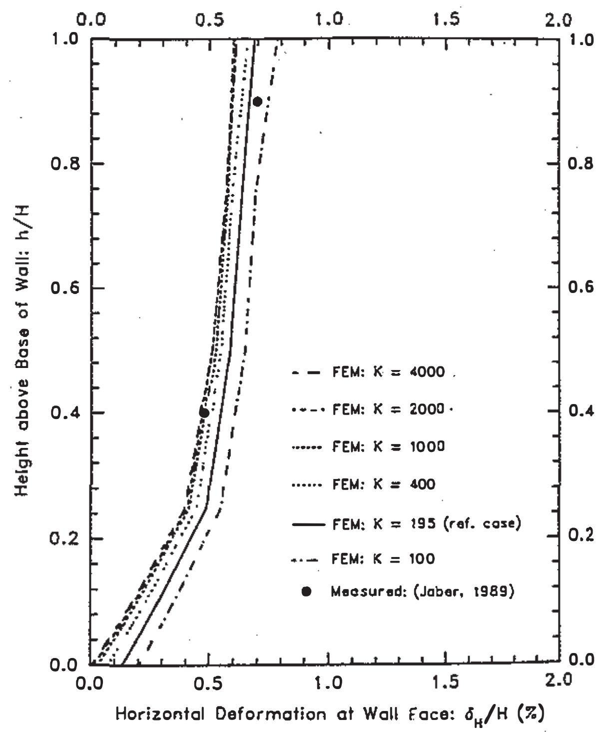

Figure 5 Effect of foundation stiffness on horizontal deformation at wall face (geogrid model).

foundation stiffness does not appear to have a significant effect on the response of the small scale model. However, the thickness of the compressible foundation was only 15% of the height of the wall in this model and this may have reduced the influence of the foundation stiffness. Hence, the relative insensitivity of wall face horizontal deformation to foundation stiffness evident in this case may only be valid for the situation of a limited thickness of compressible foundation and should not be generalized. In situations involving a larger thickness of compressible foundation, separate analyses are required for a valid assessment of the realistic effect of foundation stiffness on the deformation of a reinforced soil wall system.

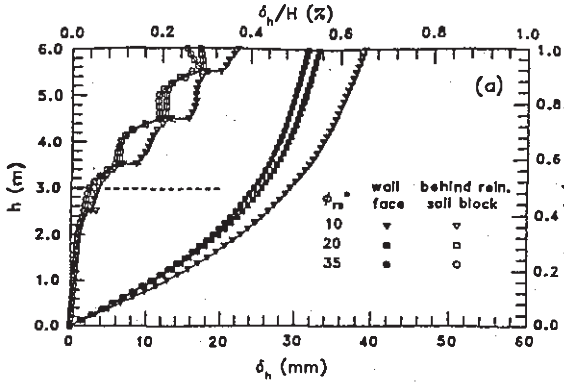

Figure 6 Deformation profiles for the effect of reinforcement/soil friction angle (ϕ_{rs}) at wall face and at back of reinforced soil block.

7 EFFECT OF REINFORCEMENT/SOIL INTERFACE FRICTION ANGLE

A numerical examination of the effect of reinforcement/soil friction angle ϕ_{rs} for the case of a numerical model wall constructed on a rigid foundation indicated that the reinforcement/soil friction angle ϕ_{rs} only affects the behaviour of the reinforced soil wall system for values of ϕ_{rs} smaller than two-thirds of the backfill friction angle $\phi=35°$. For these cases, slip between soil and reinforcement did occur at the end of the upper reinforcement layers, resulting in a general increase in the horizontal reaction load at the toe of the wall and an increase in the sum of the connection load between the reinforcement and the facing, but with the sum of maximum force in the reinforcement remaining unaffected until the assumed ϕ_{rs} was unrealistically low (e.g. for the case with $\phi_{rs}=10°$).

Slip between soil and reinforcement generally induces a larger horizontal soil pressure at the wall face and consequently a larger toe reaction and larger connection loads result. Even though slip in the upper layers limits the force they can carry, slip could be compensated by a redistribution of stress and force in the system. Thus there is a redistribution of maximum forces among the reinforcement layers but their sum remains practically the same. However, since this also means an increase in the toe reaction it again highlights the potential importance of foundation strength and stiffness.

The consequence of slip (i.e. in the upper layers) is an increase in the horizontal deformation at the wall face as is evident in Figure 6. This increase arises from an increase in the soil and reinforcement strains in the reinforced soil block and especially, the soil strains in the unreinforced zone above the zero force line. However, even though there is significant slip in the upper layers, the wall is still stable. Thus, although slip in the upper layers limits the force they can carry, force is redistributed to the lower layers of reinforcement to re-establish equilibrium. This increases the strain in the lower reinforcement layers and, hence the strain in the soil also increases since strain compatibility between the reinforcement and soil is still maintained at most locations in the lower reinforcement layers.

