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Influence of wall yielding on lateral stresses in unreinforced and reinforced fills

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INFLUENCE OF WALL YIELDING ON LATERAL STRESSES IN UNREINFORCED AND REINFORCED FILLS

by

A McGown*, R T Murray and K Z Andrawes*

Economic design of soil retaining structures involves satisfying two conflicting requirements. First the soil must be permitted to strain sufficiently to develop shearing resistance and to mobilise interaction with reinforcing elements. Second the strains must be limited such that wall movements are acceptable and do not introduce problems of serviceability.

The principle of controlled yielding of model retaining walls has been investigated employing a retaining wall facility specially developed at the University of Strathclyde. This facility has enabled the influence of a wide range of wall stiffnesses on displacement and lateral loading to be assessed. A series of tests has been carried out employing Leighton-Buzzard sand as backfill in both unreinforced and reinforced states. Figure 5 of the report shows the non-dimensional stress distributions on the lateral boundary of a fully constrained wall and four further walls supported by spring systems of different stiffness. The figure also shows the calculated stress distributions based on 'at-rest' (K_o) and 'active' (K_a) earth pressure conditions assuming a frictionless wall. The corresponding lateral boundary movements are shown in non-dimensional form in Figure 6 of the report. For the purposes of establishing wall movement, measurements were made with respect to a vertical datum line passing through the initial position of the lowermost unit along which the facing units were first positioned. On the basis of this procedure the movement appears to involve rotation about the top. This behaviour contrasts with that normally obtained by the conventional practice of setting each facing unit sequentially to align with the unit immediately below when the fill has reached that level. The movements in this case are considered cumulative and give an impression of rotation about the base. The stress results shown in Figure 5 support the contention that soil behaviour more closely reflects rotational movement about the top and indicates that the conventional approach for assessing wall movement is misleading in relation to the factors which control the development of soil stresses and strains.

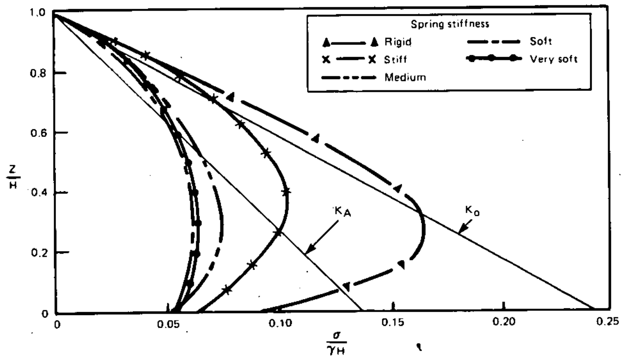

Fig. 5 Lateral stress distribution with sand backfill

*University of Strathclyde

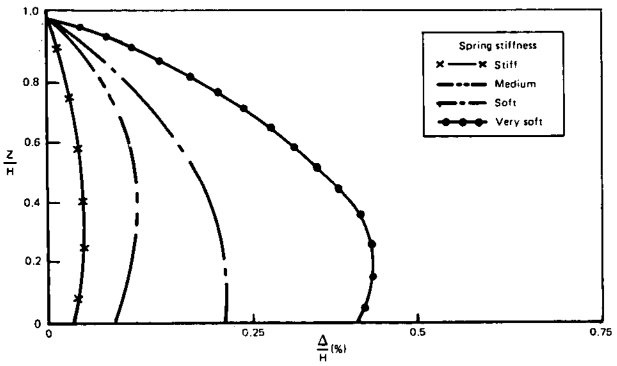

Fig. 6 Distributions of movements with sand backfill for the facing units set to a vertical datum

The results shown in Figures 5 and 6 on unreinforced backfills, as well as further data for reinforced backfills presented in the report, indicate that the largest lateral boundary stresses were associated with the wall supported by springs of greatest stiffness and the smallest stresses with the wall supported by springs of least stiffness. Such behaviour can be attributed to greater mobilised shear strength of the soil and tensile resistance of the reinforcement as the soil strains increase with progressive yielding of the lateral boundary.

Possible methods of developing controlled yielding of earth retaining structures during construction are described which permits lateral boundary stresses to be reduced without significant movements of the facing.

The work described in this Digest was carried out in the Ground Engineering Division of the Structures Group of TRRL.

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CONTENTS

INFLUENCE OF WALL YIELDING ON LATERAL STRESSES IN UNREINFORCED AND REINFORCED FILLS

ABSTRACT

The relations between boundary yielding and the state of lateral stress in unreinforced and reinforced sand backfills has been investigated at laboratory model scale. The results have shown that lateral expansion of the backfill is necessary to attain the minimum force acting on a retaining structure. The study has also shown that such expansion of a reinforced backfill can reduce the lateral stresses to significantly below that corresponding to the 'active' earth pressure condition for an unreinforced fill.

Descriptions are also given of methods of achieving controlled yielding of lateral boundaries to attain the minimum stresses acting on a wall and thus avoid problems of unserviceability of the wall or facing units.

Although the results were obtained from laboratory models, such information is of considerable significance in relation to the economic design and construction of full-scale retaining structures.

1 INTRODUCTION

The economic design of both conventional and reinforced soil retaining structures involves satisfying two conflicting requirements of soil-structure interaction behaviour. The first requirement is that the soil must be allowed to strain sufficiently to develop shearing resistance and thus minimise the lateral force to be resisted by the structure. This is especially relevant to reinforced soil structures wherein it is also necessary to strain the soil in order to develop tensile resistance in the reinforcement through interface friction and adhesion. The second requirement is that the soil strains must be limited such that the resulting deformations at lateral boundaries will not cause problems of structural serviceability. Very often the final design solution is controlled by the need to limit lateral boundary deformations, particularly with poor quality backfills and with reinforced soil structures employing extensible materials. Thus reliable data are needed to permit the optimum design solution of minimum lateral stress and associated wall movement to be established.

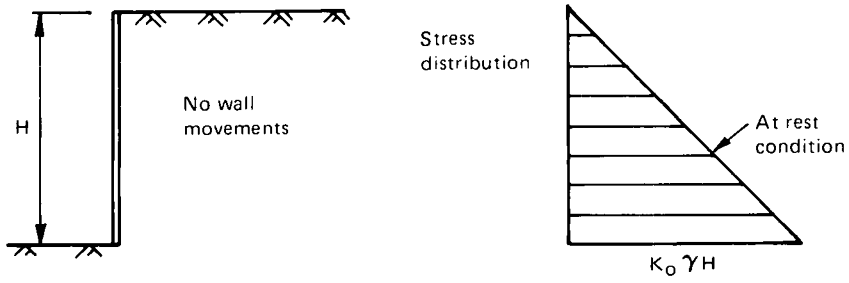
To illustrate the relation between lateral boundary deformations and the states of stress in unreinforced and reinforced backfills, the results from laboratory model retaining walls are summarised in this report. Possible methods of developing controlled yielding of the lateral boundary of soil retaining structures during construction are then described which allow both of the performance requirements of soil retaining structures to be more efficiently satisfied.

2 STATES OF STRESS IN UNREINFORCED AND REINFORCED BACKFILL

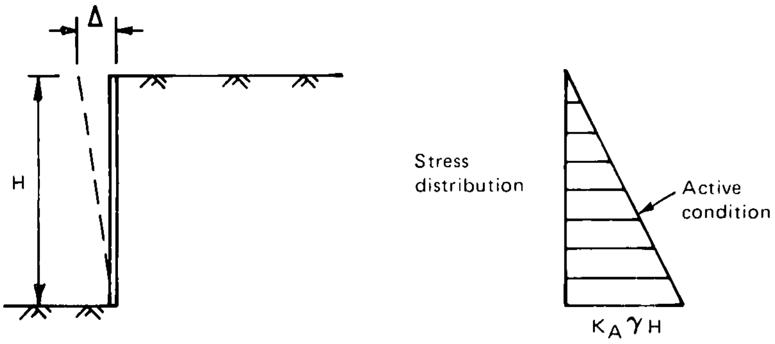
The state of stress in the backfill to a retaining structure is dependent on the shearing resistance which can be mobilised, the amount and pattern of deformations at the lateral boundary, Figure 1, and the construction process employed.

