International Geotechnical Symposium on Theory and Practice of Earth Reinforcement / Fukuoka Japan / 5-7 October 1988
 ISBN 90 6191 820 0

# Predicting the behaviour of reinforced soil structures

C.J.F.P.Jones
*University of Newcastle upon Tyne, UK*

ABSTRACT: The paper considers the factors which influence the behaviour of reinforced soil structures and gives details of the computer prediction which won a NATO competition held in Canada in 1987. Information on parameter selection and results not previously published are provided. In addition, the advantages of the use of finite element models in the design and analysis of reinforced soil is discussed, particularly, with regard to their ability to take into account the influence of different construction techniques and the presence of weak subsoils, both of which are recognised as being of major significance in determining the behaviour of this form of structure.

## 1 INTRODUCTION

The analysis of reinforced soil structures is conventionally divided into consideration of the external or global stability of the structure and the internal stability. Analysis of the external stability follows normal practice used with gravity retaining walls.

The usual analytical methods used for internal analysis are semi-empirical. Two methods are predominant; the tie-back method which is used by the Department of Transport (1978) in the United Kingdom Design Manual, and the coherent gravity method developed in France by LCPC (1979). Both methods are robust design aids, they make no pretence to model accurately the behaviour of field structures either with respect to strains developed during or after construction or resulting from site conditions. In the case of site conditions the presence of weak subsoils is recognised as being of importance in determining the true behaviour of structures particularly in respect of global movements, Jones and Edwards (1980). The nature and scale of some of these movements is such that it is unrealistic to ignore their effects on the distribution of stress within the reinforced soil mass, Brady (1987). In addition, the construction technique used, particularly that associated with the facing/reinforcement connections or the presence of yielding back-fill, has been shown to have a dominant effect on reinforcement stresses, Naylor (1978), Jones (1979) and McGowan et al (1987).

The factors which influence the behaviour of any reinforced earth structure are identified in Table 1. The information sought by a designer is typically; strain - both of the soil and of individual reinforcing elements within the structure occurring both during construction and post construction; tension - along the reinforcement and at the connections; bearing pressure distribution and the global stability criteria; and the effects of surcharge loading.

The system capable of providing this range of information whilst at the same time taking into account the significant factors which influence the behaviour of the structure is the finite element method.

## 2 FINITE ELEMENT MODELS

A range of finite element models and structural idealisations may be used. The structure can be modelled in two dimensions (2D) or three dimensions (3D), the latter is expensive, but may be necessary with unusual structural geometries.

The simplest finite element analysis typically idealises reinforced earth construction as in Figure 1. The structure is assumed to be built in one

Table 1

| Reinforcement | Soil | Construction |
|---|---|---|
| Composition | Particle Size | Construction System |
| Durability | Grading | Compaction |
| Form | Index Properties | |
| Surface Properties | Mineral Content | Facing |
| Dimensions | Durability | |
| Strength | Availability | |
| Stiffness | | |
| **Reinforcement Distribution** | **Soil State** | **Structures** |
| Location | Density | Geometry |
| Spacing | Confinement | End Use |
| Orientation | State of Stress | Aesthetics |
| | Degree of Saturation | |
| | Drainage | |

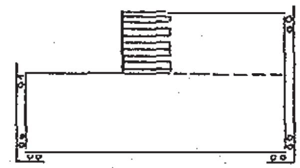
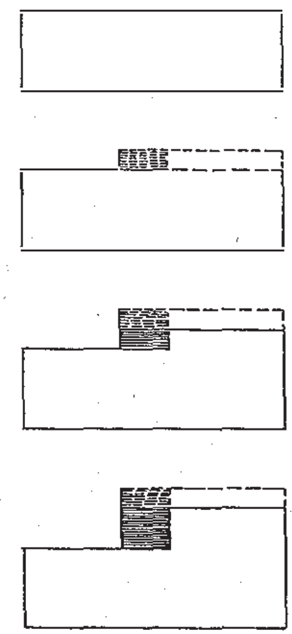
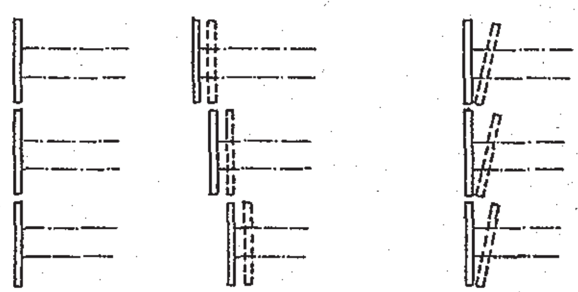


Figure 1.



a. b. c. d.

