Parametric Finite Element Investigation of Reinforced Soil Retaining Walls

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ABSTRACT: This paper presents the details of a finite element technique that has successfully predicted the performance of two reinforced soil retaining walls constructed using different methods of construction. The numerical and experimental results show that the method of construction has significant influence on the performance of these structures which is not accounted for in the conventional design procedures. Another factor which influences the strength and stiffness behaviour of reinforced soil structures is the dilation of soils. The increased shear strength of dilatant soils play an important role in their behaviour. The effect of dilation angle on the response of reinforced soil retaining walls is clearly shown by the numerical results presented in this paper. The results presented in the paper confirm the validity of some of the assumptions made in the current limit equilibrium design methods with regard to the location of internal failure surface. Various parameters employed in this paper have been obtained from independent laboratory tests.

1 INTRODUCTION

Finite element analyses have accurately predicted the performance of many full-scale instrumented laboratory reinforced soil retaining walls. These models can predict both the deformation and strength behaviour of reinforced soil structures quite accurately as demonstrated by the results from two prediction symposia, e.g. Bathurst and Koerner (1988) and Wu et al. (1992).

This paper describes a finite element model developed by the authors and its application to the prediction of response of four reinforced soil retaining walls built using two different methods of construction and two different backfill soils. It is demonstrated that the finite element models can predict the qualitative difference in the performance of walls constructed using different construction methods and backfill materials. The influence of dilation behaviour of soil on the strength and stiffness of reinforced soil walls is clearly shown from the results presented in this paper. The paper further demonstrates that it is possible to improve the performance of reinforced soil structures built of poor backfill soils by using a sandwich technique in which thin layers of high strength soil are provided around the reinforcement.

2 EXPERIMENTAL DATA

The test data employed for calibrating the finite element model was obtained from testing full-scale instrumented laboratory reinforced retaining walls taken to failure under uniform surcharge. Two types of construction and two different soil types were employed in these walls as described below.

2.1 RMC trial walls

The laboratory test models were 2.4m wide, 6m long, and 3.5m high and were constructed with a coarse sand backfill (e.g. Bathurst et al. 1988, Bathurst et al. 1989). The front facing of wall consisted of three independent sections: two outer sections of 0.7m wide and a central section 1m wide. The response of the walls were measured in and behind the central portion to minimize the influence of side wall friction effects on the measured data. The walls were reinforced with four layers of a bi-axial polyethylene geogrid oriented in the weak direction and extending 3m into the walls.

Two different facing treatments were considered, one in which the full-height panels of 3m were used and the other in which the wall was made up of incrementally placed panels. The full-height panels were supported laterally during the soil placement and compaction. The incremental wall was constructed using 0.75m high panels which were released sequentially as the height of compacted soil increased behind the panels. Layers of foam rubber were placed between the incremental panels to provide some vertical compressibility to the facing. The facing units were seated on a levelling pad that acted as a pin connection.

Surcharge pressure increments were applied over the full surface area of the backfill by inflating air bags constrained between the backfill and a framework at the top of the wall. Each increment of surcharge was applied for a minimum of 100 hours to monitor the creep induced deformations in the structure. The surcharge increments were increased until the failure of the walls.

2.2 Denver trial walls

As part of a prediction symposium, two trial walls were built at the University of Colorado at Denver as described by Wu et al. (1992). One wall was constructed with a granular soil backfill and the second with a silty clay. The walls were 3m high, 2.1m long and 1.22m wide. The facing of the walls comprised of a series of incrementally placed 0.28m square timber logs connected by 12.7mm thick plywood boards at the back face. The facing technique is based on a procedure developed by the Colorado Department of Transportation. The walls were reinforced with 12 layers of a non-woven heat-bonded polypropylene geotextile extending 1.68m into the backfill. Each geotextile layer was wrapped around the plywood and overlapped with the next layer of reinforcement for a distance of 0.92m. Surcharge pressure increments were applied using air bags similar to the arrangement at RMC.

3 FINITE ELEMENT MODELS

The finite element program GEOFEM developed at the Royal Military College of Canada, Kingston has been used to simulate the performance of the above four walls, Karpurapu and Bathurst (1994). Discrete finite element approach has been used in the program. Plane strain conditions have been used in the simulated by neglecting the side wall friction effects.

