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Instrumented Field Performance of Vertical Reinforced Earth Wall

Faisal Hj. Ali[1] and Bujang B.K. Huat[2]

[1]*Department of Civil Engineering,*
59100 Universiti Malaya, Kuala Lumpur, Malaysia
[2]*Department of Civil and Environmental Engineering,*
Universiti Pertanian Malaysia,
43400 UPM Serdang, Selangor Darul Ehsan, Malaysia

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ABSTRAK

Kertas kerja ini memperihalkan cerapan dan keputusan ujian luar yang telah dijalankan ke atas sebuah tembok penahan yang dibina di Bangsar, Kuala Lumpur. Kajian ini melibatkan penempatan sebanyak 98 tolok-terikan di atas 24 jalur penenulang dan pemasangan sebuah meter condong. Dua ujian tarik keluar juga dijalankan untuk menentukan pekali geseran ketara. Prestasi tembok tanah bertetulang diawasi dan dianalisiskan. Daya-daya tegangan maksimum dalam jalur-jalur penenulang di hujung kala pembinaan didapati hampir menepati nilai-nilai teori. Tiada pergerakan mendatar berlebihan dikesani disepanjang tiga bulan setengah selepas pembinaan dilakukan.

ABSTRACT

This paper presents the site observation and results of full-scale investigations of a section of an earth retaining wall constructed at Bangsar, Kuala Lumpur. The studies involved instrumenting 24 reinforcing strips with 98 strain gauges and installation of an inclinometer casing. Two pull out tests were also performed to determine the apparent friction coefficient. The performance of the reinforced earth wall was monitored and analysed. Field observations on maximum tensile forces in reinforcing strips at the end of construction were in reasonably good agreement with theoretical values. No appreciable horizontal movement was detected during the first three and a half months after construction.

Keywords: Galvanised mild steel strip, reinforced earth wall

INTRODUCTION

Reinforced earth (RE) is a composite material constituted of frictional backfill material reinforced by linear flexible strips generally placed horizontally. It made its debut in Malaysia in early 1982 about nineteen years after its invention by the French engineer and architect Hendri Vidal in 1963. In 1968, the first major RE project was built in France. Today, more than ten thousand RE structures have been built and three structures are completed and placed in service every day somewhere in the world (Vidal 1986). Up to 1987 about 35 RE structures had been built in Malaysia (Chiu *et al.* 1987).

Mining sand, quarry dust, river sand and residual granite soil are commonly used backfill material for RE structures in Malaysia. Since the mining sand is found in great abundance and within easy access, it has become the most commonly used backfill material in Malaysia. In fact, the cheap and easy availability of mining sand is one of the important factors that contribute to the rapid growth and development of RE structures in this country.

Purpose of Investigation

The procedures for the design of the reinforced earth retaining wall are described in the technical memorandum BE3/78 published by the British Department of Transport (1978) and the 'Recommendations and Rules of the Art for Reinforced Earth Structures' issued by the French Ministry of Transport (FMOT 1979). These design procedures are based partly on the classical soil mechanics concepts and employ a number of simplifying assumptions and semi-empirical equations (through experience and studies gained in France, U.K. and elsewhere with reinforced earth structures).

In order to evaluate the reliability of the foregoing theoretical design equations and assumptions (especially under Malaysian construction and backfill conditions), a study of the behaviour of a reinforced earth retaining structure was carried out at a construction site in Bangsar.

Project Description

In one of the development projects in Bangsar, rows of 3 storey apartments and condominiums had been constructed. Due to the existing topography, the 2 access roads serving these differ by 6 to 8 m in level. Because of the close proximity of these 2 access roads and difference in levels, some form of retaining earth structure was required. A reinforced earth wall with an average height of 7.5 m was proposed and constructed.

Geologically, the site is underlain by the Kenny Hill Formation of the Permo-carboniferous age. Subsurface exploration carried out previously around that area (Chiu *et al.* 1987) revealed that the overburden soil consists of residual soil derived from quartzitic sandstone interbedded with shale. The SPT value reached 50 at a depth of about 1.5 m below ground level.

DESIGN CONSIDERATIONS

Both FMOT and BE3/78 guidelines were used, whenever appropriate, in the analysis and design of this retaining wall.

BE3/78 stipulates that the minimum length of reinforcing element, to satisfy bond requirements, shall be the bigger of

(i) 0.8 times the height of the wall (i.e. 0.8 × 7.5 m = 6.0 m)

(ii) 5 m

As such a length of reinforcing strip of 6 m was selected. High adherence ribbed galvanized mild steel strips were chosen for their good frictional adherence characteristics with the granular backfill material.

