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The internal stability of reinforced earth walls

Stabilite interne de murs en terre armée

SUMMARY

La plupart des essais de murs en terre armee réalisés sur modèles réduits ont eu pour but de déterminer les modes de rupture. Les résultats ainsi obtenus ont permis le développement de critères de dimensionnement vis à vis des risques de rupture par cassure des armatures ou par glissement des armatures. Dans notre étude, des essais sur modèles ont été réalisés pour étudier la stabilité interne de murs en terre armée, juste après la construction. 35 murs ont été construits jusqu'à une hauteur maximum de 50 cm. La longueur des armatures est constante et égale à 40 cm, mais les espacements verticaux et horizontaux entre armatures ont varié. La distribution des contraintes le long des armatures a été mesurée à différents niveaux. Les contraintes verticales et horizontales dans le sol, ont été déterminées à l'aide de cellules de contrainte à enroulement, spécialement mises au point pour cette étude. Les déformations horizontales des murs ont été observées, à l'endroit ou les contraintes verticales ont été mesurées. Les valeurs des contraintes maximum mesurées dans les armatures sont comparées à celles prévues par les théories classiques et à une récente théorie énergétique des contraintes. Le paramètre sans dimension χ et le coefficient de sécurité vis à vis du glissement des armatures situées à différents niveaux sont calculés et comparés à ceux obtenus à partir des diverses théories, ainsi qu'aux valeurs expérimentales obtenues par les auteurs.

INTRODUCTION

Over the past ten years model studies on reinforced earth walls have been reported from investigators in France, the United States of America, the United Kingdom and Japan. Most of these model tests were based on an ultimate strength concept, where the height of the wall was increased until failure was observed under various configurations of tie length, spacing and cross-sectional area. Little attempt has been made to assess the stability of ties at different wall levels in terms of pull-out or breaking, or to check the assumptions on which the theoretical design approaches were based.

The model tests described in this paper were designed to investigate more fully the behaviour of a reinforced earth wall under working rather than failure conditions. Measurements were taken of tie tension, and strains and stresses within the soil, and the results have been compared with existing design theories, with a new Energy theory and also with observations from a full scale wall.

THE MODEL AND INSTRUMENTATION

The model tests were carried out in a rigid box 900mm square and 500mm high, these dimensions having been determined as the smallest size of box compatible with minimum edge effects. Interlocking perspex panels 6mm thick were used as the wall facing and the ties were of perspex 400mm long, 22mm wide, and 1.4mm thick. The cross section chosen for the ties ensured that the stresses developed would be well below the ultimate strength of the perspex and would result in elastic behaviour. The sand used as backfill was uniformly graded within the size range 0.150 to 0.425 mm. It was deposited in the model using a raining device with a constant height of fall to achieve a uniform density of 1.615 gm/cm^3 (relative density = 76.5%) for all the tests. At this density, the angle of internal friction of the sand was 40° and the coefficient of friction between the sand and the perspex was 0.398.

Each of the model walls was constructed by placing sand in a controlled manner in 50mm layers behind the wall facing panels until the wall reached its maximum height of 500mm. Measurements of stress in the ties, and strains and stresses in the sand were made as the model was being constructed. Tie stress was measured by electrical resistance strain gauges, the instrumented ties having been calibrated under direct loading before being introduced into the model. Horizontal and vertical strain measurements in the sand fill were taken using free-field strain coils. This type of coil was also used to measure the horizontal movement of the facing panels. Redshaw type pressure cells were used to measure the vertical stress distribution within the sand, the cells having been calibrated under plane strain conditions.

TESTS AND TEST RESULTS

In the model tests, five different configurations of tie spacing and panel size were studied and are summarised in Table 1. A number of identical models were built for each configuration and a total of 35 walls were investigated.

Tie spacing		Facing elements	
Vertical ΔH(mm)	Horizontal S (mm)	Width (mm)	Height (mm)
250	100	300	250
83.3	100	300	250
83.3	150	300	250
83.3	300	300	250
100	150	150	100

TABLE 1. MODEL WALL DESIGN PARAMETERS.