Figure 2.



a. b. c.

Figure 3.

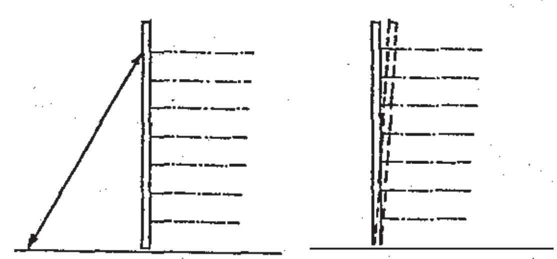


Figure 4.

step and loading is applied by 'switching on' gravity. A closer idealisation is to model the construction in stages, Figure 2 (a–d). This has the advantage of providing a more realistic loading for the subsoil and accurate modelling of non linear soils using this technique may be achieved. However, true idealisation can only be achieved if the construction of the reinforced soil block is mimicked by the finite element model as different construction techniques impose their own in-built stresses and strains. A comparison between the construction of a vertical reinforced soil structure built using individual facing panels and that built using a full height facing propped during construction illustrates the nature of these differences, Figure 3 and Figure 4.

Using a discrete panel system the elevation of the facing will follow the movements shown in Figure 3 (b or c), although the static condition shown in Figure 3 (a) is frequently believed to occur. At stage 1 of the construction, the facing panel is typically rotated backwards towards the fill; during fill placing and compaction, the facing

Table 2

| VARIABLE | COMPOSITE MATERIAL (Unit Cell) | SPECIAL ELEMENTS | 'FULL' MODEL |
|---|---|---|---|
| Foundation | ✓ | ✓ | ✓ |
| Stage Construction | ✓ | ✓ | ✓ |
| Fill Properties | × | (✓) | ✓ |
| Reinforcement Properties | × | (✓) | ✓* |
| Reinforcement Prestress | × | × | ✓ |
| Stress Distribution in Reinforcement | × | ✓ | ✓ |
| Facing/ Reinforcement Connection Stresses | × | ✓ | ✓ |
| Compaction Stresses in Fill | × | × | ✓ |
| Construction Technique (Incremental - Full Height) | × | × | ✓ |
| Compressible Backfill Layers | × | ✓ | ✓ |

(✓) Assumes part composite material
✓* 2D analysis sheet or grid reinforcement 3D analysis strip reinforcement

straightens and moves forward an element ($\delta$1) dependent upon the nature of the reinforcement and its interaction with the soil. The small movement ($\delta$1) will be greater with extensible reinforcement and may be negligible with very stiff reinforcement. In the case of a propped full height facing the rotation and movement is primarily dependent upon the stiffness of the reinforcement and the effects of the fill are of secondary importance, WYMCC (1983).

Idealisation of the reinforced soil block can be made in a number of ways which can be conventionally grouped into three forms:

A. Unit cell approach, in which reinforced earth is modelled as a pseudoelastic material.
B. Use of special elements.
C. Full idealisation with the fill and reinforcement being considered separately.

Method A is convenient when global effects predominate but suffers from the disadvantage of being a simple model. The use of a special element, such as that developed by Naylor (1978), which permits reinforcements to slip (slip strip), reflects the influence of sub soil conditions on the structure but usually does not provide a true idealisation of the construction process. A full idealisation of the fill and the reinforcement using standard finite elements is the preferred approach but one which few have attempted because of the complexities introduced by the number of individual reinforcing elements and the subtleties of the construction techniques. Some forms of reinforcement, typically strips, demand a 3D analysis if a full idealisation is to be attempted. When the reinforcement is in the form of a sheet or grid producing a complete layer of reinforcement the analysis can be reduced to a 2D plane strain condition, the geometry of the overall structure permitting.