For a fixed, rigid-faced retaining wall, no lateral soil strains are permitted and the soil backfill may therefore be considered to be in an 'at rest' (K_o) condition Figure 1(a). However, the magnitudes of lateral boundary stresses in this condition may attain larger values, particularly if the compaction process has a significant influence. The influence of any reinforcements in the soil is likely to be very small, the only tensile resistance in these reinforcements being generated by the compaction process, which tends to be fairly localised.

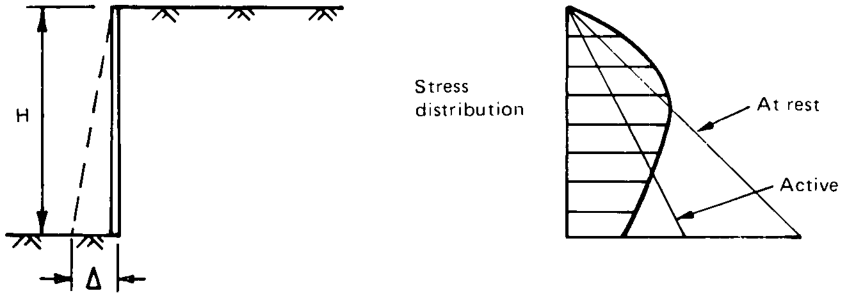
When the magnitude and pattern of outward movements of the lateral boundary are such that the peak shearing resistance of an unreinforced soil backfill is mobilised over the full height of the structure, a condition rarely attained in practice, then a minimum value of lateral boundary stress is established which is known as the 'active' (K_A) condition, Figure 1(b). Where the pattern of deformation of the lateral boundary is such that peak shearing resistance is not fully mobilised at all locations but sufficient overall movement has taken place, 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, Figures 1(c) and (d).



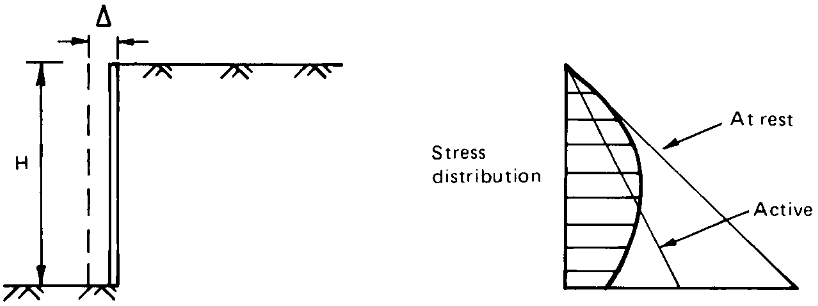
(a) Fixed rigid wall



(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

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. In this state, the lateral boundary deformations could also be very small and the soil in the reinforced structure may be in a state of stress close to its 'at rest' condition, thus the composite reinforced soil exhibits an apparent cohesion or increased angle of internal friction, (Schlosser and Vidal, 1969).

Thus to attain the minimum value of 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 and so produce the most economic and safe form of soil retaining structure.

3 MODEL RETAINING WALL STUDIES

The principle of lateral boundary yielding has been investigated at the University of Strathclyde at model scale employing a 1.0 m high × 0.45 m wide wall mounted in a rigid, glass sided tank 1.17 m high × 0.45 m wide × 1.92 m long, as shown in Plate 1, (Fahim, 1983; Lee, 1985; McGown et al, 1987). Details of the 1 m high retaining wall construction with reinforced backfill are shown in Plate 2. It can be seen from Figure 2, that the wall is composed of twenty separate facing units, each unit comprising a PTFE covered facing plate mounted on a load cell to allow the loads applied at the various levels to be monitored directly. The facing units are fixed to spring loaded shafts as shown in Figure 3. The stiffness of the springs may be varied over a wide range as detailed in Table 1, and they can be employed singly or in pairs. Thus the amount of yielding which occurs is controlled by the stiffness of the springs such that the system with the weakest springs allows sufficient deformation of the lateral boundary to mobilise peak shear strength in the soil. The amount of deformation occurring is monitored by LVDT's mounted directly on the rear of the spring loaded shafts.

A series of tests were carried out in this apparatus using Leighton Buzzard sand as backfill. The sand had the grading shown in Figure 4 and was placed at a dry density of 1.73 t/m^3 using a sand raining technique. The angle of friction corresponding to this density was 49.6° as measured in the shear box apparatus. In some tests the sand was reinforced by one layer of geogrid, the properties of which are detailed in Appendix 1.

Figure 5 shows the stress distributions on the lateral boundary of a fully constrained wall and four other walls supported by spring systems of different but