The tension distribution along the ties is typified by Fig. 1 which shows a variation in tension along the ties from a low value at the panel to a maximum within the front half of the tie, falling off to zero at the free end. A similar pattern of tension distribution was noted from the results from the other

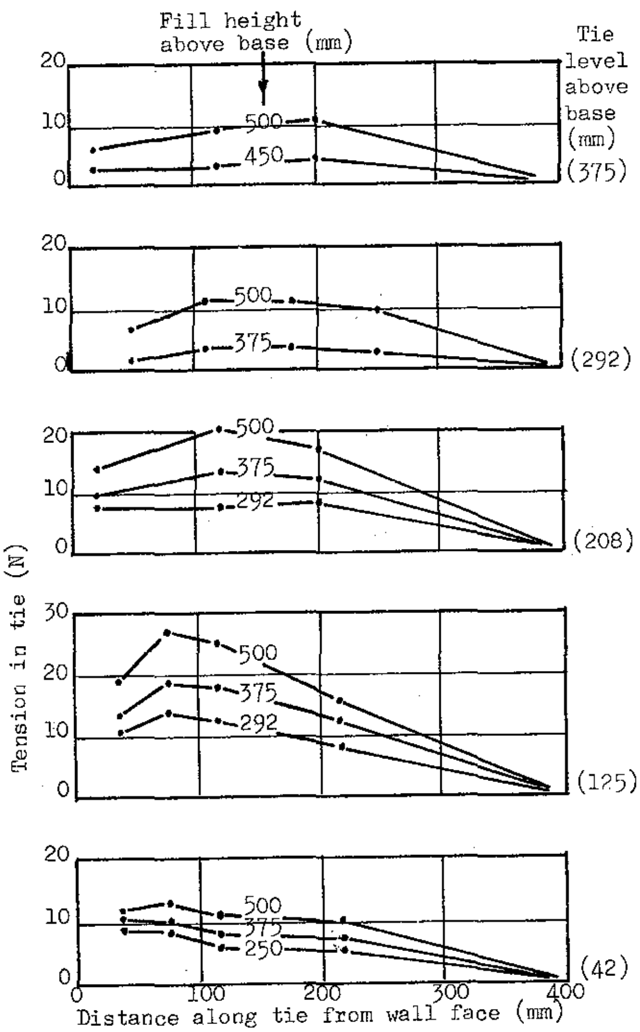

Fig. 1. Tension Variation Along Ties in Model Wall (ΔH = 83.3mm, S = 100 mm)

models with different vertical and horizontal tie spacings. Similar distributions of tension along reinforcing ties have been reported from observations on full scale walls by Finlay and Sutherland (1977), and by Al-Hussaini & Perry (1978).

The free-field strain coils were used to measure horizontal strains developed within the backfill between the ties on a vertical section normal to the facing panels. The coils were installed at 50mm, 150mm and 250mm distance back from the facing, and at three levels within the 500mm wall height. It was found that generally the measured horizontal strain was a maximum near the wall and decreased towards the interior. None of the walls was constructed to failure, but the model with the smallest number of ties indicated the largest strains. Fig. 2 shows the measured strains with this wall at its full 500mm height, and shows the decrease in strain mentioned above. In fact, in the case of this wall, the strain over a section at about mid-height of the wall is negative at some distance from the facing. Positive strain values imply expansion of the soil mass, while negative values imply compression. It appears from Fig. 2 that expansion of the soil occurs near the wall, becomes less with distance into the fill, and changes to compression over part of the fill height at about half the length of the tie. Although the wall was not taken to failure, the trend of these results seems to confirm the mechanism of active and resistant zones proposed as a failure model by Juran and Schlosser (1978).

Too few locations have been gauged in the present test series to do more than indicate a trend, but further tests with more strain coils would perhaps lead to a better understanding of the behaviour of the fill surrounding the ties, and the way in which the tie stresses are transferred into the soil.