In the design, two failure modes were considered for the internal stability of the wall, i.e. the pull out and tension failure. The corrosion resistance of the reinforcing strips was also considered and a sacrificial thickness of 0.75 mm per face of the strip was provided, which was based on the standard material specification for the RE components of all RE structures constructed in Malaysia. The designed imposed surcharge load on top of the retaining wall was assumed to be 20 kPa to cater for the vehicles.

The tensile rupture of the reinforcing element was also checked at the bolted connection since the cross-section at this point was the minimum. The reinforced earth structure was also checked for external stability in terms of sliding, overturning and bearing failure. The safety factor against failure was found to be at least 3. The complete internal and external stability cross-checks were carried out using a computer programme.

The backfill material used in this reinforced earth retaining wall was mining sand obtained from Puchong. The particle size distribution of the sand fill is given in *Fig. 1*. The pH value of this sand varies between 5.2 - 8.88 and the resistivity ranges from 5,300 ohm cm to 75,000 ohm cm (Chiu *et al.* 1987) easily fulfilled the French specifications.

CONSTRUCTION

Construction was preceded by erecting a concrete levelling footing for accurate placing of the first row of facing panels. Sand fill was then placed

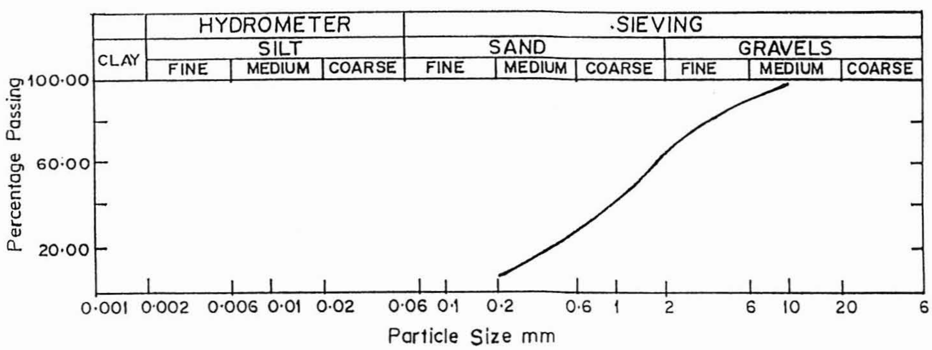

Fig. 1. Grading curve for the mining sand

and compacted in layers. As the level of fill was built up progressively, the metallic reinforcement was placed at the required levels. The compaction was carried out using a 10 ton vibromax roller and was kept 1.5 m away from the wall. A small pedestrian vibrating plate compactor was used to compact the backfill within 1.5 m behind the facing panels. Polyester foam was pushed into each vertical joint with a wedge or knife to ensure that fines did not escape. Corkboard was placed on the top edge of the panel to prevent concrete to concrete contact.

INSTRUMENTATION

The field instrumentation for monitoring the behaviour of the structures was carried out at a single test section. *Fig.2* shows the location of instruments. The instruments used are summarized in the instrumentation schedule in Table 1.

TABLE 1
Types of instrumentation

Number	Instrument	Purpose
98	Electrical resistance type strain gauge	Measurement of tension in the reinforcing strips. Strain gauges were mounted in pairs on both sides of the strips to take account of longitudinal bending.
1	Thermocouple	Measurement of soil temperature.
1	Inclinometer	Measurement of movements of reinforced earth structure

The strain gauges were mounted in pairs on both sides of the strips to take account of longitudinal bending. Prior to placement in the fill, the reinforcing strips were calibrated at the laboratory by applying successive increments of static loads to the instrumented strips (see *Fig. 3*). During installation the pairs of strain gauges were shielded in short lengths of P.V.C. tube/sleeves to protect them from sand backfill.

Calibration of Instrumented Reinforcing Strips

The typical calibration graph of microstrain versus load is shown in *Fig 4*. Top and bottom strain gauges at any specified location do not exhibit the

