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EXPERIMENTAL RETAINING WALL FACILITY – LATERAL STRESS MEASUREMENTS WITH SAND BACKFILL

by

D R Carder BSc PhD, R G Pocock
and
R T Murray BSc M Inst HE

Earthworks and Underground Pipes Division
Structures Department
Transport and Road Research Laboratory
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ABSTRACT

As part of the TRRL research programme to investigate soil-structure interaction, a pilot scale earth retaining wall has been built at the Laboratory sufficiently large to avoid any scale effects influencing the results and to enable normal construction methods to be used. This report describes the experimental retaining wall and its facilities and gives details of the initial experiments to measure the lateral soil pressure by compaction of a washed sand, and the active and passive pressures produced when the wall was moved away from and into the soil respectively.

The experimental evidence shows that the residual earth pressures produced by the compaction of sand behind a rigid retaining wall are significantly higher than would be expected from the self-weight of the soil alone. However, only very small movements (< 4mm) of the test wall away from the soil were sufficient to reduce the earth pressures to the active condition for a fill height equivalent to 3.4 metres. A study of the passive case showed that a peak lateral thrust occurred on a metre high test wall after a movement of about 25mm of the wall into the soil.

1. INTRODUCTION

The design of earth retaining structures is at present based on simplified theories which, despite major advances in other fields of soil mechanics, have not changed in principle during this century. In these theories, simplifying assumptions are made and fairly large factors of safety are introduced to cover uncertainties. With more reliable information on the earth pressures involved and the factors which control them it is probable that significant savings will be achieved in the design and construction of earth retaining structures. These savings are likely to result from a numerical reduction in the factors of safety and an increased use of low grade materials for backfilling behind retaining structures.

Most of the previous work on this subject has been theoretical or limited to small-scale studies using granular back-fill material. Some field investigations have been made but these have been hampered by the difficulty of isolating the various factors, the lack of reliable instruments and the problems of interpreting the measurements. To overcome some of those problems an experimental retaining wall incorporating 2-metre square articulated steel panels has been built at the Laboratory of sufficiently large dimensions to avoid any scale effects influencing the results and to enable normal construction methods to be used.

It is known that high residual earth pressures can develop behind rigid structures during the compaction of the fill and that these pressures are often larger than those used in the design of structures. In this programme of research the magnitude of these pressures will be monitored for a range of backfill materials and the effect of wall movements on the pressures studied. This report describes the experimental retaining wall facility and gives details of the initial experiments to measure the lateral soil pressures produced by compaction of a washed sand, and the active and passive pressures produced when the wall was moved away from and into the soil respectively.

2. EXPERIMENTAL RETAINING WALL

The experimental retaining wall is sited in a pilot scale building at the Laboratory and is positioned within a concrete trough so that the interaction between the soil and the wall is divorced from the surrounding building and not influenced by any external movements. To allow additional measurements to be made of the influence of wall rigidity on the earth pressure, a 1 metre thick reinforced concrete wall has also been constructed opposite to the metal wall so that pressures developed during the compaction process can be measured simultaneously on both walls. The design of the trough and the position of the two walls is shown in Fig. 1.

The experimental metal wall is shown in Plate 1 and consists of three 2-metre square articulated steel panels. The outer wall panels serve to protect the instrumented centre panel from any side effects which could otherwise have influenced the recorded stress levels. A jacking system capable of developing a total thrust of about 2 Meganewtons is sited behind the wall and permits translational movements of up to 400mm and rotations from the vertical through an angle of 17 degrees. The distribution of stress on the centre panel is measured using three vertical profiles of pressure cells as shown in Plate 1. In addition this panel is supported by vertical and horizontal load cells which record the total force acting on the panel. A similar arrangement of pressure cells is provided on a metal panel inset in the reinforced concrete support wall as is shown in Plate 2.

