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REDUCTION OF LATERAL FORCES IN RETAINING WALLS BY CONTROLLED YIELDING

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EXECUTIVE SUMMARY

Strain behaviour of the backfill is an important consideration with most types of retaining structure. In the case of reinforced soil, the interaction between the soil and reinforcement requires some measure of relative strain to allow the reinforcement to operate effectively. There is an optimum value of relative strain that produces the maximum available shearing and tensile resistance and methods of inducing controlled strain could significantly improve the strength and stability of retaining structures without greatly increasing cost. Scope for strains to occur in retaining structures can be of importance for other reasons such as permitting cohesive backfill some latitude for expansion through "wetting-up" or by thermal expansion associated with portal frames and certain types of "jointless" structures.

The Report reviews work carried out into the development of a wall yielding technique in which controlled movements are imposed on the internal boundaries of retaining structures to reduce the lateral forces acting on these structure. The experimental studies were carried out in association with the University of Strathclyde and involved investigations of the behaviour of both model and large scale reinforced soil and conventional retaining walls.

Non-dimensional distributions of lateral stress and boundary movements for model walls with various stiffnesses showed that the smallest pressures in unreinforced fill were associated with the largest boundary movements. These produced conventional "minimum" horizontal pressure distributions that conformed with the "active" condition as could be expected from classical soil mechanics. The corresponding lateral stress distributions and boundary movements for walls of various stiffness with reinforced fill demonstrated that controlled yielding could produce horizontal pressure distributions significantly below the active condition. This behaviour can be attributed to greater mobilised shear resistance of the soil and tensile resistance of the reinforcement as the magnitude of the soil strains increase with progressive yielding of the lateral boundary.

The large scale study was carried out to check the validity of the results of the small models and involved comparisons of the lateral pressures induced in rigid and yielding walls with reinforced and unreinforced fill. Both steel and polymeric reinforcements were used in the study. Representative horizontal pressure data from the different sections showed that the largest pressure distributions were associated with the "rigid" boundary condition and that for this case the reinforcement makes little contribution to alleviating lateral pressures. Much lower pressures were obtained, however, from the wall yielding case with reinforced fill; at some elevations less than 50% of the active value was observed. These reductions can be attributed to the induced strains permitting the soil to mobilise higher shear strengths and at the same time invoking a greater contribution of resistance from the reinforcement.

The Report also describes the use of finite element analysis to simulate the effect of yielding in ameliorating the horizontal stresses on walls. The CRISP package was used in a two-dimensional form, with a Mohr-Coulomb constitutive model being adopted for the soil. The analysis was compared with results from the large scale study. These comparisons highlighted a number of problems with the CRISP analysis, in particular its inadequacy in dealing with hysteresis loops, such as those that occur with compaction, and an inability to model very soft layers. However, the finite element analysis was useful in providing further support for the view that the yielding wall technique offers an economic and convenient solution for reducing the lateral forces on retaining structures.

REDUCTION OF LATERAL FORCES IN RETAINING WALLS BY CONTROLLED YIELDING

ABSTRACT

Small scale model studies were undertaken in association with the University of Strathclyde to investigate the relation between strain and mobilised strength in both unreinforced and reinforced soil structures. These studies clearly demonstrated that the controlled development of strain fields in reinforced soil backfill during construction permitted the soil and reinforcement strengths to be fully utilised and produced a significant reduction in post-construction wall movements. As the results had been obtained on small scale laboratory models, it was decided to test their validity by observing the behaviour of large scale walls constructed in the retaining wall facility at the Transport Research Laboratory.

The data obtained from the large scale walls constructed using different methods confirmed the findings of the small scale model wall studies. In particular the data showed that, for both unreinforced and reinforced soil walls, the magnitudes and distributions of lateral earth pressures on the walls are greatly influenced by the amount and mode of lateral boundary yielding during and after construction. It was also shown that filling and compaction processes can "lock-in" significant stresses into the backfill. Thus, to ensure reliable estimates of the lateral earth pressures associated with unreinforced or reinforced backfills, consideration must be given to the anticipated movements of the structure and backfill and to the influence of the construction process. The separate effects of construction and boundary yielding on internal behaviour are not easily quantified, but the application of the yielding wall technique offers a relatively simple and economic means of ensuring greater effectiveness of the soil and reinforcements and for controlling post-construction wall movements.

The Report also describes the use of finite element analysis to simulate the effect of yielding in ameliorating the horizontal stresses on walls. The CRISP package (Britto and Gunn, 1987) was used in a two-dimensional form, with a Mohr-Coulomb constitutive model being adopted for the soil. The analysis was compared with results from the large scale study. These comparisons highlighted a number of problems with the CRISP analysis, in particular the inadequacy of the analysis in dealing with hysteresis loops, such as those that occur with compaction, and an inability to model very soft layers. However, the finite element analysis was useful in providing further support for the view that the yielding wall technique offers an economic and convenient solution for reducing the lateral forces on retaining structures.

1. INTRODUCTION

The strength of soil is determined by a number of factors such as the shape and size of particles, moisture condition and compressibility. However, for a particular type of soil in a given condition, the mobilised soil strength varies with the amount of strain permitted to occur. Thus relatively low strengths occur at both low and high strains and a peak strength is produced between these extremes at a particular value of strain. It is clear, therefore, that the most effective design, in terms of safety and cost, will correspond to the condition where the strains are those required to mobilise the peak shear strength of the backfill.

Strain behaviour is also an important consideration with other aspects and types of retaining structure (Simpson, 1992). In the case of reinforced soil, for example, the interaction between the soil and reinforcement requires some relative strain to allow the reinforcement to operate effectively. As before, there is an optimum value of relative strain that produces the maximum available resistance. The scope for strains to occur in retaining structures can be important for other reasons such as permitting cohesive backfill some latitude for expansion through "wetting-up" or by thermal expansion associated with portal frames and certain types of "jointless" structures.

This Report reviews the development of a wall yielding technique in which the movements of the internal boundaries of retaining structures are controlled to reduce the lateral forces acting on them. The experimental studies were carried out in association with the University of Strathclyde and involved investigations of the behaviour of both model and large scale reinforced soil and conventional retaining walls.

The Report also describes a finite element (FE) simulation of the effect of wall yielding on the large scale structures. Details of the analytical model are given and an examination carried out of the extent to which the analytical model reproduced the performance of the large scale structures. The analytical study was carried out with assistance from Babtie Geotechnical under a sub-contract to TRL.

2. EARTH PRESSURES AND YIELDING WALL CONCEPT

It is important to recognise the influence of different modes of wall movement on earth pressure distributions for effective use of the yielding wall principle. The state of stress in the backfill to a retaining structure is dependent on the shearing resistance mobilised, the amount and pattern of deformations at the lateral boundary, and the construction process employed (Fig 1). For a fixed, rigid-faced retaining wall in which no lateral soil strains are permitted the backfill may be considered to be in an "at rest" (K_o) condition (Fig 1a). However, because of the compaction process, the lateral boundary stresses at any level may attain larger values than those consistent with the overlying weight of fill. In the case of a reinforced soil structure, particularly where extensible reinforcements are employed, the reinforcements are unlikely to be effective with the soil in this stress state, as the only tensile resistance in the reinforcements is generated by the compaction process, which tends to have a fairly localised influence on reinforcement tension.

When the magnitude and pattern of outward movements of the lateral boundary are such that the peak shearing resistance of an unreinforced backfill is mobilised over the full height of the structure, then a minimum value of lateral boundary stress is established (Fig 1b). This is known as the "active" (K_a) condition, but is rarely fully attained in practice. Where the pattern of deformation of the lateral boundary is such that peak shearing resistance is not fully mobilised at all locations, then the total lateral force developed is generally similar to that for the condition of rotation about the base, although the distribution of lateral stress over the wall height can be radically different (Figs 1c and 1d).

In reinforced backfill, outward lateral boundary movements induce soil-reinforcement interaction by interface friction or adhesion which in turn develops tensile resistance in the reinforcements. This can result in lateral boundary stresses below those corresponding to "active" earth pressures for the unreinforced soil, even though the soil in the reinforced structure may not have mobilised its peak shearing resistance. Conceptually, with a large number of reinforcement layers having sufficient stiffness and strength, it should be possible to reduce the lateral boundary stresses to almost zero. Therefore, to attain the minimum lateral boundary stresses in unreinforced backfills or the optimum balance of forces in the soil and reinforcements of reinforced backfills, controlled lateral expansion should be allowed to take place, thus producing the most economic form of soil retaining structure without compromising safety.

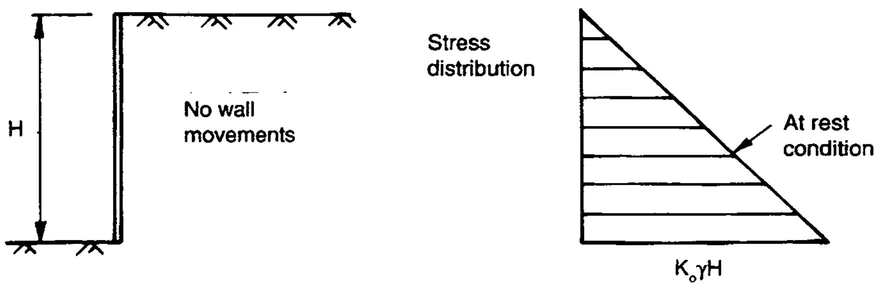
3. MODEL RETAINING WALL STUDIES

The principle of lateral boundary yielding has been investigated at model scale employing a purpose built retaining wall facility at the University of Strathclyde. The facility consists of 1.0m high x 0.45m wide wall mounted in a rigid, glass sided tank 1.17m high x 0.45m wide x 1.92m long (Ahmad, 1989; Lee, 1985; McGown et al, 1987). The wall is constructed from twenty individual facing units, attached to spring loaded shafts. The stiffness of the springs may be varied over a wide range and can thus be used to control the amount of yielding. The design of the facility is such that with the weakest springs installed in the system, sufficient deformation of the lateral boundary occurs to mobilise the peak shear strength of the soil. The deformations were monitored directly on the rear of the spring loaded shafts.

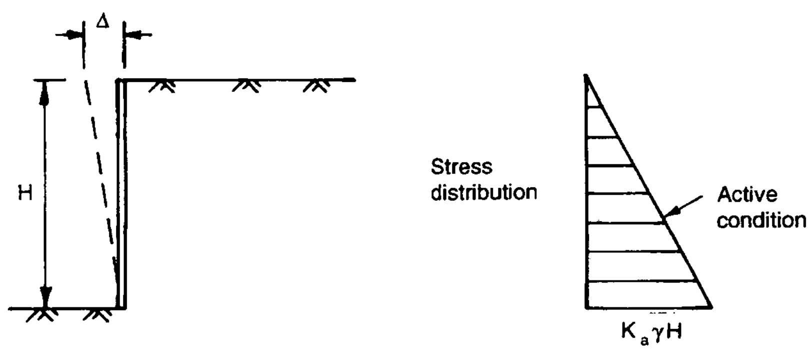
A series of tests was carried out in this apparatus using a uniformly graded Leighton Buzzard sand as backfill. The sand had a uniformity coefficient of 1.22 and was placed at a dry density of 1.73Mg/m^3 using a sand raining technique. The angle of friction corresponding to this density was 49.6° as measured in a shear box apparatus. In some tests the sand was reinforced by a layer of geogrid.

Fig 2 shows the stress distributions on the lateral boundary for five different boundary conditions ranging from a fully constrained wall to the case of very soft springs. Note that in each model, the same spring stiffness was used over the full height of wall. The results are presented in non-dimensional form by expressing the recorded lateral stress (σ_h) as a proportion of the vertical stress (γH), where H is the overall height of the wall and γ is the unit weight of the backfill. The non-dimensional stresses are plotted versus the ratio (z/H), where z is the height above the base of the wall to the point being considered. Also shown on the figure are the calculated distributions of lateral boundary stress, based on the coefficients of both "at-rest" (K_o) and "active" (K_a) earth pressure for a frictionless wall. It is apparent from this figure that in all cases, the stresses at the top of the wall are close to the "at rest" (K_o) condition, and close to the "active" (K_a) condition in the lower part of the wall. The very low stresses at or near the base of the wall are a consequence of shear stresses developed on the rough rigid foundation.

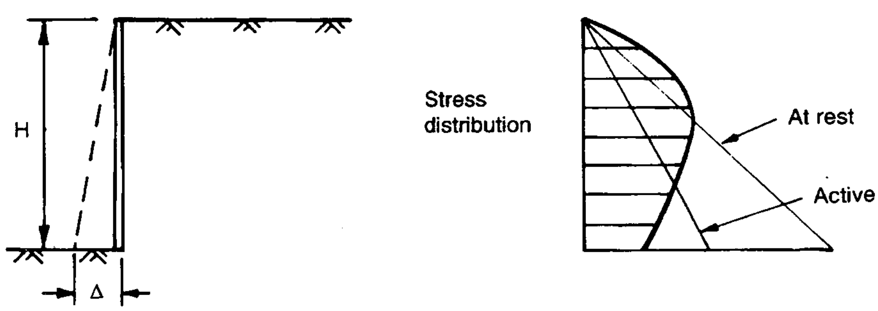
For the purposes of establishing wall movement, each test involved setting all of the wall facing units to correspond with a vertical datum line passing through the initial position of the lowermost unit. This procedure can be considered as providing a direct measurement of soil deformation behind each facing unit. For the stress distributions shown in Fig 2, the corresponding lateral boundary movements measured in this way are shown in Fig 3, in non-dimensional form, Δ/H. Note that Δ is the lateral movement at height z above the base of the wall of height H. An