Figure 1 shows a typical mesh used to simulate the behaviour of full-height panel RMC

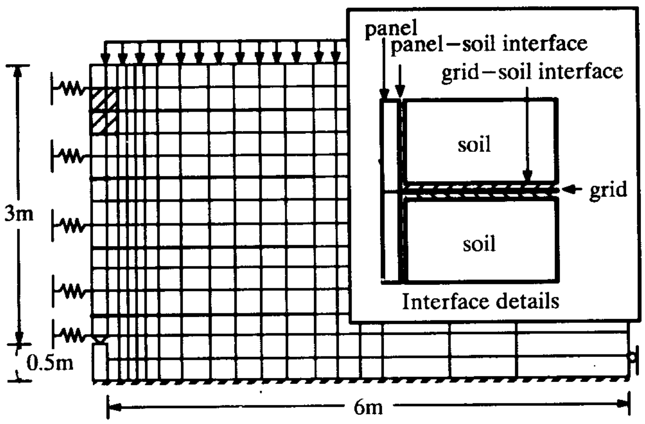


Figure 1 **Finite element mesh for RMC full-height panel wall**

wall. Similar meshes have been employed to simulate the other three walls. The meshes for RMC walls consisted of approximately 1700 nodal points, 650 elements and about 3300 degrees of freedom. The meshes for Denver trial walls consisted of 2000 nodal points, 200 elements, and 3700 degrees of freedom. The top surface of backfill was free to move laterally in the RMC walls and also for the Class-A predictions of Denver trial walls. The measured data for Denver walls has shown that significant friction forces were developed at the air bag-soil interface. Hence, in the Class-C predictions for Denver walls, all the nodes at the top surface of the backfill were constrained from moving in the lateral direction. The compressible foam layers in RMC incremental wall were simulated by using continuum elements with a modulus corresponding to that of the foam layers.

The constitutive behaviour of soil was simulated using a modified form of hyperbolic model that includes a dilation parameter to predict volume change behaviour in dense granular soils. The stiffness of the soil was described by tangent Young's modulus and tangent bulk modulus values which are expressed as a function of confining pressure, Duncan et al. (1980). This simplified constitutive model is easy to use for several reasons. The material parameters in this model can be easily determined from simple laboratory tests. The stiffness matrix in this model is symmetric, unlike in the more advanced plasticity models, leading to considerable economy in solution time and memory space required for simulations. The hyperbolic parameters were determined from triaxial test and direct shear test data.

The nonlinear time dependent behaviour of geosynthetic reinforcement layers was modelled using a second order polynomial relation between the load and strain. The equations were fitted to the 100-hour isochronous creep test data. The stiffness of the reinforcement was computed as a tangent slope. As the geosynthetic materials are flexible in nature, compressive forces were not allowed to develop in the reinforcement layers.

The interfaces were modelled using two independent stiffness coefficients, one in the shear direction and the other in the normal direction. The shear behaviour was simulated using a stick-slip type model in which the shear stiffness was high when the shear stress is less than the shear strength to enforce perfect bond. When the shear stress exceeds the shear strength, stiffness was set to a small value to allow for slip. The normal stiffness was set to a small value when the normal stresses become tensile to allow for debonding at the interfaces.

4 COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

4.1 Ultimate surcharge pressures

The predicted failure surcharge pressures for RMC walls were 83 kPa and 75 kPa for the full-height panel wall and incremental wall tests compare favourably with the respective measured values of 80 kPa and 70 kPa. When the soil dilation angle was neglected, the predicted surcharge pressures were much below the measured values.

The Class-A predicted surcharge pressures for Denver walls were 131 kPa and 83 kPa for the granular and cohesive soil backfill walls respectively (versus 200 kPa and 234 kPa). After the presentation of results during the symposium it was realised that significant boundary forces existed in the test walls. Incorporation of these boundary conditions in the finite element models has improved the prediction for granular soil wall to 186 kPa. In addition to this correction, the properties from unconsolidated-undrained triaxial compression tests had to be used to increase the failure surcharge pressure of cohesive soil backfill wall to 248 kPa which is in close agreement to the measured value, Karpurapu and Bathurst (1992a,b). This exercise clearly shows the need to accurately model boundary conditions and to use representative soil parameters in numerical simulations.