The metal test wall has been designed to ensure minimum structural deformation and incorporates an adjustment system that allows movements to be controlled very accurately. Reinforced concrete pillars have been erected on the concrete trough close to the edges of the retaining wall and the movement of each of the wall panels can be related to these pillars. As the pillars may displace very slightly under the stress conditions set up by the placement of the soil, two independent techniques were employed for monitoring their movement. In the first method, a laser beam directed between two piles located beyond the influence of the structure acted as a reference datum to which movements of the metal wall were related. The second method utilised the neutral axis location between the two walls (Fig. 1) and measurements of the wall movements were obtained relative to this axis employing an invar tape and precision optical plummet. The reproducibility of successive measurements using the two systems was always better than 0.05mm and the overall accuracy was considered to be close to this figure, although large changes in temperature were found to adversely affect the precision of the laser. Further details of the two methods are given in Appendix 1.

3. SOIL PRESSURE CELLS

The lateral earth pressures acting on the wall were measured using three types of soil pressure cell employing different operating principles. One type operated on an hydraulic principle, a second type employed pneumatic air pressure and the third type used bonded electrical resistance strain gauges. A full description of these cells together with a discussion of their operating performance in different soil conditions is given in an earlier publication[1] All three types of cell were constructed with an overall diameter of 140mm and were mounted flush with the surface of the wall in three vertical profiles as shown in Plate 1. During compaction of the soil, the loading face of the strain gauge cell was locked in position to avoid damage resulting from the large dynamic stresses induced by the vibrating roller; the cell being released when filling was complete.

4. PROPERTIES OF THE SOIL

For the initial investigation a uniformly-graded washed sand from Bramshill (Hampshire) was used. The particle-size distribution of the sand is shown in Fig. 2 and its specific gravity was determined as 2.63. A vibrating hammer test was carried out in accordance with BS1377[2] to determine the relationship between dry density and moisture content for the granular soil and the results are shown in Fig. 3. The optimum moisture content for compaction of the sand was found to be 10 per cent and during the filling operations the moisture content of the sand was maintained as near to this figure as possible. Subsequent measurements on the compacted fill showed that its average moisture content and bulk density were 10.5% and 2.0 Mg/m^3 respectively.

5. EXPERIMENTAL PROCEDURE

The sand was spread and compacted in 0.15 m layers behind both walls to a final height of 2 metres. The compaction plant used was a 1.3 Mg twin-roll vibrating roller and Plate 3 shows the roller compacting the sand against the wall. Six passes of the roller were used to compact the fill and the closest the roller edge came to the retaining walls was a distance of about 0.15 m. During construction the plant was removed after compaction of each layer and measurements were made of the pressures acting on the walls together with the magnitude of the movements. Frequent measurements of soil density and moisture content were also taken to provide information as to the soil condition.

Preliminary experiments on the compacted fill had shown that a very slight movement ($<$ 0.5mm) of the 2 metre high wall away from the soil was sufficient to cause a significant reduction in the measured stress. For this reason the active condition was studied after first surcharging the fill with concrete blocks to produce a uniform surcharge stress of 27 kPa which corresponded to an additional height of fill of 1.4 metres. The experiment could then be more accurately controlled because of the proportionally larger displacements induced by a higher wall. The active condition studied corresponded to a uniform translation of the wall away from the soil in increments of 0.1mm.

For the passive study the sand was placed and compacted in the usual way, although only 1 metre height of fill was used to avoid overloading the jacking system. The wall was then jacked uniformly into the soil until the total horizontal thrust measured by the load cells began to fall, indicating that the limiting shear strength of the soil had been exceeded.

6. RESULTS

6.1 Residual stresses after compaction

The distribution of the residual stresses on the metal retaining wall is shown in Fig. 4 for each of the three profiles of pressure cell types. In this figure corrections have been made for the appropriate cell factors (ie. the ratios of measured to applied stress), which were determined as 0.85, 1.01 and 2.41 for the strain gauge, hydraulic and pneumatic cells respectively. These factors were established for each cell type by first determining the apparent total lateral stress on the wall from the stress distribution for that particular profile of cells. The cell factor was then calculated as the ratio of the total stress recorded by the cells to the actual stress as measured by the load cells. Previous work[1] had indicated that cell factors were influenced by the level of applied stress but in this work where only a limited range of pressure occurred (5–25 kPa) it was considered justifiable to assume a constant factor. This method was preferred to using a factor determined from the laboratory calibration of pressure cells, particularly as the pressure cell readings were relatively small and in the region where the laboratory calibrations were considered less accurate. Unfortunately, as the procedure of locking the strain gauge cells was found to introduce errors in the readings, the results from these gauges were not as reliable as those of the other cells. Also shown plotted in Fig. 4 is the displacement at each level of the wall from the stage when soil was first compacted at that level until compaction to full height was complete. Any such recorded displacement of the wall away from the soil produced a reduction in the residual stress measured, when the filling was completed.

