Experimental Investigation on Model Reinforced Retaining Walls

by

M. Hoshiya*

J.N. Mandal**

Introduction

Reinforced earth can be defined as a soil mass composed primarily of fill material strengthened by the thin metallic reinforcing strips which interact with soil through friction and/or adhesion. The concept of reinforced earth is, however, not a mid 20th century invention. As a matter of fact, it might serve as a moral booster to wild life conservationists to know that reinforced earth was used extensively in the animal kingdom. Some animals and birds used straw and branches mixed with soil to build their habitations. Even the ancient men used reinforced earth for various purposes. Husk was widely used by villagers to increase the strength of the soil. Man has widely used straw for many thousands of years to improve the quality of clay bricks. The use of bamboo mat and coconut piles for building up core walls of bunds was familiar in Kerala. Even pile group may be considered as a reinforcing system.

Since Vidal (1966) was the first to introduce the principle of reinforced earth, model studies on reinforced earth walls have been reported by several authors (Al-Hussaini (1977), Al-Hussaini and Perry (1978), Bell et. al. (1975), Broms (1977), Bassett and Last (1978), Holtz (1978), Romstad et. al. (1976), Richardson and Lee (1975), Salomone et. al. (1971), Schlosser and Long (1974), Shen et. al. (1976) and Wager and Holtz (1976)). Lareal and Bacot (1973) considered the internal and external stability conditions to derive a critical length of strips to govern the cut off failure or the failure due to shortage of frictional force. They also evaluated the critical height of retaining structure in terms of width, thickness and length of strips. Thanhlong *et. al.* (1973) also carried out a similar type of experimental work on a two dimensional prototype model. For design, Lee *et. al.* (1973) established the analytical methods by the Rankine and Coulomb theory for retaining structures or for embankments on soft foundation by Harr (19) using the probability theory. Bell and Steward (1977) have used the woven polyester fabric for the retaining structures. The design of fabric reinforced retaining structures have also been developed by Broms (1978). Some early field experimentations have been reported by Holtz (1975) and Holtz and Massarsch (1976). Consequently, the detailed laboratory studies of reinforced earth using fabric have also been described by Holtz (1977) and Holtz and Broms (1977).

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* Professor of Civil Engineering, M.I.T., Tokyo, Japan.

** Assistant Professor, Civil Engineering Department, I.I.T., Bombay, India.

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However, many unknows, uncertainties and complexities are still involved in the design of reinforced earth retaining walls on the basis of soil properties. Therefore, the basic mechanism of reinforced earth structures is the main object of this present laboratory model studies. The loading arrangement and the placement of strips in reinforced earth wall are shown in Figs. 1 and 2 respectively for this investigation. The load carrying capacity of the overall structures, frictional resistance of strips and the deformation behaviours of reinforced earth retaining walls are mainly discussed and reported in this paper.

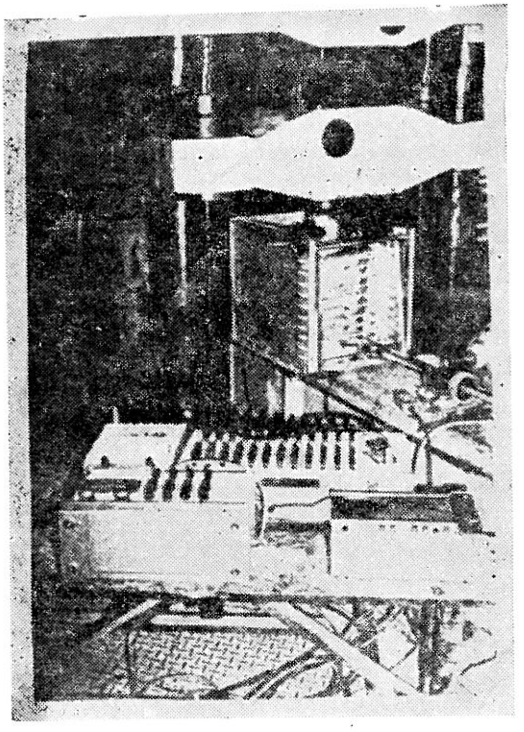

FIGURE 1 Loading Arrangement of Reinforced Earth Wall

Reinforced Earth Model

The model tests were carried out in a box of 30 × 50×41.5 cm high. The box is made of steel frame and transparent plastic plates so that the behaviour of the wall may be observed during the experiments. The skin elements were made of zinc galvanized steel of thickness 0.03 mm and the thickness of the brass strips were 0.05 mm. The major components of the experimental reinforced earth wall are shown in Fig. 3. Figures 4 and 5. respectively represent the cross-sections of the retaining wall and a plan of the second layer from the foundation. The height of the wall is 31 cm as shown in Fig. 4. The soil used as backfill was uniformly fine graded sand. The minimum and maximum dry density of the sand in the laboratory tests was 1.31 and 1.60 g/cc respectively. The sand was rained into the model using a raining device from a

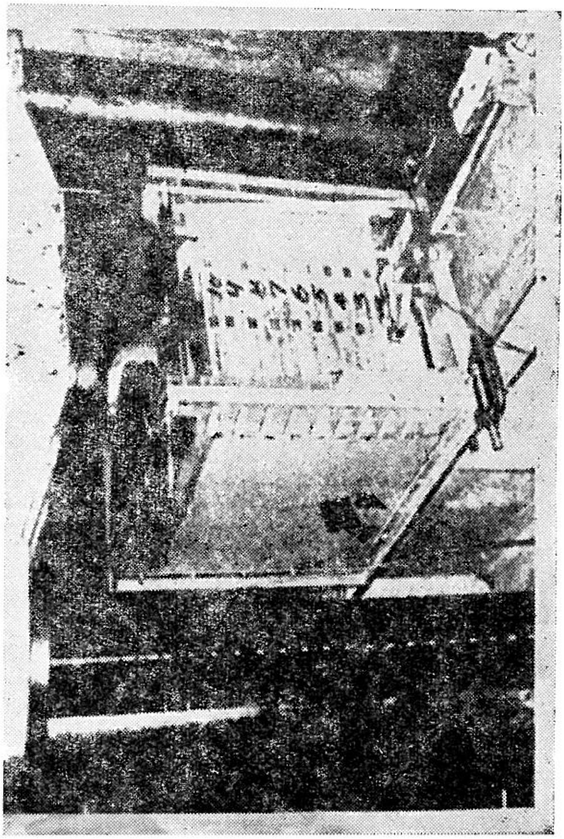

FIGURE 2 Placement of Strips in Reinforced Earth Wall

constant height to achieve an average density of 1.5 g/cc for all the tests. At this density, the angle of internal friction of the sand was 39° and the coefficient of friction between the sand and the reinforcing material was 24° as obtained from the direct shear tests.

A load cell and a pullout device were designed and fabricated for the measurement of the pullout forces of strips. The test strip was to be connected to the edge of the device in which the deflection of the test piece due to bending was to be taken to estimate the pullout force through a pair of strain gauges as shown in Fig. 6. The calibration constant of the load cell was determined and the relation between the strain meter reading in micro strain (ϵ_o) from the strain gauges mounted on the test pieces in a wheatstone bridge configuration and the pullout force (F_p) was obtained with a high accuracy. The correlation coeffieient is 0.99 as given in Fig. 7. For a consistent data to be obtained, the speed of pullout test was fixed to be 6 mm/min.