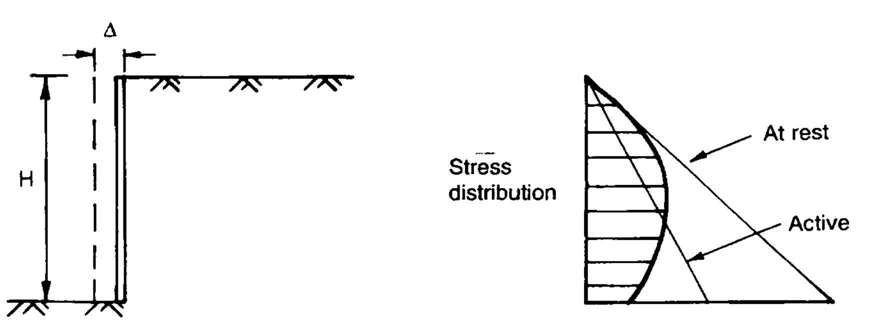
(a) Fixed rigid wall



(b) Rigid wall free to rotate about base



(c) Rigid wall free to rotate about top



(d) Rigid wall free to translate

Fig.1 Lateral pressure distributions associated with different wall movements

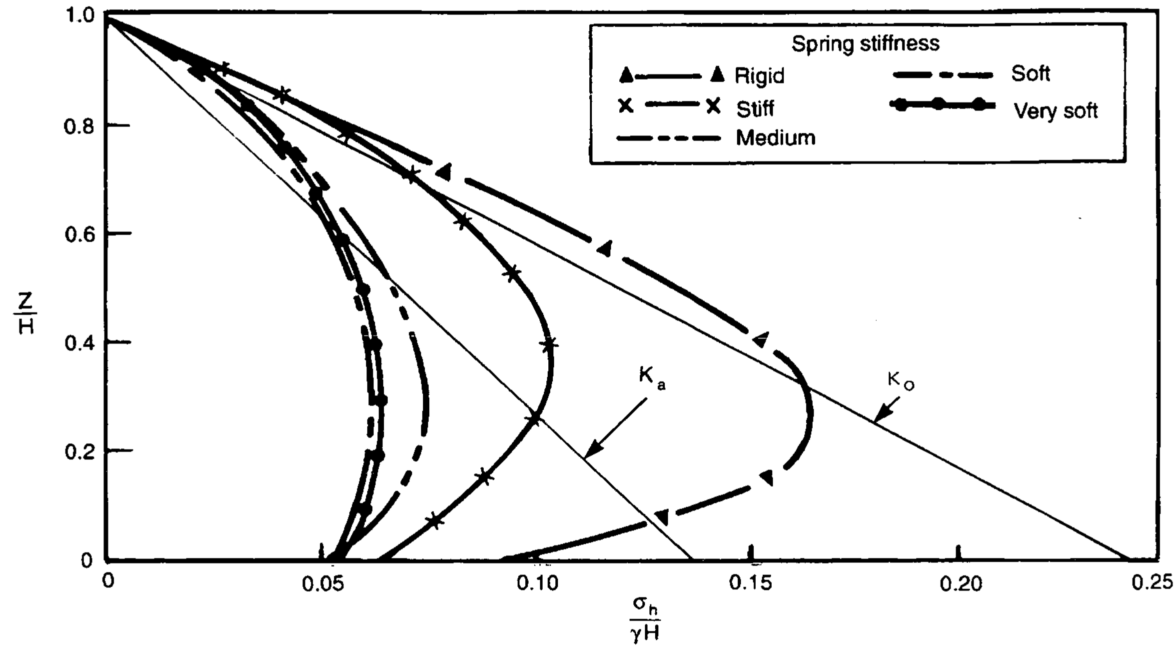


Fig.2 Lateral stress distributions with sand backfill

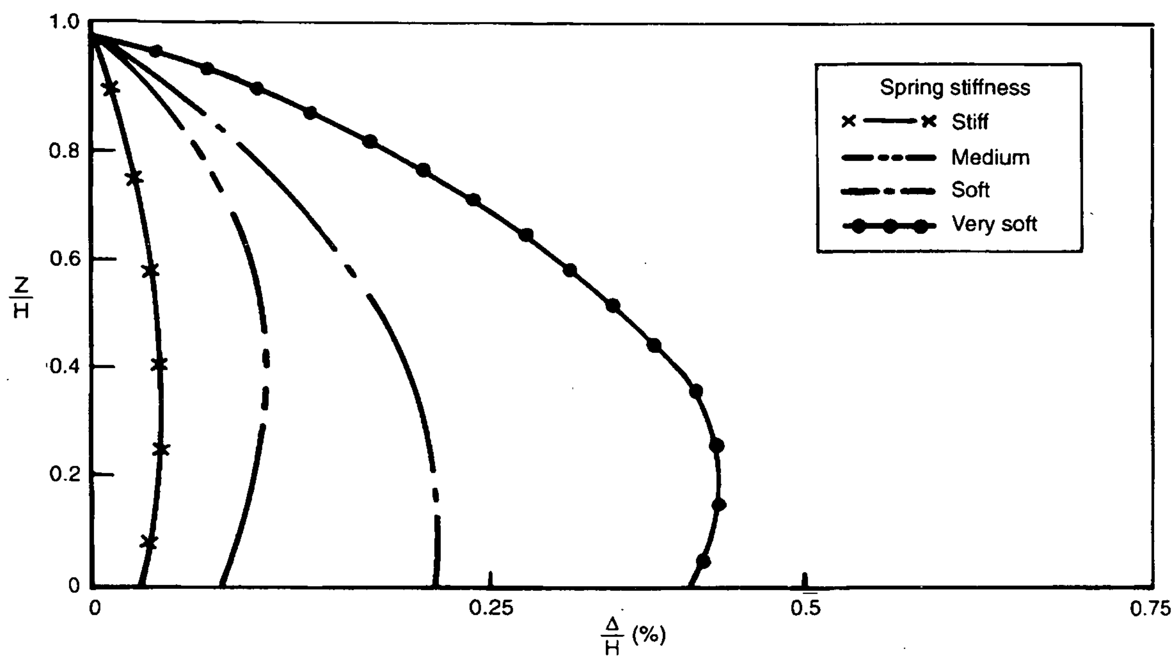


Fig.3 Distributions of movements with sand backfill for the facing units set to a vertical datum

alternative approach to this mode of establishing the movements of the wall would involve setting each facing unit sequentially as construction proceeds to align with the unit immediately below, after the fill has reached the top of this lower unit. The resulting pattern of movements for this approach, again corresponding to the stress distribution shown in Fig 2, is presented in Fig 4. As they represent the accumulated movements of the wall units, they are not indicative of the actual soil movements at any particular level, other than at the base. However, this method of aligning the facing units and measuring movements is typical of that used in practice.

Consideration of the movement profiles shown in Figs 3 and 4 provides contrasting impressions of wall behaviour. In the former case it is apparent that the movements closely represent rotation about the top of the wall while in the latter, the movement appears to involve rotation about the base. The stress distribution data shown in Fig 2 support the contention that soil behaviour more closely reflects

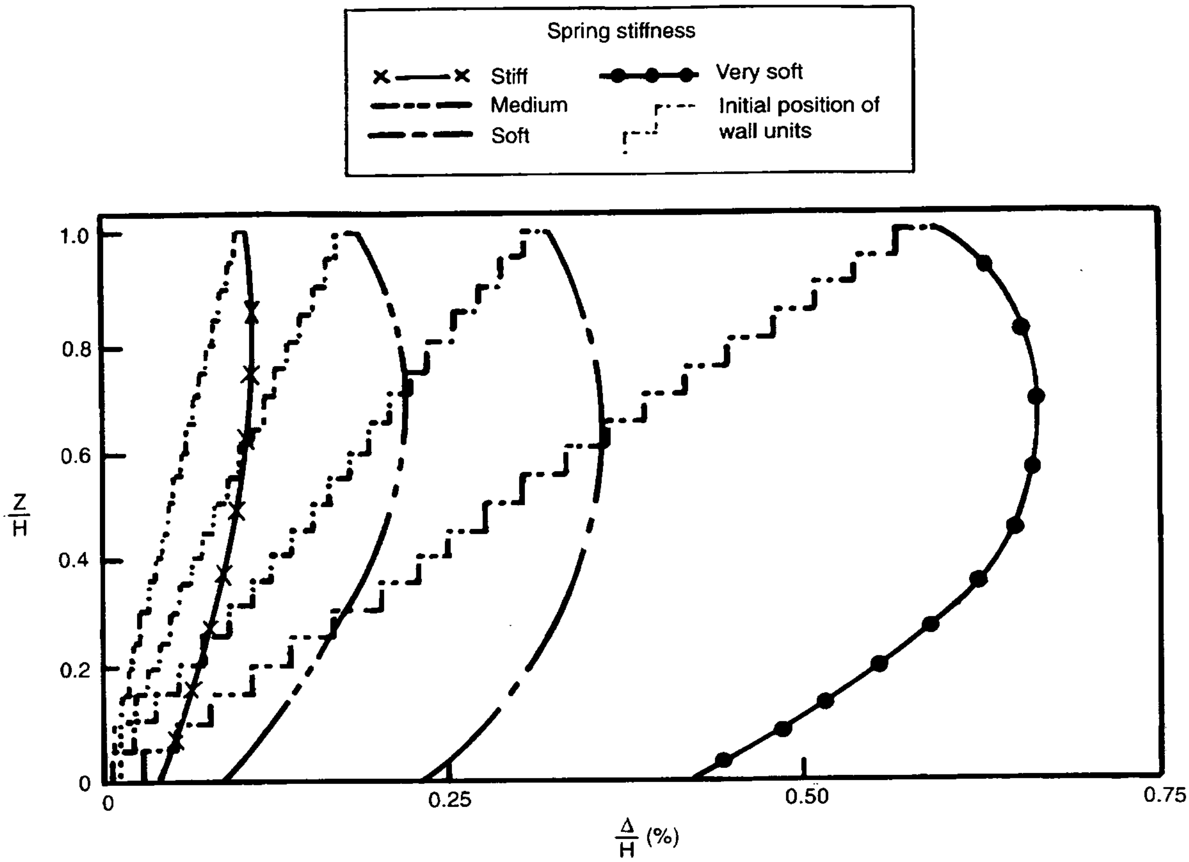


Fig.4 Distributions of accumulated movements for walls supporting sand backfill

rotational movement about the top of the wall. The conventional approach of presenting wall movement data in accumulated form is thus misleading with regard to the mechanisms controlling the development of soil stresses and strains.

Non-dimensional distributions of lateral stress and boundary movements for walls with various spring stiffnesses incorporating a single layer of reinforcement at mid-height of the model wall are presented in Figs 5 and 6 respectively.

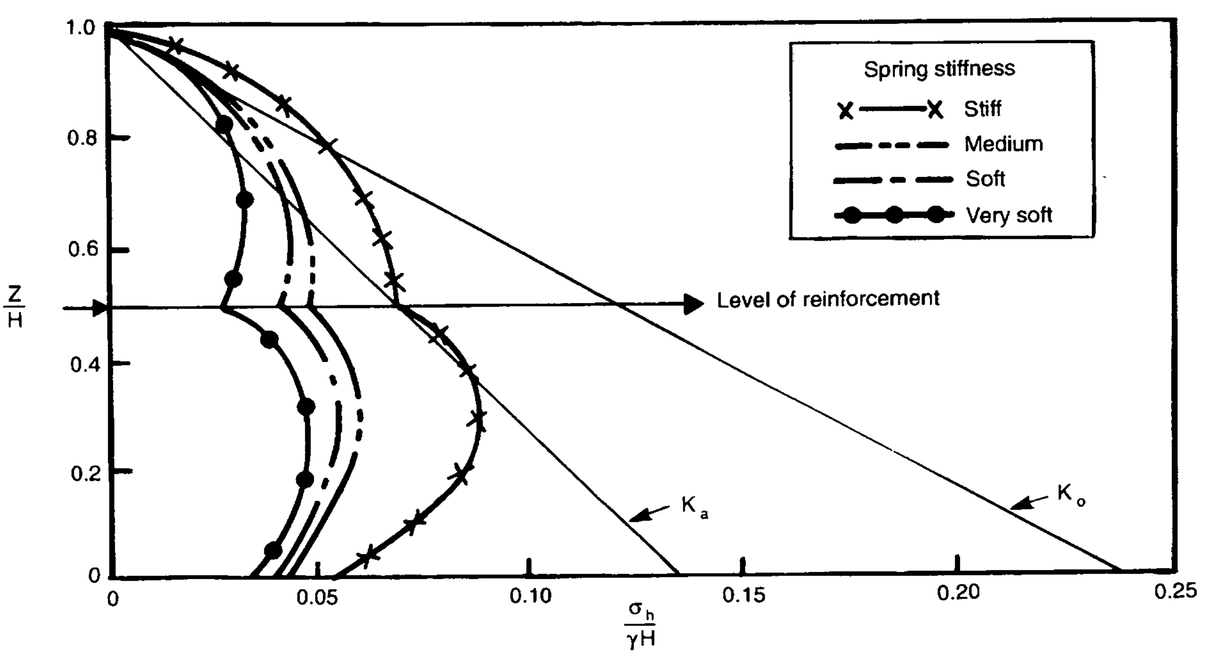


Fig.5 Lateral stress distribution with sand backfill and one layer of geogrid reinforcement

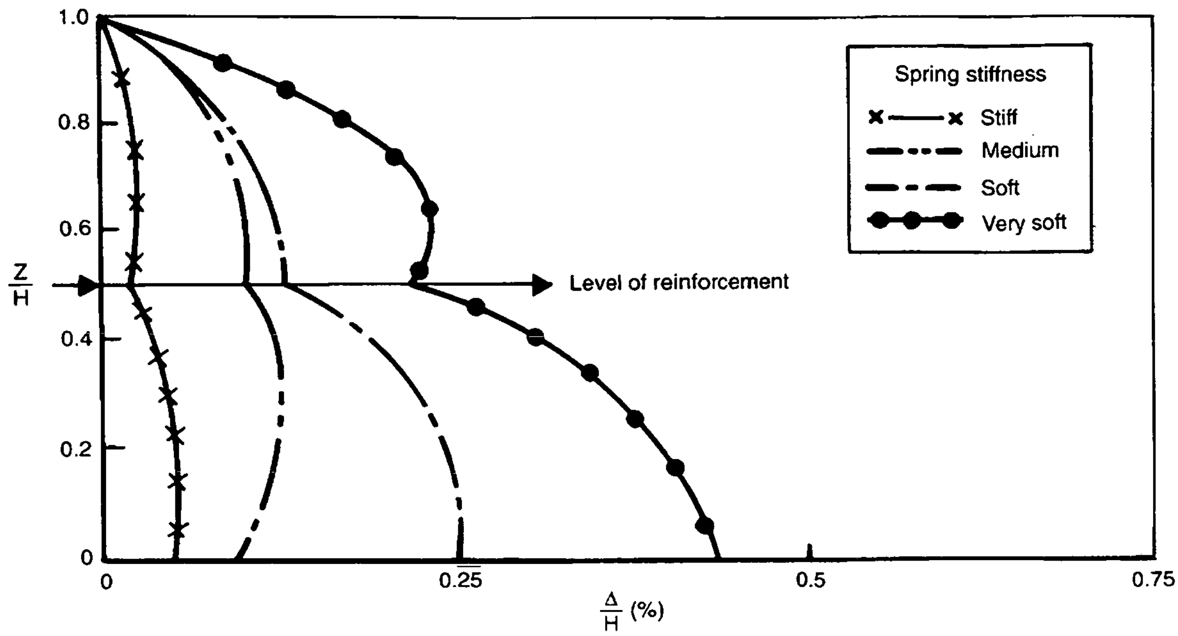


Fig.6 Distribution of movements with sand backfill and one layer of geogrid reinforcement for the facing units set to a vertical datum

The distributions of boundary movement in the latter figure were determined on the basis of the procedure used for Fig 3. As shown in Fig 5, the largest stresses were associated with the wall supported by the springs of greatest stiffnesses and the smallest stresses with the wall supported by springs of least stiffness. The corresponding lateral stress distributions and boundary movements for walls of various stiffness and with ten equally spaced layers of reinforcement are shown in Fig 7. Also included in the figure for comparison purposes are the results obtained for unreinforced fill and for fill with one layer of reinforcement. It can be seen from Fig 7 that with increased boundary displacement, the lateral stresses reduce for all backfill conditions. It is also apparent that the lateral stresses associated with reinforced backfills can be reduced significantly below the active condition for the unreinforced soil with increasing boundary displacement. This behaviour can be attributed to greater mobilised shear resistance of the soil and tensile resistance of the reinforcement as the magnitude of the soil strains increase with progressive yielding of the lateral boundary.

4. LARGE SCALE EXPERIMENTAL STUDY

The large scale experiment involved the construction of a series of 2m high retaining walls, some of which had soil reinforcement, within various bays of a facility at the Transport Research Laboratory (Loke, 1991; McGown et al, 1992). These walls were constructed to investigate the lateral forces on the facing of each wall to allow comparisons between unreinforced fill, and fill reinforced with steel or geogrid for different boundary conditions. The plan view of the facility showing the arrangement of the bays is given in Fig 8. Details of the components employed in each bay are given in Table 1. Note that the section of steel wall referred to in Fig 8 could be rotated about the base to allow external control of any boundary yielding for comparison with a compressible boundary layer in the rigid sections of the retaining wall facility.

During construction, the steel wall was supported by a jacking system which was intended to prevent movements. However, as discussed later, some "slack" in the supports and deflection of the metal plates forming the structure occurred allowing minor yielding of the fill. Controlled yielding for the rigid concrete section of the facility was achieved during construction by means of a layer of compressible material incorporated between the backfill and the wall. Two further bays referred to as G and H in Table 1 comprised full height panel walls that were propped during construction. Bay G also had a compressible layer between the backfill and the wall. The reinforcements were not attached to the facing units during construction but were allowed to move freely as the backfill was compacted. After completion of the full height of backfill, the reinforcements in Bays G and H were "locked on" to the facing units and the props removed.