The ability of the different finite element models to accommodate the criteria which influence the behaviour of reinforced earth structures is detailed in Table 2.

## 3 REINFORCED EARTH PREDICTION USING FINITE ELEMENT METHODS

The best test for any analytical system is its ability to produce accurate (Class A) predictions of the behaviour and performance of a structure.

A Class A prediction competition was held as part of a NATO Advanced Research Workshop on the applications of polymeric reinforcement in soil reinforced structures, held at the Royal Military College (RMC) Canada in June 1987. Two vertical reinforced earth walls were constructed by RMC prior to the symposium. The walls were formed using an incremental facing and a propped full height facing. Participants at the symposium were asked to provide Class A predictions of the behaviour of both structures at elapsed times (100 and 1000 hours) after construction and following the addition of a range of surcharge loadings. The required information included: deformation /time response of the facing; strain

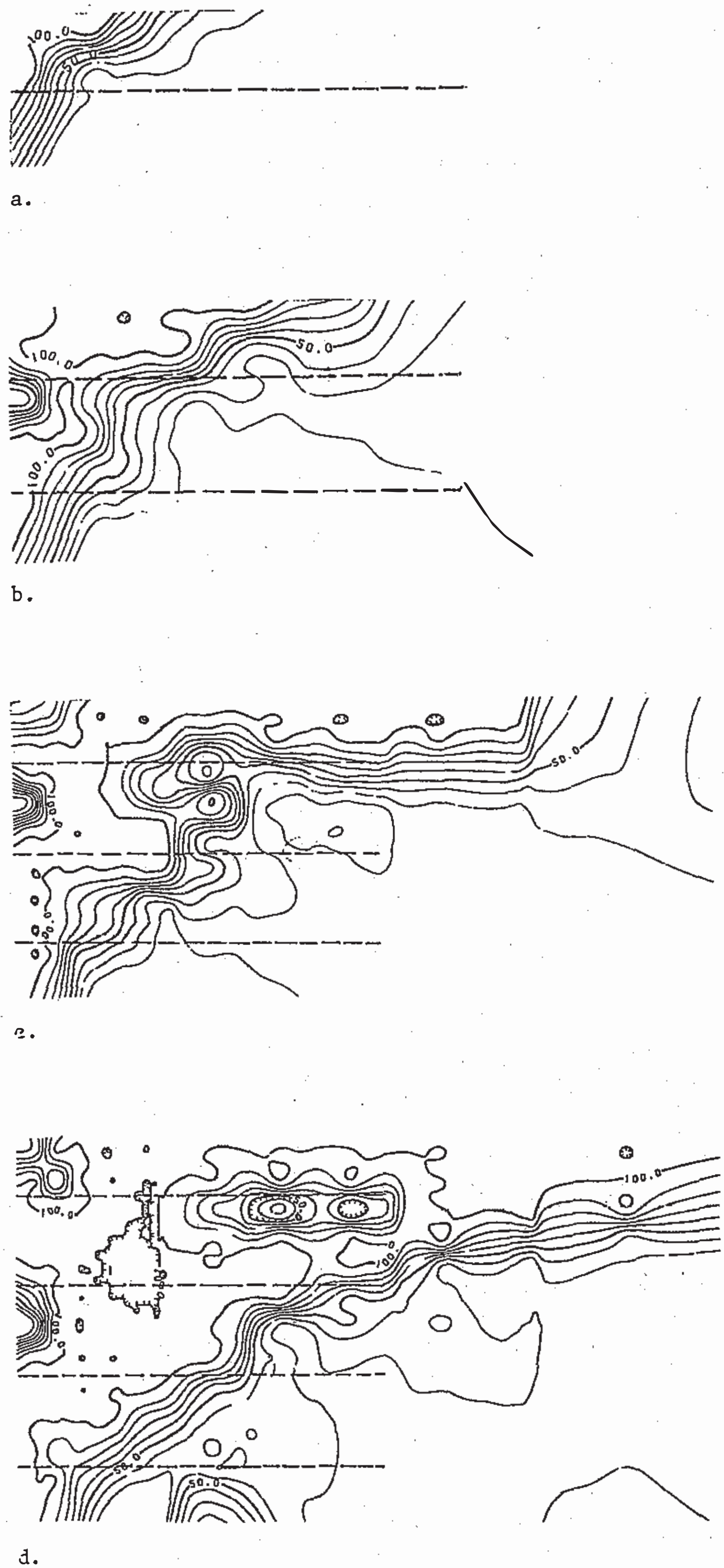
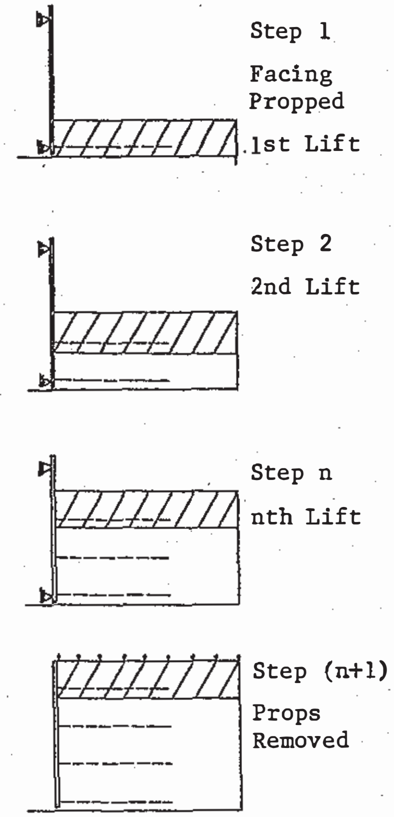
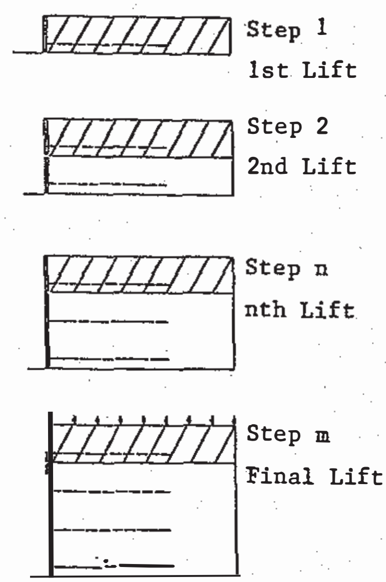