Each of the model was constructed by placing the sand in 31 mm layers behind the wall facing panels until the wall reached its final height. After the completion of final layer, the vertical load was applied through

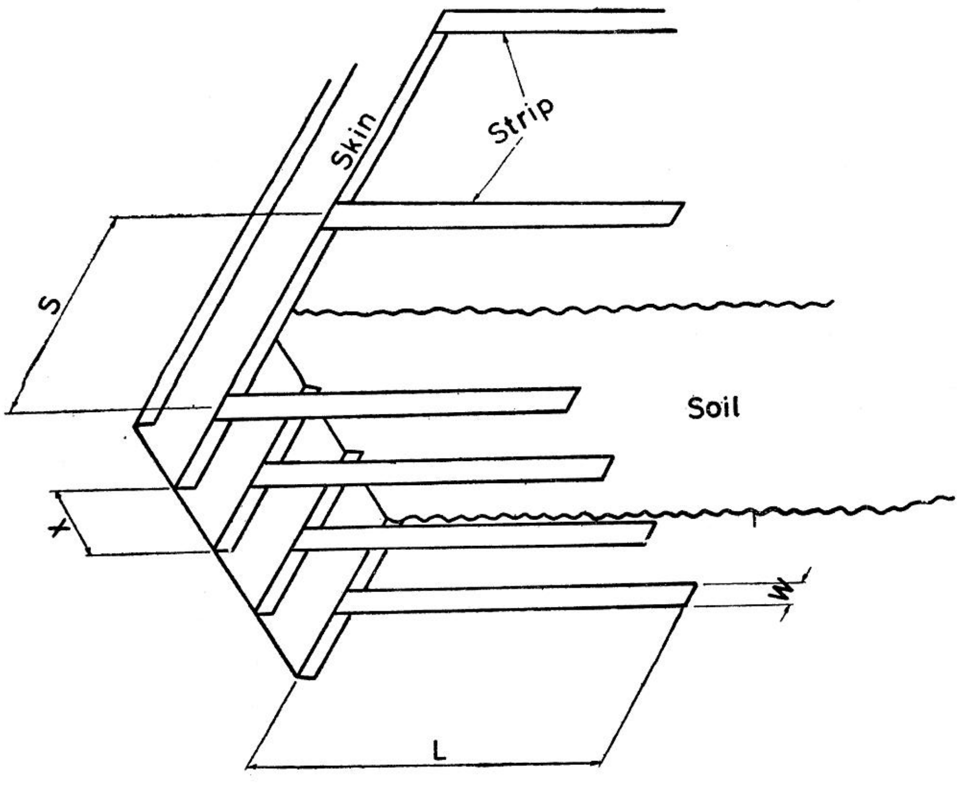

FIGURE 3 Major Components of Reinforced Earth Wall

a steel ball of 4.5 cm diameter on a bearing plate of 23×29×1 cm made of steel, placed on the top of the soil. The total weight of the ball and the bearing plate was 15.628 kg.

Aim of Model Tests

The pullout test, load carrying capacity test of the wall and the deformation behaviour of the wall were studied in this present experimental work. The pullout test is intended to investigate the strength of frictional grip between sand backfill and strips, with special focus on its ultimate value at the limit state. The strip at the middle position on the second layer was connected to the pullout device and tested.

The main object of the capability test was to comprehend the limit state of the wall and consequently the tests were carried out by varying the width and length of strips. The vertical load (Q) was gradually increased and the yield strength (Q_{max}) and the failure surfaces were measured just prior to the collapse. The deformation of the wall and the distribution of the horizontal earth pressure in the limit state—both were found to vary nonlinearily. Thus, the deformation behaviour was carefully studied in conjunction with the load carrying capacity of the reinforced earth wall.

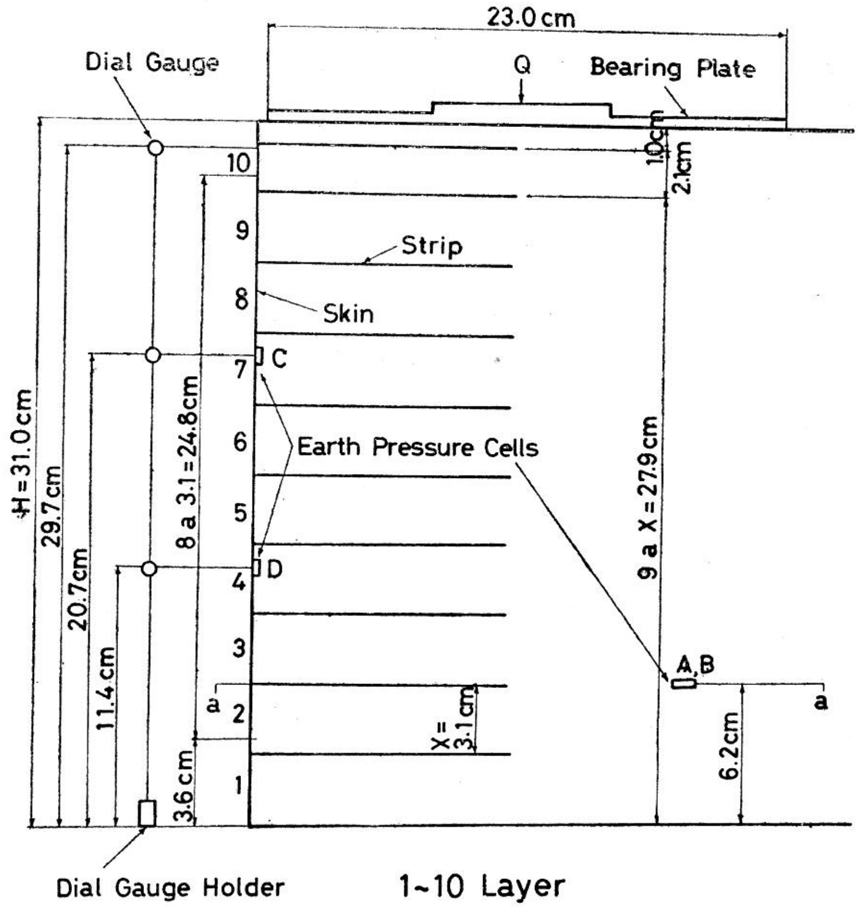

FIGURE 4 Cross Section of Reinforced Earth Wall

Interpretation of Test Results

The key factors of the prototype models may be cited from Lee's analysis in Fig. 8. Figure 8a shows a case where every strip includes the wedge slope BC at an angle $\theta = 45° - \frac{\phi}{2}$; and Fig. 8*b* shows another case where some strips are included within the line BC. ϕ is angle of internal friction of sand. Figure 8 *c* shows the distribution of the horizontal earth pressure, whose intensity at depth '*d*' is given by $\sigma_h = K_a(\gamma d + q)$, where $K_a = \tan^2 (45° - \frac{\phi}{2})$, q is the surcharge at the top, γ is the unit weight of sand and ϕ is the depth below the surface of the fill.