The backfill employed was a uniformly graded sand having a uniformity coefficient of about 3. Subsequent measurements on the compacted fill showed that average moisture content and bulk unit weight were 9.9% and 18.03kN/m^3 respectively. The angle of friction of the soil at the compacted density was measured as 47° in triaxial tests. The

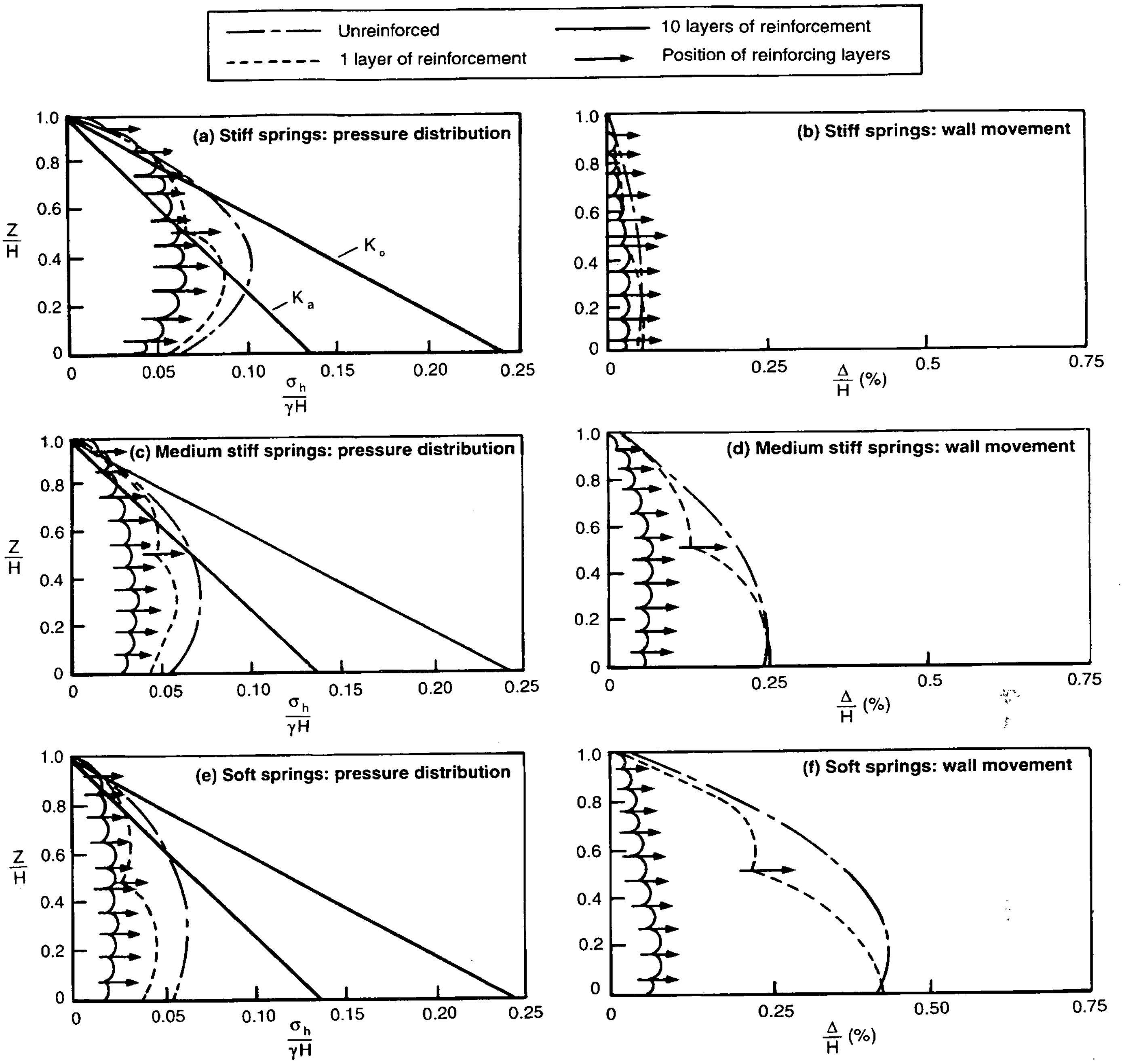


Fig.7 Lateral pressures and movements of the yielding wall

TABLE 1

Details of components used in the various bays

Bay	Facility	Compressible boundary	Reinforcement	Facing connection
A	Rotational steel section	No	None	No
B	Fixed	Yes	None	No
C	Rotational steel section	No	Steel	No
D	Fixed	Yes	Steel	No
E	Rotational steel section	No	Geogrid	No
F	Fixed	Yes	Geogrid	No
G	Propped panel	Yes	Geogrid	At end of construction
H	Propped panel	No	Geogrid	At end of construction

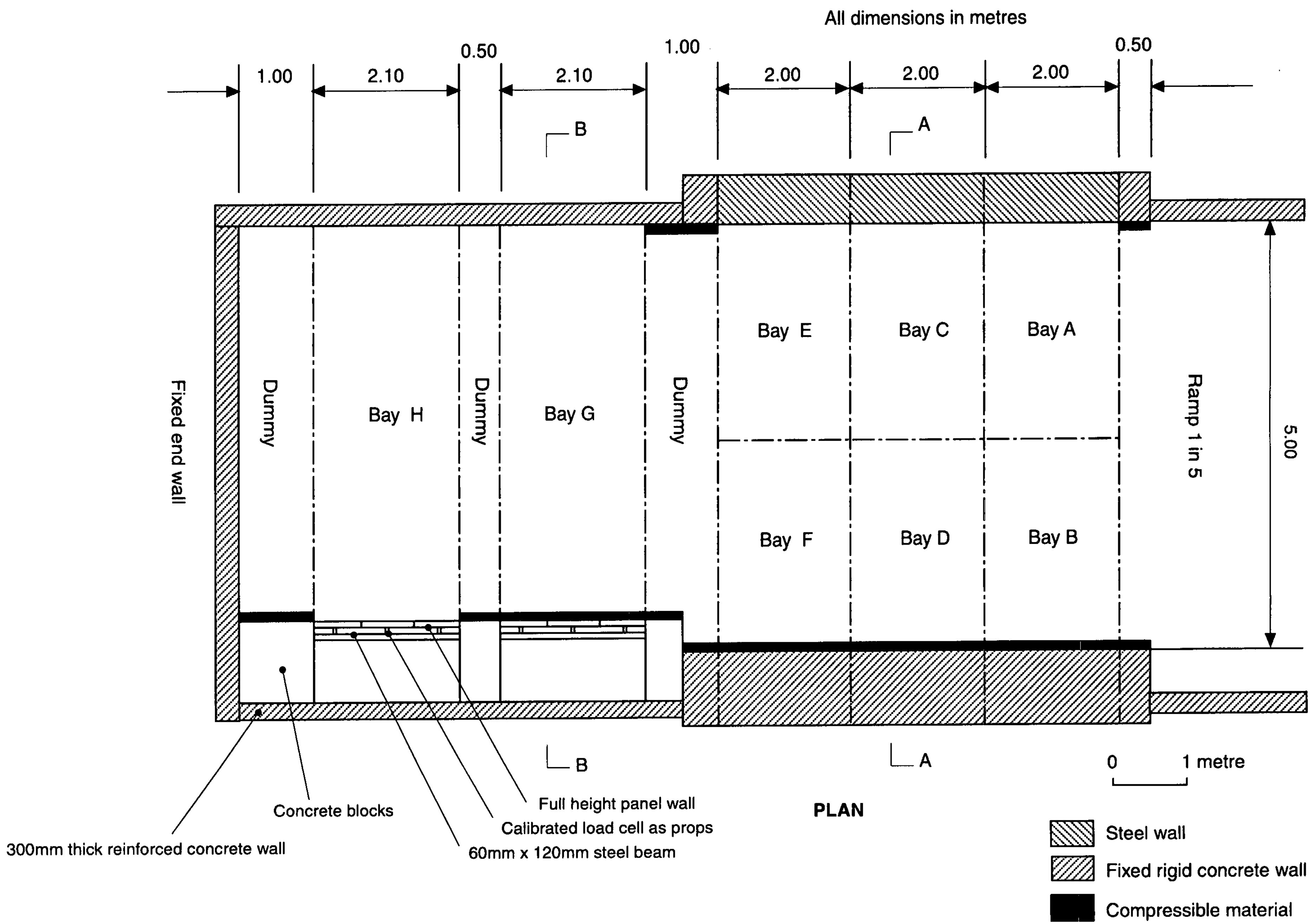


Fig. 8 Plan view of retaining wall facility showing bay arrangement (after Loke, 1991)

compressible material used adjacent to selected sections of wall was a 150mm thick layer of polyurethane foam. The compressibility of this material was determined as 0.0135kN/m^2/mm for the horizontal pressure range applied in the studies.

Three layers of reinforcements at 0.7m spacings were installed during construction in the appropriate bays as indicated in Table 1. The same vertical spacings were employed for both the steel and geogrid reinforcement and corresponded to elevations above the base of 0.30, 1.0 and 1.7m. A horizontal spacing of 0.3m was employed for the steel strips. The properties of both types of reinforcement are given in Table 2.

Strains in the reinforcements were monitored by electrical resistance strain gauges attached to both the steel strips and geogrids and additionally by strain inductance coils (Bison Instruments Inc, undated) attached to the geogrids. Horizontal earth pressures were measured at selected locations using pneumatic pressure cells mounted flush with the surface of the wall. These cells were also employed to measure the vertical pressure at the base of the structure. Other observations which were made included the use of dial gauges to measure wall movements and strain coils for monitoring the deformation of the compressible material.

4.1 RESULTS

Comprehensive data were obtained from the large scale study but only the main results pertaining to the effect of wall yielding are considered in this Report. The results from each of the three sections of the facility are considered separately and then compared in Section 4.2.

4.1.1 Rotational steel section of wall

The horizontal pressure distributions acting on the section of steel wall (Bays A, C and E) during construction are shown Fig 9. As can be seen from the figure, large horizontal pressures were observed by the end of construction which were attributed to the influence of compaction. Although the data show some scatter, this may be a measure of the variability of compactive effort used on the backfill at different levels. At the end of construction, an outward rotation was induced about the base of the steel wall in Bays A, C and E which corresponded to 1.5mm of movement at the top. Observations on this section of wall indicated that the horizontal pressures generally corresponded to the Coulomb active condition assuming a wall friction angle (δ) of 35° (Fig 10). This figure shows the data for Bay C but reductions in horizontal pressures were also observed for the unreinforced and reinforced backfills in Bays A and E respectively. The horizontal pressures observed in the metal and polymer reinforced backfills were similar at all stages.

The tension distributions in the steel reinforcement of Bay C are shown in Fig 11. Prior to wall rotation, the strain gauge observations on the steel reinforcements showed tensile loads of between 0.5 and 2kN/m. These values increased to between 2 and 4kN/m respectively following rotation, indicating that the reinforcements were carrying a higher proportion of the lateral load while at the same time the horizontal force on the wall reduced. The strain observations on the geogrid reinforcement ranged from about 0.18% at the bottom level to about 0.05% at the top. On rotation of the wall, these strains increased to about 0.2% at the base, whilst a much larger increase to about 0.1% occurred at the top. These values corresponded to loads of about 2.5kN/m and 1.2kN/m in the bottom and top layers respectively.

In general, the results of the study indicated that the horizontal pressures, imposed by the unreinforced and reinforced backfills following rotation of the wall, were close to the Coulomb active condition when account was taken of wall friction. It was also apparent that wall movements were insufficient to fully mobilise the tensile strength of the reinforcements, particularly in the case of the geogrid.

TABLE 2

Properties of reinforcements

Type of reinforcement	Property	Value
Reinforced Earth Company high adherence galvanised steel strips	Length	1.85m
	Width	40mm
	Thickness	5mm
	Minimum tensile strength	346.5N/mm^2
	Elastic modulus	185kN/mm^2
	Interface friction coefficient	0.85
Tensar SR80 geogrid	Length	1.60m
	Width	Full width of bay
	Characteristic tensile strength (120 years at 20°C)	30.5kN/m
	Interface friction coefficient	1.0

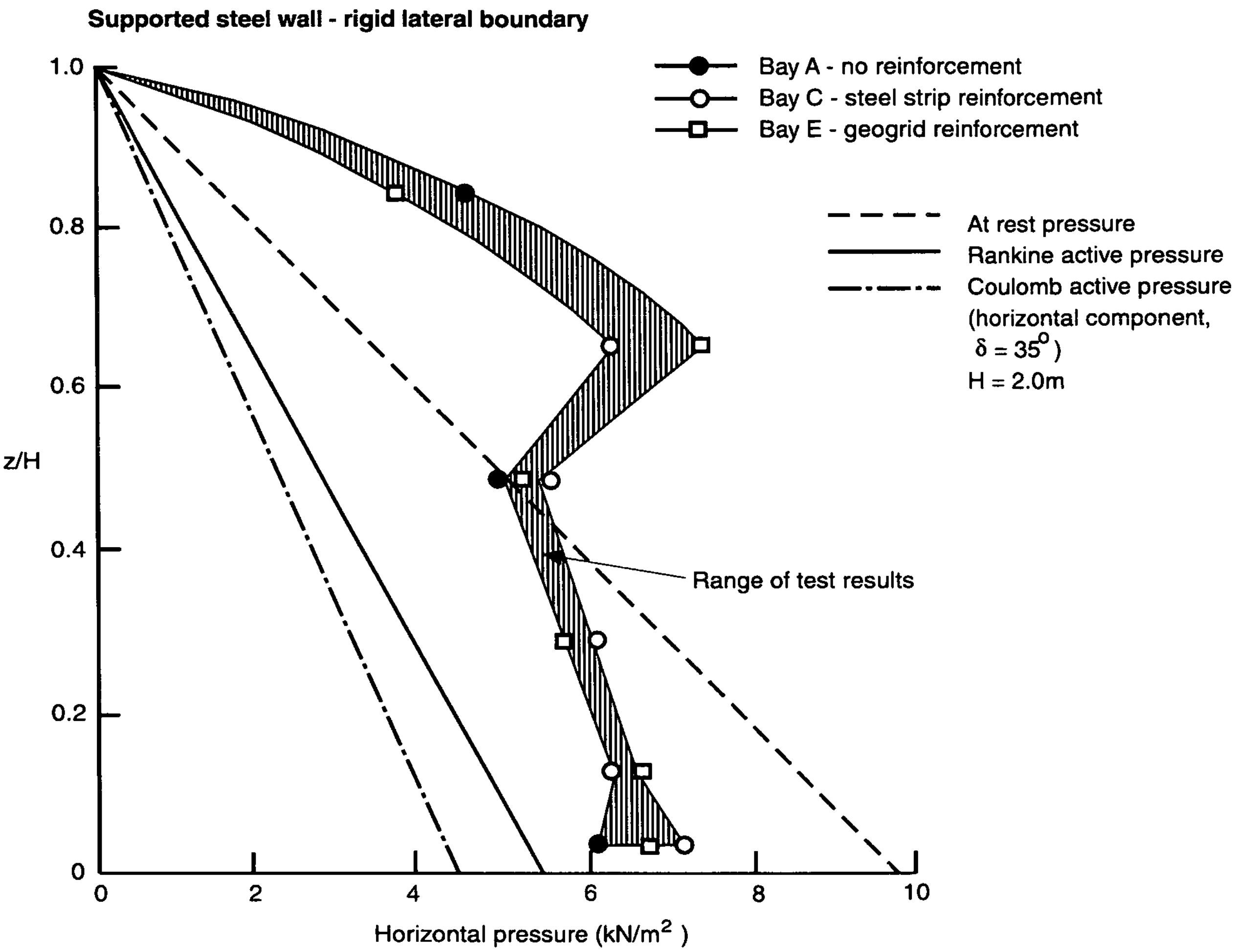


Fig. 9 Horizontal earth pressure distributions of Bays A, C and E at the end of construction (after Loke, 1991)

4.1.2 Rigid concrete wall with compressible boundary

The presence of the layer of compressible material adjacent to the wall permitted movements of the backfill to develop progressively during the filling and compaction operations. The deformation profile of the compressible layer at the end of construction is shown in Fig 12. The strains associated with this deformation significantly reduced the horizontal pressures against the wall in Bays B, D and F. Although the horizontal pressures observed for the unreinforced backfill (Bay B) were greater than those obtained from the reinforced fill, they were much less than the values produced during construction at the same elevation in the metal wall (Fig 9). The reduction in lateral force in the reinforced fill below the active condition, and at some elevations to a value about 50% of that in the unreinforced fill, is clearly attributable to the resistance mobilised by the reinforcements. As previously observed on the section of metal wall, there were no significant differences in horizontal pressure between Bays D and F with steel and geogrid reinforcement. The fact that the horizontal pressures acting on the unreinforced wall are below the Rankine active condition near the base is attributable to wall friction in association with arching due to base friction. This effect may also be present in the observations of the reinforced backfill although the compressible layer is likely to change the friction characteristics at the interface and the behaviour is difficult to quantify.

The tension forces generated in the steel reinforcements and the strains measured in the geogrid reinforcements are shown in Figs 13 and 14 respectively. Although the horizontal pressures were generally less than observed in the metal wall after the rotational movements had been applied, the range of the tensions developed in the steel reinforcement were similar at between 1 and 4.5kN/m: the strains in the geogrid were in the range 0.1 and 0.3%. These results are to be expected as any reduction in horizontal force acting on the wall would be compensated by greater forces being mobilised in the reinforcement.