8 CONCLUSIONS

The following conclusions summarize of the findings of this paper with respect to the cases examined:

(1) For reinforced soil walls constructed with wrap-back type facings, the intermediate layers that form part of the facings, especially those lower down the wall, appear to be effective in sharing the load carried by the main layers of reinforcement and in reducing the wall deformation, provided that curtailment of these intermediate layers is not too far away from the anticipated failure plane.

(2) The location of panel connection and facing panel continuity only exhibit minor effects on the behaviour of reinforced soil wall systems. Their effect on the force in reinforcement and deformation at the wall face have been shown to be insignificant.

(3) The effect of facing rigidity is shown to be rather significant in the case of a rigid foundation. A less rigid facing will be less effective in transferring force to the foundation and will result in larger force in the reinforcement layers lower down the wall. Consequently, a small facing stiffness will lead to an increase in the horizontal deformation at the wall face and a shift in the location of the maximum wall face deformation. However, this all assumes a rigid base and the benefits may not be as evident for a more flexible or yielding base.

(4) Because the major portion of the reinforced soil zone is mostly in a general plastic state of stress and plastic strain prevails, the deformation modulus of the backfill soil is largely irrelevant. Therefore, the effect of backfill soil stiffness on the behaviour of reinforced soil wall system is relatively insignificant.

(5) Numerical results presented for the case of a compressible granular foundation of limited thickness (15% of wall height) indicate that a reduction in foundation stiffness only results in a slight increase in wall face deformation but insignificant variation in reinforcement force. However, this conclusion should not be generalized to situations where the thickness of the compressible foundation is significant or for soft or clayey foundations. Under those circumstances, separate analyses are necessary to assess the effect of foundation stiffness on the response of the reinforced soil wall system.

(6) Numerical results indicate that for the cases examined as long as the soil/reinforcement friction angle ϕ_n is larger than about 20°, slip was not a problem and there was no variation in the response of the reinforced soil wall due to a change in ϕ_n. For the case of low values of ϕ_n in which significant slip occurred in the upper layers of reinforcement, there was a redistribution of force to the layers of reinforcement lower down the wall and a subsequently larger horizontal deformation at the wall face.

ACKNOWLEDGEMENT

The research reported in this paper was funded by the Natural Sciences and Engineering Council of Canada under grant A1007.

REFERENCES

Bathurst, R.J., Karpurapu, R. and Jarrett, P.M. (1992). Finite element analysis of a geogrid reinforced soil wall. *Grouting, Soil Improvement and Geosynthetics*, Vol. 2, ASCE Geotechnical Special Publication No. 30, 1213-1224.

Ho, S.K. and Rowe, R.K. (1994). Predicted behaviour of two centrifugal model soil walls. *ASCE Journal of Geotechnical Engineering*, Vol. 120, No. 10, 1845-1873.

Ho, S.K. and Rowe, R.K. (1996). Effect of wall geometry on the behaviour of reinforced soil walls. *Geotechnical Research Centre Report*, GEOT-8-96, Dept. of Civil Engineering, University of Western Ontario, London, Canada.

Jaber, M.B. (1989). Behaviour of reinforced soil walls in centrifuge model tests. Ph.D. thesis, University of California at Berkeley.

Jewell, R.A. and Milligan, G.W.E. (1989). Deformation calculation for reinforced soil walls. *Proc. 12th Int. Conf. Soil Mech. Found. Eng.*, Rio de Janeiro, Vol. 2, 1257-1262.

Rowe, R.K. and Ho, S.K. (1993). A review of the behaviour of reinforced soil walls. *International Symposium on Earth Reinforcement Practice*, Kyushu, 801-830.

Rowe, R.K. and Ho, S.K. (1995). Soil-structure interaction in reinforced soil walls. *Geotechnical Research Centre Report*, GEOT-18-95, Dept. of Civil Engineering, University of Western Ontario, London, Canada.

Rowe, R.K. and Ho, S.K. (1996). Horizontal deformation in reinforced soil walls. *Geotechnical Research Centre Report*, GEOT-7-96, Dept. of Civil Engineering, University of Western Ontario, London, Canada.

Tatsuoka, F. (1993). Roles of facing rigidity in soil reinforcing. *Proc. International Symposium on Earth Reinforcement Practice*, Kyushu, Japan, Ochiai, I., Hayashi, S. and Otani, J., Eds., A.A. Balkema, 831-870.