Field Measurements on a Reinforced Earth Wall at Granton

Expérimentation sur un Mur en Terre Armée de Granton

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SYNOPSIS The paper presents the results of measurements obtained during and after construction of a reinforced earth wall 6.3 m high at Granton near Edinburgh, Scotland. Observed measurements included vertical and horizontal movements of the concrete facing panels and stresses in the stainless steel reinforcing strips. The observations are discussed in terms of the assumed design parameters and in comparison with similar observations on reinforced earth walls in France and the U.S.A. where steel facing elements have been used. Compaction of the fill material is seen as an important factor influencing wall movement and stresses in the reinforcing strips. It is concluded that construction procedure plays an important role in the subsequent behaviour of this type of wall.

INTRODUCTION

Increasing the strength of a soil mass by the introduction of some type of reinforcement has been practiced since Roman times. A rational design method for the use of reinforcement in soil was advanced by H. Vidal (1966). Schlosser and Vidal (1969) presented methods of calculation and described laboratory studies on model walls and field measurements made on a 10 m high wall at Incarville. Lee, Adams and Vagneron (1973) reviewed the design methods for reinforced earth walls and found them to be realistic on the basis of small scale laboratory tests. Chang (1974) reported field studies of a reinforced earth wall about 13 m high in Los Angeles County, and Chang, Forsyth and Beaton (1974) further described this work.

The reinforcing material consists normally of thin strips of stainless steel, galvanised steel or aluminium alloy laid out horizontally and attached by bolts at the front of the wall to light metal facing elements of semi-elliptical shape and about 0.3 m high. Alternatively the facing elements can consist of interlocking concrete panels approximately 1.5 m square to which the reinforcing strips are attached.

Comparatively few reinforced earth walls have been built in the United Kingdom. Price (1975) describes the first of these which was constructed at Granton near Edinburgh and the present paper reports the measurements which were made during and after the construction of this wall. The wall at Granton was faced with concrete panels as distinct from the Incarville and Los Angeles County walls where curved metal strips were used. Price states that the Granton wall was designed and constructed to the same specifications as used in France. The wall is 106 m long varying in height from 1.79 m to 7.17 m.

INSTRUMENTATION OF WALL

The section at which the measurements were made was 6.3 m high and is shown in cross section and part elevation on Fig. 1. The interlocking facing slabs are 1.5 m square, 0.18 m thick and the joints between are not butt joints but are stepped. A packing layer was placed on the inner face of each joint and porous blocks were placed immediately behind the wall to cater for seepage. The bottom panels were alternately full size and half size slabs to give a chequered pattern and so eliminate continuous horizontal joints. The stainless steel reinforcing strips were 80 mm by 1.5 mm in section and were 6.5 m long. Four strips were attached to each panel at the spacing shown. Construction proceeded by erecting each lower panel on the foundation strip, compacting the fill material to the level of the lower strip location, fixing the strips, then compacting the fill on top of them. In order to prevent undue horizontal displacements, the panels in the lowest row were propped during placement of the fill. The upper panels were not propped, timber wedges being placed in the front of each stepped joint to restrict tilt of the panels.

The vertical and horizontal movements of each panel and the wall as a whole were monitored by measurements on steel pins inserted in the panels and designated p to v on Fig. 1. A precise level in conjunction with an invar steel staff and a parallel plate micrometer was used for the vertical measurements. The construction operations precluded the establishment of a permanent datum line in front of the wall to which horizontal movements could be referred. Instead an invar steel rod in a guide tube was concreted into the stone pitching behind the wall and was led through the bottom panel to the front of the wall. Horizontal movements were then obtained by use of a demountable datum bar which was brought to the vertical by means of a striding level before micrometer readings were made to each of the steel pins, and to the end of the invar steel datum rod.