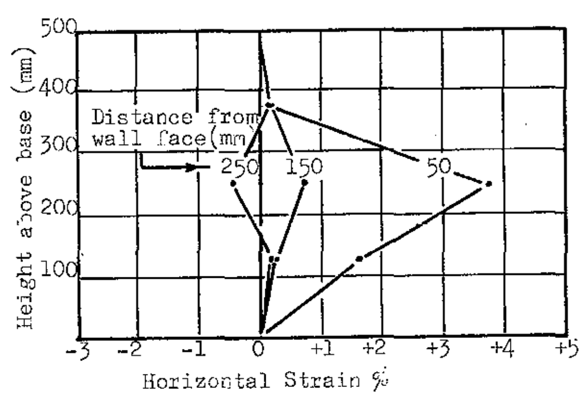

Fig. 2. Variation in Horizontal Strain within Fill (ΔH = 250mm, S = 100mm)

To assess the behaviour of the strain coils, the strains measured in the fill at the different levels were integrated to obtain calculated values for wall panel movement, and these values were compared with the measured values of panel movement. The results are shown in Fig. 3 for two of the model walls and show reasonable agreement, thus giving confidence in the strain coil measurements within the fill despite the fact that relatively few coils were used.

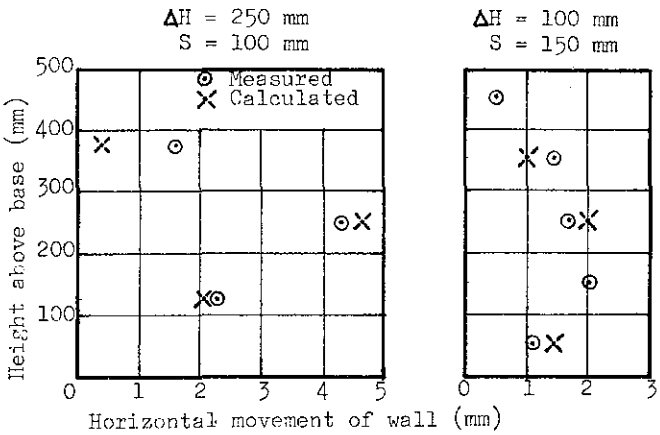

Fig. 3. Measured and calculated horizontal wall movements under 500mm fill height.

The measurements of vertical strain in the model walls indicated slightly higher strains near the wall face. These should have corresponded to higher vertical pressures but this was not obtained from the pressure cells and casts doubt on the reliability of such measurements as has been similarly noted by other investigators such as Lee et al (1973).

THEORETICAL ANALYSIS OF REINFORCED EARTH WALLS

The original methods of designing reinforced earth structures were based on conventional earth pressure theories such as Rankine and Coulomb, the Rankine approach still being that most widely used in practice. It is a simple and convenient method but one which has limitations as has been pointed out by Schlosser and Vidal (1969) and subsequent investigators. The method assumes the back-fill to be a homogeneous and isotropic material and so ignores the modifying influence of the ties. The distribution of tension in the ties obtained increases linearly with depth and the maximum tension in a tie is implied to occur at the wall face. Neither of these points is confirmed by measurements on model and full scale walls and in general it has been found that the Rankine method overestimates the tie tensions.

More sophisticated methods have been advanced for the analysis and design of reinforced earth walls. For example the finite element approach has been proposed by Chang J.C. (1974), Banerjee (1975), Naylor (1978), and Salomone et al (1978). Juran and Schlosser (1978) presented a general method involving a hypothetical failure surface and using a mathematical model based on the theory of plasticity. The disadvantages of the more recent methods of analysis are that for them to be effective, the difficulties of making accurate assumptions as to the soil model and the soil properties must be overcome. They have resulted in varied success as reviewed by Osman (1977). In addition, they can be inconvenient to apply as compared with the simple Rankine approach.

Osman (1977) has advanced a method of analysis which has been designated the Energy Method. It is based on a consideration of the equilibrium of the external work due to earth pressure and the internal strain energy stored in the ties, and can take into account

(i) The effect of the tie length on the magnitude of tension.
(ii) The variation of tension along a particular tie and the distribution of tension in the ties with depth.
(iii) The deflected shape of the wall facing.