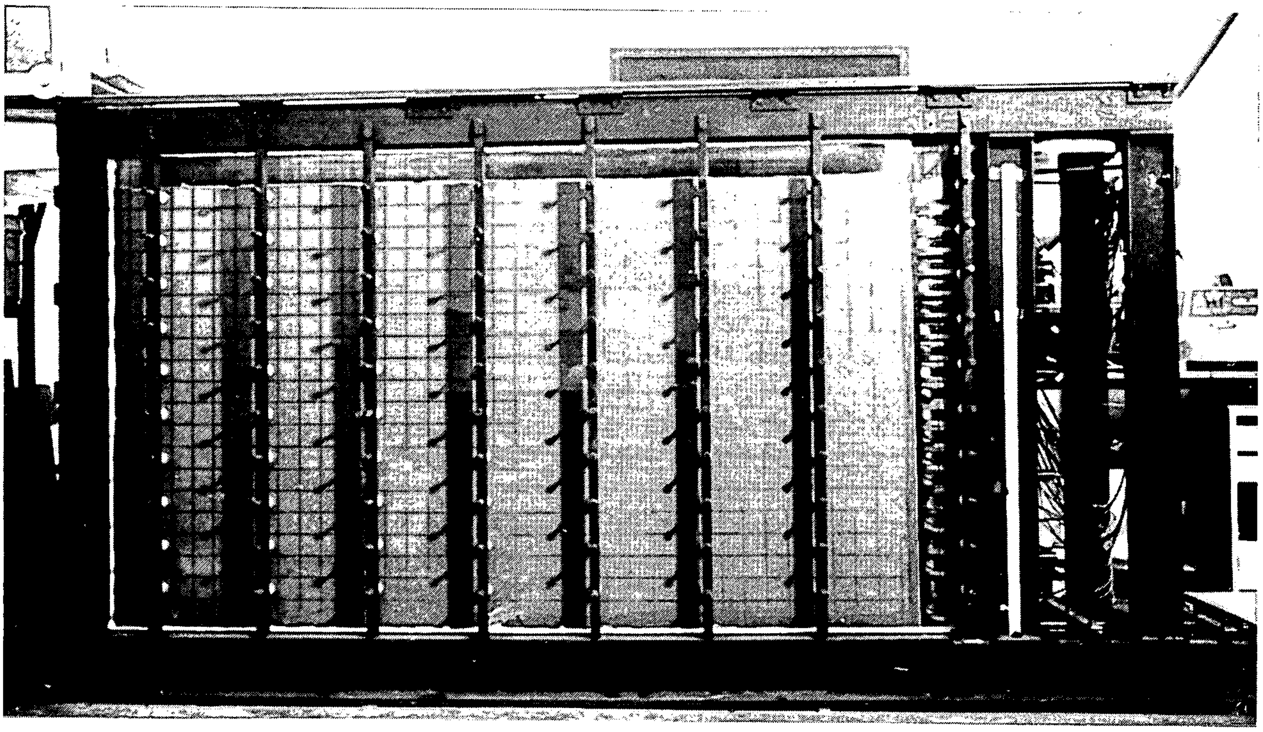


Plate 1 Model retaining wall facility

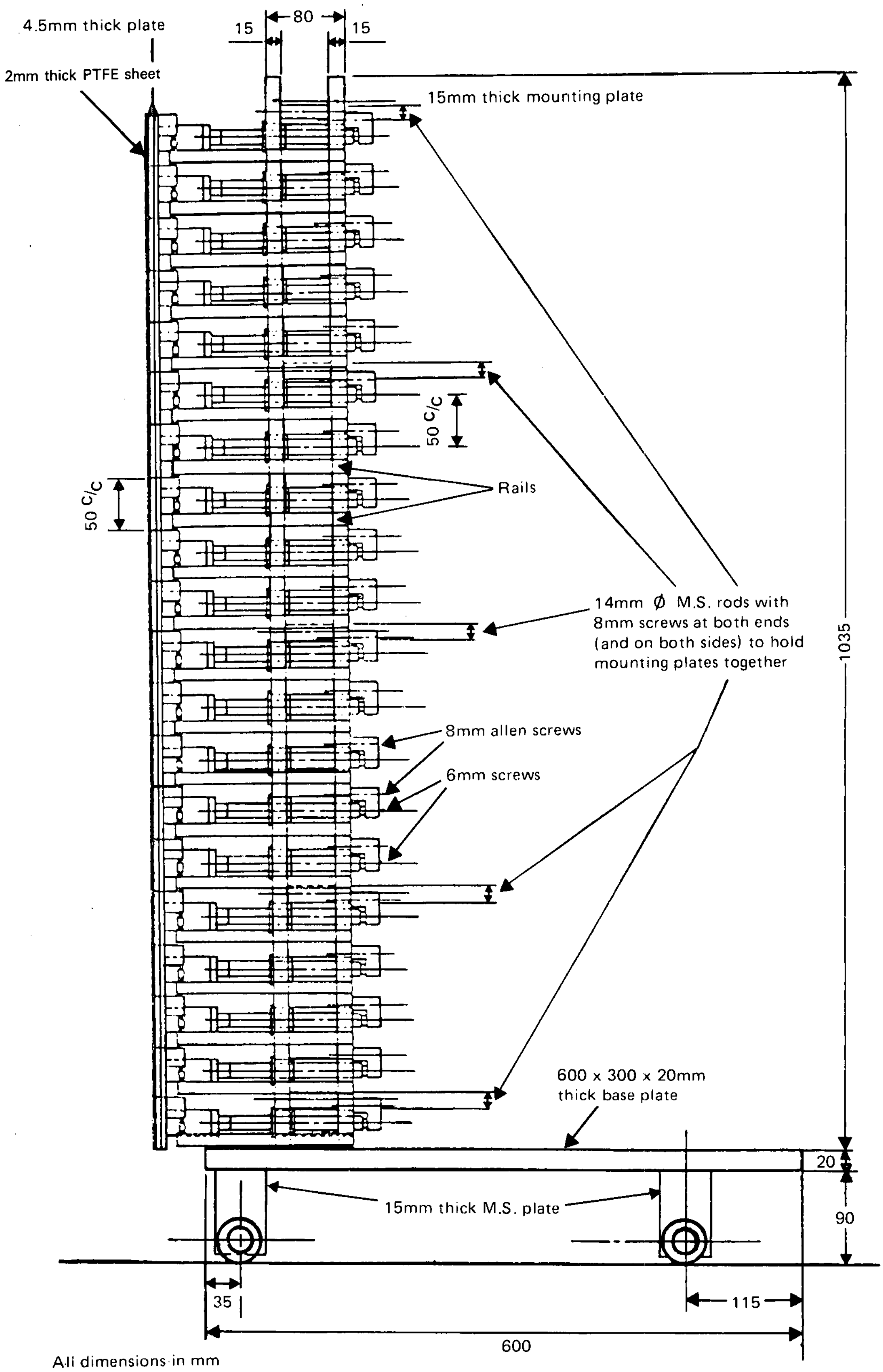


Fig. 2 Side elevation of retaining wall facility

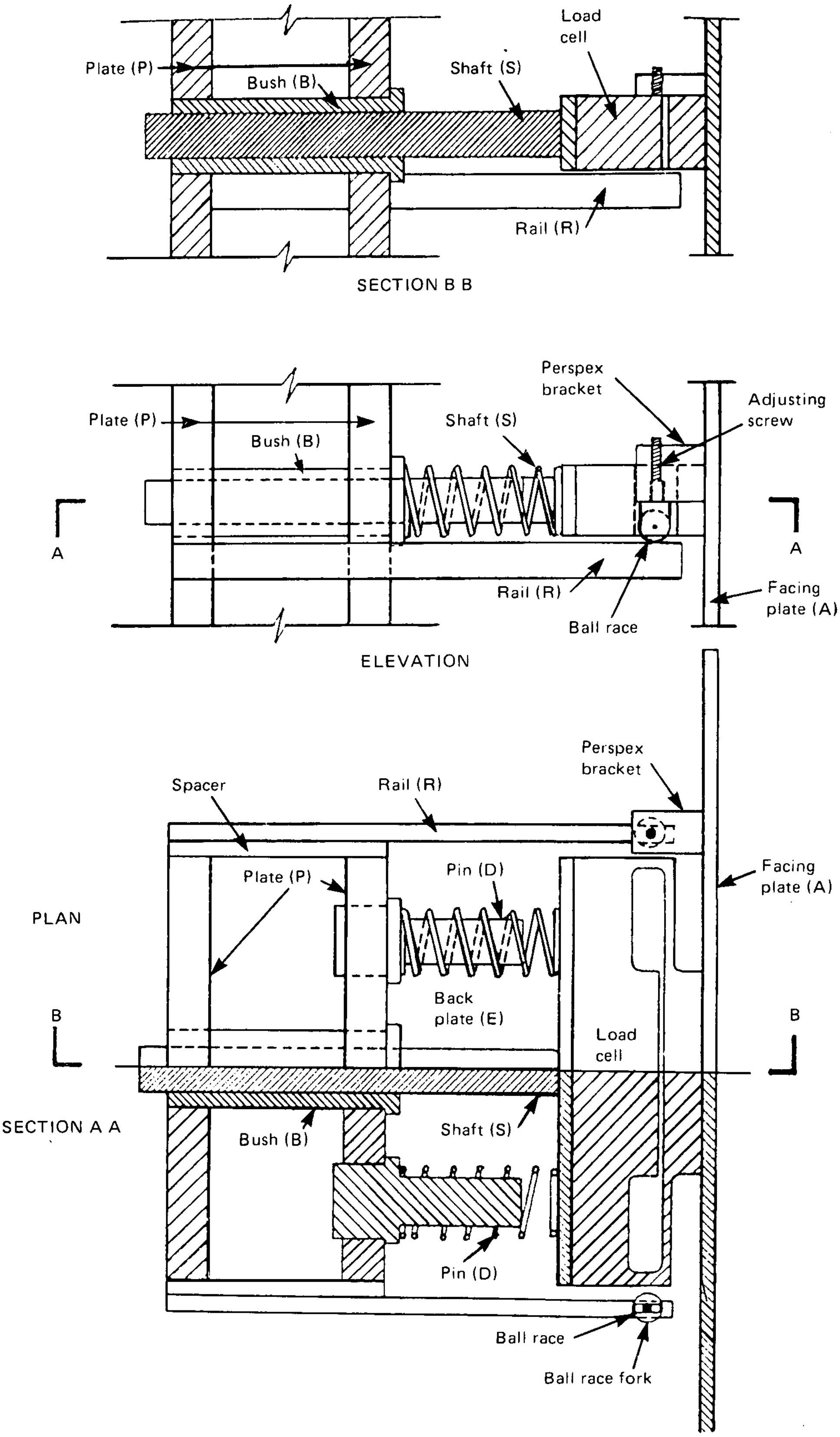


Fig. 3 Details of the facing units and spring loaded shafts

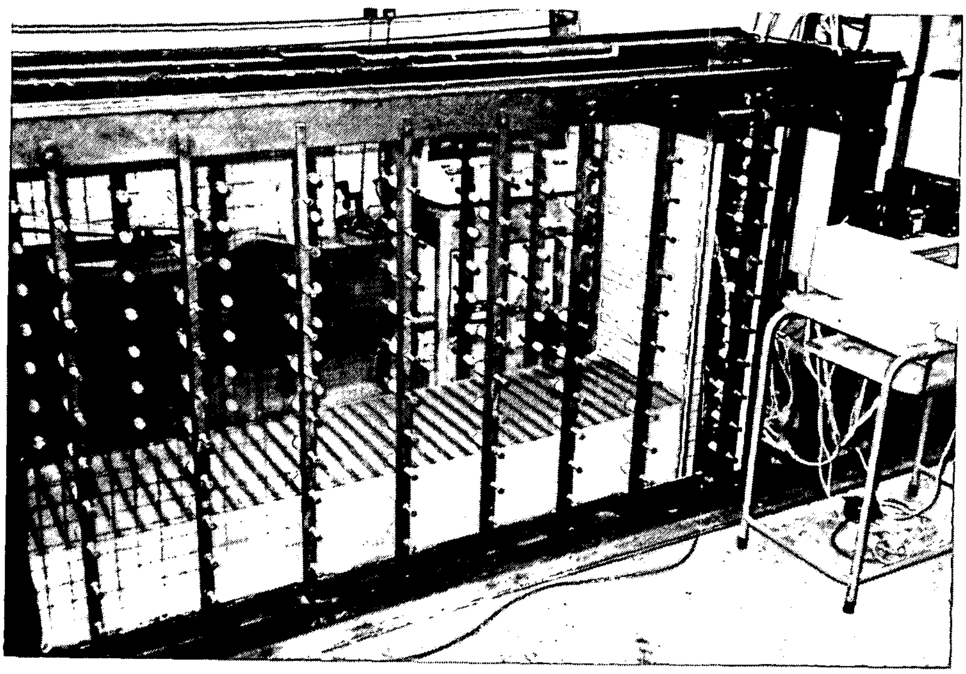


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Plate 2 Details of retaining wall construction with reinforced backfill