Electrical resistance foil strain gauges were installed on 20 of the reinforcing strips attached to 8 panels (A to H). Five of the strips (A2,B2,C2,D2 and D3) were vertically in line and were gauged at five positions throughout their length. Strips E4,F4,G4 and H4, also vertically in line, were gauged over

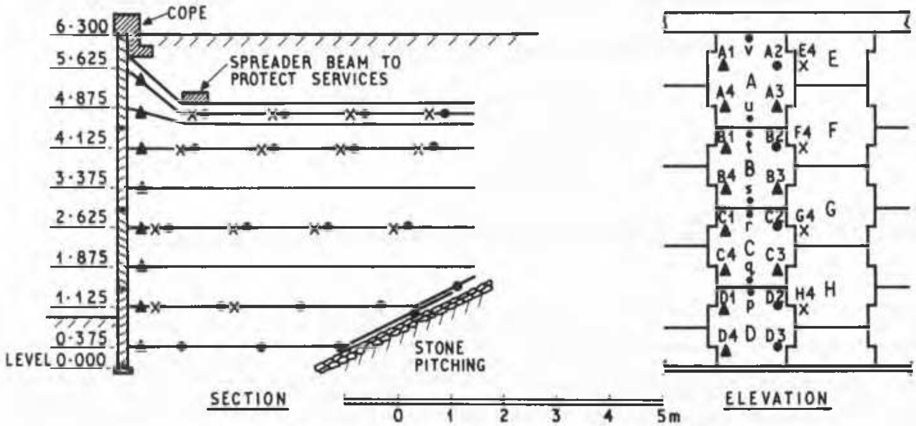

Fig. 1. Instrumentation of wall.

their lengths. These strips were at corresponding levels to four of the gauged strips on panels A to D but were attached to the lower part of the panels. The remaining strips on panels A to D were instrumented immediately behind the face of the wall. A four-arm bridge configuration was used at each of the 50 instrumented positions to eliminate bending and temperature effects and the gauges were installed and calibrated in the laboratory. The instrumentation was intended to determine the magnitude and variation of stresses in strips at different levels, to compare the stresses in strips at the same level in adjacent panels, and to measure the pressure transmitted to the facing slabs. Measurements of wall movements and strains were made for a period of about a year covering the construction and post-construction phases.

PROPERTIES OF BACKFILL MATERIAL

The fill material used within the reinforced wall and beyond the wall was burnt oil shale, a locally available waste product known as blaes. 85% of the material was in the sand and gravel size ranges. The field density was measured as construction proceeded, the average unit weight being 16.65 kN/m^3 at a moisture content of 21%. The material is not completely cohesionless and undrained triaxial compression tests carried out at the average field density gave c_u = 41.4 kN/m^2 and $\phi = 46°$. The coefficient of friction between the material and the stainless steel strips was found to be 0.32 in laboratory tests. In the design calculations a Rankine coefficient of active earth pressure $K_a = 0.3$ had been assumed which corresponds to $\phi = 32.6°$. The K_a value for the backfill material as actually placed was 0.163.

MOVEMENT OF FACING PANELS.

Vertical Movement. The vertical movements of the four panels A,B,C and D are shown in Fig. 2. There was a continual closing up of the joints between the panels from the time of erection to about one month after the carriageway was opened to traffic. The total vertical movement was 35 mm over the total height of 6.3 m. The joint between panels A and B closed 5 mm while those between B and C and C and D closed approximately 10 mm. These joint movements probably occurred when the timber wedges were adjusted and removed, and indicate the importance of suitable construction techniques being adopted.

Horizontal Movement. Due to the construction operations the first measurement of horizontal movement could not be taken when a panel was initially set up but had to be delayed until part of the fill had been placed. The horizontal movements of panels consisted of two components. The first due to outward tilt of the panel was very much larger than the second which arose from outward horizontal movement at the joints and which was on average 4.7 mm. The variation of outward tilt with time on each of the four panels is shown on Fig. 3. On the assumption that the panels were initially set vertical each panel had tilted substantially by the time the first reading was taken. Forward tilting continued until the fill placement was