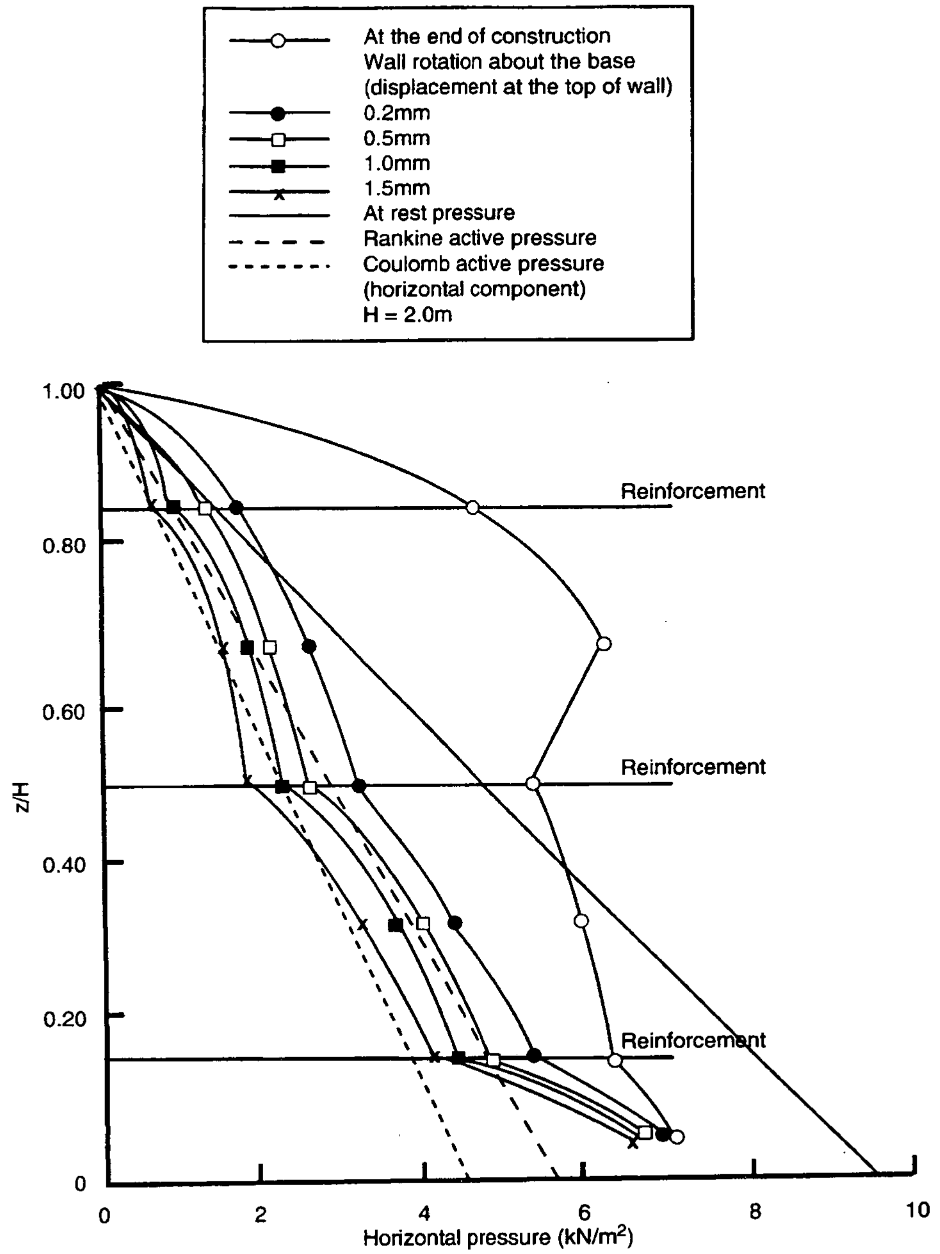


Fig. 10 Effect of rotation about the base of the wall on the horizontal earth pressure in Bay C (steel strip reinforcement) (after Loke, 1991)

4.1.3 Propped panel wall with both rigid and compressible boundaries

During construction of the wall, the props were maintained in place but the compressible layer adjacent to Bay G allowed the backfill to deform progressively, and the horizontal pressures measured (Fig 15a) were small and similar to those induced in Bays D and F (Fig 12). In contrast, relatively large horizontal pressures were developed against the panel wall in Bay H which did not have a compressible layer (Fig 15a). These pressures were comparable to those observed acting on the steel section of wall (Fig 9). After attachment of the reinforcements to the wall, the props were removed and although virtually no change occurred to the lateral pressures in Bay G, a significant reduction occurred in Bay H. However, the pressures in the upper part of this latter panel still exceeded the K_0 value (Fig 15b). At lower levels the horizontal pressures were similar in magnitude, or below, those estimated from the Coulomb analysis. It was noted that the post-construction pressures in Bay H were the highest recorded in the study and could be attributable to a lower friction coefficient between the fill and panel wall.

The strains observed in the geogrid reinforcements at the end of construction in Bay H (Fig 16) were comparable to those measured in Bay E confirming that these were induced by the filling and compaction pressures. After "locking on" the reinforcements and removal of the props, the changes in reinforcement strains in Bay G during the post-

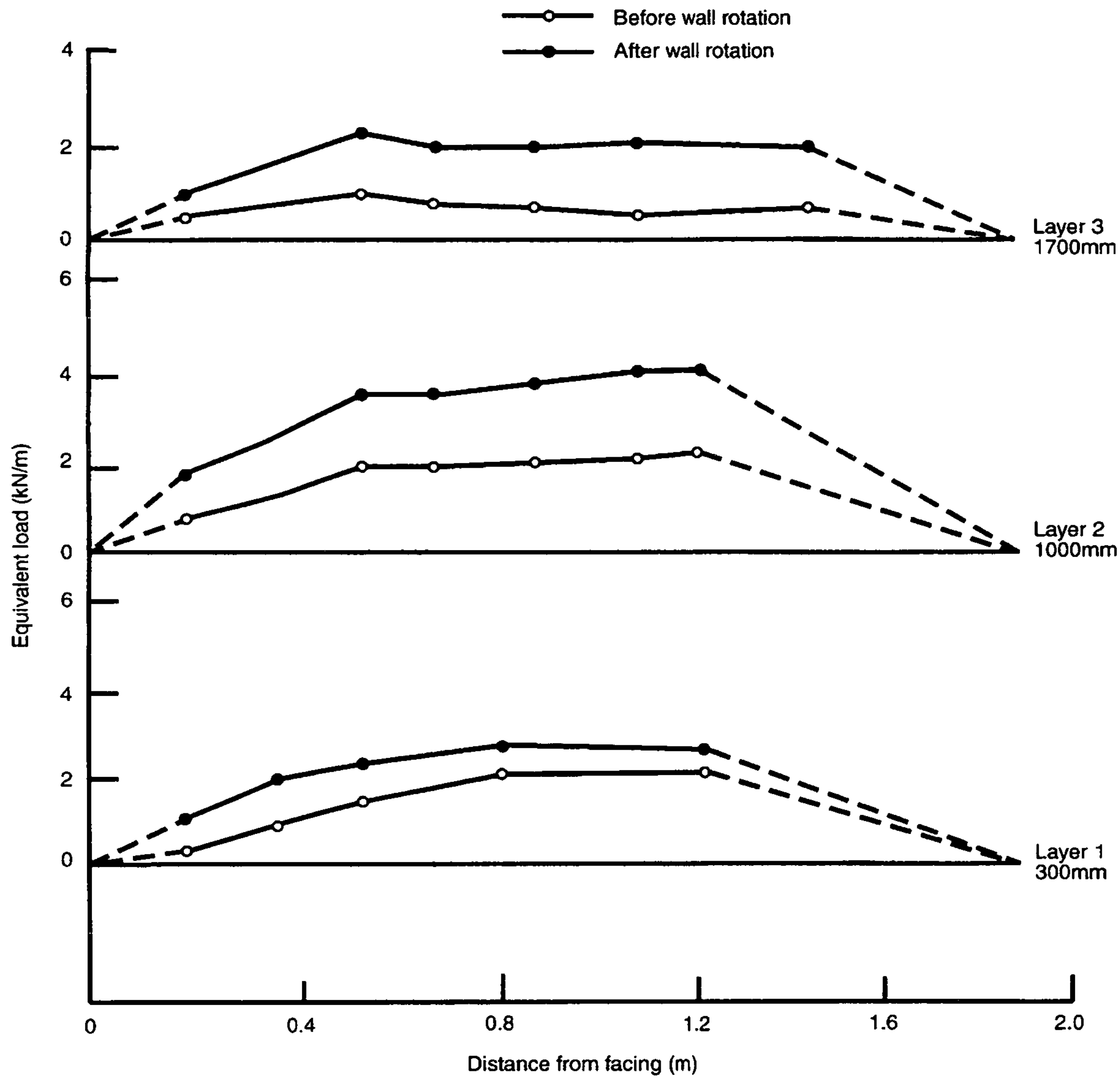


Fig. 11 Tension distributions along steel strips in Bay C before and after wall rotation (after Loke, 1991)

construction phase were small and occurred principally at short distances from the facing, being largest in the top reinforcement layer. However, in Bay H the strains in the geogrids increased significantly confirming that large post-construction movements occurred within the fill (Fig 17). The form of the strain distribution shown in Fig 17 is of special interest as the results indicate peak values adjacent to the face and approximately linear reductions in strain over the reinforcement length. These distributions are typical of the forms produced in pull-out tests.

4.2 COMPARISON OF RESULTS FROM DIFFERENT SECTIONS

Representative horizontal pressure data from the four different sections reinforced with geogrids are given in Fig 18. These include sections with and without yielding wall capabilities. A comparison of the data from Bays A, C and E shown in Fig 9 suggests that the case of unreinforced fill would correspond to the upper pressure envelope in Fig 18. It is apparent from Fig 18 that the largest pressure distributions are associated with the "rigid" boundary condition and that, for this condition, the reinforcement makes little contribution to alleviating lateral pressures. This applies, of course, for unattached elements but it does not appear likely from the study that attachment would significantly change the results. The wall rotation case (E) is close to the classical "active" condition when the full strength of the fill is mobilised (Fig 1) and produces the conventional "minimum" horizontal pressure distribution. Much lower pressures are obtained, however, from the wall yielding case with reinforced fill, at some elevations less than 50% of the active value has been observed. These reductions can be attributed to a combination of permitting strains in the soil to mobilise higher shear strengths and at the same time invoking a greater contribution of resistance from the reinforcement.

Fixed rigid concrete wall - Compressible lateral boundary

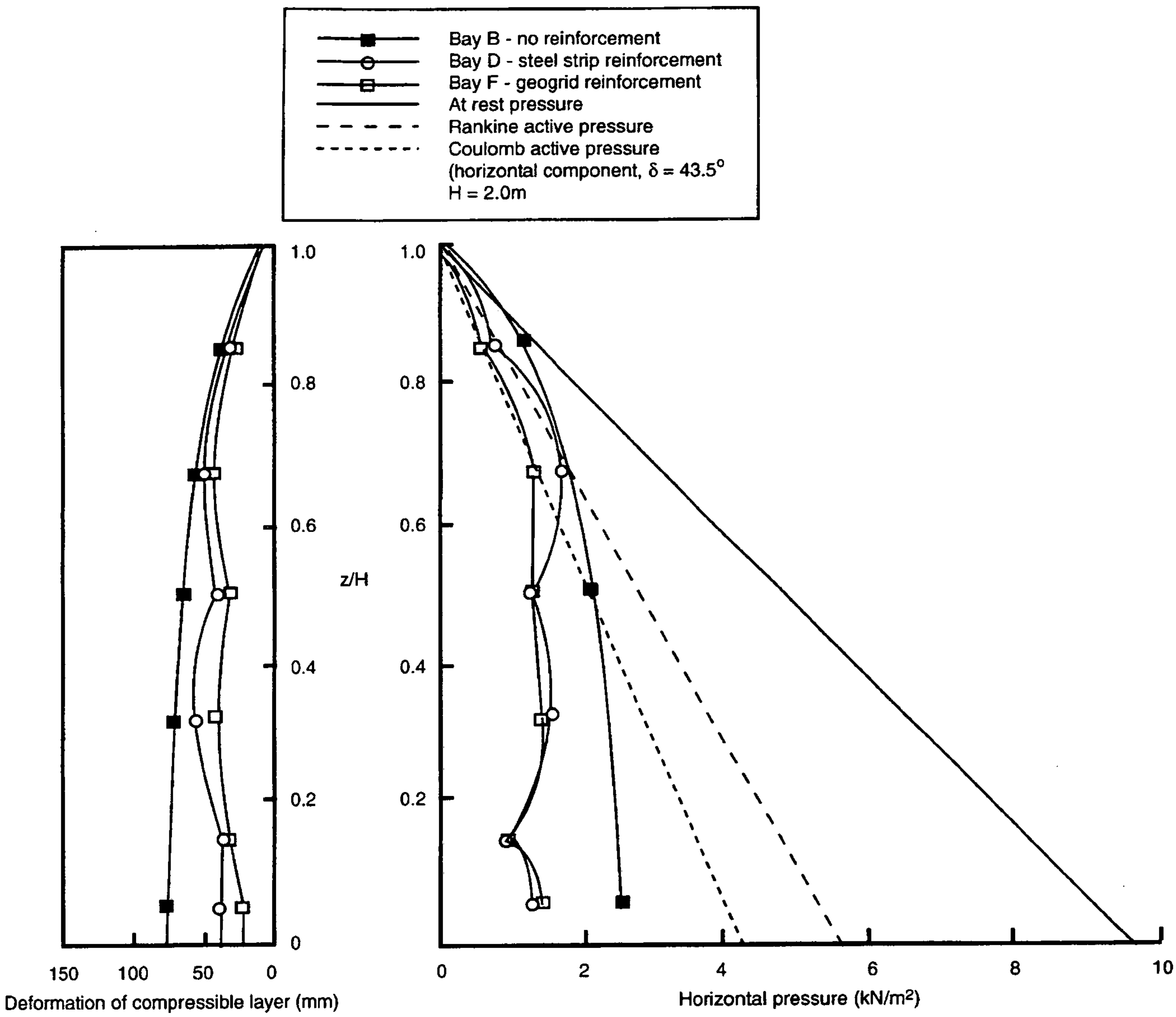


Fig. 12 Comparison of horizontal earth pressure distributions and deformations of the compressible material in Bays B, D and F at the end of construction (after Loke, 1991)

5. FINITE ELEMENT ANALYSIS

Finite element (FE) analysis incorporating non-linear material behaviour is a potentially powerful tool for examining the relation between yield and stress in a retaining structure. Finite element analyses usually give a good representation at strains not far above the elastic range, but develop increasing computational problems at strains near to failure.

For the purposes of finite element assessment, two sections of "rigid" wall and two sections of "yielding" wall were selected with one bay in each section having unreinforced fill and the other having fill reinforced with steel strips. The particular bays chosen were A, B, C and D (Table 1 and Fig 8). As previously described, the steel section of the facility incorporating Bays A and C was supported by hydraulic jacks and because of play within the propping system and deflection of the steel plates, there was a movement of about 0.5mm in the upper part and 1mm at the base of the wall during placement of the fill. The compressible material referred to in Section 4 was attached to the wall in Bays B and D before the fill was placed to allow "yielding". Details of the steel reinforcement are given in Table 2.