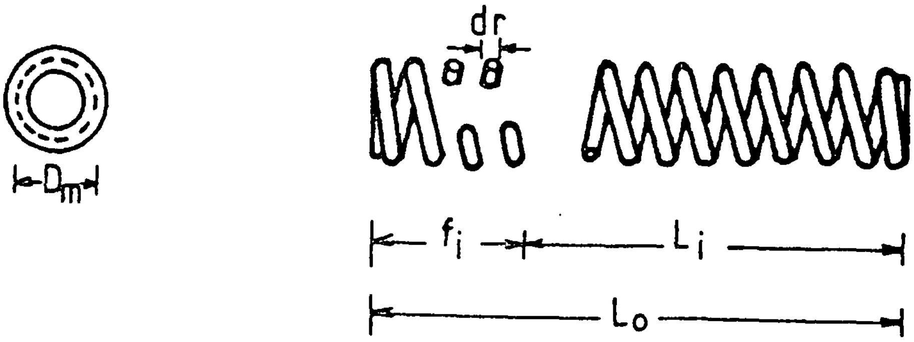


TABLE 1.

Details of the spring used in the Yielding Walls

Type	dr	D_m	L_o	L_i	P_i	P_i/f_i	Material
Stiff (used as a pair)	4.0	25.0	41.0	22.9	709.88	39.7	Stainless Steel
Medium (used as a pair)	2.5	20.0	54.0	21.9	243.43	7.54	Stainless Steel
Soft (used as a pair)	2.5	20.0	108.0	43.8	486.86	3.77	Stainless Steel
Very Soft (used singly)							

where:—

dr = Wire diameter (mm)
D_m = Mean coil diameter (mm)
L_o = Free length (mm)
L_i = *Loaded length (mm)*

P_i = Load at Li (N)
f_i = Deformation at Load Pi (mm)
R_i/f_i = Spring stiffness (N/mm)

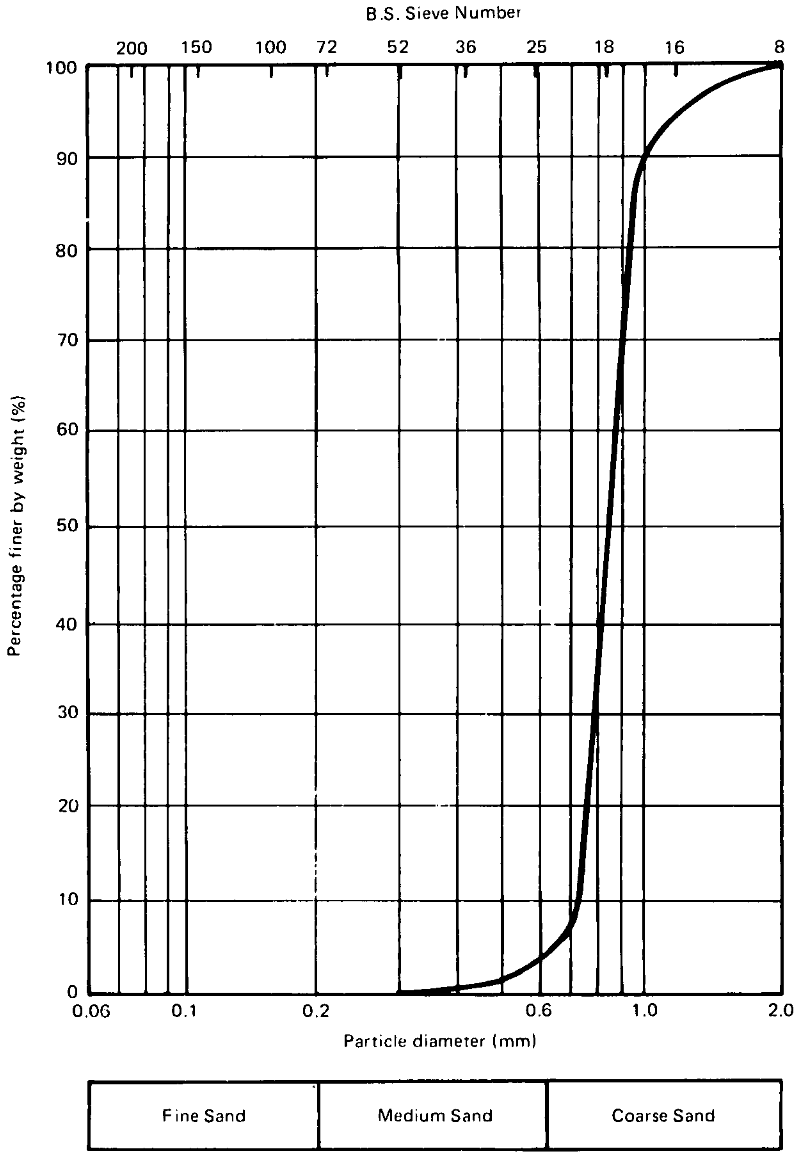


Fig. 4 Particle size distribution curve for Leighton Buzzard sand

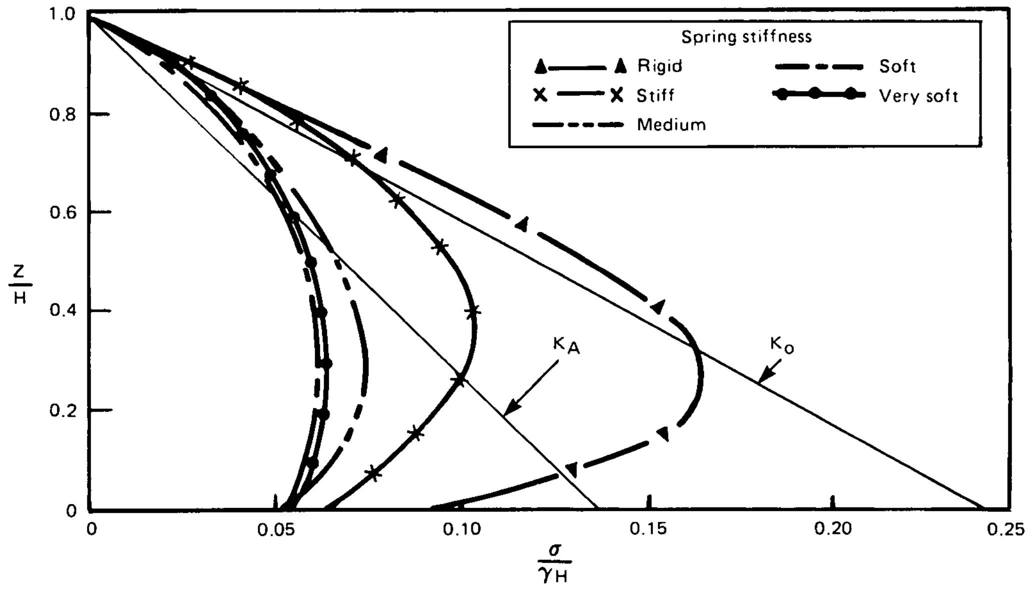


Fig. 5 Lateral stress distribution with sand backfill

uniform stiffnesses. The results are presented in non-dimensional form by expressing the recorded stress (σ) as a proportion of the vertical stress (γ H), where γ is the unit weight of the backfill and H is the full height of the wall, versus the height factor (Z/H), where Z is the height above the base of the wall of 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_0) 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_0) conditions, and close to the 'active' (K_A) conditions 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 Figure 5 the corresponding lateral boundary movements measured in this way are shown as in Figure 6, in non-dimensional form, (with Δ the lateral movement at height Z above the base of the wall of full height H).