4.2 Effect of dilation angle on numerical predictions

When the dilation angle (ψ=15°) was neglected in the analysis, the predicted lateral displacements were excessive as illustrated in **Figure 2** for RMC full-height propped panel wall. The same trend was obtained for the incremental panel wall also. The predicted surcharge pressures without dilation were 50 and 60 kPa for incremental and full-height walls which are less than the measured values.

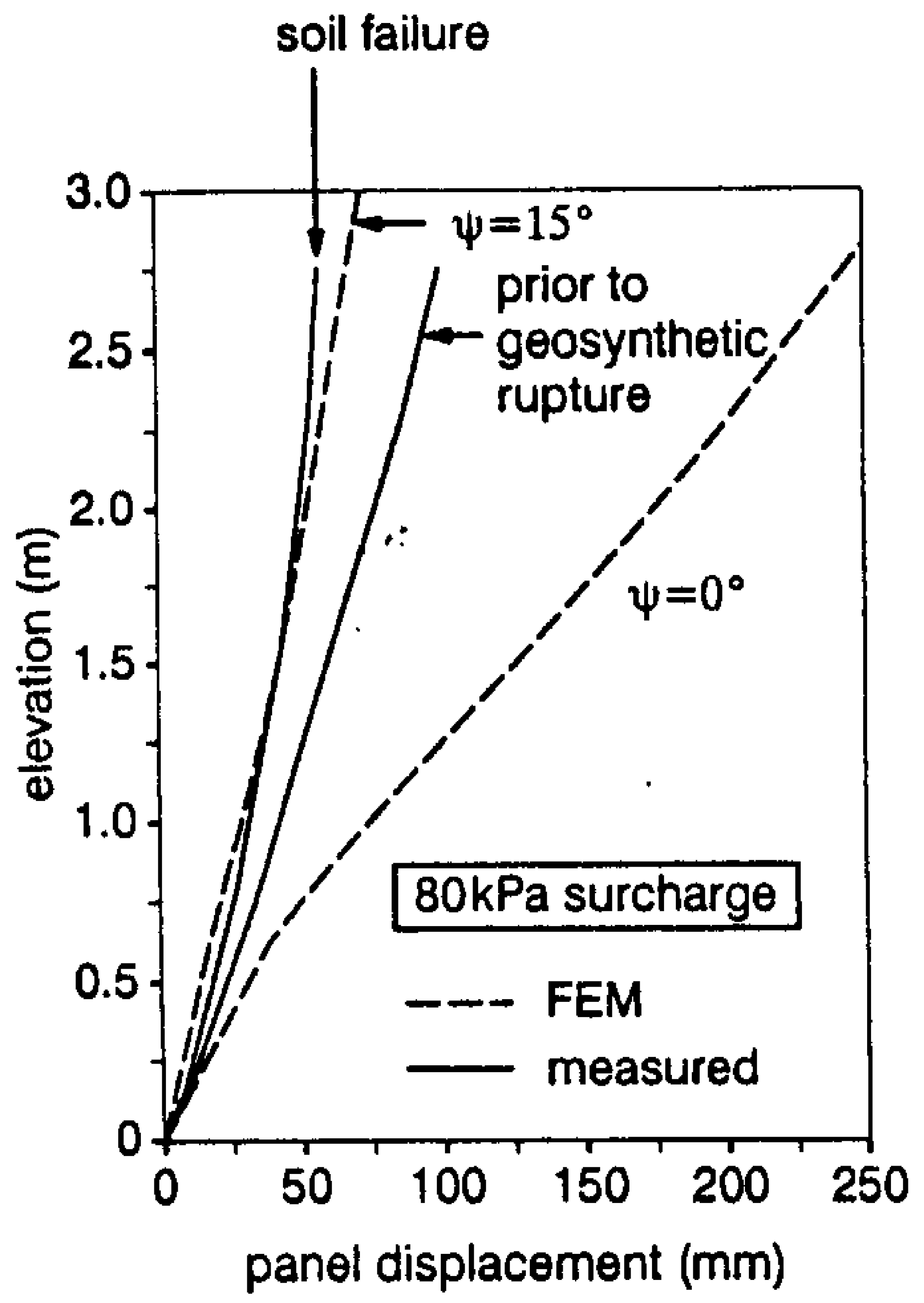