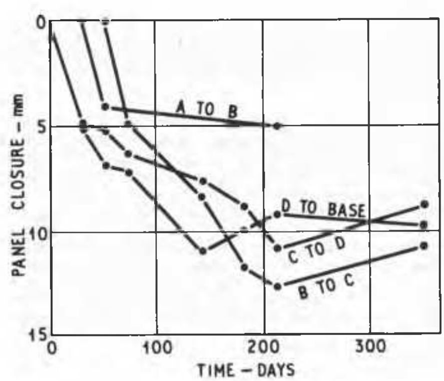

Fig. 2. Vertical movements of panels.

completed and then virtually ceased. The horizontal movements were induced by the compaction process and the lowest panel D which was propped had by far the smallest tilt. The overall outward tilt of the finished wall was 1° 18' or 2.3% and as in the case of the vertical movements points to the importance of adopting construction techniques with regard to panel support and compaction procedures which will permit control of the panel movements during the erection process.

As will be discussed later the panel movements can have a marked influence on the stresses developed in the reinforcing strips.

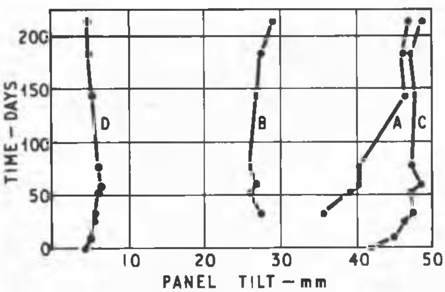

Fig. 3. Variations of panel tilt with time.

METHODS OF ANALYSIS OF REINFORCED EARTH WALLS

Before discussing the stresses measured in the reinforcing strips at Granton and those observed at the Incarville and Los Angeles County walls the methods of calculating those stresses will be briefly reviewed. The normally accepted basis of calculation is conventional earth pressure theory leading to

$$T = K_a \cdot \gamma \cdot H \cdot d \cdot \Delta H \quad \text{.......... (1)}$$

where T is the tensile force in the strip, K_a the active earth pressure coefficient, γ the unit weight, H the height of fill above the strip, ΔH the vertical distance between strips, and d the horizontal spacing of the strips. This presumes a uniform distribution of vertical stress along the strip and relatively minor modifications result if a trapezoidal distribution is taken although Schlosser and Long (1974) stated that equation (1) is valid for the dimensions of the Granton wall. Nevertheless they recommended that the tensile force obtained from equation (1) should be reduced. Chang, Forsyth and Beaton (1974) suggested that the maximum tensile force in a strip corresponds to K_o the coefficient of earth pressure at rest rather than K_a. These methods of calculation give a uniform tensile stress along the length of each strip. Banerjee (1975) referred to a finite element analysis, Banerjee (1973), from which he found the distribution of the non-dimensional tension coefficient $T/\gamma.H.d.\Delta H$ in any strip to be approximately parabolic with a maximum value of 0.35 occurring approximately at its mid-length. Chang (1974) also proposed a finite element method of analysis which led to a small variation in tensile stress along a strip when applied to the Los Angeles County wall.

The results from the Incarville, Los Angeles County and Granton walls can now be considered in terms of the results from the above analytical methods.

RESULTS FROM INCARVILLE AND LOS ANGELES COUNTY WALLS

Schlosser and Vidal (1969) report K values, based on earth pressure cell readings, near the top of the Incarville wall of 0.5 to 0.6 and a K value of 0.35 near its base compared with $K_a = 0.22$ for the backfill material which had a ϕ value of approximately 40°. They attribute the high values of K to be probably due to the effects of compaction. Their measurements of tensile stress in the strips showed substantial variations although in general they concluded that the tensile force reached a peak close to the wall face and that the tensile force decreased from this peak to the free end. Long, Schlosser, Guegan and Legeay (1973) indicate a distribution of tensile stresses measured at Incarville which are not quite typical of the majority of the results. Schlosser and Vidal draw attention to the effect of compaction in developing tensile stresses substantially greater than those predicted by formula based on active earth pressure coefficients.