An 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 Figure 5, would be as presented in Figure 7. 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 Figures 6 and 7 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 Figure 5 support the contention that soil behaviour more closely reflects 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 stiffness incorporating a single layer of reinforcement at mid-height are presented in Figures 8 and 9 respectively. The distribution of boundary movement in the latter figure were determined on the basis of the procedure used for Figure 6. As shown in Figure 8, the largest stresses were associated with the wall supported by the springs of greatest stiffness and the smallest stresses with the wall supported by springs of least stiffness.

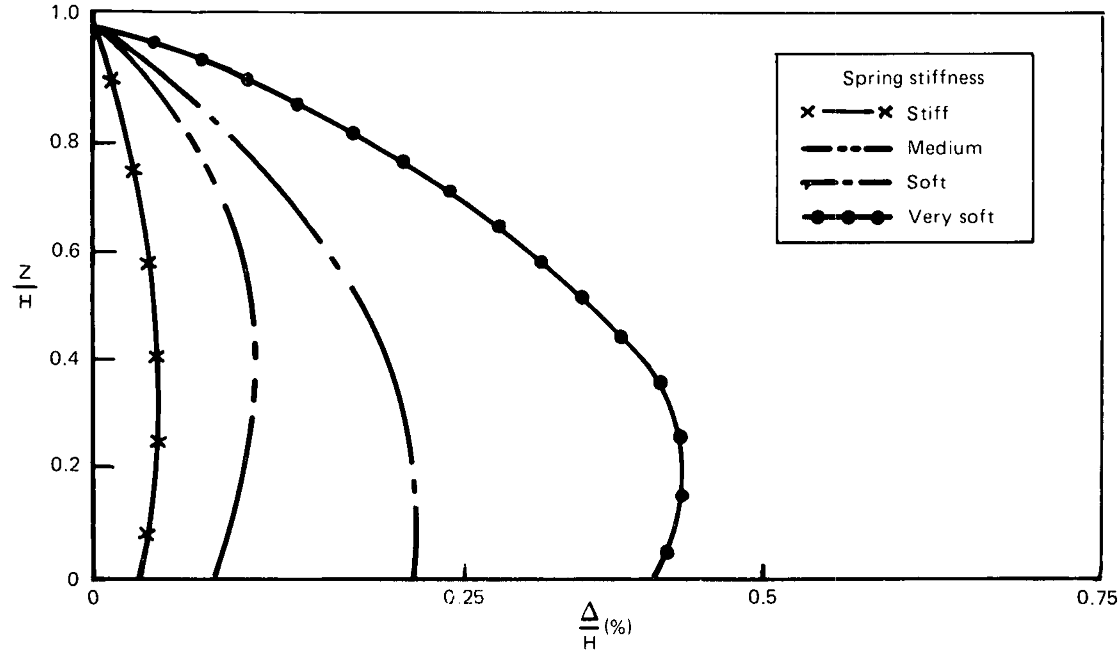


Fig. 6 Distributions of movements with sand backfill for the facing units set to a vertical datum

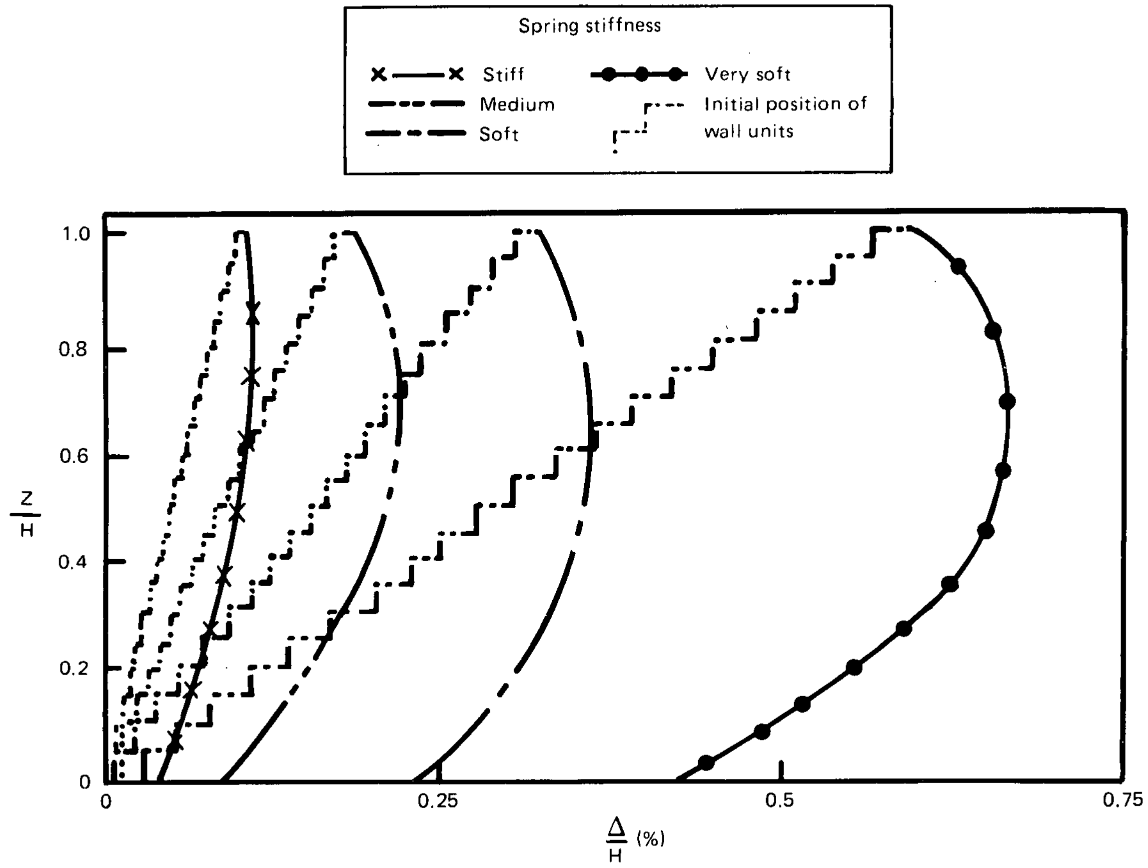


Fig. 7 Distributions of accumulated movements for walls supporting sand backfill

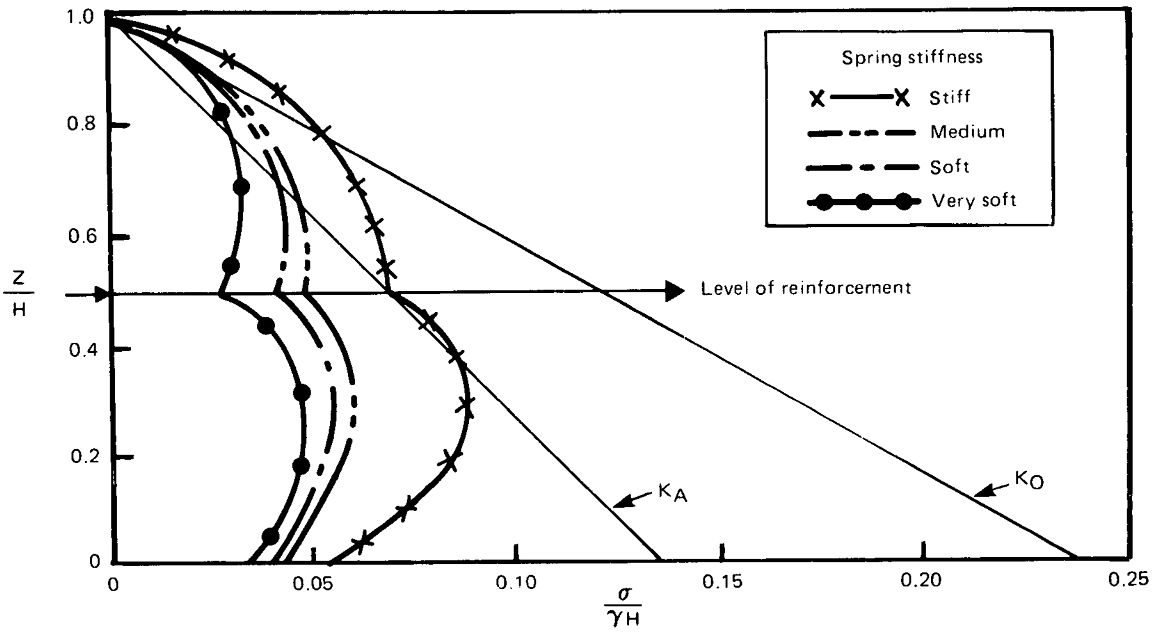


Fig. 8 Lateral stress distribution with sand backfill and one layer of geogrid reinforcement