Energy relationships can be established from the elastic deformations of the wall facing and the ties due to the earth pressure and the tension in the ties. Fig. 4 is a generalisation of the earth pressure distribution and the deflected shape of the wall. The total external work done by the earth pressure U_{ext} can be obtained from the expression

$$U_{ext} = S \int_0^H p(Z).\ y(Z)\ dZ$$

where $p(Z)$ = the earth pressure function
$y(Z)$ = the wall deflection function
S = wall width.

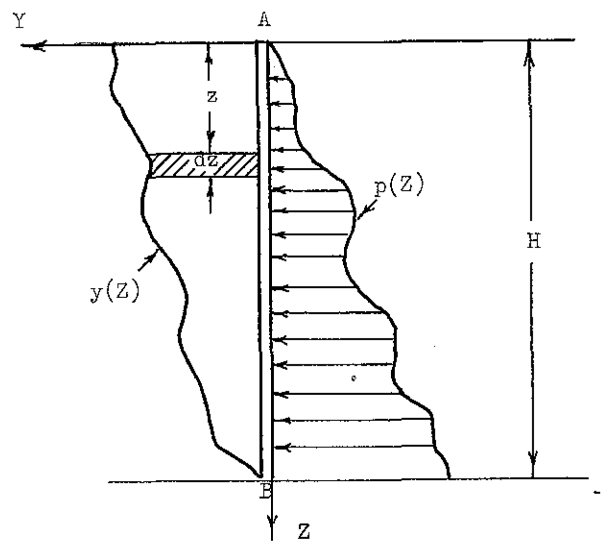

Fig. 4. Energy Theory Parameters

It is assumed that the external work done is stored in the ties as an elastic strain energy which can be calculated if the tie tension distribution is known. Assumptions must be made regarding the earth pressure distribution on the wall, the variation in tension along the ties and the deflected shape of the wall.

Taking into account previous observations made on walls, it was assumed that

(i) the distribution of tension along a tie was linear with the intensity at the wall face half the maximum intensity.
(ii) the wall face deflection was parabolic and a function of the earth pressure and the modulus of elasticity of the reinforced earth wall acting as a composite material.

(iii) the earth pressure distribution was hydrostatic.

From these assumptions the following expressions were obtained which permit the direct calculation of various relevant parameters in a rapid and convenient manner.

Max. tension in tie at depth h, $T = \sqrt{\frac{6K_a^{2.5}}{L}}\ \gamma.h.\Delta H.S\ \sqrt{H-h}$

Max. tie tension in wall, $T_{max} = \sqrt{\frac{8K_a^{2.5}}{9L}}\ \gamma.\Delta H.S.H^{1.5}$

Critical wall height, $H_c = \left(\frac{R_t}{\gamma.\Delta H.S}\ \sqrt{\frac{9\ L}{8\ K_a^{2.5}}}\right)^{0.67}$

Safety factor against tie pull-out, $S.F. = \frac{2.\ b.f.\ L^{1.5}}{S.\ \Delta H\ \sqrt{6\ K_a^{2.5}(H-h)}}$

where h = fill height above tie level
H = total fill height above base of wall
ΔH = vertical tie spacing
L = tie length
S = horizontal tie spacing
γ = unit weight of soil
K_a = coefficient of active earth pressure
R_t = tensile strength of tie material
b = tie width
f = coefficient of friction tie/soil

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

Figs. 5 and 6 show the values of maximum tie tension measured in two of the model walls. Also shown are the theoretical maximum tie tension envelopes derived from Rankine for both K_a and K_o conditions, from the limit state approach of Juran and Schlosser (1978) and from the Energy Theory, Osman (1977). The theories, other than Rankine, indicate a distribution of tie tension which increases to a maximum and then decreases towards the base of the wall to a value very much less than the Rankine values. The measured distributions in Figs. 5 and 6 follow this pattern, the measured stresses in Fig. 5 being reasonably close to the theoretical. The theoretical tie tensions in the upper 40% of the wall height correspond approximately to the Rankine K_o condition. The measured values in Fig. 5 agreed with this pattern which has also been observed in other model walls and also in full scale walls as reported by Schlosser and Long (1974) and Finlay and Sutherland (1977).