Chang, Forsyth and Beaton (1974) report for the Los Angeles County wall that the stresses in some of the strips decreased with time while in others there was an increase in stress with time. They also found that the highest stresses developed in the inner middle portion of the strips and that the maximum stresses corresponded to a coefficient of earth pressure approaching the K_o value as against the K_a value normally used in design.

RESULTS FROM GRANTON WALL

A number of the strain readings at the Granton wall, particularly on the upper strips, were unreliable. This appeared to be due to insulation breakdown no doubt influenced by the extra handling and bending to which the strips were subjected in the area of the spreader beam shown in Fig. 1. However the strips at lower levels of the wall functioned satisfactorily. This was fortunate as it meant that the behaviour of the strips could be observed under fill ranging in height from 0.4 m to 5.6 m.

Fig. 4 shows the measured tensile stresses for strips C2, D2 and D3 and the tensile stresses measured in strips F4, G4 and H4 are shown in Fig. 5. The general pattern is of the stress increasing from the face of the wall to a maximum at a point within the front half of the strip and then decreasing towards zero at the free end of the strip. An exception was strip D3 where very small stresses were measured at the wall face under different heights of fill and this was no doubt due to the outward restriction of movement on this bottom panel. After the wall was completed there was no change in the stresses measured in the strips.

Table I shows the maximum and average stresses measured on five strips under various heights of backfill, the stresses for strip D3 being found by interpolation to allow comparison with the fill heights above the other strips. The wall was designed using $K_a = 0.3$ but the value corresponding to the backfill as placed was 0.163. The calculated average stresses in each strip for K_a values of 0.3 and 0.163 are also shown in Table I.

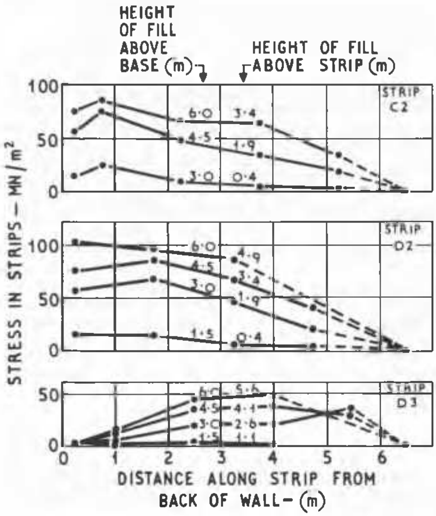

Fig. 4. Variation in tensile stress along strips C2, D2, D3.

According to conventional design theory the same average stress should be developed in all strips subjected to the same height of backfill. A comparison of the average measured stresses in strips C2 and D2 shows the stresses developed in these strips to be in reasonable agreement. Likewise the average stresses and distribution of stresses in strips F4 and G4 agree reasonably well but the stresses in these strips are about 20% less than those in C2 and D2. Strips C2 and D2 were attached to the top of their panels while strips F4 and G4 were fixed to the bottom of their panels and it would appear that the stresses mobilised were influenced by the horizontal movements to which the strips were subjected. In Fig. 6 the increase of average stress is shown for the various strips under increasing heights of fill.

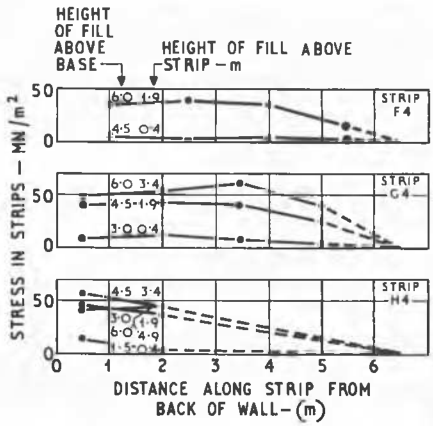

Fig. 5. Variation in tensile stress along strips F4, G4, H4.

Strip D3 was the bottom strip in the bottom panel, a panel which underwent very little horizontal movement. Fig. 6 indicates that the stress built up to values which reflected the relative horizontal movements of the strips.