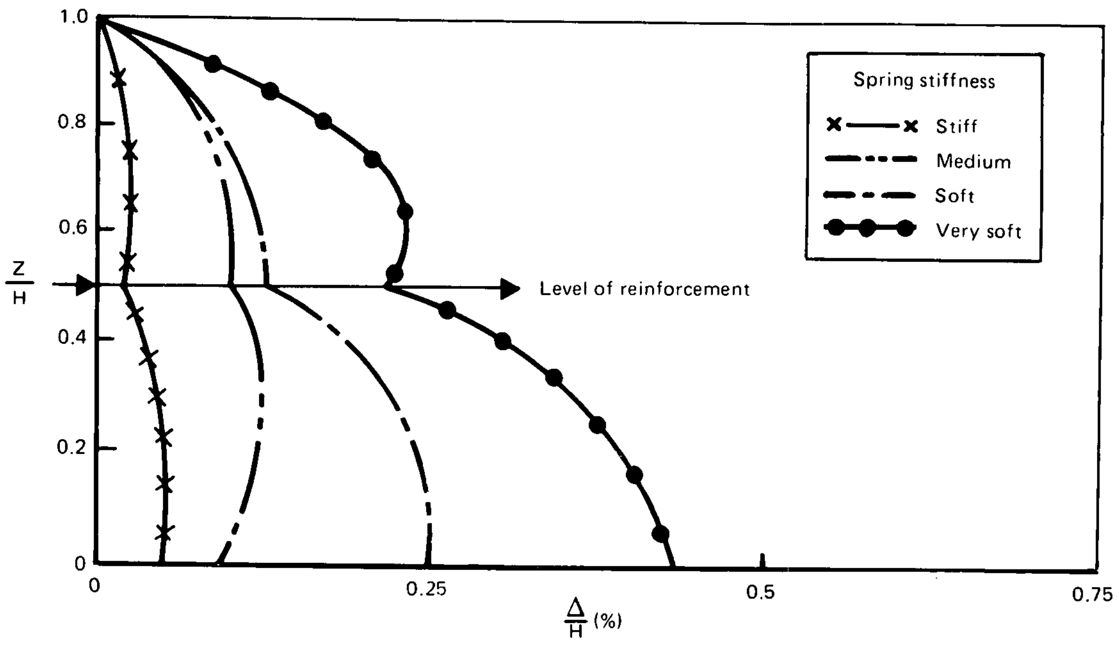


Fig. 9 **Distribution of movements with sand backfill and one layer of geogrid reinforcement for the facing units set to a vertical datum**

The corresponding lateral stress distributions and boundary movements for walls of various stiffness and with ten equally spaced layers of reinforcement are shown in Figure 10. 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 Figure 10 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 conditions 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 CONTROLLED YIELDING OF LATERAL BOUNDARIES OF SOIL RETAINING STRUCTURES

In practice, a simple method of inducing lateral boundary yielding is to provide a compressible layer between the wall, or facing unit and the backfill. Providing this layer is sufficiently compressible then it will allow the development of the necessary lateral expansion of backfills and so establish the minimum possible lateral boundary stresses without the need for movements of the wall facing. However, it will be necessary to control the construction process by imposing limitations on the size of plant that can operate close to the wall, otherwise the compressible layer might become fully compressed during compaction of the fill and so lose its effectiveness for reducing lateral forces at a later stage. Moreover, it is desirable that the layer should have some 'elastic' recovery properties such that it can rebound after compaction and so avoid cracks developing in the backfill.

For unreinforced backfills there does not appear to be any major construction difficulty associated with the use of a compressible layer behind a wall.

For reinforced backfills, it will be necessary to temporarily hold the facing units in place during construction by propping or some other arrangement, whilst allowing the unattached reinforcements and soil to expand laterally by virtue of the compressible layer behind the facing units. After completion of the backfilling operations the reinforcements are attached to the facing units and the temporary support to the wall or facing unit can then be removed, Figure 11. If the reinforcing elements are extensible and subject to creep under load, then it is possible to delay the final locking up of reinforcements to the facing units for a relatively short period to allow the large majority of time dependent strains in the reinforcements to occur prior to their attachment to the facing units, so reducing possible post construction movements.