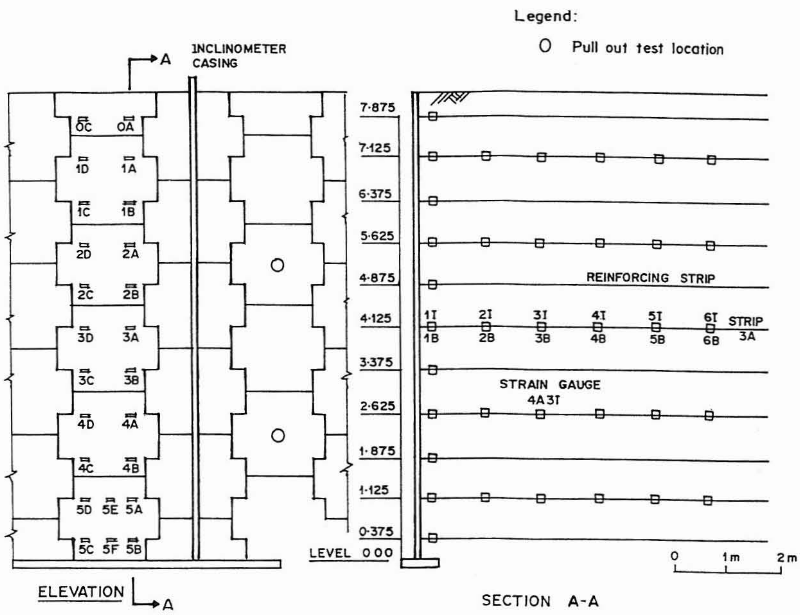

Fig. 2. Instrumentation locations

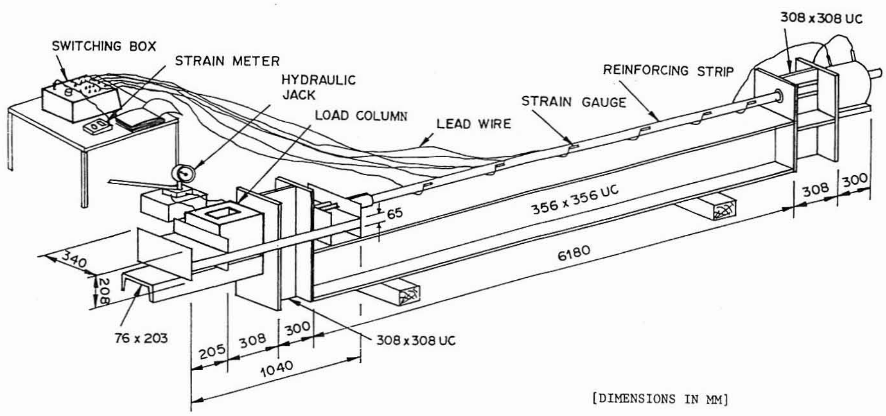

Fig. 3. Calibration set-up

same reading for a given load (see *Fig. 4*). The difference could be attributed to the existence of a slight unavoidable eccentricity as a result of which the top and bottom were not equally tensioned during calibration.

There is also a slight "kink" in the calibration graph (*Fig. 4*). Initially, the gradient is steeper i.e. from 0 to 0.2 ton. This is contradictory to the linear stress-strain relationship of galvanized steel. This phenomenon is not however unexpected. The instrumented reinforcing strip was not taut at zero load. The first load increment would straighten out the initial

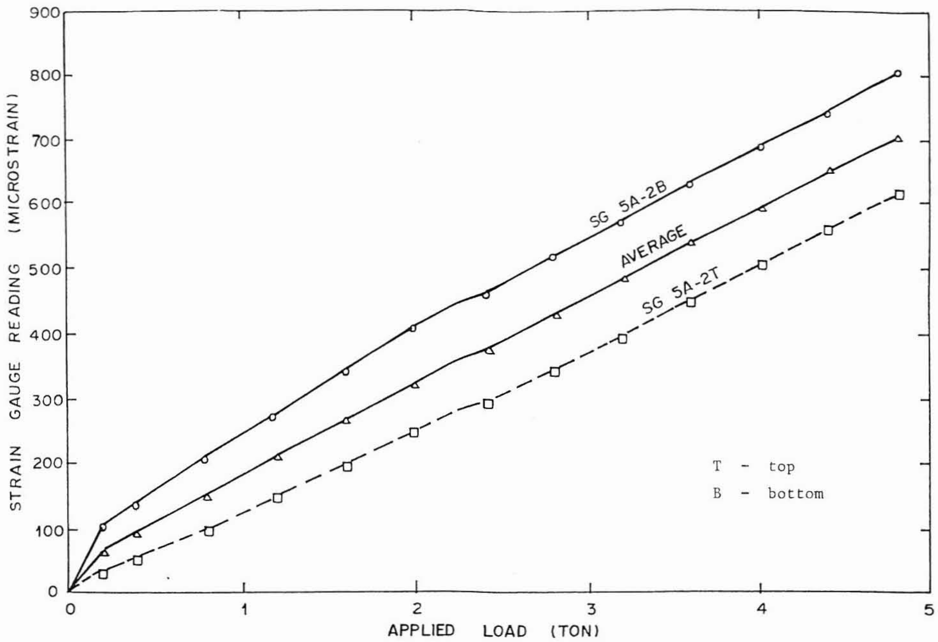

Fig. 4. Typical calibration curve

relaxed profile of the reinforcing strip and once the strip had been straightened, the additional increment would stress the strip. Thus, greater deformation would be registered at the initial part of the calibration.