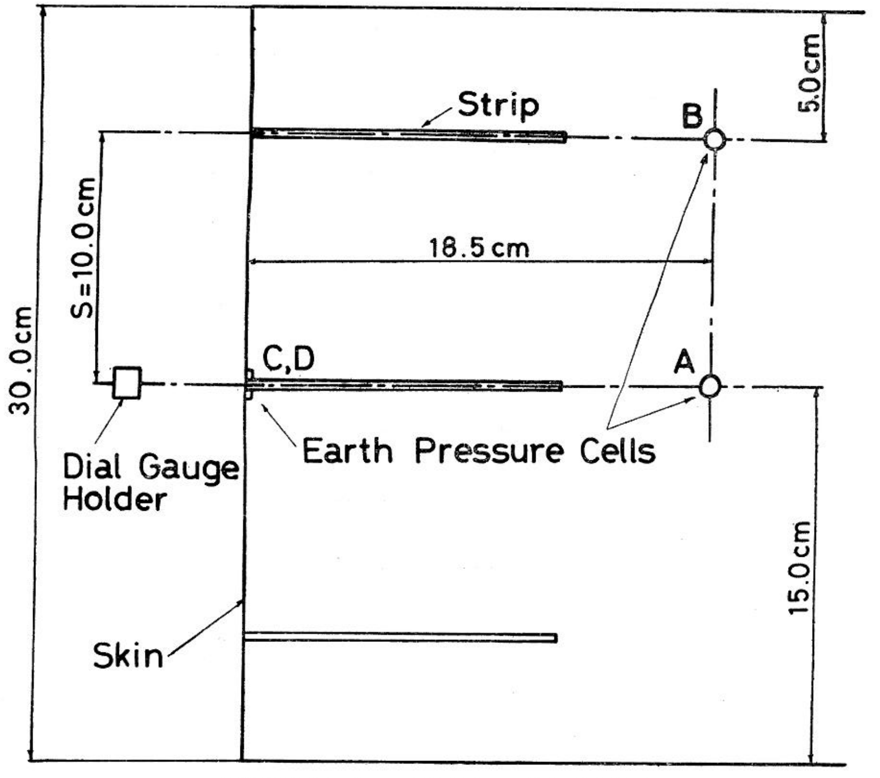

FIGURE 5 Plan of Reinforced Earth Wall

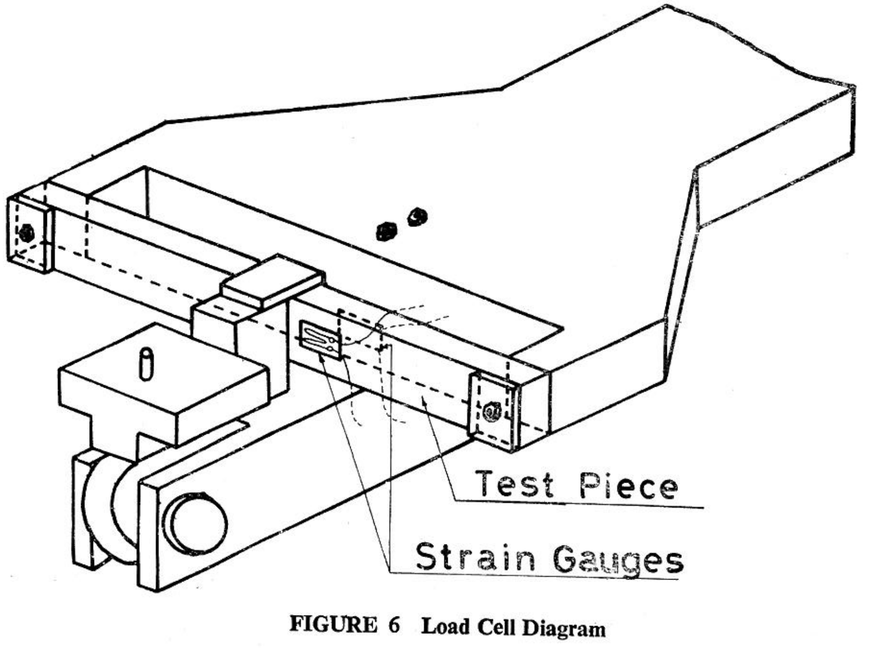

FIGURE 6 Load Cell Diagram

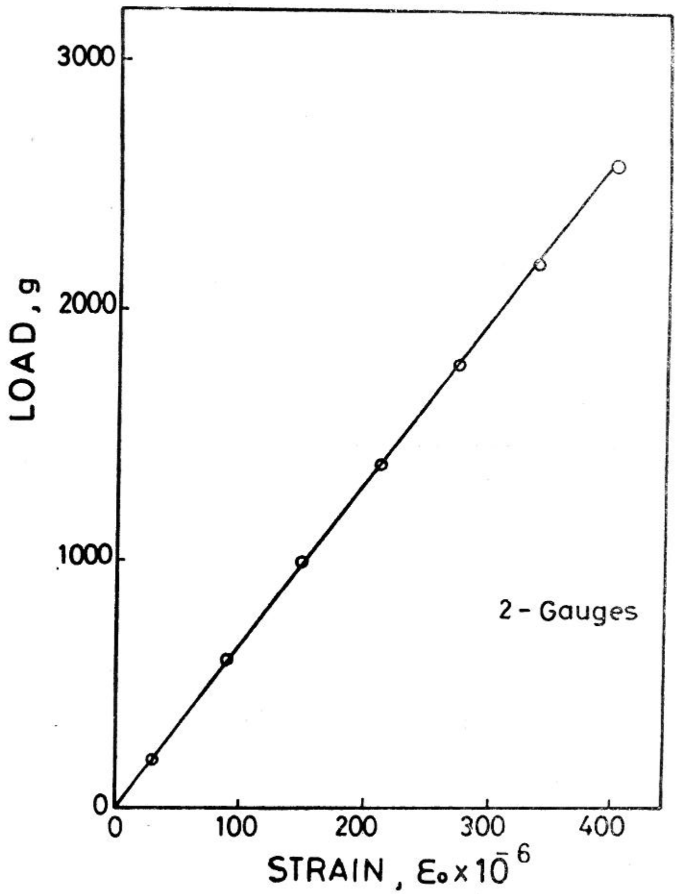

FIGURE 7 Load Strain Curve of Load Cell

Based on the pullout test, the friction force may be expressed as *follows :*

$$F_L \text{ or } F_l = F_P + F_e \quad ...(1)$$

where

$$F_L = 2\, L\, W\, (\gamma d + q) \tan \phi_u \quad ...(2)$$

and

$$F_l = 2\, l\, W\, (\gamma d + q) \tan \phi_u \quad ...(3)$$

Here, F_L is the upper bound of the frictional resistance assuming that the total length of the strip is effective for the friction; F_l is the lower bound of frictional resistance taking the effective portion only behind the wedge slope ; F_P is the measured pullout force ; F_e is the horizontal earth pressure carried out by the test strip ; L is total length of strip ; l is the