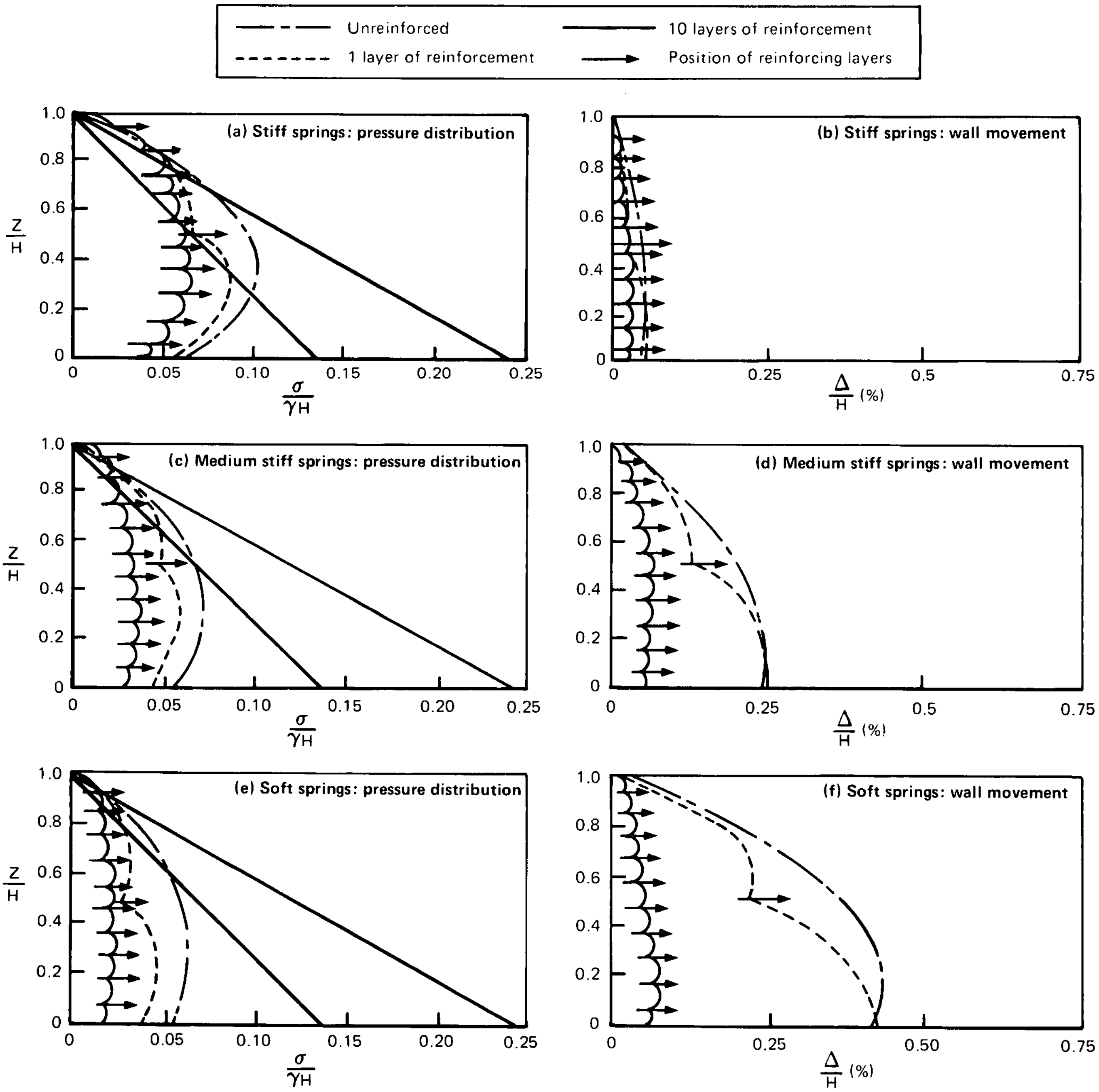


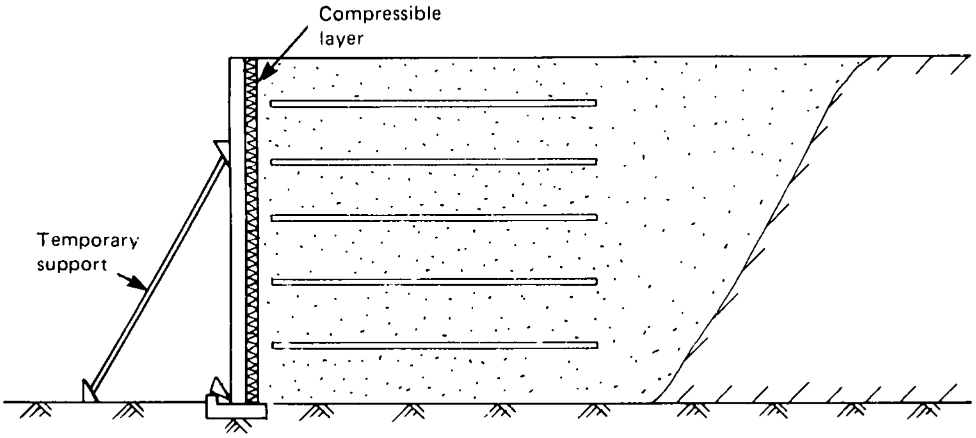
Fig. 10 Lateral pressures and movements of the yielding wall

Methods for temporarily locking, unlocking and relocking reinforcing elements to facing units have been developed previously (Murray and Irwin, 1981), as shown in Figure 12, and could be used in conjunction with the compressible layer construction method. These techniques were developed to relieve pressures on facing units but their use with the compressible layer is an enhancement which ensures that their effect on stress distribution is more uniformly and widely spread.

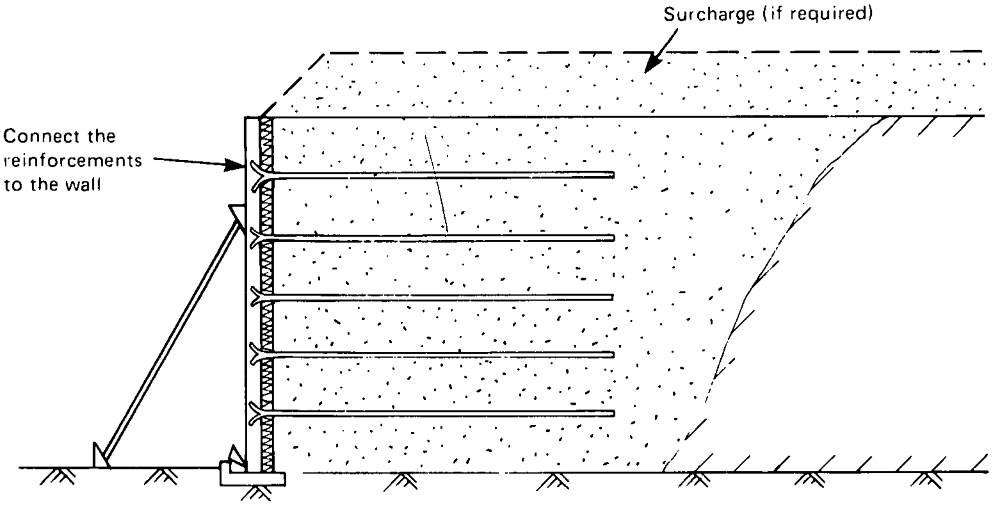
Further, in many situations the compressible layer may serve a dual role by acting as a drainage layer, so producing further reductions in the imposed stresses by lowering the groundwater table.

5 CONCLUSIONS

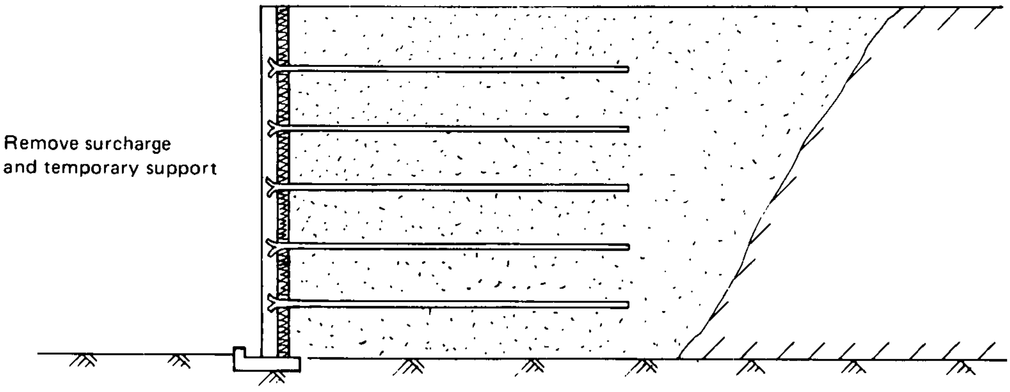
1. A comprehensive study of the lateral boundary stresses and movements developed in a specially constructed laboratory wall facility has been carried out. The results from this study indicate that the lateral stress distributions were greatly influenced by