The average modulus value E (based on the average between the top and bottom readings) for the instrumented strips is 222.5 kN/mm^2 with a standard deviation of 18 kN/mm^2. This E value is about 10% higher than the published E value of galvanized steel. The difference may be due to eccentricity and non-uniform stress distribution along the cross-section of the strip which may be caused by the bolted connection used in calibrating the strip.

The loading and unloading graphs do not fall on the same path due to hysteresis. Generally, after the 10th cycle of loading and unloading the loop remained almost constant. 70 cycles of loading and unloading were applied to one of the strips. It was found that after the 10th cycle the loop remained almost constant which indicated that locked-in stresses had been sufficiently reduced. Therefore 10 cycles of cyclic loading and unloading were applied to the rest of the strip.

PERFORMANCE OF REINFORCED EARTH WALL

The construction of the reinforced earth wall took about 3 months and readings were taken on strain gauges and inclinometer during and at certain intervals after construction. However, the results presented here are mainly for the conditions when the full height of earth fill had been placed and one and a half months thereafter. The representative sample of results is discussed.

TENSILE FORCES IN REINFORCING STRIPS

A typical plot of strain gauge readings versus levels of backfilling is shown in *Fig. 5*. It is noted that the strain readings on the opposite sides of a strip at any given location are different due to a slight eccentricity and longitudinal bending. Therefore the average values of the top and bottom strain gauge readings were determined to obtain the axial strain at that point. From this average strain, the axial tensile forces are read directly from the corresponding calibration graphs.

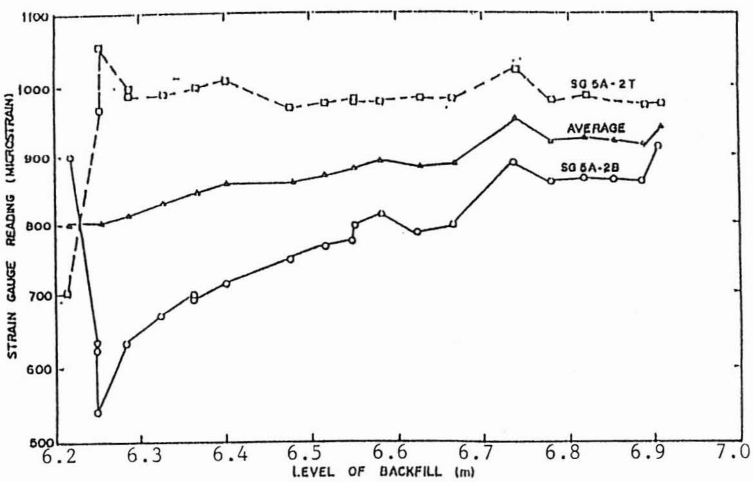

Fig. 5. Typical plot of strain gauge reading vs. level of backfill

From *Fig. 5* it can be seen that the initial readings of the top and bottom strain gauges were erratic, probably as a result of movements induced by placement and compaction of the initial overlying layers of fill. However average strain gauge readings increase with height of backfill.

The results of tensile force distribution in reinforcing strips at the end of construction and one and a half months after construction are shown in *Fig. 6*. The recorded tensions in the strips had increased by almost 25% one and a half months after the end of construction. This increase was most probably caused by stress redistribution resulting from ground movement. The tensile force increases from the face of the wall to a maximum at a point within the front half and then decreases to zero at the free end (see *Fig. 6*). The locus of points of maximum tensile force (*Fig. 7*) generally follow the shape of the failure surface assumed in the coherent gravity method, in which the failure mode is analogous to the mechanism of failure met in the case of a cohesionless soil supported by a rigid wall which is rotating around its top. As it has been illustrated by Terzaghi (*Fig. 8*) this failure mode leads to different states of stress within the active zone which results in different distributions of lateral stress from the classical pressure distribution (Rankine's active pressure). The line joining the points of maximum tension is orthogonal to the ground surface and they meet at a distance of approximately 0.3H from the wall where H is the overall height of the wall. When the soil and the strips are placed layer after layer, the upper part of the active zone, being confined by the skin and by the passive zone, cannot expand laterally and consequently the major portion of this zone is maintained at a state of stress higher than Ka stress conditions (Schlosser 1982). Therefore, the soil tends to fail in such a way that the only motion admitted to the upper active zone is vertical translation.