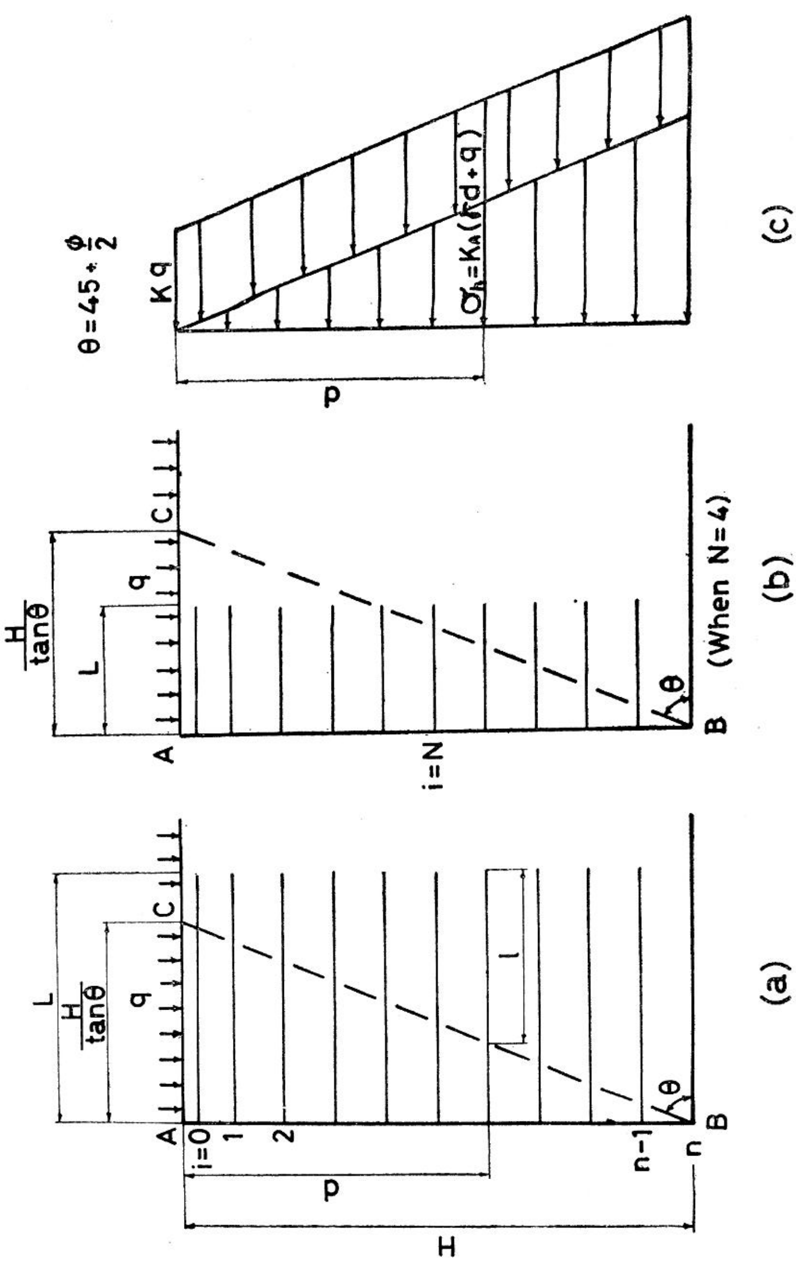

FIGURE 8 Key Factors in Design from Lee (1973)

effective length of strip ; W is the width of the strip and ϕ_u is the angle of friction between the reinforcing strip and the surrounding soil. Now the horizontal earth pressure may be written as :

$$F_e = K_a\,(\gamma d + q)\,S\,X \qquad \ldots(4)$$

where S is the horizontal spacing of the strips; X is the vertical spacing of the strips and K_a is the coefficient of active earth pressure.

Therefore, the coefficient of internal sliding friction may be documented by introducing Eqs. (2), (3) and (4) to Eq. (1) as follows :

$$\tan \phi_u L = \frac{F_p + F_e}{2\,L\,W\,(\gamma d+q)}$$

or $\ldots(5)$

$$\tan \phi_u\, l = \frac{F_p + F_e}{2\,l\,W\,(\gamma d+q)}$$

As to the capacity test, Lee *et. al.* (1973) formulated the safety factors by Rankine method (R); Coulomb force method (CF) and Coulomb moment method (CM). Since R method is based on the local stability of walls and is not compatible with the aim to examine the stability of the overall structure, only the formulas by CF and CM may be used in the comparison with the experimental results.

The safety factors are given by

$$F_{cf} = \frac{4\,W \tan \phi_u}{Ka\,\gamma'\,H^2\,S} \sum_{i=N}^{n} (i\,\gamma\,x + q)\,[L-(h-i)\;x \tan\;(45^\circ - \frac{\phi}{2})] \qquad \ldots(6)$$

$$F_{cm} = \frac{12\,W x\,\tan \phi_u}{Ka\,\gamma''\,H^3\,S} \sum_{i=N}^{n} (n-i)\,(i\gamma\,x + q)\,x\,[L-(n-i)\,x \tan\,(45^\circ - \frac{\phi}{2})] \qquad \ldots(7)$$

where

$$\gamma' = \gamma + \frac{2q}{H} \quad \text{and } \gamma'' = \gamma + \frac{3\,q}{H}$$

Results and Discussions

The pullout forces near the limit state (i.e. the stress corresponding to the maximum load applied to the specimen) as the time goes are shown in Fig. 9. The peak values were considered as the pullout forces of strips. Figure 10 shows the pullout force (F_p), the friction force (F_L or F_l) and their combination versus the vertical earth pressure, ($\gamma d + q$). The average of measured vertical earth pressure (σ_v) is also shown in the vertical axis. The

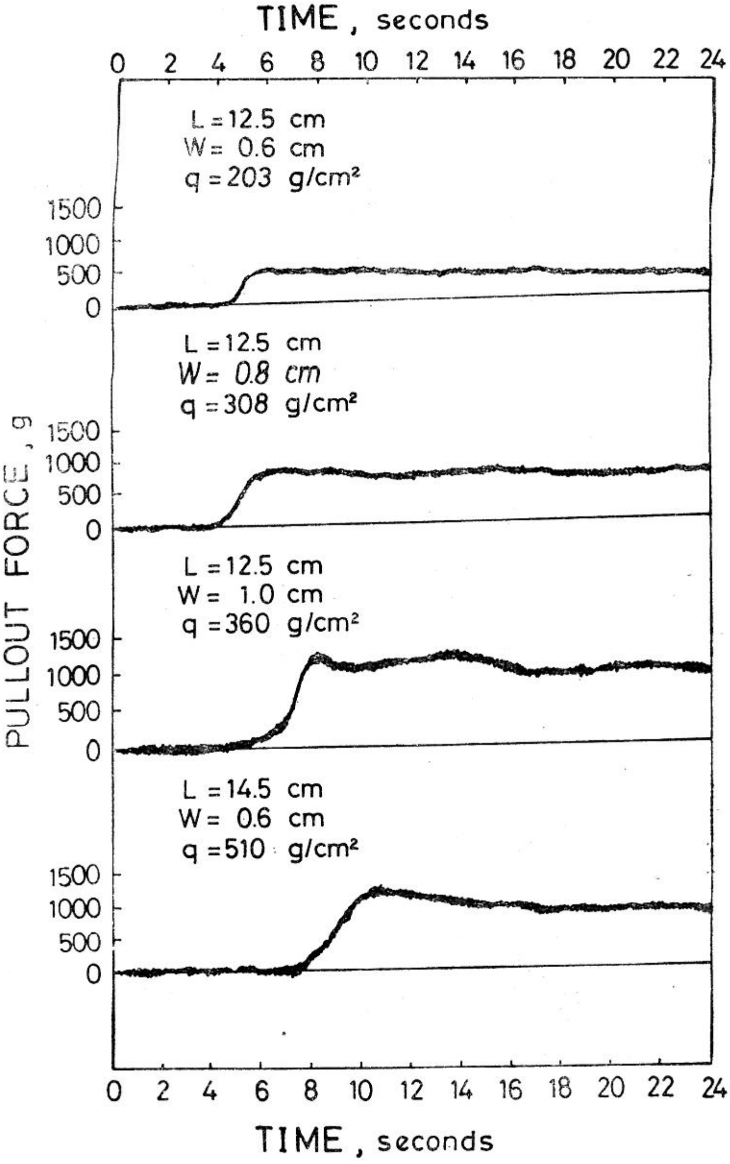

FIGURE 9 Pullout Force at Limit State

pullout force (F_p) and the vertical earth pressure were found to be linearly related. It is also indicated that the relation of Eq. (1) is satisfactory by analysis. Figure 11 represents the coefficients of frictional sliding resistance. When the vertical load increases, the coefficients of frictional sliding resistance decrease and approach the value 0.444 which was obtained by direct shear test. Figure 12 presents these coefficients for strips of different widths and lengths. Most of them are slightly greater than 0.444. The frictional rations (α and β) are given in Fig. 13. Figure 14