The non-dimensional tension parameter $\chi = \frac{T_{max}}{\gamma.h.\Delta H.S}$ can be used to assess the distribution of tie tension with depth. The Rankine theory predicts a constant value of χ at different wall levels, while Banerjee (1975) using a finite element method for walls in service , indicates a near constant value of 0.35. Juran and Schlosser's theory and the Energy theory each indicate a variation in χ with fill height above tie level. In the present study, the non-dimensional tension parameter, χ, was computed from the observed maximum tie tensions at different levels in walls built to a maximum height of 500mm. The experimental results are plotted against fill

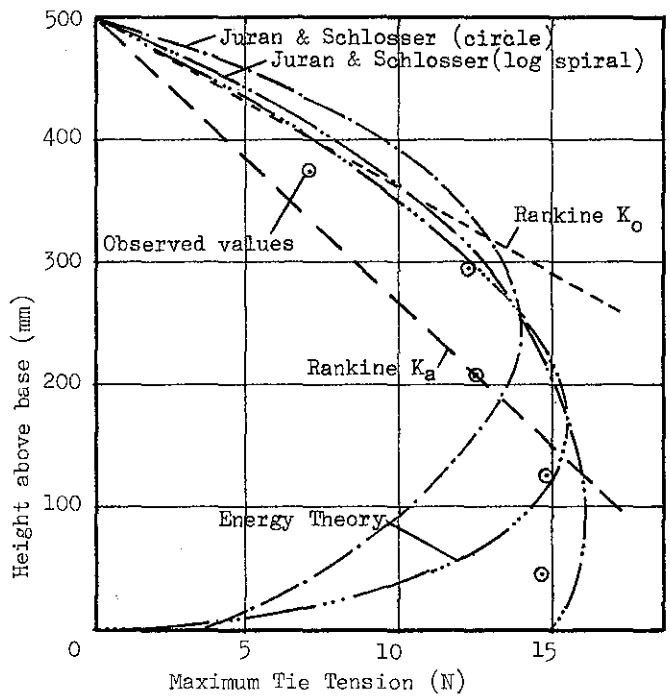

Fig. 5. Observed & theoretical max. tie tensions
ΔH = 83.3 mm, S = 150 mm

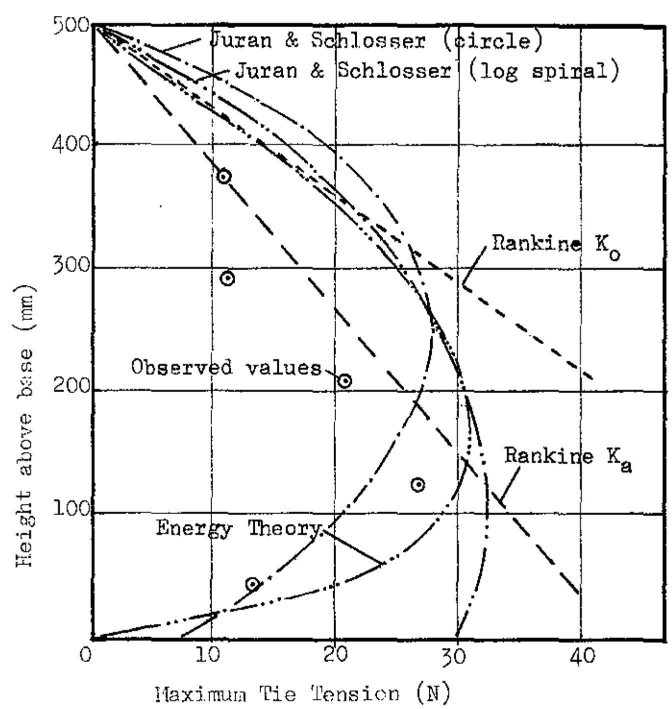

Fig. 6. Observed & theoretical max. tie tensions
ΔH = 83.3 mm, S = 300mm

height above tie level in Fig. 7 and can be compared with the predictions from the Rankine theory, Banerjee's approach, Juran's theory and the Energy theory. Although there is a large scatter in the experimental points, Juran's theory and the Energy theory appear to reflect the trend of these points more than the other predictions.