Fig. 9 shows that T_o/T_{max} is on average equal to 0.52 and is always less than 0.75 where

T_o = tensile force at the point of attachment of the reinforcement to the facing.

T_{max} = maximum tensile force in the strip.

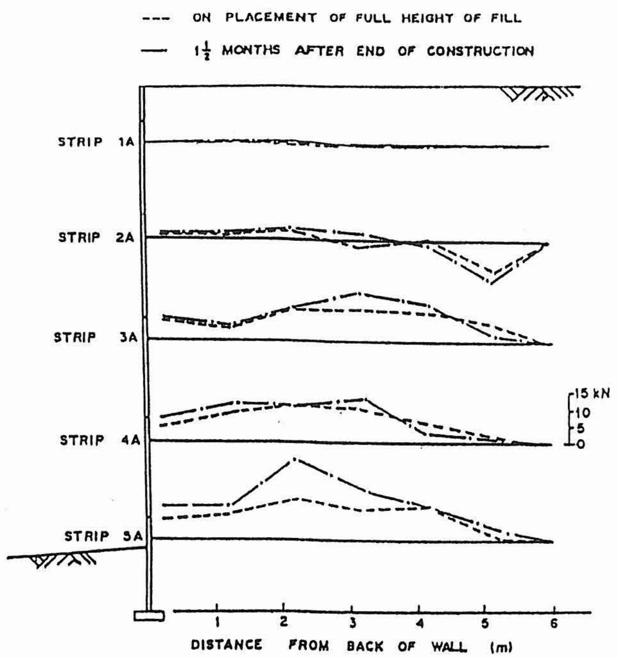

Fig. 6. Tensile force distribution in reinforcing strips on placement of full height of fill and 1 1/2 months after end of construction

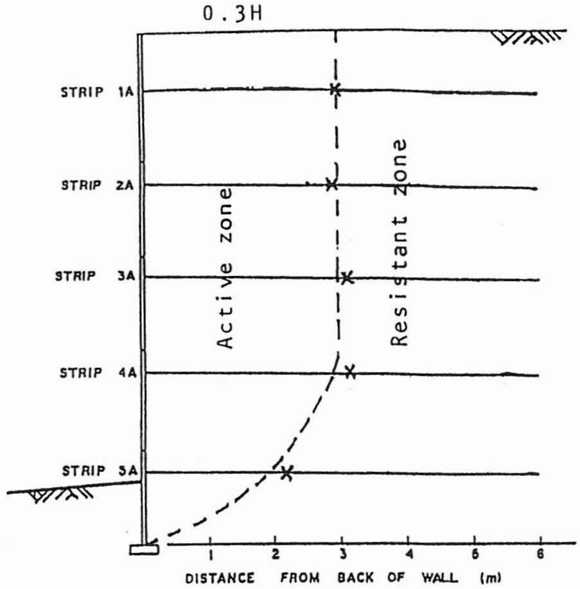

Fig. 7. Locus of maximum tensile forces (Steel strip reinforced wall)

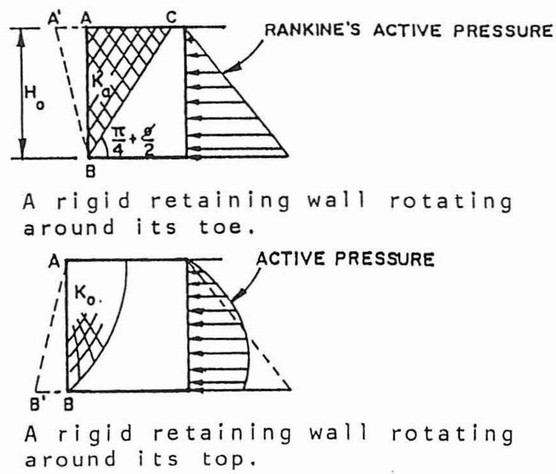

Fig. 8. Effect of wall movement on lateral earth pressure (Terzaghi)

This ratio satisfies the recommendation given in the "Recommendations and Rules of the Art for Reinforced Earth Structures" issued by the French Ministry of Transport.