The results of a further experiment in which the stresses were recorded on both the metal retaining wall and the reinforced concrete wall are shown in Fig. 5. In this particular experiment only two vertical profiles of pressures were obtained for the metal wall as instruments were not available for the third profile. The pressure cell results for the metal retaining wall were corrected as described above using the value of total thrust measured by the load cells. The cell factors determined were then applied to correct the pressure cell readings obtained for the concrete wall.

A summary of these results is presented in Fig. 6 where the average distributions of stress are plotted. Fig 6(a) shows the comparison between the results of the two separate experiments on the metal retaining wall, whilst Fig 6(b) relates to the second experiment only and demonstrates that slightly higher stresses were recorded on the reinforced concrete wall than on the metal test wall. In both cases significantly higher lateral stresses were recorded than were calculated from the product of the coefficient of earth pressure at rest (Ko) and the self weight of the soil alone.

6.2 The active condition

The variation in the forces acting horizontally and vertically downwards on a metre length of retaining wall are shown plotted against wall movement in Fig 7. The minimum values of the forces occurred after a wall movement of 4mm, although most of the reduction in force took place during the first millimetre of wall movement.

6.3 The passive condition

The results for the passive study using 1 metre of fill are shown in Fig 8. A peak horizontal thrust of nearly a 100 kN per metre length of wall was recorded after jacking the wall a distance of about 25mm into the sand. In this case a fairly large upward force was measured on the wall face in contrast to the downward force normally acting on the retaining structure.

7. DISCUSSION

Current design practice for earth retaining structures is such that no allowance is made for the pressures which result from the action of the compaction plant. The experimental evidence for a compacted sand backfill presented in Fig 6(a) shows that the residual earth pressures on the top metre of the test wall were significantly higher than would be expected from the self weight of the soil alone. If account is taken of the yielding of the test wall (Fig 4), even larger residual stresses might be expected behind a completely rigid structure. This has been proven by the results for the more rigid reinforced concrete wall as shown in Fig 6(b) where larger stresses were recorded than with the metal test wall. Although the magnitude of the residual stresses will depend on the type and size of the compaction plant employed, the maximum stresses at the very top of the wall cannot exceed the lateral pressure calculated using the coefficient of earth pressure for unloading $(K_O{}^1)$[3,4]. This unloading line is shown plotted in Fig 6 and was calculated on the assumption that Ko^1 equals 1/Ko. The value of Ko itself was calculated from Jaky's equation[5] that Ko = 1 − sin ϕ for granular soils, where ϕ is the angle of internal friction and was found from triaxial tests to be 38.7°.

Normal design procedure has been to assume that the yield of the wall is sufficient to relieve these residual compaction stresses and to mobilise the full shearing strength of the backfill. This study has provided reliable data on the magnitude of the wall movements necessary to achieve the active condition. For an equivalent height of sand of 3.4 metres a wall movement of only 1mm was sufficient to cause a 70% reduction in the lateral stress against the wall as was shown in Fig 7. Thus, provided a wall of this height was sufficiently flexible to permit a slightly larger movement of 4mm subsequent to the completion of filling, then the active value for the earth pressure is a justifiable design criteria. This result is in close agreement with the work of Terzaghi[6] who reported that the minimum value of earth pressure for a dry sand occurred after a lateral movement one-thousandth of the depth of fill.