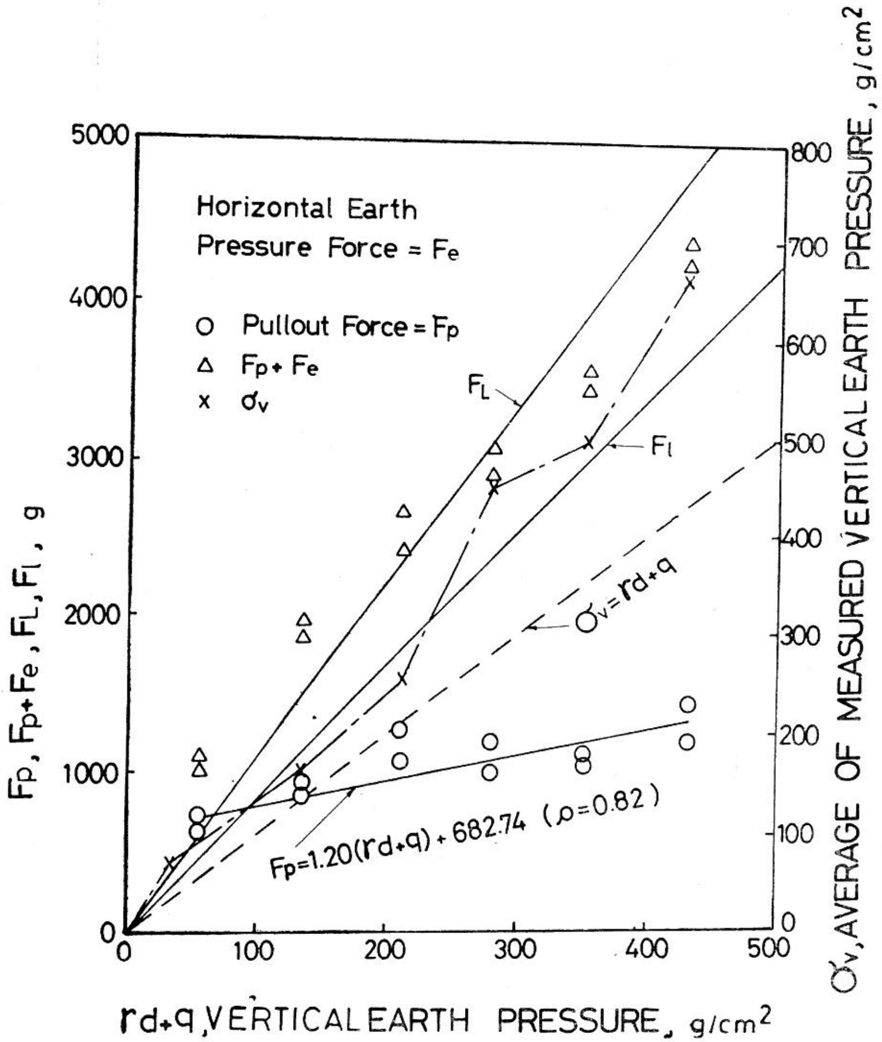

FIGURE 10 Frictional Resistance and Sum of Pullout Force and Horizontal Force

shows the coefficients of frictions versus $1/\sigma_v$ for the strip length of 12.5 cm for strip width of 1.0 cm, for vertical spacing of the strips 10 cm and for horizontal spacing of the strips 3.1 cm.

The yield strengths (Q_{max}) just prior to the collapse of walls are given in Figs. 15 and 16, where the yield strength varies linearly with the

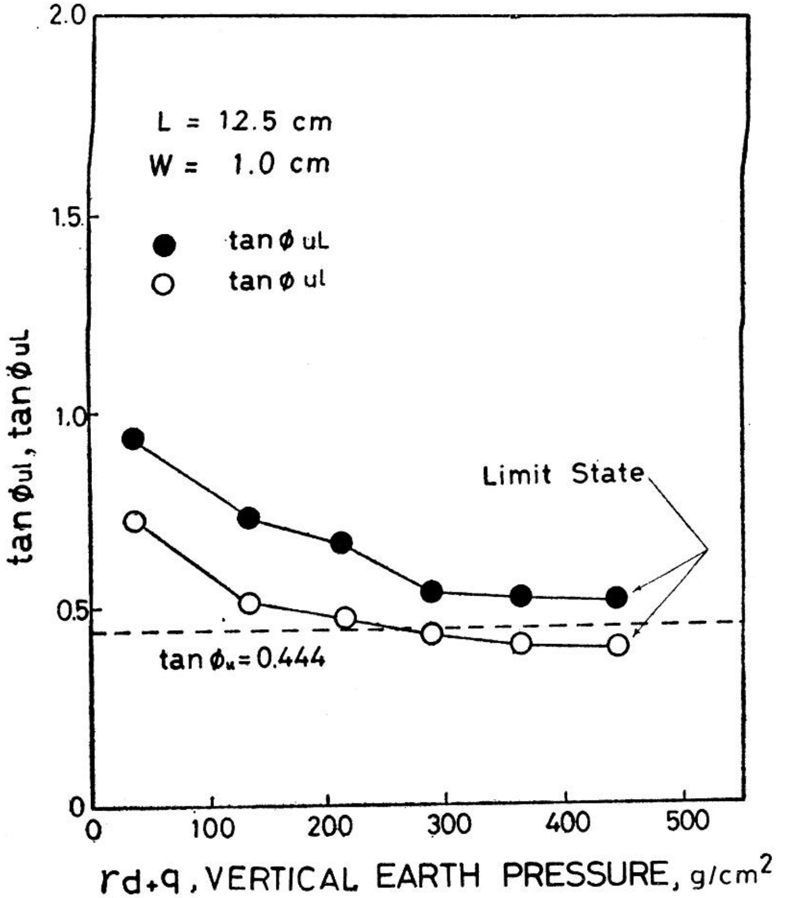

FIGURE 11 Coefficient of Frictional Sliding Resistance

width and length of strips. It is observed that the deviations of data are small and this is mainlydue to the careful compaction while building the walls. Figures 17 and 18 show the safety factors F_{cf} and F_{cm} which are, respectively, the ratios of the total frictional resistance against the total horizontal earth pressure which are supported by each strip and of the moment due to the frictional forces of each layer and since the evaluated F_{cf} and F_{cm} are less than unity, it may be concluded that the actual frictional resistances developed on the soil strip intersurface are far greater than the theoretically predicted ones. Thus the analysis of retaining walls based on Eqs. (6) and (7) give a conservative design. The failure surfaces of the retaining walls are also reported in this paper. Figure 19 shows that in case of $Q_{max} = 292.628$ kg the failure surfaces are produced at two different locations. Although the deviations are great,