The strain gauges on the strips performed satisfactorily and allowed the behaviour of the strips to be observed, except for strain gauges on

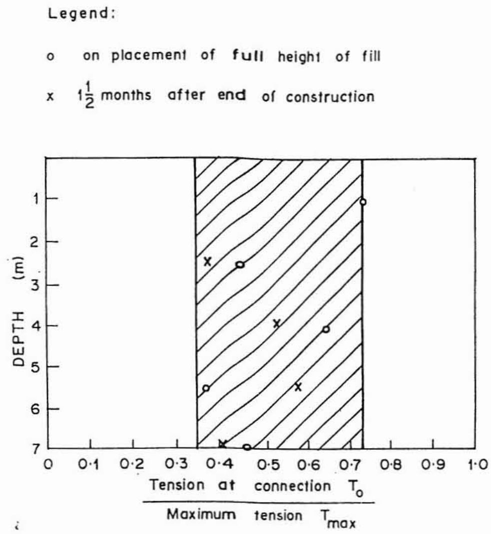

Fig. 9. Measured tension at connection (T_0) compared with maximum tension in the strips (T_{max})

strips 1A and 2A which at some locations registered compression forces on placement of backfill (see *Fig.6*). It is thought that such anomalies may, to some extent, be due to the effect of bending and lateral restraint which can be quite significant at these top levels where the induced tensile forces are relatively small and this effect is further enhanced if the strips were not properly placed and stretched before laying the top layer of the soil. Table 2 presents the comparison between the field values of maximum tensile forces and the corresponding theoretical values determined by the coherent gravity method and the tie back wedge method. All the measured values are less than the theoretical ones. However, the lower levels (reinforcing strips 3A, 4A & 5A) give theoretical values reasonably close to the measured ones. Field values of reinforcing strips 1A and 2A were very much smaller than those of calculations. Earlier it has been shown that some strain gauges on these strips have given unrealistic results for the reasons already stated.

Since no load cell had been installed on the facing panels, direct measurement of pressure on the facing cannot be made. On the assumption that the forces indicated by the gauges near the facing would represent the forces sustained by these panels, the lateral force acting on each facing panel can be worked out indirectly by adding up the forces measured at connections to that panel. Comparison between the forces on the facing panels at different depths (obtained from the measured strains in the instrumented strips) and the forces generated if Rankine's active

TABLE 2
Comparison of measured maximum tensile forces and predicted forces based on coherent gravity method and the tie back wedge method.

Reinf. strip	Measured max. tension	Predicted tension based on coherent gravity method (kN)	Predicted tension based on tie back wedge method (kN)
5A	12.7	13.29	16.36
4A	10.9	14.77	16.15
3A	9.6	11.76	10.51
2A	2.4	8.01	6.01
1A	0.4	3.41	2.23

earth pressure is assumed to act on the same panels, is presented in *Fig. 10*. The results indicated that the sum of forces at connections were small, generally in the range of 9 to 15 kN (this value is small compared to the force due to active lateral pressure acting on a conventional reinforced concrete retaining wall). Such behaviour is consistent with the ideal concept of reinforced earth as a composite material which requires only a light facing for local support and erosion protection. It can also be noted from *Fig.10* that the horizontal forces acting on the lowest panel 5 were smaller than on the upper panels 3 and 4. This trend is in accordance with the pressure distribution in *Fig. 8 (b)*.

The values of the apparent coefficient of friction, f*, between ribbed reinforcing strips and soil obtained from pull-out test are compared against the values assumed in the FMOT recommended design method in *Fig 11*. The value of f* obtained from the pull-out test were 4 to 9 times higher than the designed f* value. Thus, it can be seen that the FMOT code appears to be conservative in determining the coefficient of apparent friction.

The safety factors at the end of construction evaluated from the measured forces both against the breaking (tension failure) and pull-out (adherence failure), are found to be satisfactory (see *Fig. 12*). The actual safety factors should be the smaller of the factors of safety against pull-out and tension failure. It can be noted that the factors of safety against pull-out are always greater than those against tension failure, explaining why the 2 pull-out tests conducted at site had caused the strips to fail at connections before being pulled out.