The passive resistance of the sand is also an important design consideration and for a metre high wall a maximum horizontal thrust of 100 kN was recorded after an inward wall movement of about 25mm. Assuming a triangular distribution for the lateral pressure of the sand on the retaining wall, this would correspond to a coefficient of passive resistance of about 10. This value is comparable to the coefficient of 7.9 calculated from Coulomb Theory assuming a friction angle of 15° between the sand and the metal surface of the wall. The effect that the high residual compaction stresses are likely to have on the pressures developed during the subsequent wall movement and the influence of wall friction need further investigation.

8. CONCLUSIONS

Two pilot scale retaining walls 2 metres in height with lengths exceeding 6 metres have been built at the Laboratory to study the pressures and deformations produced during and after the earth filling operations behind the walls. It is considered that the facility is sufficiently large to avoid any of the scaling effects which normally occur with models and in addition permits conventional construction techniques and compaction plant to be employed. The facility may also be used to measure the effect of other sources of compacting energy such as the passage of rail traffic and plant used for the backfill of trenches.

Initial experiments using sand backfilled behind the test walls have shown that:–

1. Significant residual lateral stresses are produced by the compaction of sand behind rigid retaining walls.

2. Only very small translations (< 4mm) of the test wall away from the soil were sufficient to develop the fully active condition of the sand for a fill height equivalent to 3.4 metres.

3. A peak lateral thrust was measured on a metre high test wall after a movement of about 25mm of the wall into the sand. The influence of wall friction on this result needs further investigation.

Further research will include a study of the lateral stresses on retaining structures backfilled with cohesive soils.

9. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Earthworks and Underground Pipes Division of the Structures Department of TRRL. The Division was under the direction of Mr J B Boden and the investigation forms part of the research programme of the Soil-Structure Interaction Section. Thanks are due to Mr I F Symons, Mr M.J Irwin, Mr J Krawczyk, Mr J Cross, and also to Mr F W L Shepard (Civil Engineering) for his assistance with designs for the system to measure wall movements.

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11. APPENDIX 1

MEASUREMENTS OF WALL MOVEMENT

Very small wall movements (< 0.5mm) were found to have a significant influence upon the lateral stresses developed on the retaining walls, and for this reason a measurement system accurate to at least 0.1mm was desirable. One of the difficulties in recording movements of such a large structure to this accuracy, was in establishing a reliable reference datum. Two independent techniques for establishing a datum are described. In the first method a laser beam is employed to relate movements of the structure to points remote from the experiment, and in the second method all measurements are related using precision optical equipment to the neutral axis location between the two retaining walls.

11.1 A reference datum employing a laser beam technique

Two metal piles were installed beyond the immediate area of the experiment as shown in Fig 9(a). On one of the piles a 2 milliwatt helium-neon "ruby" laser was mounted and on the other pile was located a graduated target screen towards which the laser beam was directed.

Intermediate between the laser and target, two reinforced concrete pillars were erected with centres at distances of 0.3m from the outer edges of the metal wall (Fig 9(a)). A zone plate was mounted alternately on each of these pillars to focus the laser onto the graduated target screen, and thus any displacement of the pillar was determined from the movement of the laser spot on the screen. Using this system the position of both reference pillars was accurately monitored and displacements as small as 0.05mm could be detected, although large fluctuations in temperatures were found to adversely effect the accuracy of measurements as is discussed later.

Once the position of the reinforced concrete pillars was established, movements of each of the three panels which comprise the metal wall were related to them. For this purpose a constant tension reference wire spanned the gap between pulleys fixed to the pillars at two different levels, and wall movements were monitored by measuring the change in distance between the reference wire and the wall face at each of the twelve indicated positions (Fig 9(b)). This measurement involved operating a micrometer the movement of which resets an "air sensor" onto the reference wire, this sensor was directly connected to a dial gauge which bears on a stainless steel plate fixed to the retaining wall. The connection between the sensor and the dial gauge was made of invar to minimise the errors produced by temperature changes. The "air sensor" is a commercially available device in which a flow of air was maintained between two fine jets. As the reference wire interrupted the flow of air between the jets, the difference in air pressure was amplified and actuated an air-operated indicator locating the position of the wire. Tests using this equipment showed that the distance between the retaining wall and the reinforced concrete pillars could be measured to an accuracy of better than ± 0.015mm.