5.1 DETAILS OF ANALYSIS

A two-dimensional finite element analysis was carried out using the CRISP program although it was recognised that

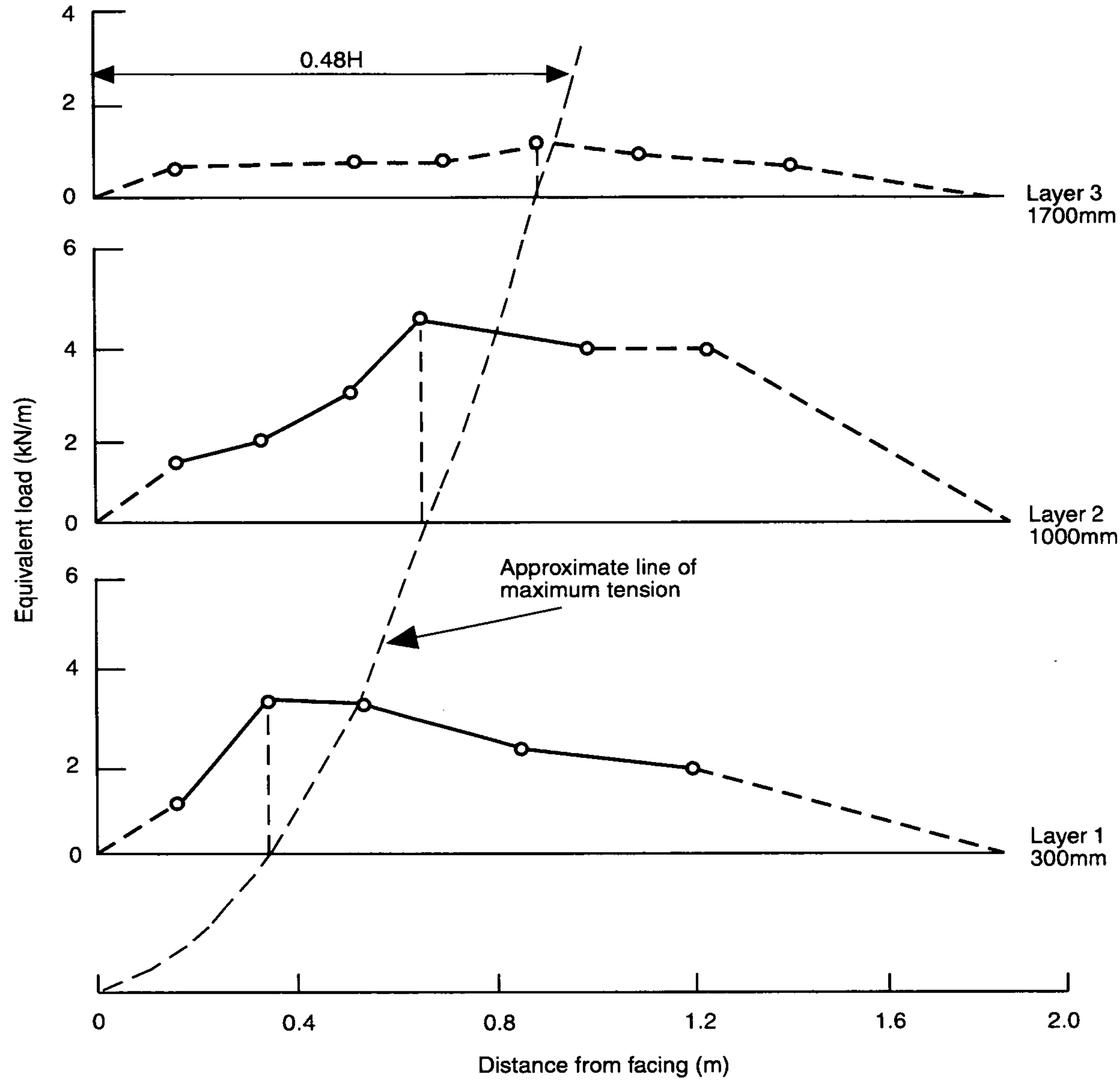


Fig. 13 Tension distributions along the steel strips in Bay D at the end of construction (after Loke, 1991)

this approach did not exactly model the three-dimensional behaviour in the proximity of the steel reinforcing strips. Two-dimensional linear strain quadrilateral (LSQ) or bar elements were used in association with the constitutive models shown in Table 3. Because of the two-dimensional analysis, the reinforcement strips were represented by a sheet of equivalent cross-sectional area to that of the strips: this had a thickness of 0.67mm.

Some difficulty was experienced in determining the properties of the compressible layer used in the large scale study. Fig 19 shows the variation of Young's modulus with strain, derived from laboratory tests, as well as values obtained from the large scale experiments. The results indicate that there is a wide variation in elasticity with strain and possibly some discrepancies in the experimental results. The selection of material properties for the FE analysis is discussed later in this Section. There were also difficulties in modelling the sequence of compaction. The procedure adopted was to apply a uniform stress over each layer of fill as it was incorporated in the analytical model. To assess the effect of compaction, three different values of uniform stress of 0, 12 and 24kN/m^2 were examined. The static stress of the compaction equipment was 5.9kN/m^2, giving a dynamic stress of twice this value.

Material properties are summarised in Table 4. It was assumed in the analysis that the angle of friction between the fill and retaining wall was the same as that of the fill as this property was not measured in the large scale study. A typical geometry used in the analysis, in this case corresponding to Bay D, is shown in Fig 20. The finite element mesh for this geometry is shown in Fig 21.

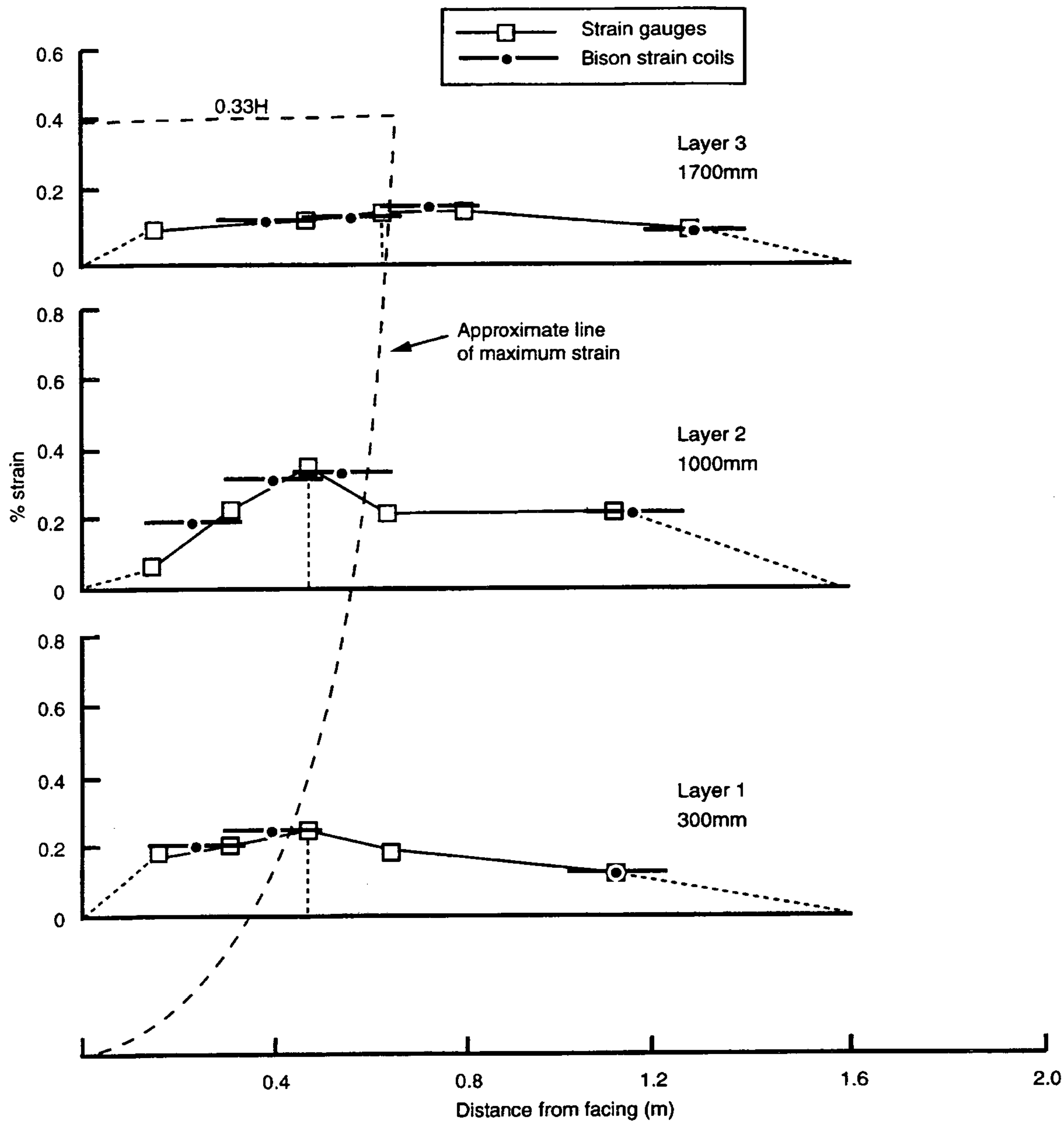


Fig. 14 Strain distributions along the geogrids in Bay F at the end of construction (after Loke, 1991)

TABLE 3

Constitutive models

Structural component	Type of element	Constitutive model
Concrete nib	LSQ	Isotropic elastic
Concrete wall	LSQ	Isotropic elastic
Compressible layer	LSQ	Isotropic elastic
Sand layer	LSQ	Mohr-Coulomb
Backfill	LSQ	Mohr-Coulomb
Reinforcement	Bar	Elastic

TABLE 4

Summary of material properties

Material	Material zone (Fig 20)	Young's modulus (MN/m²)	Poisson's ratio	Angle of friction (degs)	Cohesion (kN/m²)	Unit weight (kN/m³)
Retaining wall	2	35,000	0.1			24
Nib	1	35,000	0.1			24
Reinforcement	5	22	0.1			
Sand layer	3	80	0.2	47	1	18.1
Backfill	4	80	0.2	47	1	18.1
Compressible layer	6	1	0.2			

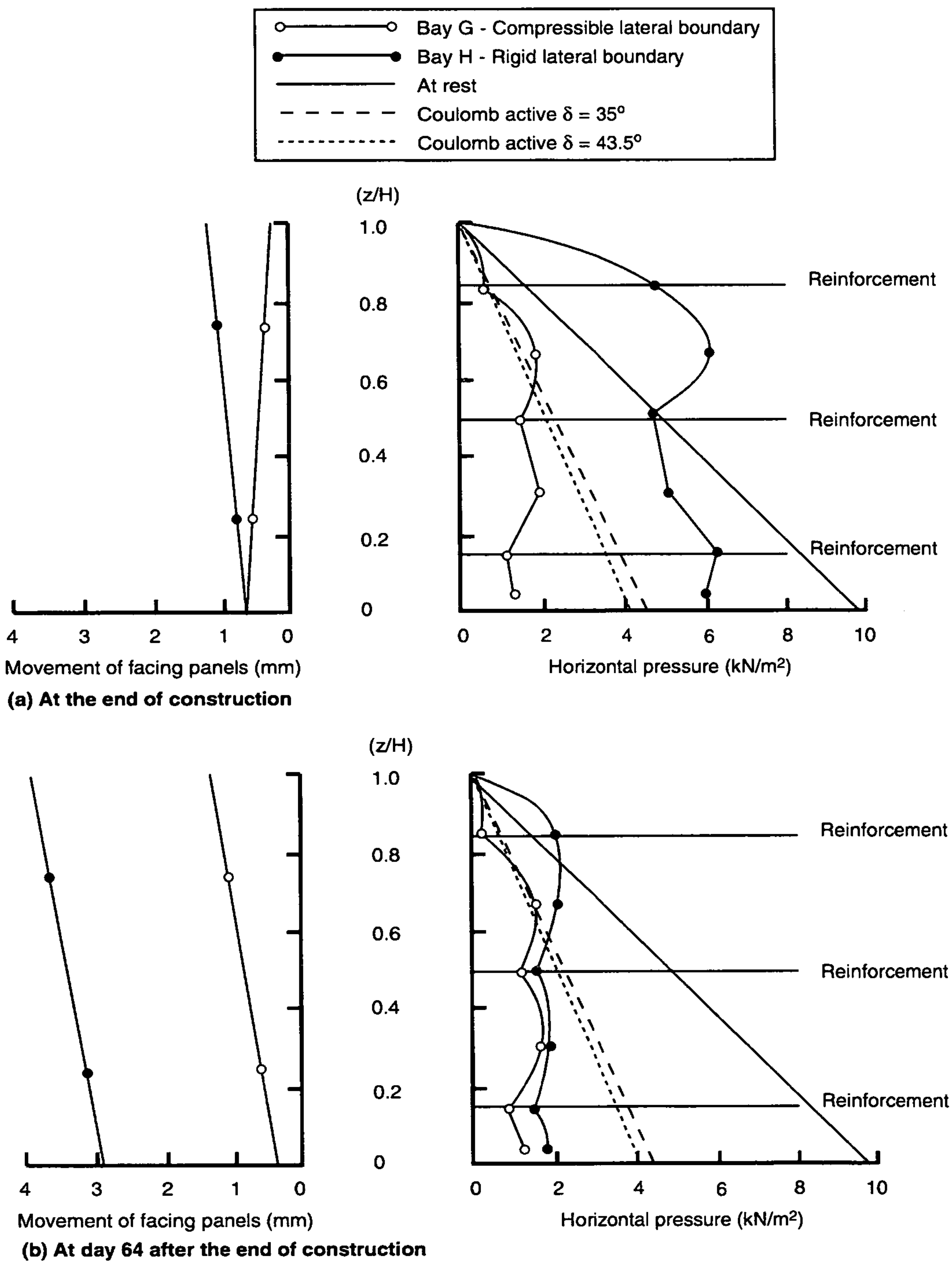


Fig. 15 Influence of the compressible layer on horizontal pressures (after Loke, 1991)

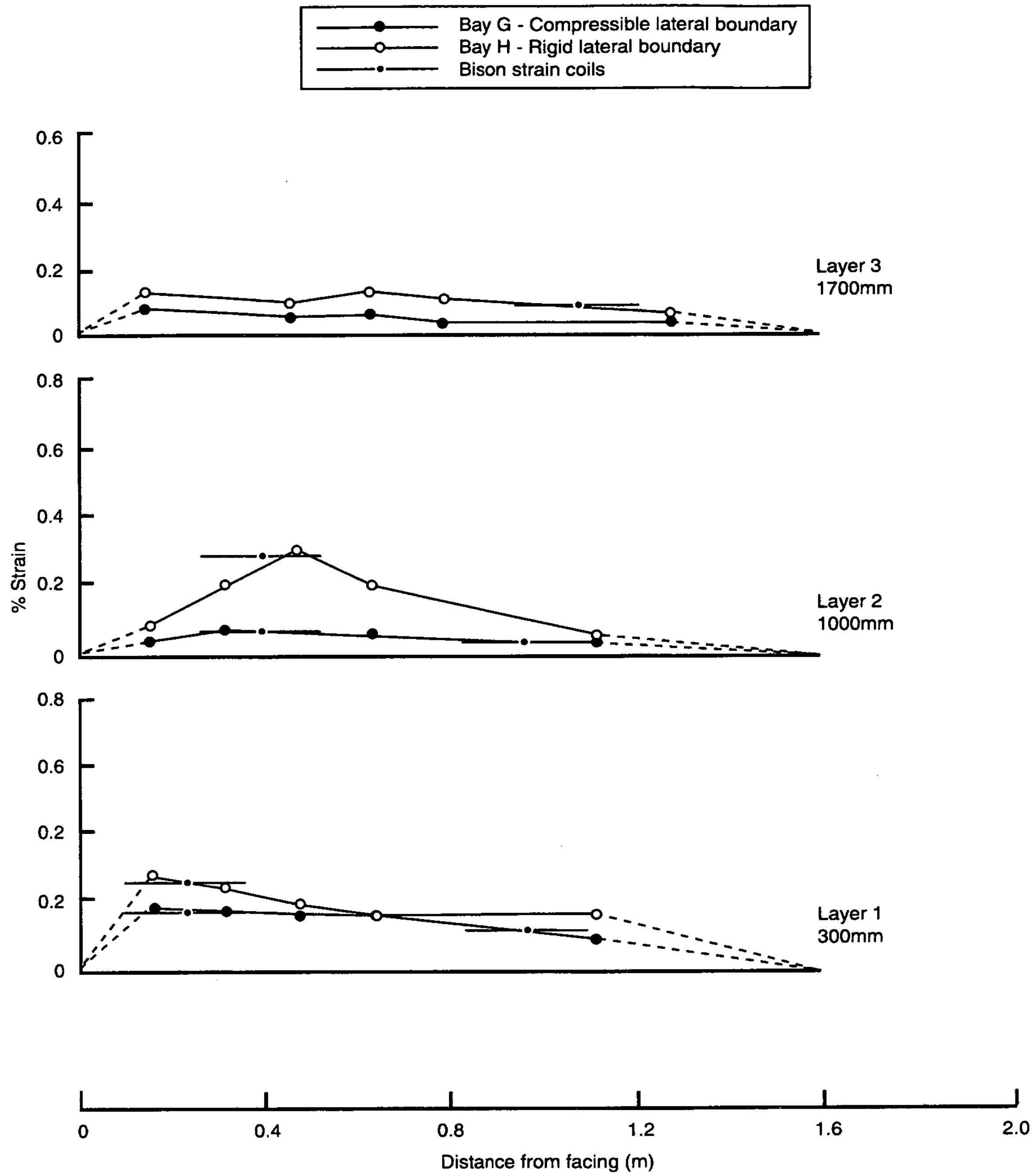


Fig. 16 Strain distributions along the geogrids in Bay G and Bay H at the end of construction (after Loke, 1991)

The sequence of placement and compaction of each layer of fill was modelled in the following way.

a. Placement of fill layer

b. Application of uniform compaction stress to fill layer

c. Removal of compaction stress from fill layer.

The construction sequence was simulated by placing the fill in layers 150mm or 200mm thick as shown in Fig 21, applying gravity and compaction stresses, and placing reinforcement where appropriate.