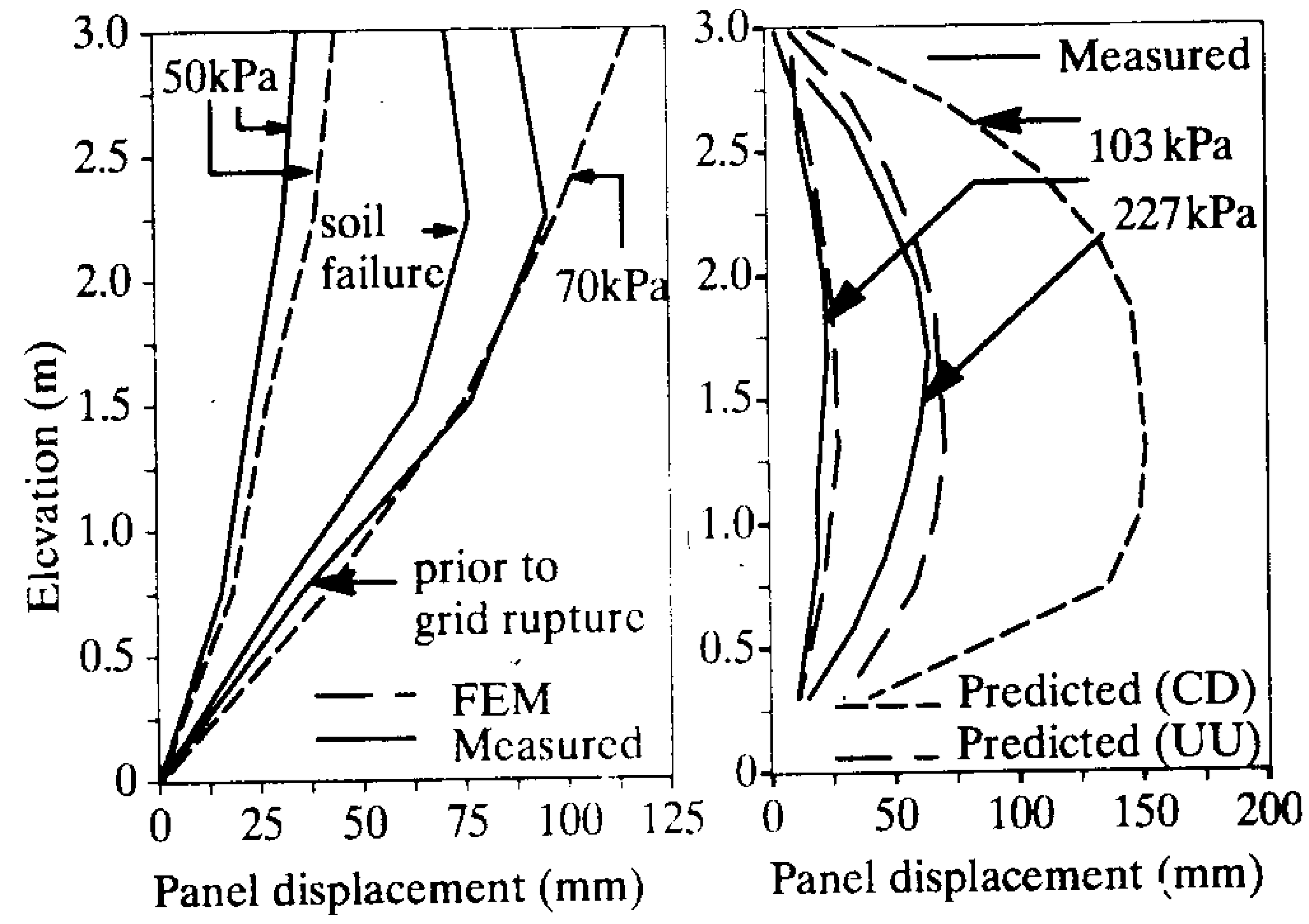
Figure 2 Effect of dilation angle on facing deformations

4.3 Lateral wall displacements

Excellent comparisons were obtained for the lateral panel displacements at various stages of loading as shown in **Figure 3**. This result confirms that deformation response of reinforced soil walls can be predicted accurately by the finite element models. It can be noticed in the figure that the use of clay soil properties from C-D tests for Denver walls leads to inaccurate results.