Figure 5. Percentage mobilised shear stress distribution in the fill and back-fill




Step (n + 2) Surcharge Loading

Figure 6. Construction sequence full height unit




Step (m + 1) Surcharge Loading

Figure 7. Construction sequence incremental facing

distribution within the reinforcement including the tensions at the connections; vertical stresses at the base of the reinforced soil block. Concise details of the materials and construction techniques used, including the loading, were provided by RMC.

One of the predictions at the symposium used a 'full' finite element model, it was the only method able to provide an answer to the 282 questions set by the prediction competition. In addition, the results from the analyses were consistently in accord with the measured values.

Complete details of the Class A prediction exercise for the NATO reinforced earth walls are given by Bathurst et al (1987).

Details of the model used in the prediction are given below. Also included are details of the mobilised shear stress distribution within and behind the reinforced soil mass, Figure 5. This information was not requested as part of the prediction exercise, however the results further illustrate the power of the finite element technique and support the use of the tie-back method for the conventional analysis particularly when extensible reinforcement is used.

The prediction was based upon a mathematical simulation of the construction and loading procedures used to construct the two models. The model used was based upon the hyperbolic equation proposed by Kondner et al (1963) and described by Duncan and Chang (1970).

$$(\sigma_1 - \sigma_3) = \frac{\epsilon}{a + b} \qquad 1.$$

in which $\sigma_1$ and $\sigma_3$ = major and minor principle stresses.