5.2 RESULTS OF ANALYSIS

5.2.1 Steel section (unyielding) wall and unreinforced fill

The relation between horizontal stress and height obtained from the FE analysis, for a rigid wall and no reinforcement in the fill, is shown in Fig 22. These results are compared both with the measured results obtained in the large scale study for Bay A, and also with an at rest (K_o) distribution. Stresses on the upper part of the wall were dominated by compaction. Three different compaction stresses were evaluated in the FE analysis, of 0, 12 and 24kN/m^2. It was

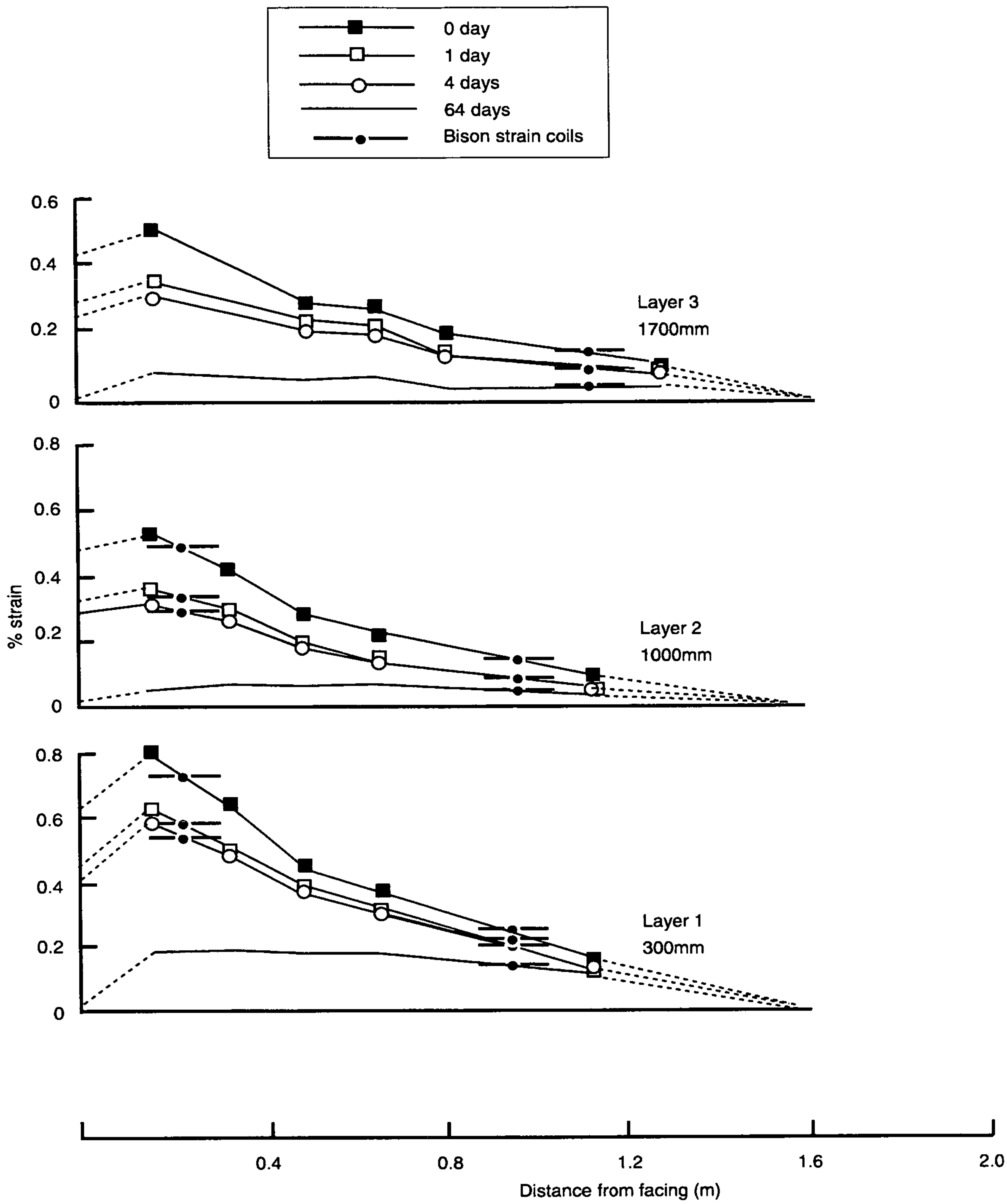


Fig. 17 Strain distributions along the geogrids in Bay H after the end of construction (after Loke, 1991)

concluded that a compaction stress of 12kN/m^2 gave the best agreement with observation, and this value was used in subsequent calculations. In the fill immediately below this region, the FE analysis showed a slight effect due to passive yield following removal of the compaction stress.

For the lower half of the wall, the FE analysis gave horizontal stresses fairly close to the K_o condition. In contrast, the stresses measured in the large scale study were intermediate between the K_o and active (K_a) conditions (Fig 9); this difference may be ascribed to the movements of the metal wall referred to previously but which were not modelled in the FE analysis.

5.2.2 Yielding wall and unreinforced fill

Because of the marked variation of elasticity with strain for the compressible layer, some preliminary FE analyses were

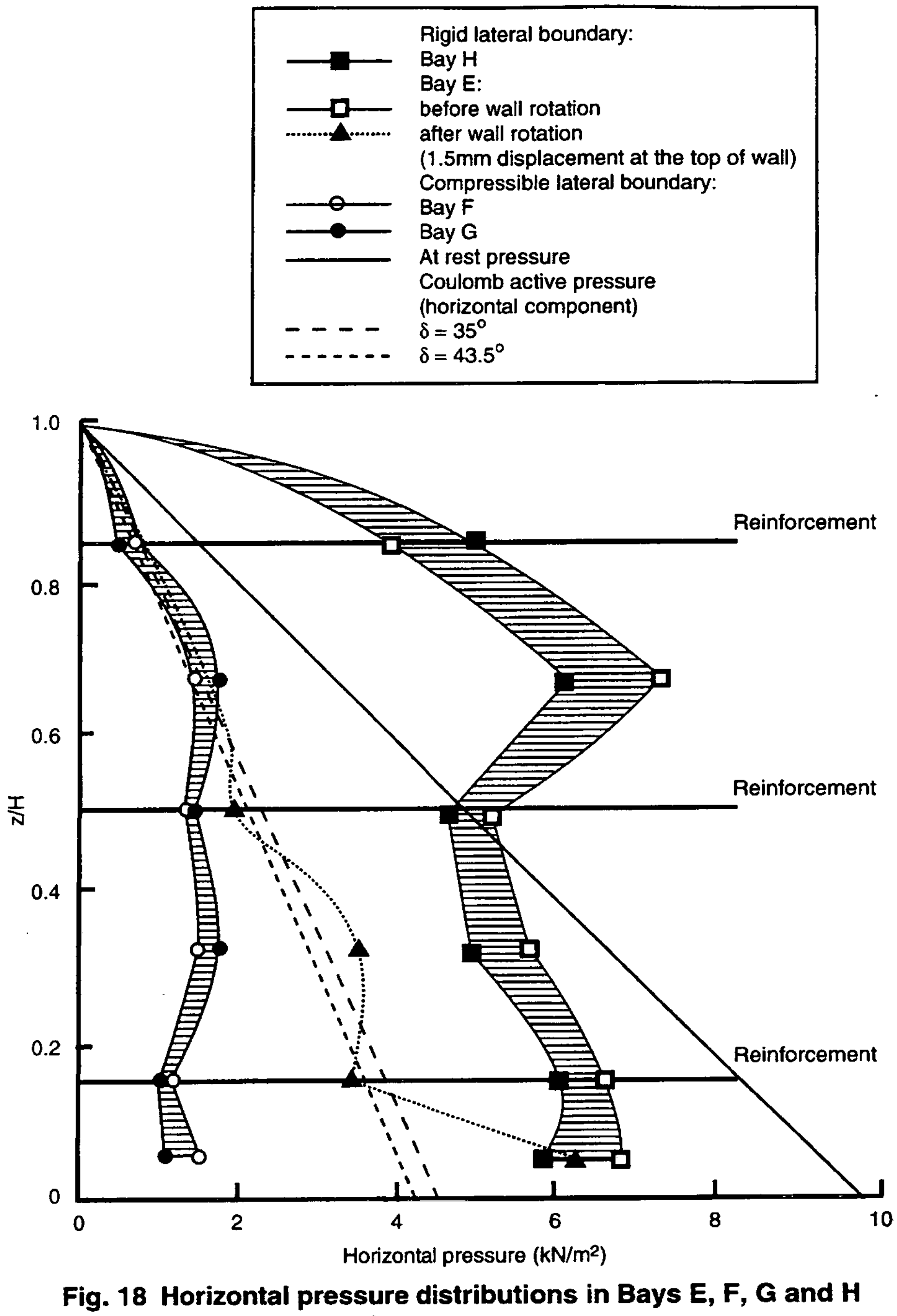


Fig. 18 Horizontal pressure distributions in Bays E, F, G and H (after Loke, 1991)

carried out to investigate the sensitivity of various values of Young's modulus for this layer (E_{layer}) on the distribution of horizontal stresses. Fig 23 shows the effect of different values of E_{layer} on stresses in the compressible layer. As would be expected, the K_o condition was obtained when E_{layer} was the same as for the soil (i.e. 80MN/m^2). When E_{layer} was reduced to 1/8th and 1/80th of this value (10 and 1MN/m^2 respectively), horizontal stresses were reduced to near the K_a condition. Any further reduction of E_{layer} introduced severe numerical problems with the analysis at the boundary between the compressible layer and fill. It was therefore decided to use a value of E_{layer} of 1MN/m^2 in subsequent calculations.

Fig 24 shows the calculated relation between horizontal stress and height in the compressible layer in Bay B. The figure also gives the results measured in the large scale study. The analysis indicates that the lateral pressures are similar to the K_a condition. Moreover, for the case of a yielding boundary, the results support those from the large

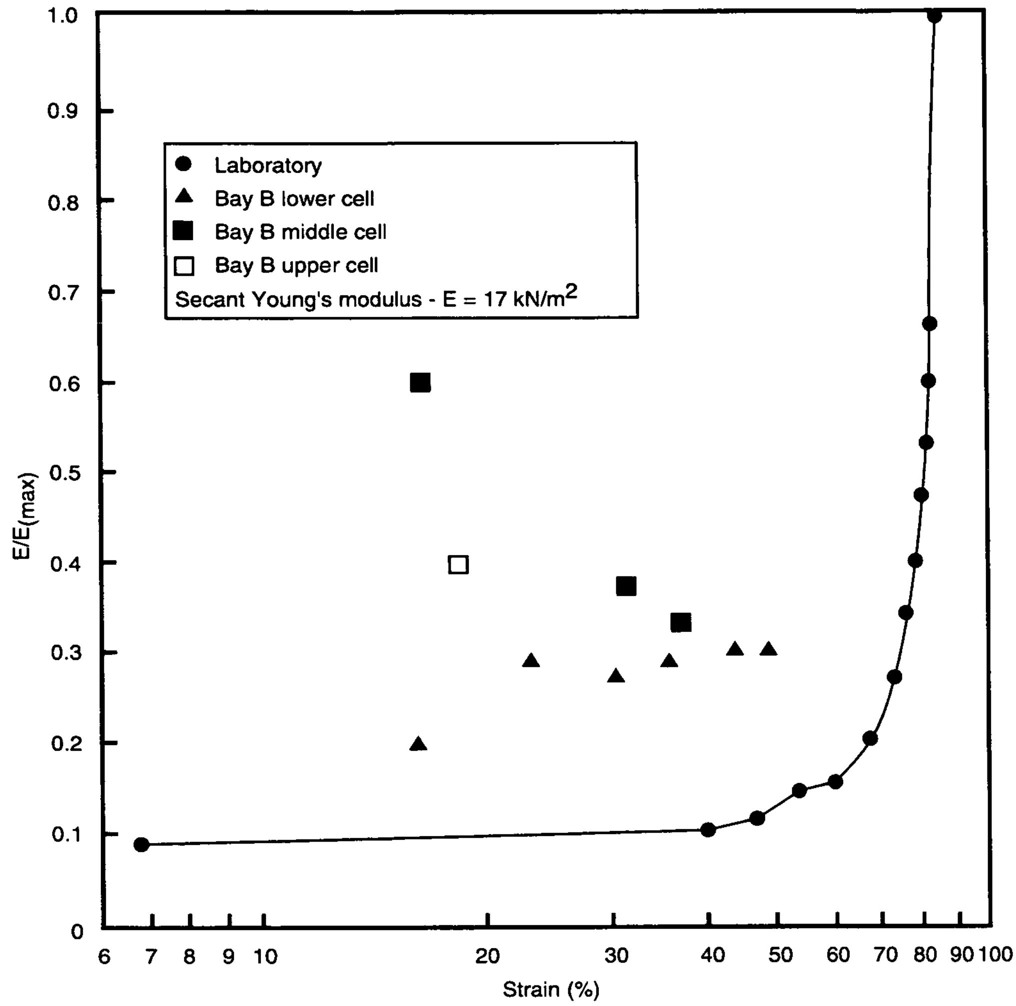


Fig.19 Relation between normalised Young's modulus and strain for compressible layer

scale study that compaction stresses are insignificant. At the base of the wall, the analytical results show a reduction in horizontal stress, whilst the large scale results show low values. This is considered to be associated with the restraint conditions induced by the base sand layer and the concrete nib.

5.2.3 Steel section (unyielding) wall and reinforced fill

The analysis modelled the conditions in Bay C of the large scale experiment. Note that for a truly rigid wall it would be expected that the earth pressure conditions would correspond to the K_0 situation apart from near the top of the structure where the influence of compaction would dominate. In addition, tensions (or compressions) developed in the reinforcements would be expected to be small as only placement and compaction of the fill could induce such forces. As shown in Fig 25, the distribution of horizontal stress obtained in the FE analysis is indeed close to the K_0 condition in the lower part of the structure. However, the form of the distribution is significantly different from the observed values also given in Fig 25. Fig 26 shows the calculated and observed tensions in the steel reinforcements, where again the results are significantly different. The calculated distributions show small compressive stresses in the upper layer of reinforcement, decreasing to very small tensile stresses in the lowest layer.

To some extent, the disparity in the calculated and observed horizontal pressure distributions shown in Fig 25 may be attributable to the yielding of the steel wall. This might explain the observed values being smaller than the K_0 condition expected. However, the differences in the upper part of the structure between calculated and observed values appears to be the result of incorrect modelling of the compaction process by the CRISP program.

To allow a correct interpretation of the controlled yielding method in a range of diverse situations there is a need to investigate the use of CRISP for conditions where hysteresis loops, such as arise with the compaction process, play a prominent role in behaviour. The results of such a study might show a need to develop CRISP further to deal with such situations more effectively. The poor results obtained from CRISP in relation to the tensions in the

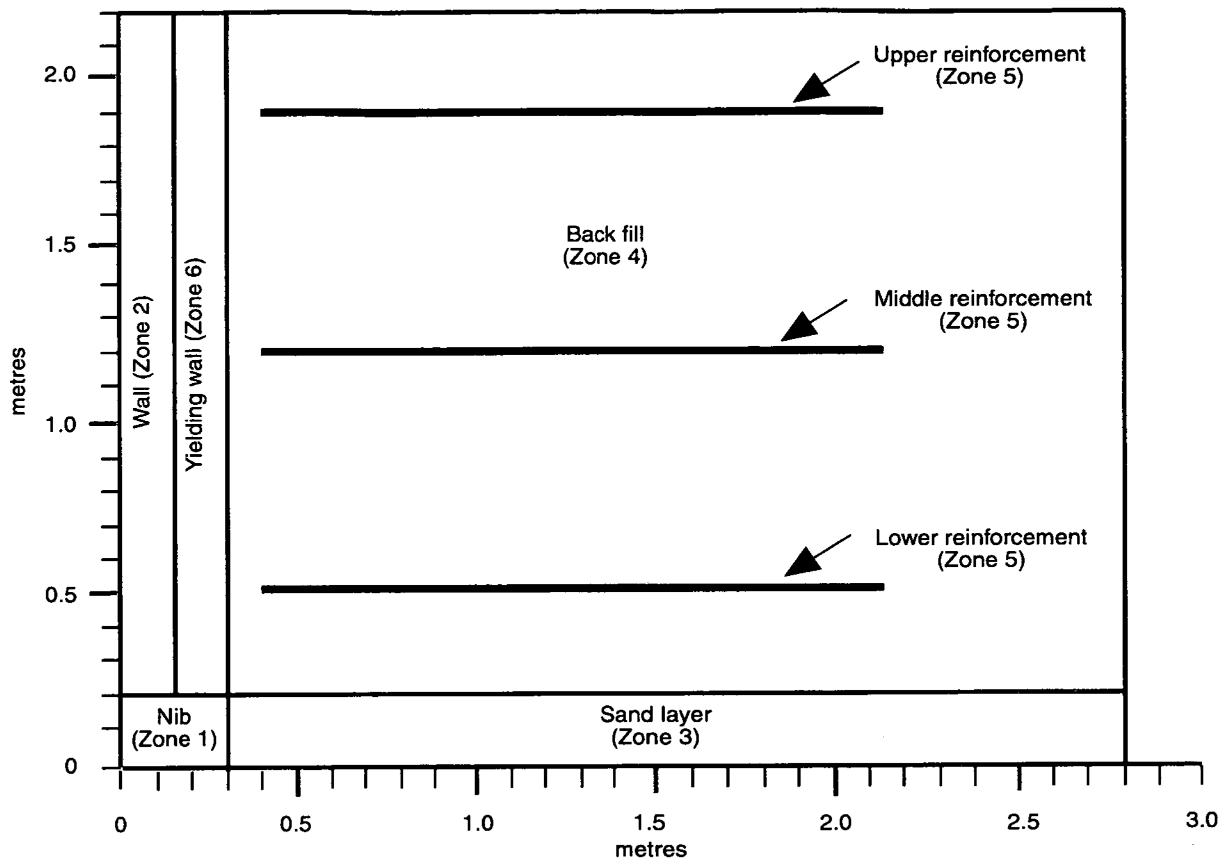


Fig. 20 Typical geometry used in finite element analysis of yielding wall

reinforcements could also be associated in part with the yielding of the metal section of wall but local variation in compactive effort could well have a significant effect on behaviour that could not be reliably modelled. It is interesting to note, however, that the calculated results show a certain consistency in that the reinforcement forces vary from compression at the top of the structure to tension at the base. This behaviour suggests that the CRISP program anticipates a much higher "locked-in" stress than actually occurs and again supports the contention that the hysteresis behaviour is not being correctly modelled.