4.4 Internal failure surfaces

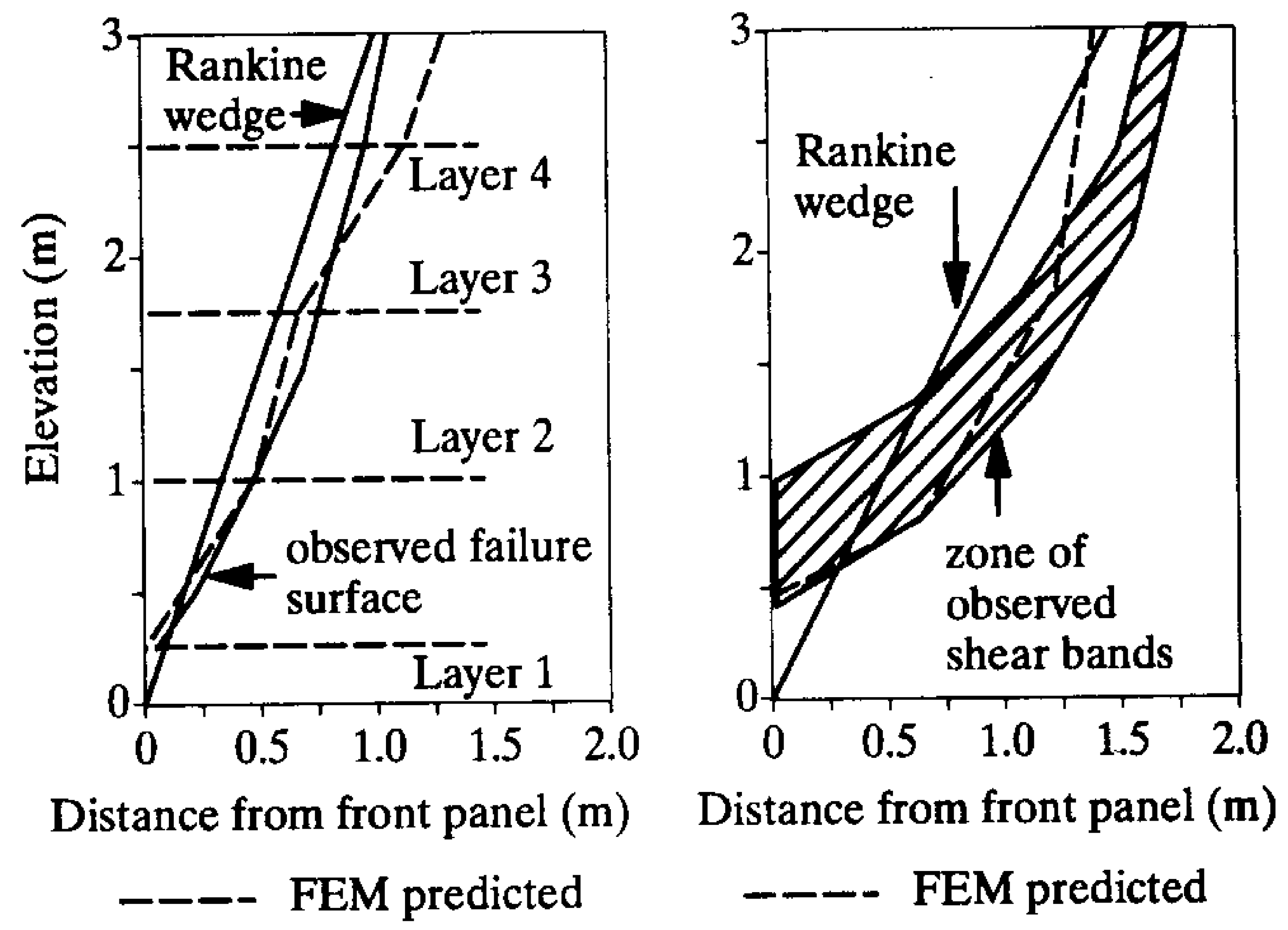
Figure 4 shows a comparison between the predicted failure surface and the observed zones of soil mass movements for RMC and Denver granular soil walls. In both cases, the observed failure surfaces are curved in shape which can be described by a log-spiral. The curvature of the failure surface in the Denver walls is more pronounced because of the larger number of reinforcement layers. In both cases, the Rankine failure surface closely approximates the zone of the failure soil mass as shown in the figure.