(a) Propped wall



(b) Propped wall and surcharge



(c) Final structure

Fig. 11 Suggested sequence of construction

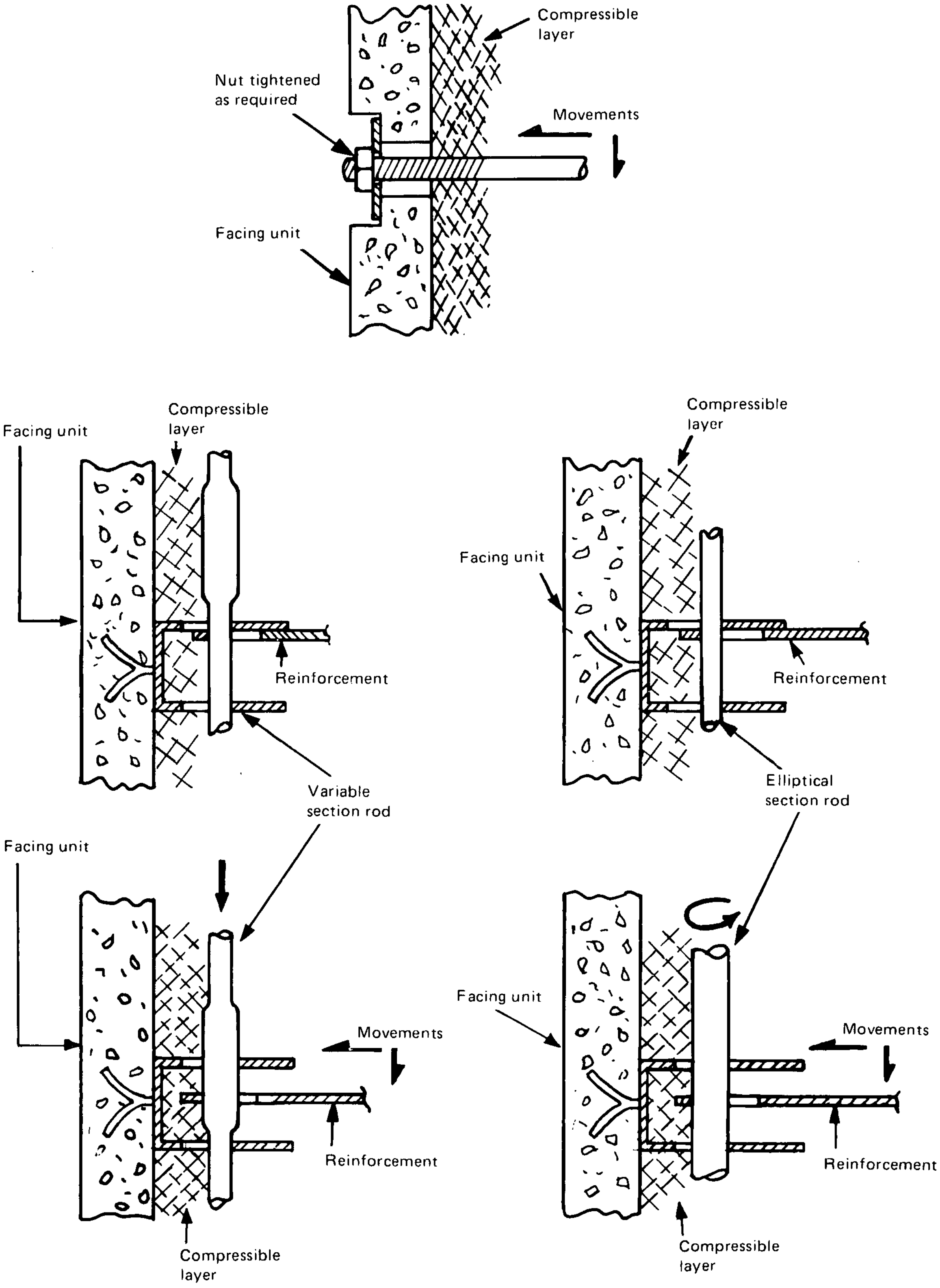


Fig. 12 Some methods of locking reinforcements to facing units

the magnitude and pattern of lateral boundary movements. This behaviour applies to both the unreinforced and reinforced sand backfills and may be attributed to the ability of the system to allow the mobilisation of the shear strength of the soil and interaction between the soil and the reinforcement.

2. An important finding of the study was that the pattern of soil movement is best represented by an incremental approach in which the movement of each facing unit is referred to its initial position rather than by the cumulative procedure normally adopted in practice to assess wall movements.

3. Based on the incremental approach of establishing wall movements, the study showed that walls constructed with a number of discrete facing units, tend to rotate about their top; a result which conflicts with the widely held assumption that rotation will take place about the base.

4. The distributions of lateral stress differed significantly from the hydrostatic forms derived on the basis of either 'at rest' or 'active' conditions and conformed most closely with a distribution indicative of rotation about the top. In this regard, the lateral stress distribution data thus support the pattern of wall movements indicated by the incremental approach.

5. Possible methods of developing controlled yielding of the lateral boundaries of soil retaining structures during construction has been identified which allows the establishment of the minimum possible lateral boundary stresses without the need for significant movements of the facing units.

6. The results presented were based on relatively small scale laboratory walls but have considerable significance in relation to full scale retaining walls and other structures. It will be essential to confirm these findings at full-scale and to further develop procedures for achieving boundary yielding in practice.

6 ACKNOWLEDGEMENTS

The work described in this Report was carried out in the Department of Civil Engineering of the University of Strathclyde in conjunction with the Ground Engineering Division of the Structures Department of TRRL.

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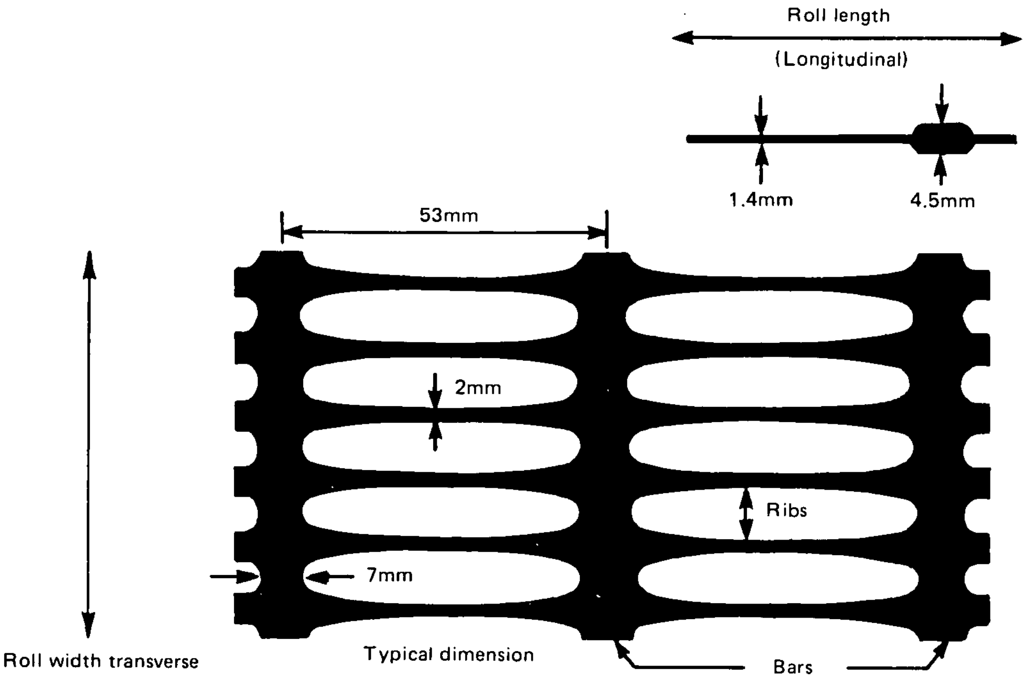
8 APPENDIX A PROPERTIES OF THE REINFORCEMENT GRIDS

The reinforcement used in these studies was a High Density Polyethylene (HDPE) grid produced by Netlon Limited and referred to as TENSAR SR2. The geometry, dimensions and load-extension relation based on the manufacturers data are shown in Figure A1



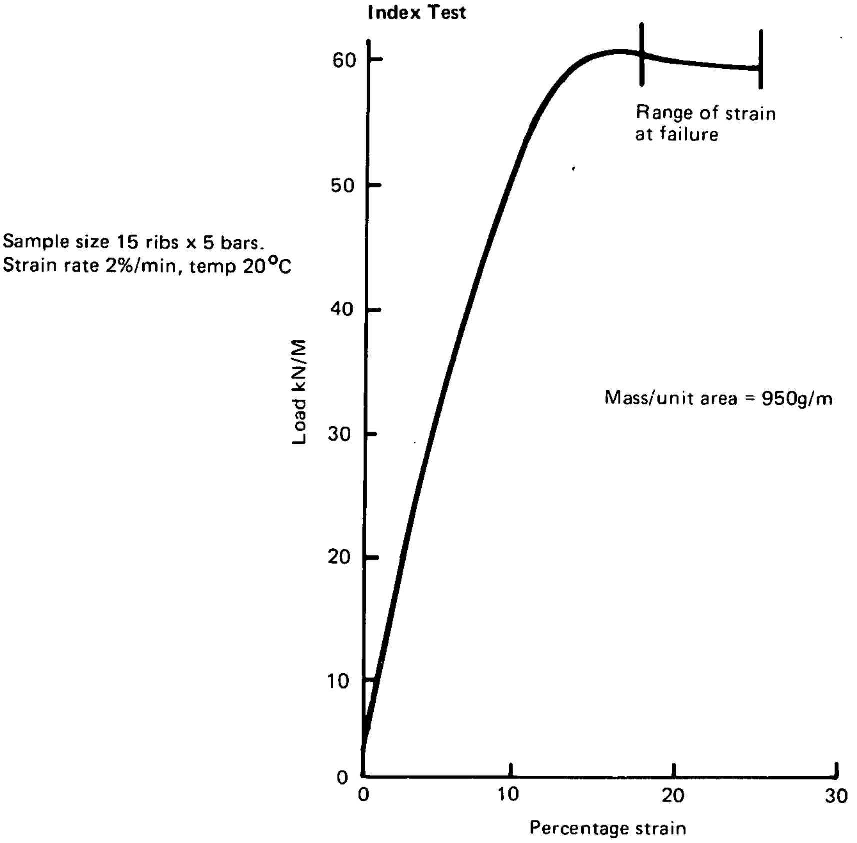


Fig. A1 Details of the geogrid reinforcements

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