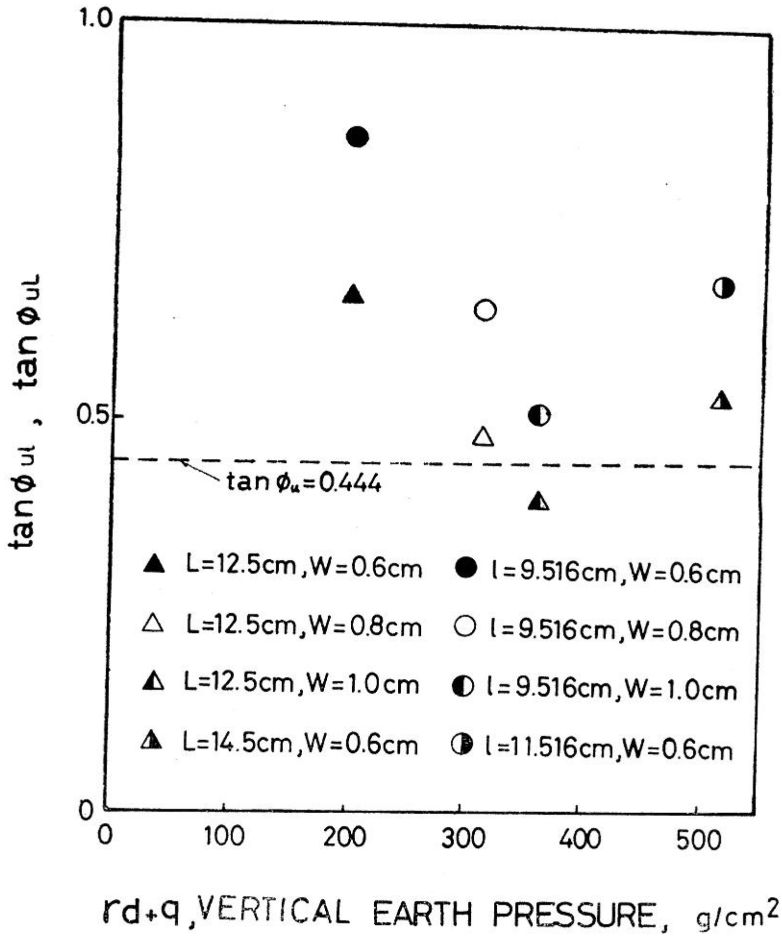

FIGURE 12 ***Coefficient of Frictional Sliding Resistance at Limit State***

these curves are mostly behind the wedge slope due to the effect of strengthing sand mass by strips. Figure 20 shows the deformation behaviours of the skin dependent upon each stage of applied load (Q) and the corresponding horizontal earth pressures are also given in the same figure. It is interesting to note that just prior to the limit state the horizontal earth pressure distribution in the near surface is greater than Rankine's linear distribution and on the contrary the distribution in the near bottom becomes smaller. This phenomenon may be comprehensively due to the arching effect.