COMPARISON OF MEASURED AND PREDICTED STRESSES

The measured stresses in the strips can be compared with the average stresses predicted by conventional design theory using equation (1). Only general comparisons can be made because of the differences between the stresses measured in different strips under the same height of fill. If the results from strip D3 are omitted since this strip is not considered to be representative, the mean of the average measured stress on each strip was about 60% of the mean of the maximum measured stress on the strips. The mean of the average measured stresses on each strip was 72% of that predicted using the design value of K_a = 0.3 and was about 30% greater than that

Strip	Level above found m	Height of fill above strip m															
		0.4				1.9				3.4				4.9			
		(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv
D3	0.38	1.0	0.5			26.8	9.7			31.3	20.2			43.0	27.0	114.9	62.
D2	1.13	16.2	8.3			69.5	40.6			87.5	57.3	79.7	43.1	101.2	72.5		
C2	2.63	25.5	8.3	9.4	5.2	75.5	38.6	44.6	24.4	84.0	55.2						
G4	2.63	13.8	6.9			43.5	33.1			60.6	45.4						
F4	4.13	13.8	3.4			42.0	29.6										

(i) Maximum measured stress (MN/m^2)
(ii) Average measured stress (MN/m^2)
(iii) Average calculated stress (MN/m^2) for K = 0.3
(iv) Average calculated stress (MN/m^2) for K = 0.163

Table I. Measured and calculated tensile stresses.

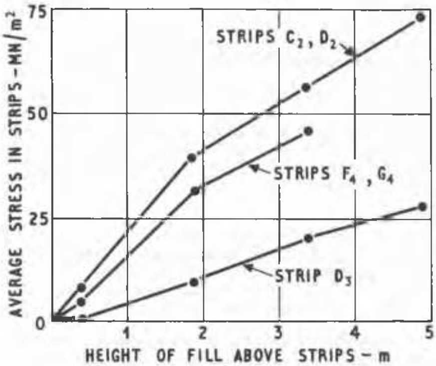

Fig. 6. Increase in average stress with increase in height of fill.

predicted using the K_a value of 0.163 corresponding to the properties of the back fill as actually placed.

Schlosser and Vidal (1969) found that K values were developed in the fill behind the Incarville wall which were substantially greater than the K_a value for the fill. Chang, Forsyth and Beaton (1974) reported for the Los Angeles County wall that the maximum measured stresses on the strips approached a value corresponding to K_o the coefficient of earth pressure at rest. At the Granton wall the K value corresponding to the average measured stresses was 0.22 while that for the average of the maximum measured stresses was 0.41. These can be compared with K_a and K_o values of 0.163 and about 0.36 respectively for the fill as placed, the K_o being quoted in all cases solely as a point of reference.

Finite element analyses of the Granton wall and of a number of model walls are at present in progress and will be the subject of a future paper. However, at this stage the statement by Banerjee (1975) that the maximum value of the non-dimensional tension coefficient in any strip is 0.35 can be investigated for the Granton wall in terms of the measured maximum stresses. The tension coefficient for 12 of the strips ranged from 0.26 to 0.82 with an average value of 0.40.

EFFECTS OF COMPACTION OF THE BACKFILL

The methods of analysing reinforced earth walls, as with most other earth retaining structures, do not take account of the possible effect of the construction operations, particularly the effects of compaction. Schlosser and Vidal (1969) comment on the influences of soil compaction on the behaviour of the strips at the Incarville wall. Visual observation of the Granton wall during compaction indicated that stresses could be transmitted to the wall face and the stresses developed in the strips, which were higher than anticipated, indicated the influence of the compacting equipment. The build up of stresses on strip D2 were measured during the placing and compaction of fill and the results are shown in Fig.7. The stresses were measured when the fill was initially spread to a depth of 0.4 m, were remeasured after bulldozer traffic had passed over the layer and finally after rolling. The average stress on the strip after rolling corresponded to a K value of 0.29 which is higher than the K_a value of 0.163. As additional material was placed on this strip the effects of compaction naturally became less and when the full height of the fill had been placed the average measured stress corresponded to a K value of 0.19.