$\epsilon$ = axial strain

a + b = constants

The asymptotic value of the soil at failure $(\sigma_1 - \sigma_3)$ is greater than the ultimate compressive strength of the soil $(\sigma_1 - \sigma_3)$ ult. but can be related to the ultimate value by the failure ratio $R_f$.

$$(\sigma_1 - \sigma_3) = R_f \, (\sigma_1 - \sigma_3)_{ult.}$$

By expressing the parameters a and b in terms of the initial tangulant modulus value ($E_i$) and the compressive strength, equation 1 may be written as

$$(\sigma_1 - \sigma_3) = \frac{\epsilon}{\frac{1}{Ei} + \frac{\epsilon R_f}{(\sigma_1 - \sigma_3)_f}} \qquad 2.$$

Equation 2 may be used to model the non linearity of soil stress-strain behaviour.

## 4 SELECTION OF PARAMETERS, CONSTRUCTION AND LOADING PROCEDURES

An incremental non linear elastic model was used with a constant Poisson's ratio $\nu$ = 0.35. No unloading-reloading was assumed. The parameters used in the model were generated from the information provided and included compaction stresses within the fill developed during stage construction, prestressing of the reinforcement, and the use of reinforcement whose stiffness varied with time. The facing elements were assumed to be elastic as was the compressible material used between the incremental facing units. Modelling of the construction process and the loading procedures are shown in Figures 6 and 7. The model covered every variable detailed in Table 2 with the exception of a compressible back-fill; the latter was not used in the construction of the trial walls.

## 5 CONCLUSIONS

The finite element technique can be used to model the subsoil conditions, the construction method, the loading and the reinforcement and soil used in a reinforced soil structure. If the correct idealisation is made and the selection of parameters is accurate, very close agreement can be achieved between the performance of the model and of the real structure. In addition, a study of the development of shear stress within the soil, the strains in the reinforcement and the movements of the facing, provide an insight into the behaviour mechanism of reinforced soil.

Although a finite element analysis represents a very large number of mathematical computations, the increase in computing power available to design offices, coupled with the reduction in computing costs, suggest that this approach to the analysis of critical or complex structures is possible and complimentary to the semi-empirical methods in general use.

## REFERENCES

Bathurst, R.J., Wawrychuk, W.F. and Jarrett, P.M. 1987. NATO advanced research workshop. Application of polymeric reinforcement in soil retaining structures. Royal Military College, Canada.

Brady, K.C. 1987. Performance of a reinforced earth bridge abutment at Carmarthen. Research report III, TRRL, Berkshire.

Department of Transport 1978. Reinforced and anchored earth retaining walls and bridge abutments for embankments. Technical Memorandum BE3/78 (Revised 1987), HMSO.

Duncan, J.M. and Chang, C.Y. 1970. Non-linear analysis of stress and strain in soils. Jour. Soil Mech. and Foundation Eng. ASCE, SM5, pp 1629-1653.

Jones, C.J.F.P. 1979. Lateral earth pressures acting on the facing units of reinforced earth structures. C.R. Coll. Int. Reinforcement des Sols, Paris.

Jones, C.J.F.P. and Edwards, L.W. 1980. Reinforced earth structures situated on soft foundations. Geotechnique, June, pp 207-211.

Laboratoire Central des Ponts et Chausees 1979. Reinforced earth structures - Recommendations - Rules of the art, Paris.

Kondner, R.L. 1963. Hyperbolic stress-strain response: cohesive soils, Jour. Soil Mech. and Foundation Div. ASCE, Vol. 85, pp 115-143.

Kondner, R.L. and Zelasko, J.S. 1963. A hyperbolic stress-strain foundation for sands. Proc. 2nd Pan-Amer. Conf. Soil Mechanics and Foundation Eng. Brazil, Vol. 1, pp 289-324.

McGown, A., Murray, R.T. and Andraws, K.Z. 1987. The influence of boundary yielding on the lateral stresses exerted by back-fills. Proc. NATO advanced research work-shop, Application of polymeric reinforcement in soil retaining structures, Canada.

Naylor, D.J. 1978. A study of reinforced earth walls allowing slip strip. Proc. ASCE Conv., Pittsburgh, pp 618-644.

West Yorkshire Metropolitan County Council, 1983. First report on trial reinforced earth retaining walls, Dewsbury ring road, Wakefield, August.