5.2.4 Yielding wall and reinforced fill

The relation between horizontal stresses and height for a yielding wall with reinforced fill is shown in Fig 27. The form of distribution produced by the CRISP analysis is somewhat different from that observed in the large scale study in Bay D, but the results show some promise in predicting smaller stresses than the Rankine active condition, although the experimental values are even lower. The corresponding tension distributions along the reinforcements for this case are shown in Fig 28. The values of tension obtained from the FE analysis are much lower than those measured in the large scale study. It could well be that the use of a lower value for E_{layer} in the analysis would have improved the agreement with the results of the study but further development work will be required with CRISP to allow very soft layers to be used. One clear outcome of the analysis, however, is that it confirms the experimental data in showing the potential benefit of a compressible layer for reducing stresses in reinforced fill to below the active value.

6. CONCLUSIONS

1. To investigate the relation between strain and mobilised strength in both unreinforced and reinforced soil structures, small scale model studies were undertaken in association with the University of Strathclyde. These studies clearly demonstrated that the controlled development of strain fields in reinforced soil backfill during construction permitted the soil and reinforcement strengths to be utilised more effectively and produced a significant reduction in post-construction wall movements. It was also shown that these objectives could be achieved by employing the "yielding wall" principle. However, as the results related only to small scale laboratory models, it was decided to test their validity by observations of the behaviour of large scale walls constructed in the retaining wall facility at TRL.

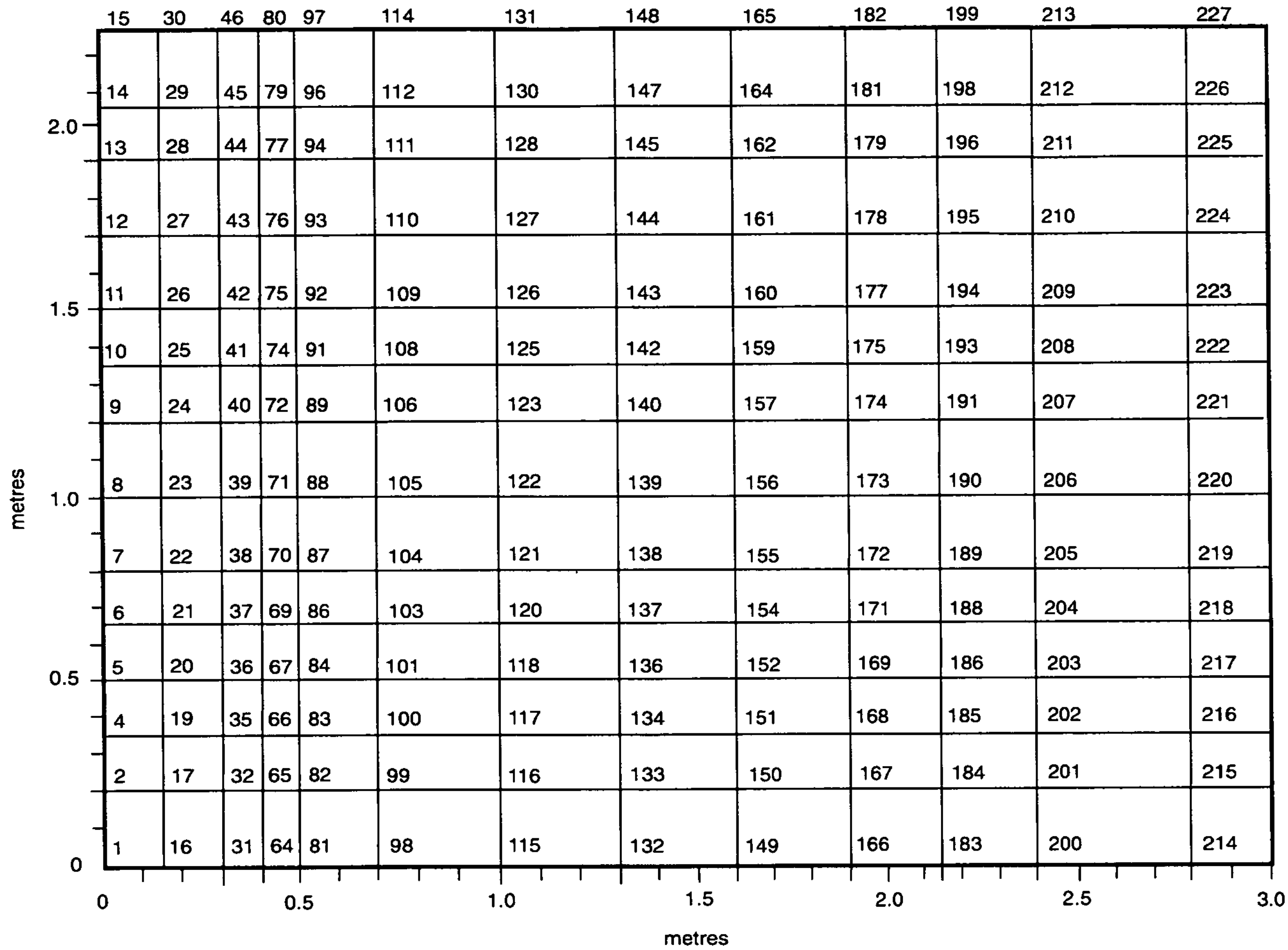


Fig. 21 Finite element mesh used in analysis

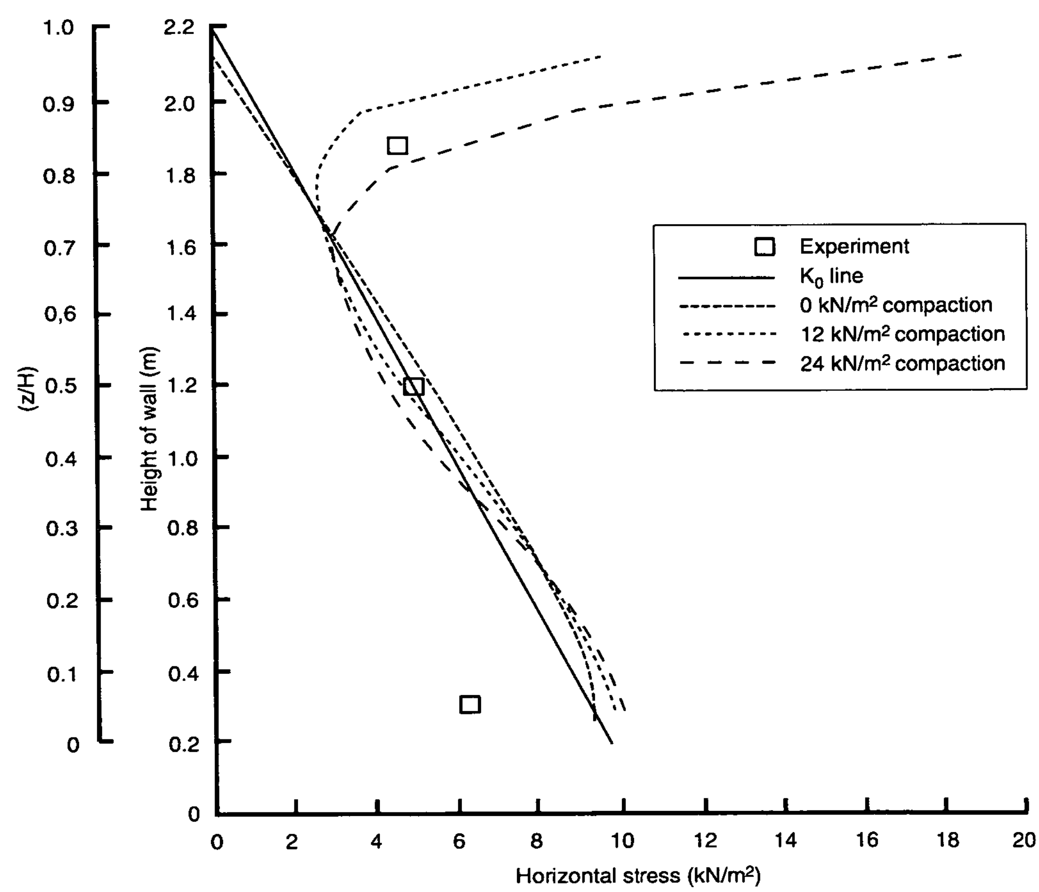


Fig. 22 Horizontal stresses for unyielding section of steel wall and unreinforced fill - Bay A

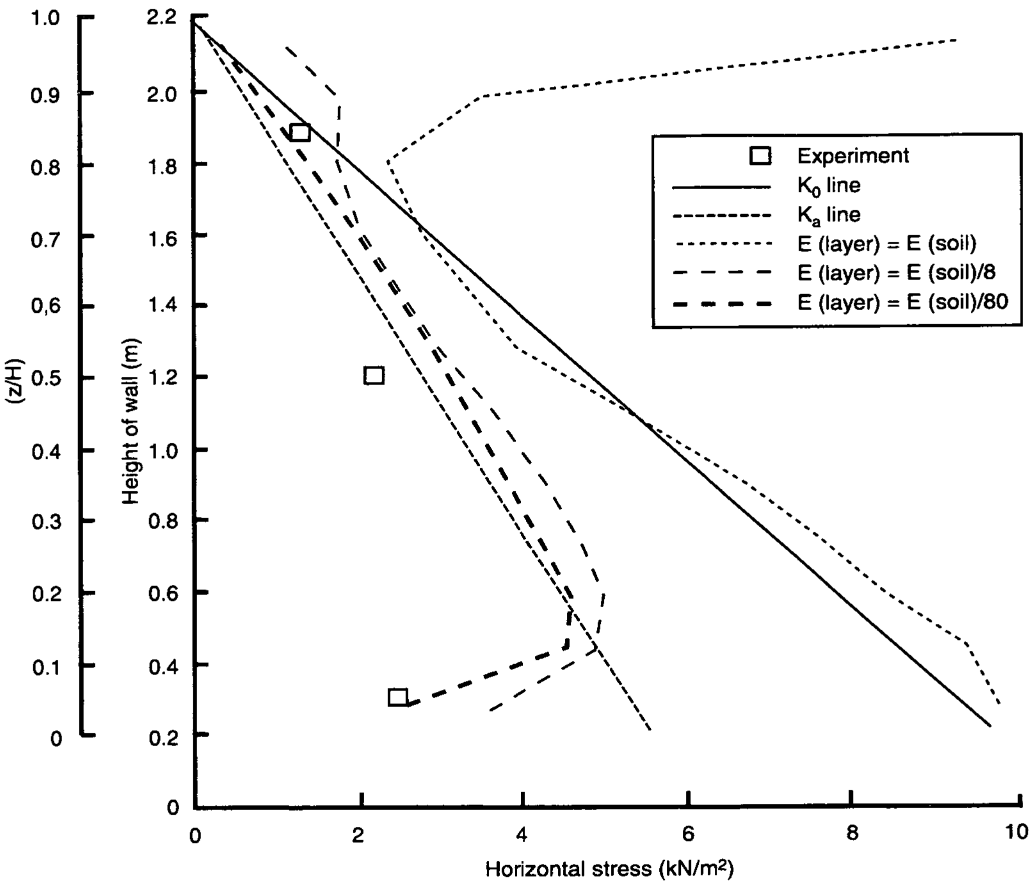


Fig. 23 Influence of compressibility of yielding layer on horizontal stresses in yielding wall and unreinforced fill - Bay B