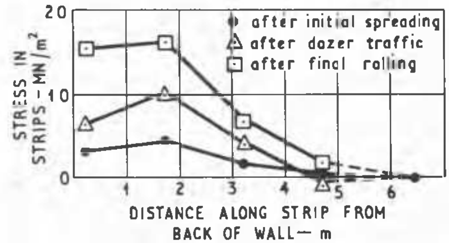

Fig. 7. Effect of compaction operations on strip D2.

PRESSURES TRANSMITTED TO THE FACING PANELS.

Price (1975) points out that in the concept of reinforced earth the facing elements are primarily a practical requirement rather than an essential part of the working principles of reinforced earth. It is hypothesised that the stresses in the soil which is not in contact with the strips are transmitted to the strips by arch action and that consequently relatively small forces are transmitted to the skin. This is probably more true with the metal facing elements than with concrete facing panels. The effect of compaction equipment could also be greater for concrete panels particularly if the equipment is trafficked too close to the wall.

The drainage layer behind the wall consisted of porous blocks and gauges were mounted on each of the four strips attached to each of the panels A to D at a distance of 0.25 m back from the wall and therefore almost immediately behind the porous blocks and practically at the extremity of the fill. On the presumption that the stresses in these gauges represent the forces that the panels have to sustain, the pressure exerted on each panel can be calculated. The distribution of the pressure on the panels for different heights of fill above the base of the wall are shown on Fig. 8. Pressures greater than those corresponding to active earth pressures for the fill material were developed at or close to the wall. These pressures were probably due to the compacting equipment being used too close to the wall.

FRICTION MOBILISED IN REINFORCING STRIPS.

The factor of safety against slip of the strips can be calculated using the measured coefficient of friction between fill and strips of 0.32 and assuming a vertical stress on each strip corresponding to the height of fill above it. On the basis of the average forces measured in the strips the factors of safety against slip were greater than two. However if the calculation is done in terms of the maximum stresses measured in the strips there is an indication that localised slip could occur when the height of fill above a strip is less than about 1.25 m. This is probably due to the relatively high stresses set up at low heights by lateral pressure on the panels due to the compaction process.

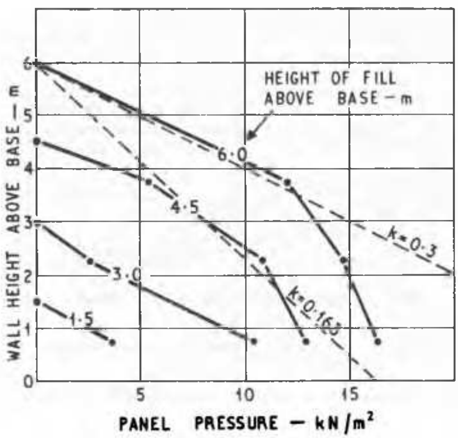

Fig. 8. Distribution of pressure on wall face.

CONCLUSIONS.

An important conclusion which can be drawn from the measurements on the reinforced earth wall at Granton is that the construction techniques used can have a pronounced effect on the stresses transmitted to the concrete facing panels and on the stresses developed in the reinforcing strips. The facing panels must be effectively supported during the construction to restrain undue horizontal and vertical movements and the compaction equipment must not be operated close to the face of the wall.

The pattern of the stress distribution along the strips showed an increase in stress from immediately behind the face of the wall to a maximum at a point within the front half of the strip and then decreasing towards zero at the end of the strip. The maximum stress in a strip was on average about 60% greater than the average stress. The stresses developed in strips appeared to be influenced by whether the strips were attached to the top or bottom of a panel.

The average stress developed in the strips was about 20% greater than would be expected from the properties of the backfill as placed but were less than those predicted by the design parameters used.

Appreciable pressures appear to have been transmitted to the facing panels from the action of the compaction equipment.

There was an adequate overall factor of safety against slipping of the strips but there was an indication of localised slip at low fill heights probably due to the compaction operations.

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