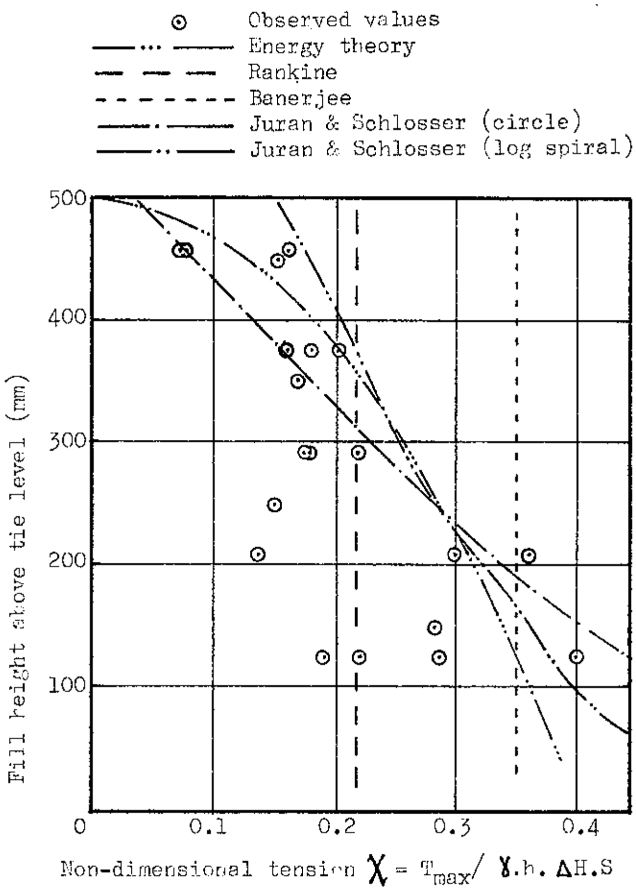

Fig. 7. Fill Height v χ for 500mm wall.

The experimental safety factors against tie pull-out were calculated from the observed tie tensions assuming only the tie length beyond the maximum tension position to be effective. The corresponding theoretical safety factors were computed on the basis of the Rankine approach assuming (a) total tie length effective, and (b) only that part of the tie length beyond the theoretical failure plane effective. Calculations based on Banerjee's method and on the Energy theory were also carried out, but it was not possible to use Juran's theory due to lack of information. The resulting relationship between safety factor and height of tie above model base is shown for one of the models in Fig. 8. The Rankine (total) and Banerjee methods predicted a constant safety factor, the Rankine (part) predicted a linearly varying safety factor, while the Energy theory resulted in a non-linear relationship which agreed reasonably well with the observed safety factors.