As mentioned earlier however, the laser system can be affected by temperature gradients in the air space along the face of the wall and, on the occasions when large changes in air temperature occurred, quite large apparent movements of the wall (± 0.2mm) were measured without causing any corresponding change in the lateral thrust on the wall. During the experiment to measure the active condition, large changes in lateral pressure occurred for very small translations of the wall (~ 0.2mm), which suggested that the measured movements of the wall using the laser were in fact misleading. The laser system was therefore better suited for use in a temperature controlled environment.

11.2 Reference to the neutral axis between the two walls

The neutral axis of the structure was chosen as a suitable reference as no movement would occur there, and because of the symmetry of the situation the neutral axis was assumed to be midway between the two retaining walls (Fig 1). Invar tapes were fixed to each side of the concrete trough at the neutral axis location and the tapes extended horizontally beneath the soil to points close to the reinforced concrete pillars. A protective casing surrounded the tapes which were maintained at constant tension by suspending weights from the ends. An automatic optical plummet was fixed to the top of each reinforced concrete pillar in turn and by measuring the change in position of a reference mark on the invar tape, any displacement of the pillars could be monitored. The position of the metal retaining wall with respect to the reinforced concrete pillars was then measured using the system described in 11.1, and all measurements could thus be related to the neutral axis location. Any deformation of the concrete wall can also be measured with respect to the neutral axis in a similar manner.