a) RMC incremental trial wall

b) Denver trial wall with clay backfill

Figure 3 Lateral deformations for RMC and Denver walls



a) Failure surfaces in RMC full-height panel wall

b) Failure surfaces in Denver granular soil wall

Figure 4 Predicted and observed failure surfaces

4.5 Strains in reinforcement layers

Figure 5 shows a comparison between the measured and predicted grid strains for the RMC trial walls. The finite element analysis is able to predict the construction induced higher grid strains at the connection point for full-height panel wall. The finite element predictions of peak reinforcement strains for all the walls agreed to within 15% and 10% for the RMC trial walls and Denver walls, Karpurapu and Bathurst (1994), Karpurapu and Bathurst (1992b).

4.6 Equivalent lateral earth pressures

Both the measured and predicted lateral pressures were much below the Rankine pressure state and agreed with other very well.

4.7 Toe forces from RMC trial walls

The range of the measured lateral toe force was approximately 15% of the total lateral force. This toe force is not considered in the design process, leading to under-estimating the lateral load carrying capacity of this class of walls by at least 15%. Excellent comparison was obtained for both vertical and horizontal toe forces in

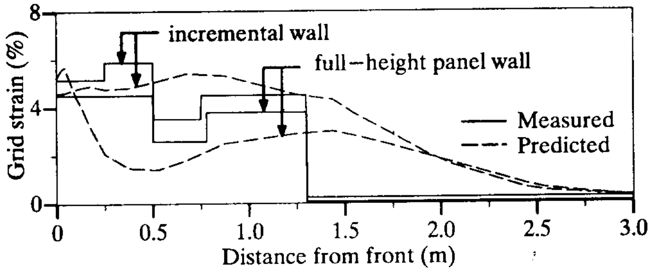


Figure 5 Grid strain distributions in top reinforcement layer at incipient collapse of RMC walls

RMC trial walls. The excellent comparison obtained for the toe reaction forces indicates that the interface model adopted in the numerical analyses.

5 IMPROVEMENT IN PERFORMANCE DUE TO THIN LAYERS OF HIGH STRENGTH SOIL LAYERS

The current industrial practice for construction of reinforced soil structures is to use highly frictional soils for backfills to ensure proper load transfer from soil to reinforcement. A technique has recently been developed in which even poor soils such as cohesive soils or soils with low friction angle can be used as backfills, Karpurapu et al. (1994) etc. The technique involves in providing a thin layer of high friction soil layers around the reinforcement layers. This construction method is termed as sandwich technique as the reinforcement layer is sandwiched between two thin layers of strong soil. The improvement in the performance of reinforced soil systems constructed using this new technique is demonstrated in this paper using numerical technique.

The problem considered for this purpose is the pressure vs. settlement behaviour of a smooth rigid strip footing (width, B=2m) resting on a reinforced sandy soil having a friction angle (ϕ) of 28°. The reinforcement has a stiffness of 100 kN/m and is provided at a depth of 1m (B/2) below the footing for a length of 2B from the centre line. The friction angle of soil placed in the sandwich layer is assumed to be 40°. The predicted pressure vs. settlement response of the footing for two thicknesses of sandwich layers (t) is shown in **Figure 6**. The thickness of sandwich layer on each side of the reinforcement is expressed in terms of the footing width (B). The ultimate pressure of footing without sandwich layer was approximately 200 kPa whereas it was approximately 260 kPa and 300 kPa with the sandwich layers.

It is clear that even a small thickness of sandwich layer increases the load bearing capacity of poor subgrade by more than 30% to 50% for the cases studied in this paper.