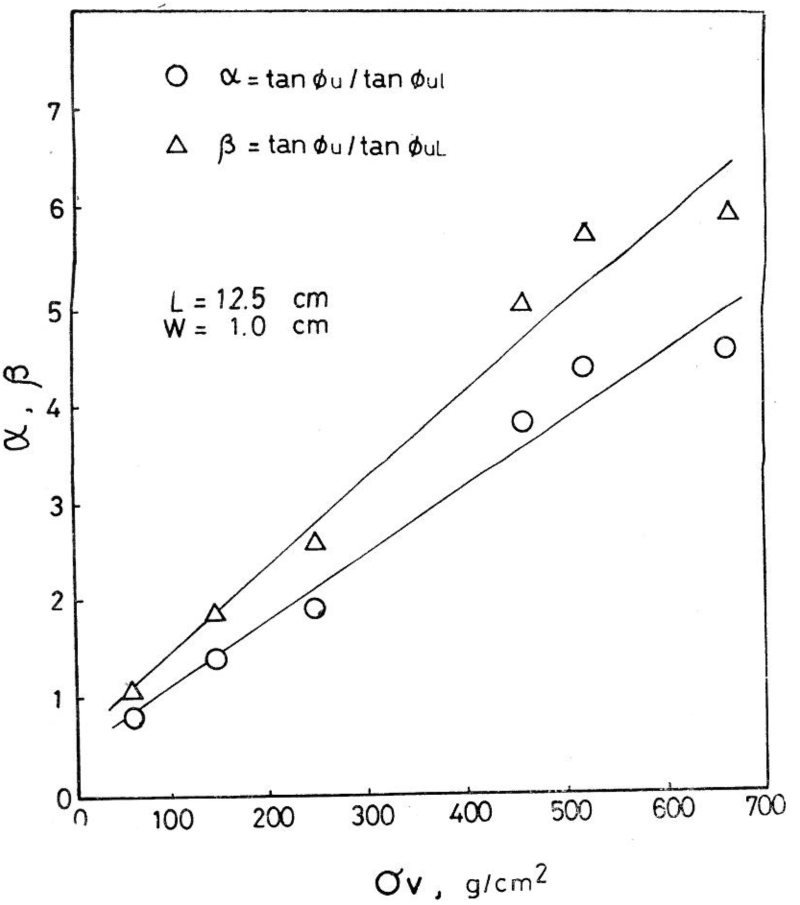

FIGURE 13 Frictional Coefficient Ratios Versus Vertical Stress

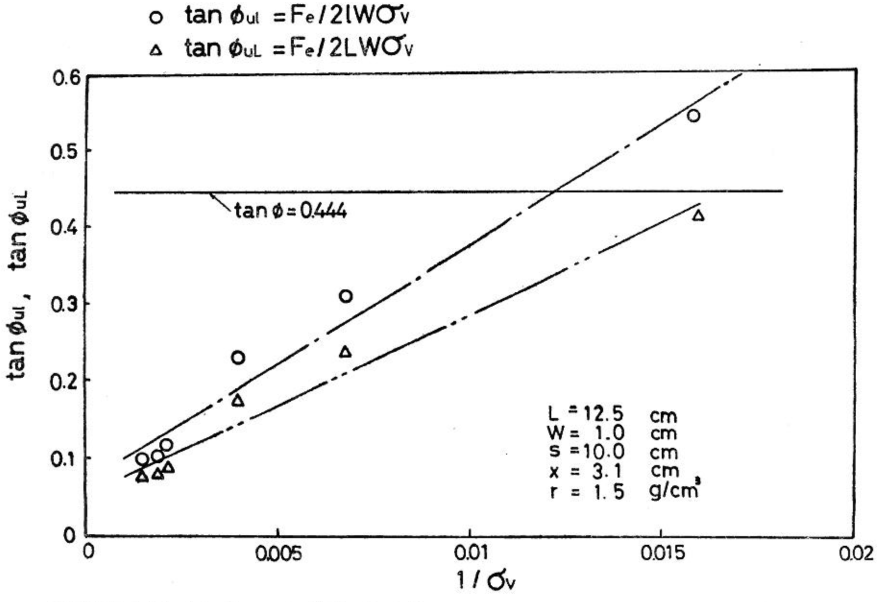

FIGURE 14 Reciprocal of Vertical Stress Versus Frictional Coefficient Curves

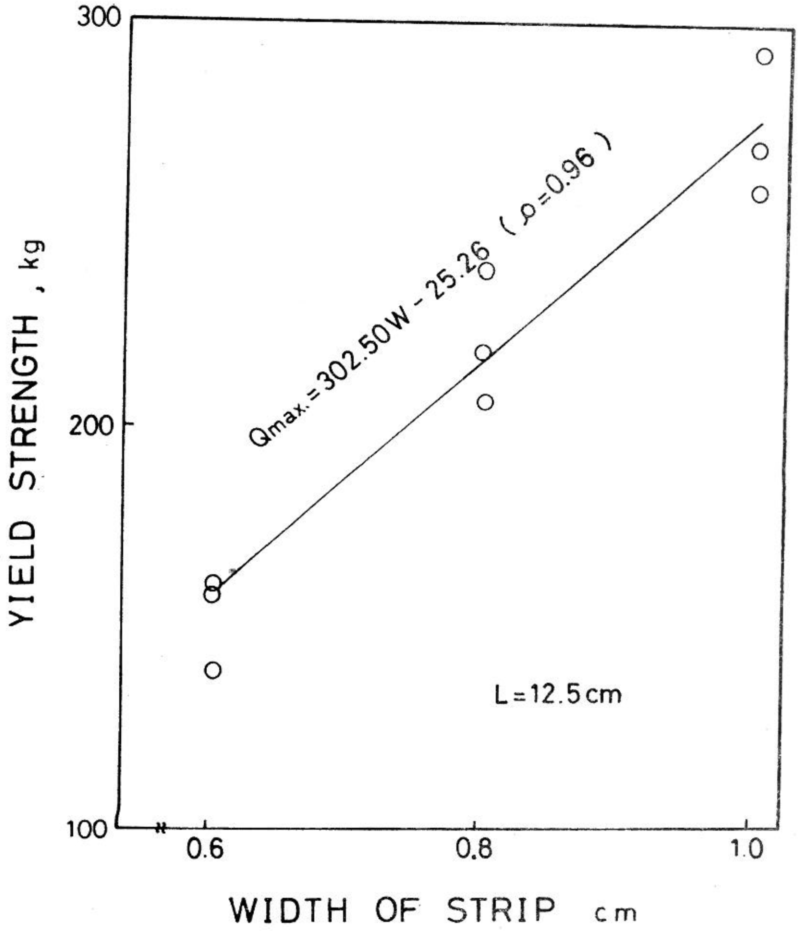

FIGURE 15 Yield Strength—Width of Strip Curve

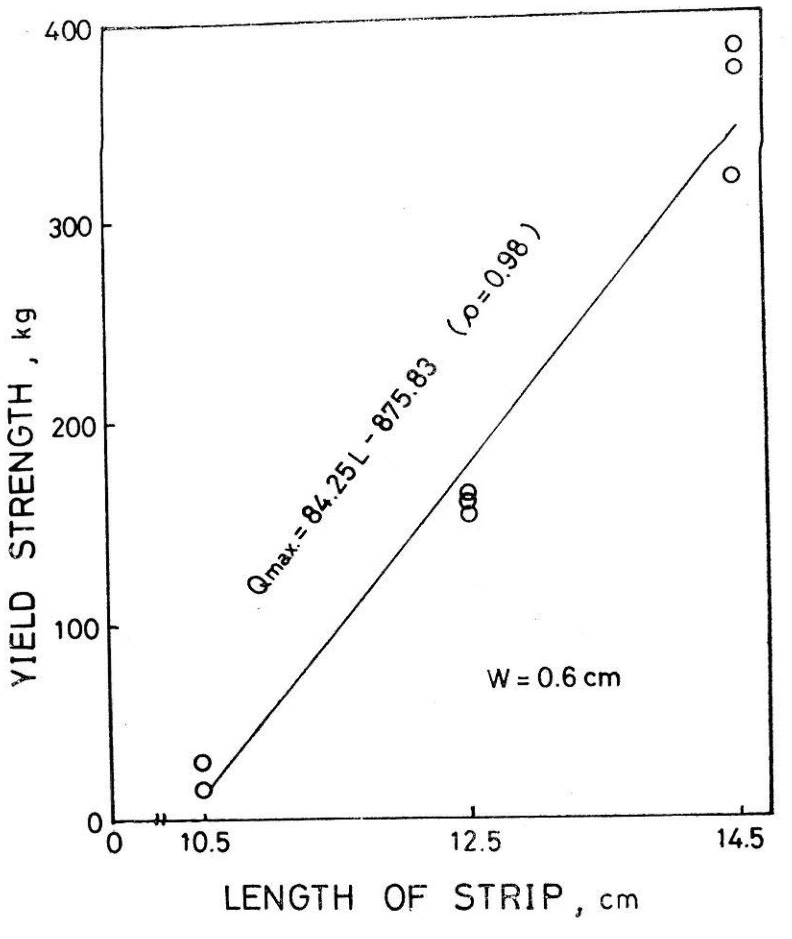

FIGURE 16 Yield Strength—Length of Strip Curve

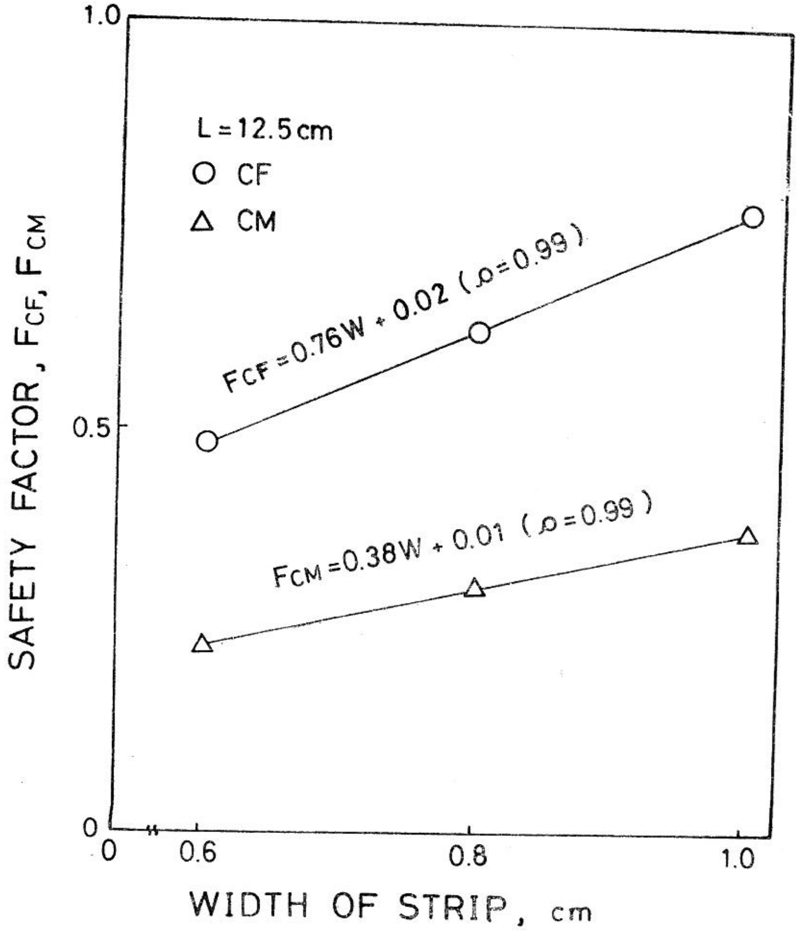

FIGURE 17 Safety Factors—Width of Strip Curves

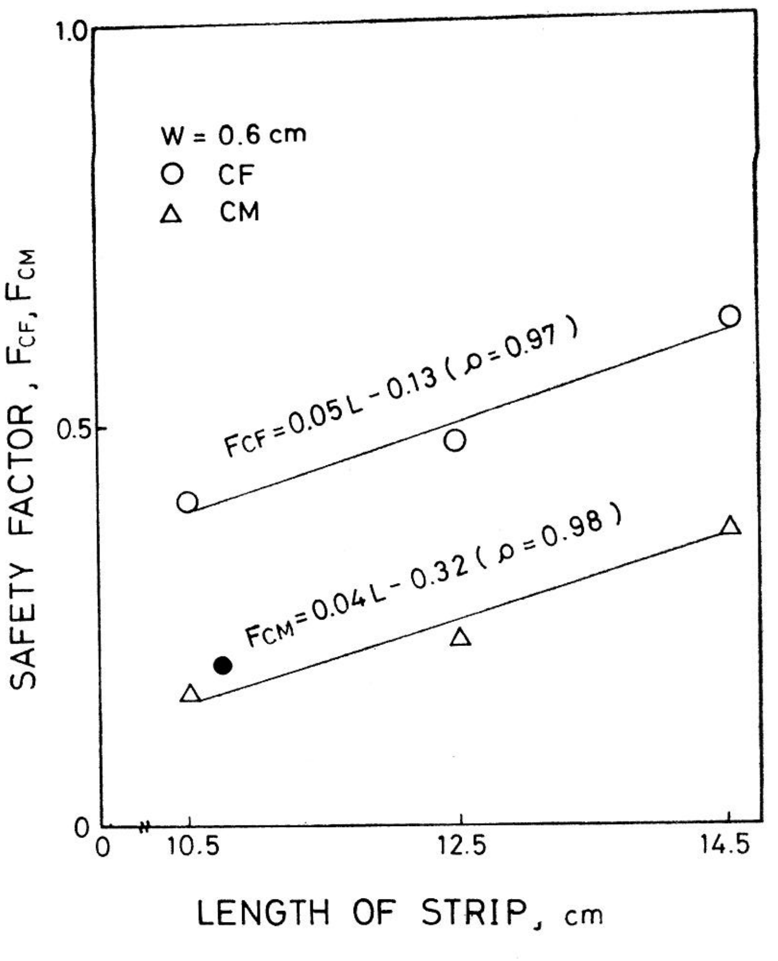

FIGURE 18 Safety Factors—Length of Strip Curves

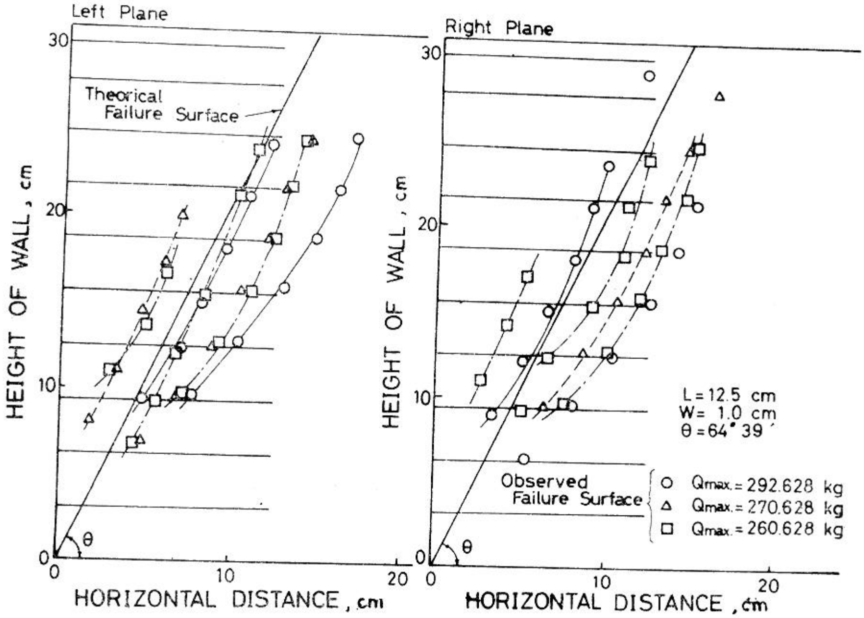

FIGURE 19 Failure Surfaces in the Backfill

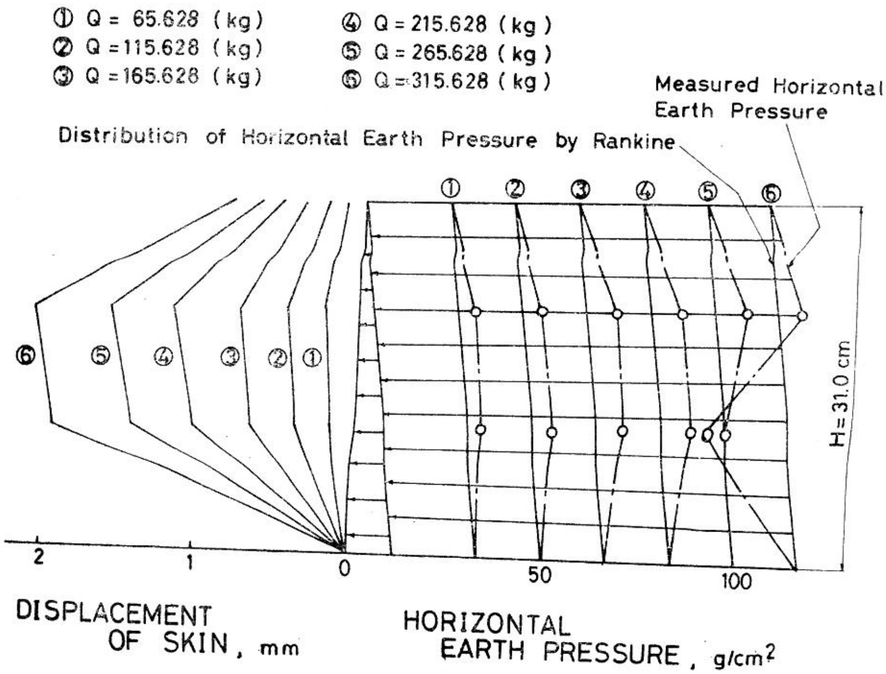

FIGURE 20 Displacement of Skin and Horizontal Earth Pressure

Summary and Conclusions

Based on the experimental results, the following observations are offered :

1. The stability of reinforced earth retaining walls in reality may be greater than predicted by the classical soil mechanics theory.
2. In the limit state, the sum of the pollout force (F_p) and the horizontal earth pressure (F_e) coincides with the frictional resistance force (F_L or F_i).
3. It seems reasonable to believe that the forces in the reinforcing strips are sensitive to the mobilised friction or adhesion based on direct shear test.
4. The coefficients of frictional sliding resistance between sand and strips are almost identical both by the direct shear test and by the prediction through the experimental test of small models.
5. The deformation of the walls is of flexible nature and the distribution of the horizontal earth pressure in the limit state differs from the linear distribution by the Rankine method.
6. The failure surfaces of the walls vary in wide ranges, even appearing behind the ends of the strips.
7. The detailed studies of failure mode in full scale structures and soil strips frictional behaviour in them are mainly needed.

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Notations

S = Horizontal distance between the reinforcing strips

L = Length of the strip

W = Width of the strip

X = Vertical distance between the reinforcement

ϵ_o = Strain of the test piece

F_p = The pull-out force

ϕ = The angle of internal friction of sand

$\tan \phi_u$ = The coefficient of friction between sand and strip

$\tan \phi_{uL}$ = The coefficient of internal sliding friction due to the total length of strip

$\tan \phi_{ul}$ = The coefficient of internal sliding friction due to the effective length of strip

γ = Unit weight of soil

q = Surcharge pressure

p = Coefficient of correlation