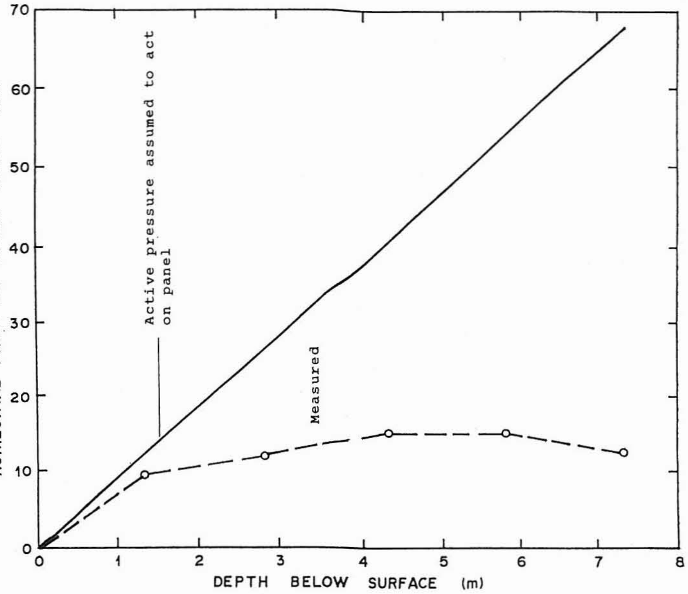

Fig. 10. Variation of horizontal force on facing panel with depth

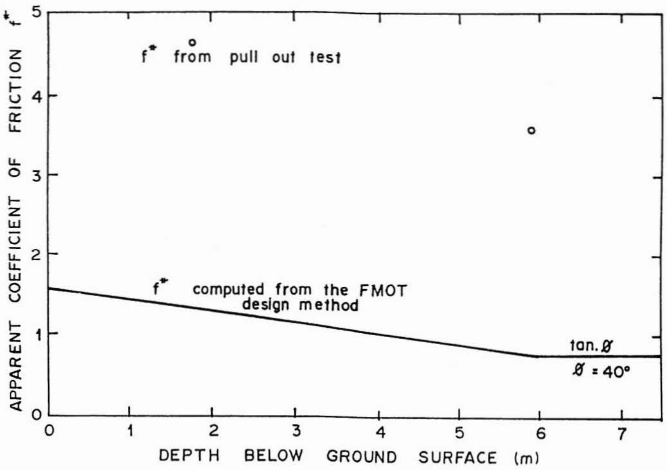

Fig. 11. Apparent coefficients of friction - theoretical values and pullout test results

Horizontal Movement of Reinforced Earth Wall

The variation of lateral movements of the reinforced earth wall with depth during and after construction is shown in *Fig. 13*. It is observed that the wall moved outwards (towards the downhill direction, A+) as the construction of the backfill progressed. The amount of the wall lateral displacement was found to be about 25 mm three and a half months after

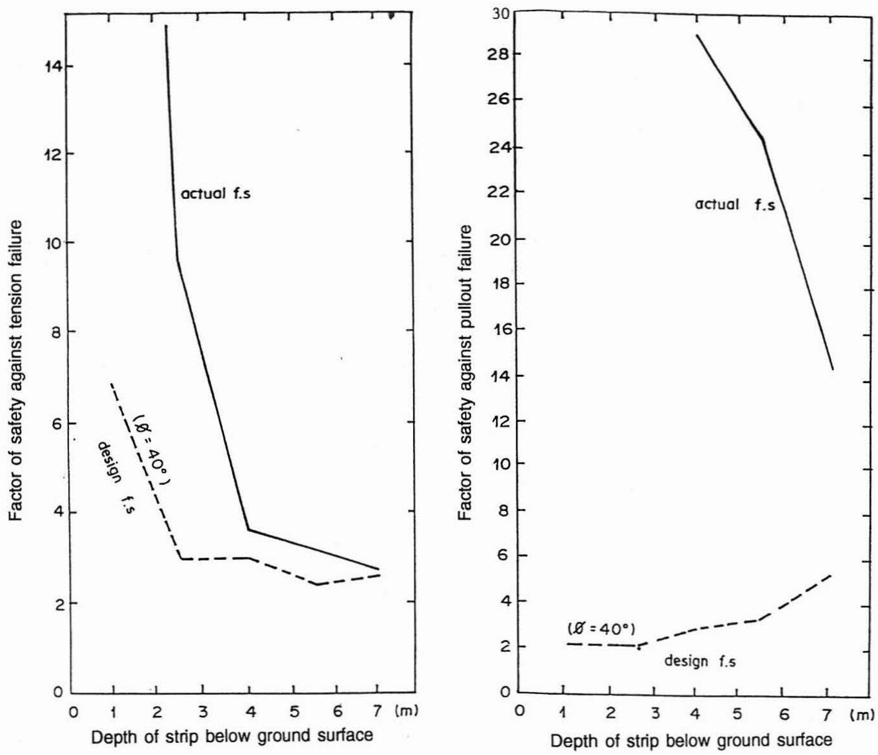

Fig. 12. Factors of safety at the end of construction

completion (taking end of construction as the reference point) which is in the same order of magnitude as have been reported in the literature.

Besides the lateral movement the soil mass moved longitudinally (in the direction parallel to the wall, B+ B -). The longitudinal displacement at three and a half months after the completion of wall was very small i.e. 6 mm *(Fig. 14)*.