6 CONCLUSIONS

A limit equilibrium type design approach for the analysis of reinforced soil structures can only check the horizontal and vertical equilibrium at the incipient collapse state. This method does not predict the deformations that the structure may undergo or the state of stresses under service load conditions. Finite element analysis may be the only alternative to

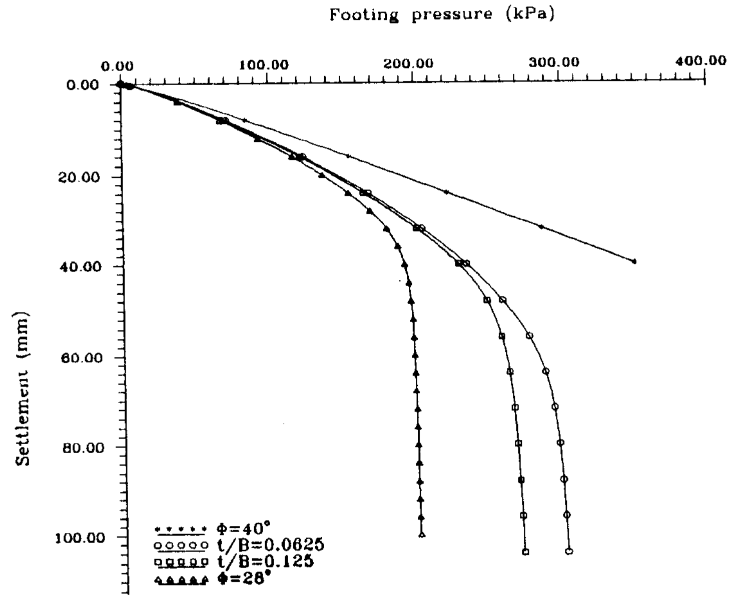


Figure 6 Pressure-settlement behaviour of strip footing

understand the deformation behaviour of these structures. It is very important to employ representative properties for the numerical analysis. This paper has demonstrated that a well formulated finite element model which uses soil properties from independent laboratory tests can successfully predict the response of these structures under both service loads and at incipient collapse state.

7 REFERENCES

Bathurst, R.J., Benjamin, D.J. and Jarrett, P.M. (1988) Laboratory study of geogrid reinforced soil walls, Geosynthetics for Soil Improvement, R. Holtz, ed., ASCE Special Publication 18, 178-192.

Bathurst, R.J., Benjamin, D.J., and Jarrett, P.M. (1989) An instrumented geogrid reinforced soil wall, Proc. XII Int. Conf. on Soil Mech. and Found. Eng., Rio de Janerio, Brazil, Vol. 2, 1223-1226.

Bathurst, R.J. and Koerner, R.M. (1988) Results of Class-A predictions for the RMC reinforced soil wall trials in The Application of Polymeric Reinforcement in Soil Retaining Structures, Ed. P.M. Jarrett and A. McGown, NATO ASI Series, Kluwer Academic Publishers, 127-171.

Karpurapu, R.G. and Bathurst, R.J. (1992a) Finite element predictions for the Colorado geosynthetic-reinforced soil retaining walls, Proc. of Int. Symp. on Geosynthetic-Reinforced Soil Retaining Walls, ed. J.T.H. Wu, A.A. Balkema, Rotterdam, 329-341.

Karpurapu, R.G. and Bathurst, R.J. (1992b) Discussion and Class C predictions for the Colorado trial Walls, Proc. of Int. Symp. on Geosynthetic-Reinforced Soil Retaining Walls, ed. J.T.H. Wu, A.A. Balkema, Rotterdam, 343-346.

Karpurapu, R., Unnikrishnan, N., and Krishnaswamy, N.R. (1994) Numerical simulation of sandwich mechanism in reinforced soil structures, Proc. 2nd Int. Workshop on Geotextiles, New Delhi, January 10-11, 38-45.

Wu, J.T.H., Qi, X., Chou, N., Ksouri, I., Helwany, M.B., and Huang, C.C. (1992) Comparison of predictions for the Denver walls, Proc. Int. Symp. on Geosynthetic-Reinforced Soil Retaining Walls, A.A. Balkema, Rotterdam, 43-60.