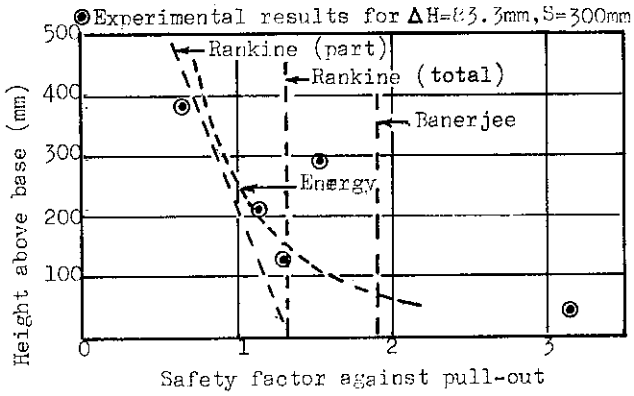

Fig. 8 - Experimental and Theoretical Safety Factors against Tie Pull-out

THE GRANTON WALL

Observations on a full scale reinforced earth retaining wall at Granton in Scotland have been reported by Finlay and Sutherland (1977), and although these observations were stated to have been affected by the construction procedures some general similarities between model studies and full scale behaviour were found. These were the tension distribution along the reinforcing ties, the variation in maximum tie tension with wall height, the relationship between χ and the fill height above tie level, and that between safety factor against pull-out and fill height above tie level. Since the measured tie tensions in the Granton wall were higher than predicted on account of the compaction procedures used on site, the observed χ values are generally higher and the observed safety factors lower than the theoretical values, no matter which theories are used. The general trend of the results obtained was, however, similar to those predicted by the Energy theory and probably by Juran & Schlosser's approach.

CONCLUSIONS

Measurements of tie tension and soil strain have been made on 35 model reinforced earth walls using 5 different configurations of tie spacing and panel size. The walls were not tested to failure but measurements were made during and after construction. The tension distributions measured in the ties showed the same trend as found previously by the authors in a full scale wall and by other investigators of model and full scale walls.

Horizontal strains measured within the backfill material indicated the presence of active and resistant zones in the backfill.

An Energy theory has been described, the results of which compare favourably with a recently proposed limit state theory by Juran & Schlosser.

Predictions from the Energy theory of the maximum tension envelopes, the χ factor, and the factor of safety against pull-out followed the trend of the experimental results, although the absolute values did not always agree. Nevertheless it is suggested that on balance the Energy theory provides a more realistic approach to the design of reinforced earth retaining walls than the present conventional approach based on the Rankine theory. It also has the advantage, compared with other recently advanced theories based on finite element and other methods, that it can be as easily applied as the Rankine method.

REFERENCES

AL-HUSSAINI, M., & PERRY E.B. (1978). "Field experiment of reinforced earth wall". Preprint 3131, Proc. ASCE Spring Convention, Pittsburgh.

BANERJEE, P.K. (1975). "Principles of analysis and design of reinforced earth retaining walls". The Highway Engineer, Journal of the Institution of Highway Engineers, London, Vol. 22, No. 1 pp 13-18.

CHANG, J.C. (1974). "Earth reinforcement techniques". Research Report, California Division of Highways Transportation report, 301 p.

FINLAY, T.W. & SUTHERLAND, H.B. (1977). "Field measurements on a reinforced earth wall at Granton". Proc. 9th Int. Conf. on Soil Mech. & Found. Eng., Tokyo.

JURAN, I. & SCHLOSSER, F. (1978). "Theoretical analysis of failure in reinforced earth structures. Preprint 3273, Proc. ASCE. Spring Convention, Pittsburgh.

LEE, K.L., ADAMS, B.D. & VAGNERON, J.M.J. (1973). "Reinforced earth retaining walls" Jnl. of the Soil Mechanics and Foundations Div., Proc. ASCE, Vol. 99, No. SM10 pp 745-764.

NAYLOR, D.J. (1978). "A study of reinforced earth walls allowing strip slip". Preprint 3129 Proc. ASCE Spring Convention, Pittsburgh.

OSMAN, M.A. (1977). "An analytical and experimental study of reinforced earth retaining walls". Ph.D. thesis, Glasgow University.

SALOMONE, W.G., HOLTZ, R.D., AND KOVACS, W.D.,(1978). "A new soil reinforcement interaction model". Preprint 3126, Proc. ASCE Spring Convention, Pittsburgh.

SCHLOSSER, F., LONG, N.T. (1974). "Recent results in French research on reinforced earth". Jnl. of the Construction Div., Proc. ASCE, Vol. 100, No. CO3, pp 223-237.

SCHLOSSER, F. & VIDAL H. (1969). "Reinforced earth". Bulletin de Liaison des Laboratoires Routier des Ponts et Chaussees, No. 41, 44 pp., France.