CONCLUSION

Observations on actual wall behaviour have played an important role in verifying the assumptions used in design. Useful information on the develop-construction of the structure has been obtained. The tensile force increases from the face of the wall to a maximum at a point within the front half and then decreases to zero at the free end. The locus of points of maximum tensile force generally follow the shape of the failure surface assumed in the coherent gravity method. The performance monitoring has shown that the post construction movement of the reinforced soil

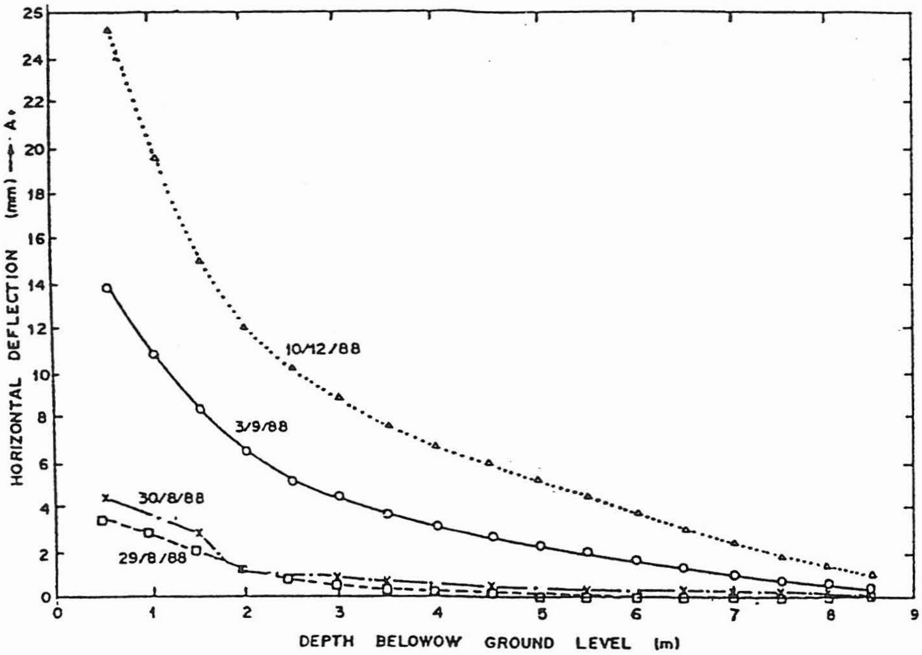

Fig. 13. Horizontal movement (perpendicular to wall face) vs. depth for the steel strip reinforced wall

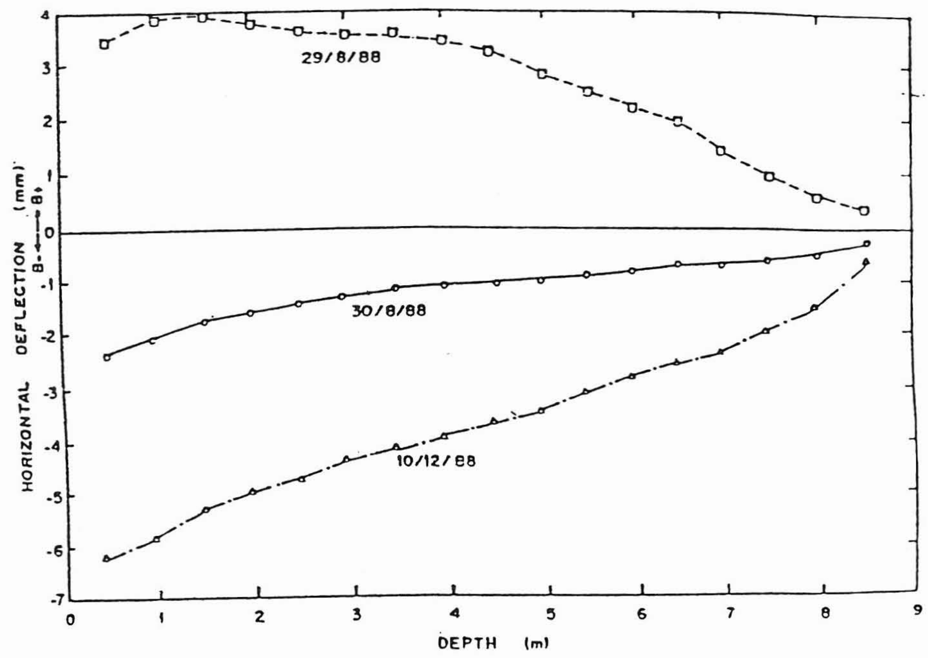

Fig. 14. Horizontal movement (parallel to the wall) vs. depth for the steel strip reinforced wall

structure is small. It is also found that the tensile loads in soil reinforcements are within the permissible limits.

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