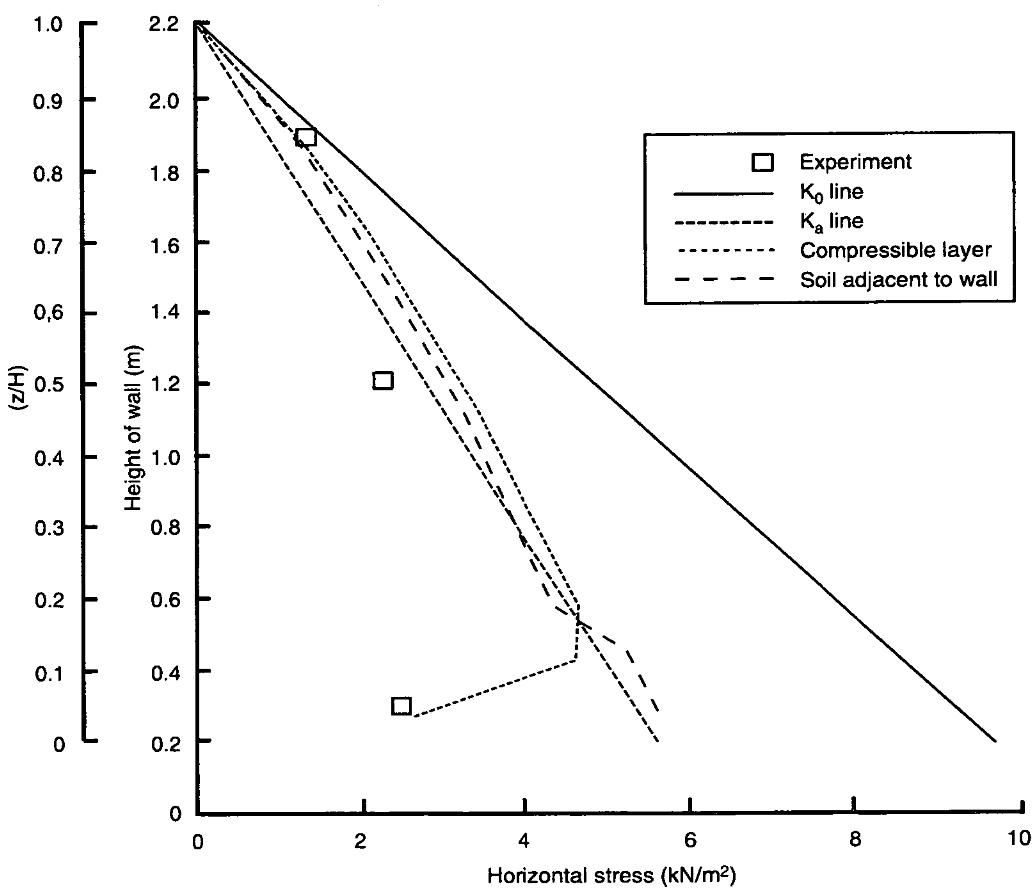


Fig. 24 Horizontal stresses for yielding wall and unreinforced fill - Bay B

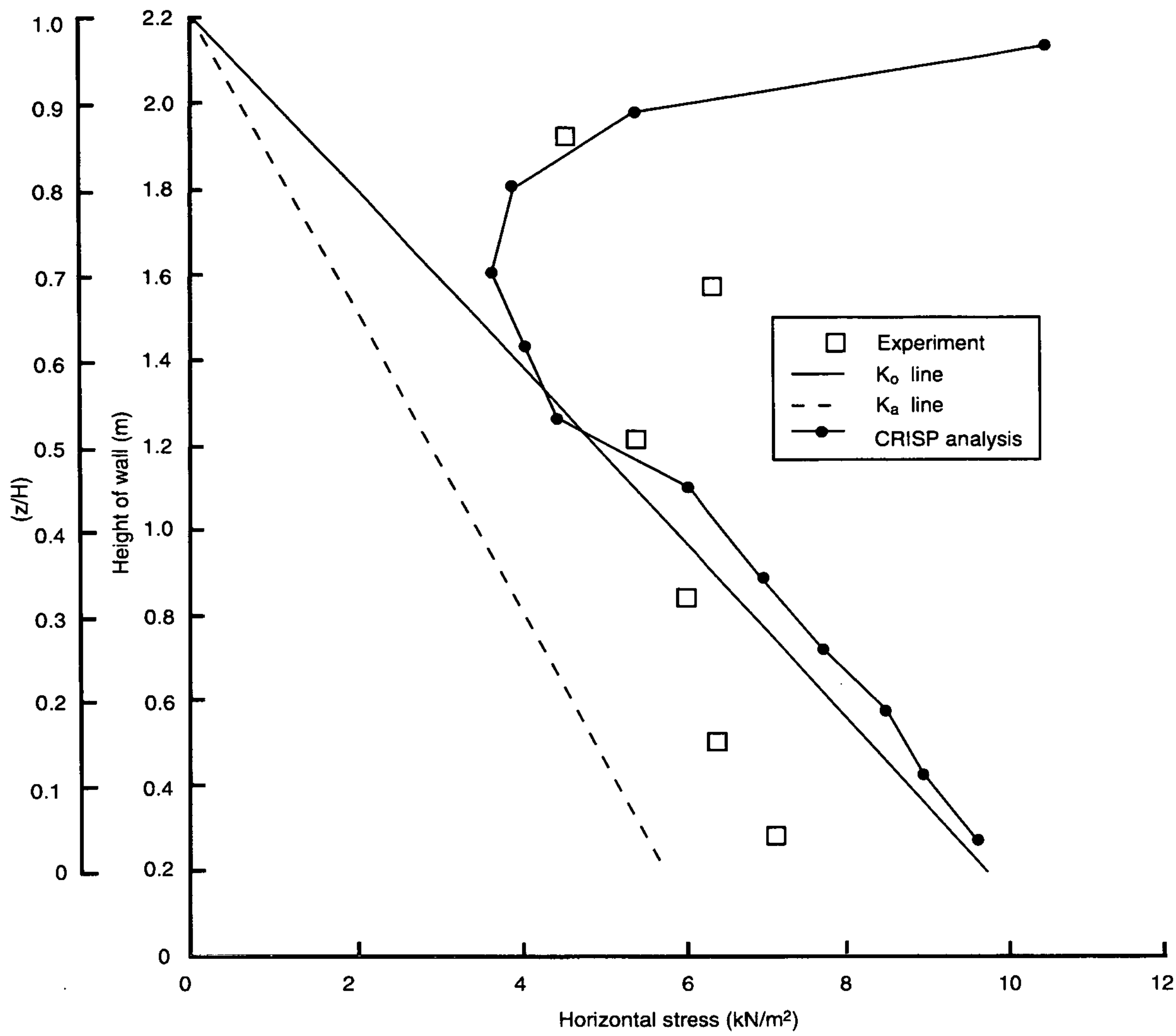


Fig. 25 Horizontal stresses for unyielding section of steel wall and reinforced fill - Bay C

2. The data obtained from the large scale walls incorporating different construction methods confirmed the findings of the small scale model wall studies. In particular, the data showed that for both unreinforced and reinforced soil walls the magnitudes and distributions of lateral earth pressures on the walls are greatly influenced by the amount and mode of lateral boundary yielding during and after construction. It was also shown that filling and compaction processes can "lock-in" significant stresses into the backfill. Thus, to ensure reliable estimates of the lateral earth pressures associated with unreinforced or reinforced backfills, consideration must be given to the anticipated movements of the structure and backfill and to the influence of the construction process. The separate effects of construction and boundary yielding on internal behaviour are not easily quantified, but the application of the yielding wall technique offers a relatively simple and economic means of obtaining maximum effect from the soil and reinforcements, and for controlling post-construction wall movements.

3. Strain behaviour is a critical consideration in reinforced soil walls in which post-construction boundary deformations are required to be kept to a minimum. For those structures which have been constructed on a conventional basis, such a requirement inhibits the development of strains in the soil and restricts the mobilisation of soil friction, thereby inducing high lateral earth pressures. It may also restrict the mobilisation of full interface friction between the soil and reinforcement and thus limit the development of the associated tensile stresses in the reinforcements which are required for enhancing stability. The constraints on boundary movements are of particular significance for polymeric reinforcements in which a higher strain is needed to generate their available strength than with steel reinforcements. A consequence of imposing

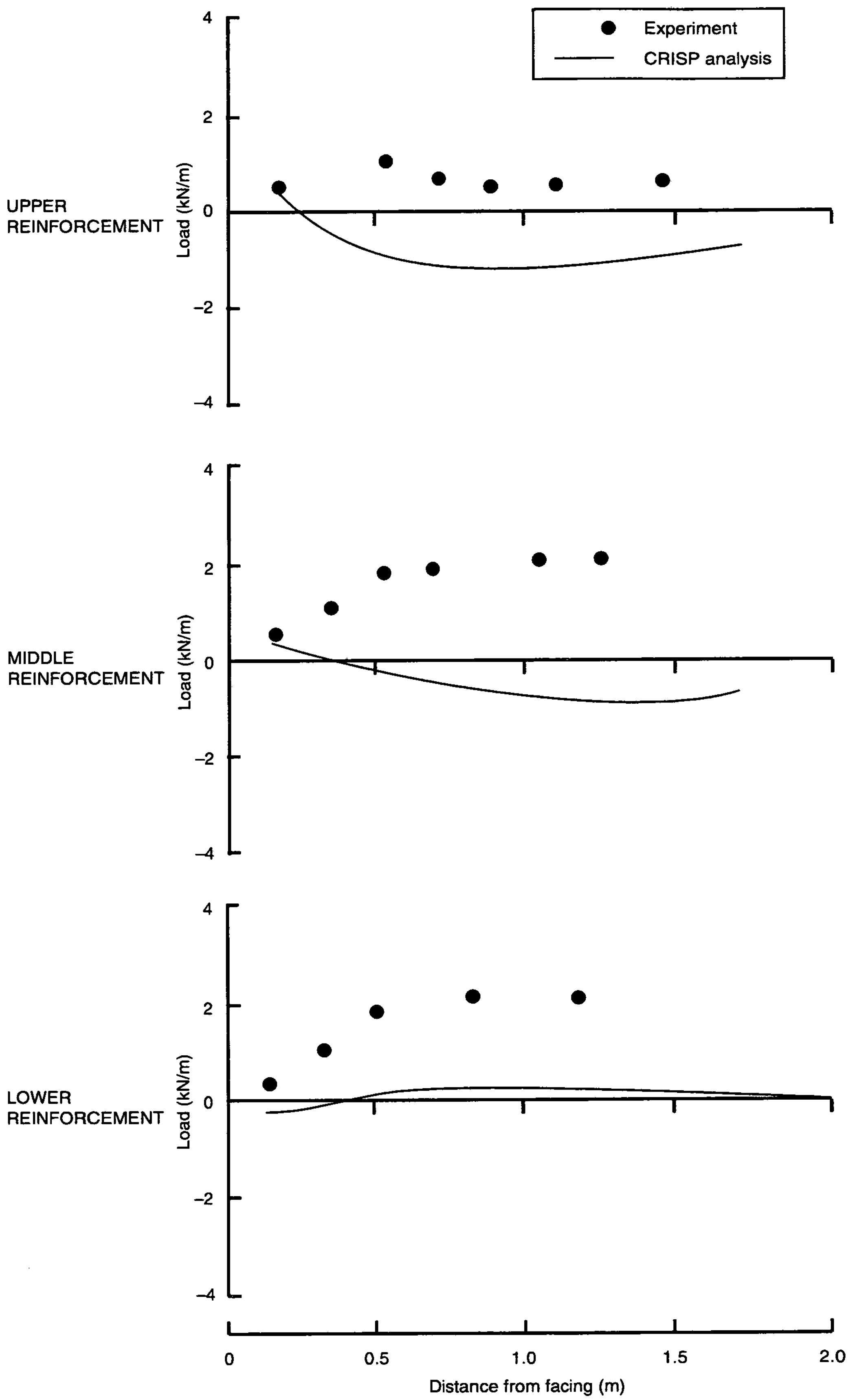


Fig. 26 Calculated and observed tensions for steel wall and reinforced fill - Bay C

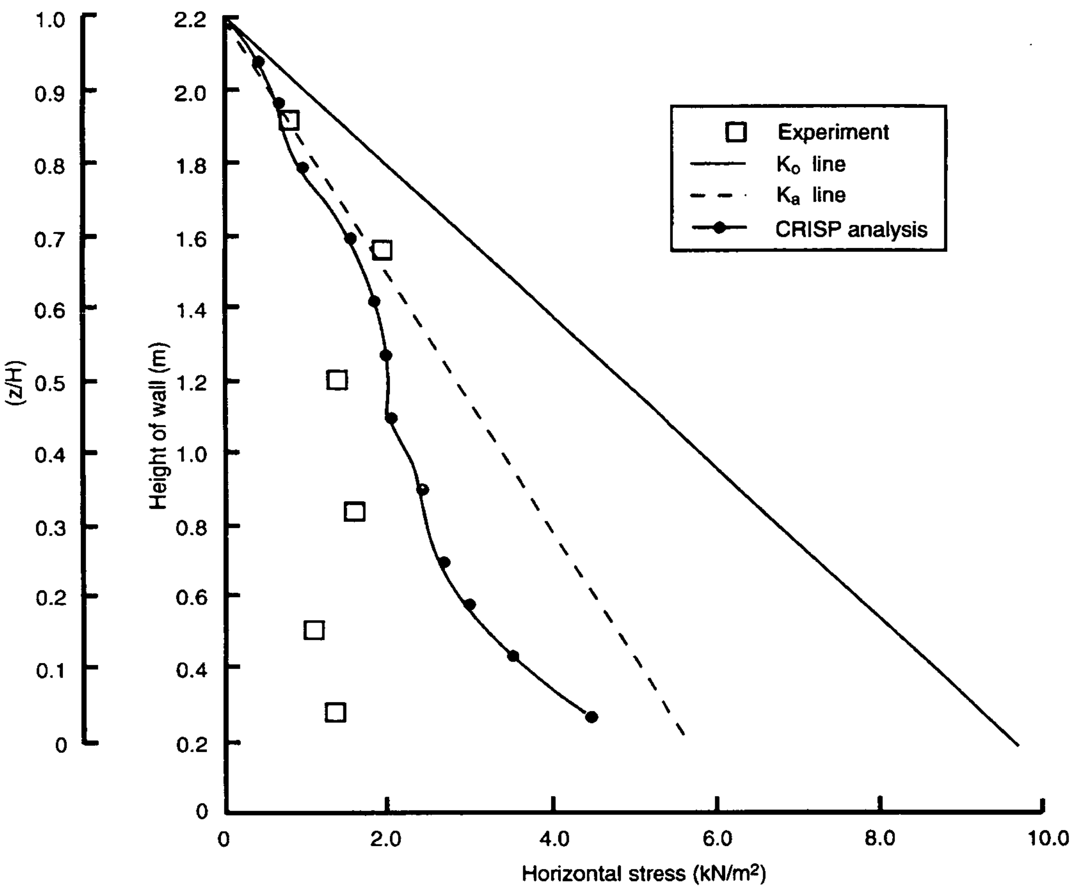


Fig. 27 Horizontal stresses for reinforced fill - Bay D

limitations on strain is to produce structures which are over-designed.

4. The Report also describes the use of finite element analysis to simulate the effect of yielding in ameliorating the horizontal stresses on walls. The CRISP package was used in a two-dimensional form, with a Mohr-Coulomb constitutive model for the soil. The analysis was compared with results from the large scale study. These comparisons highlighted a number of problems with the CRISP analysis, in particular the inadequacy of the analysis for dealing with hysteresis loops, such as those that occur with compaction, and an inability to model very soft layers. However, the finite element analysis was useful in providing further support for the view that the yielding wall technique offers an economic and convenient solution for reducing the lateral forces on retaining structures.

5. The use of yielding wall techniques incorporating compressible layers may be particularly useful with integral abutments where the stiffness of the structure, combined with diurnal and seasonal thermal movements, is likely to result in high horizontal pressures, unless measures are taken to ameliorate them.

7. ACKNOWLEDGEMENTS

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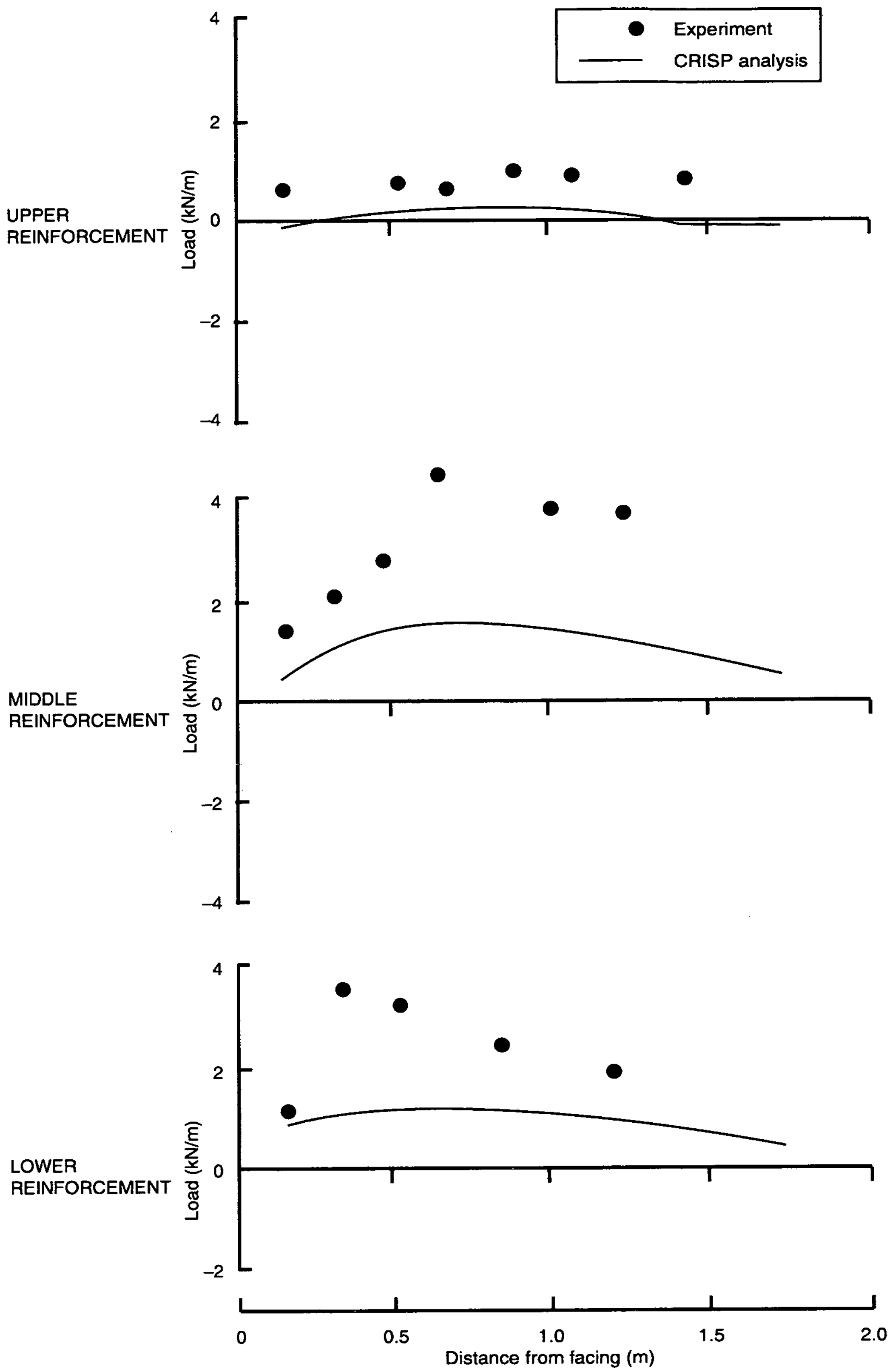

Fig. 28 Reinforcement tensions for yielding wall and reinforced fill - Bay D

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