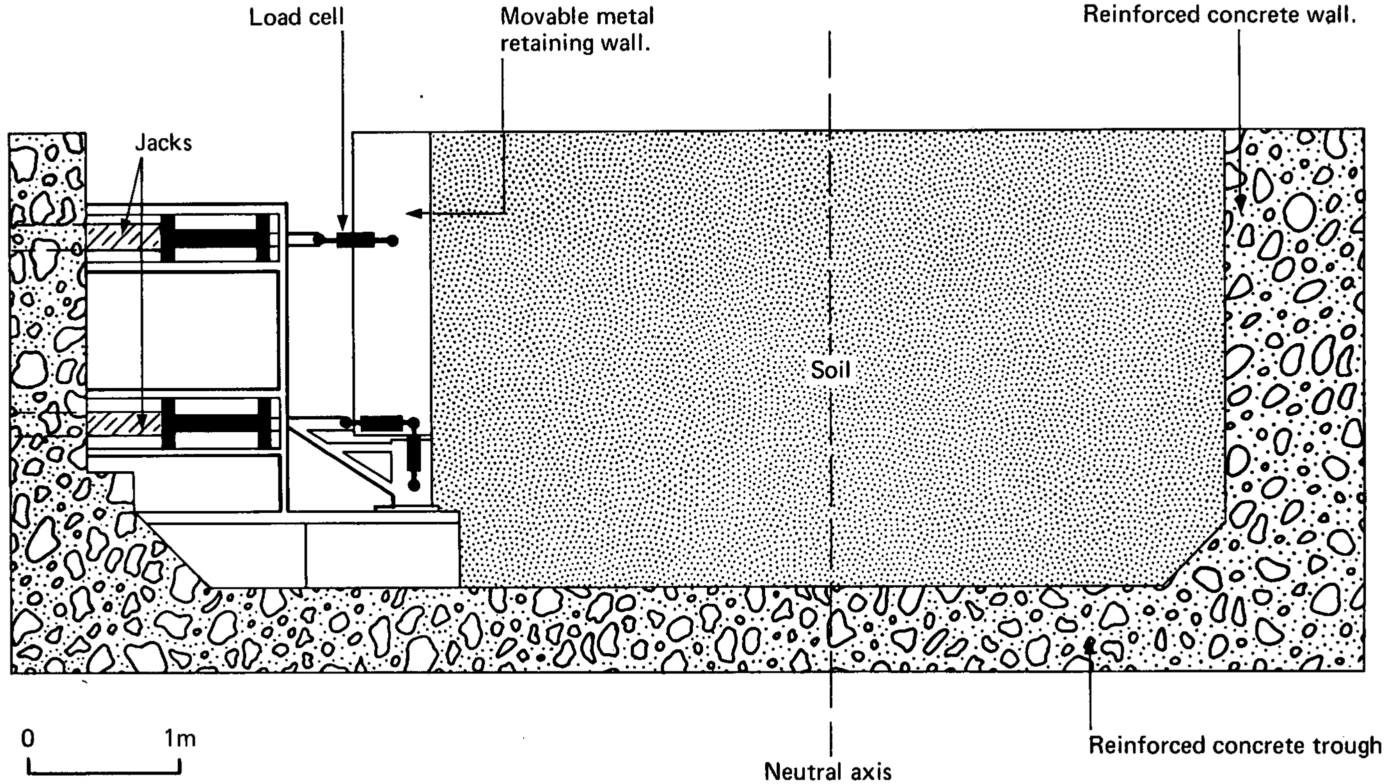


Fig. 1 THE EXPERIMENTAL RETAINING WALL.

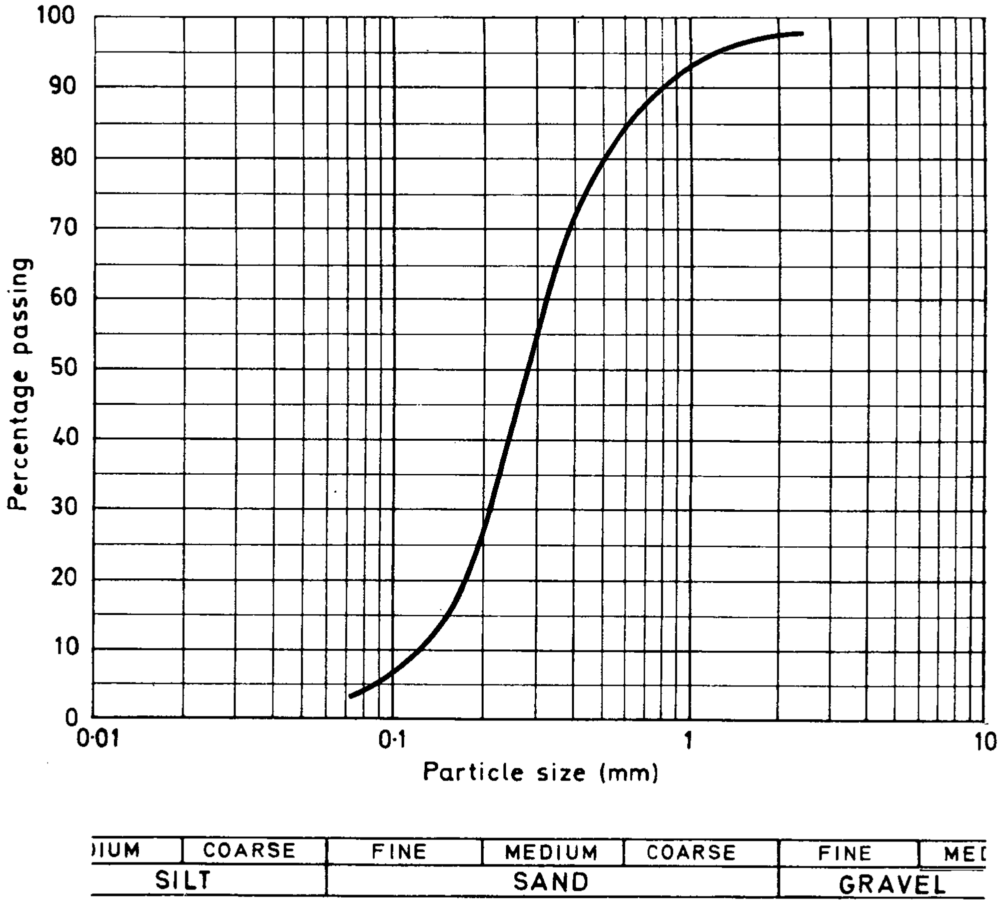


Fig. 2 PARTICLE SIZE DISTRIBUTION FOR THE WASHED SAND

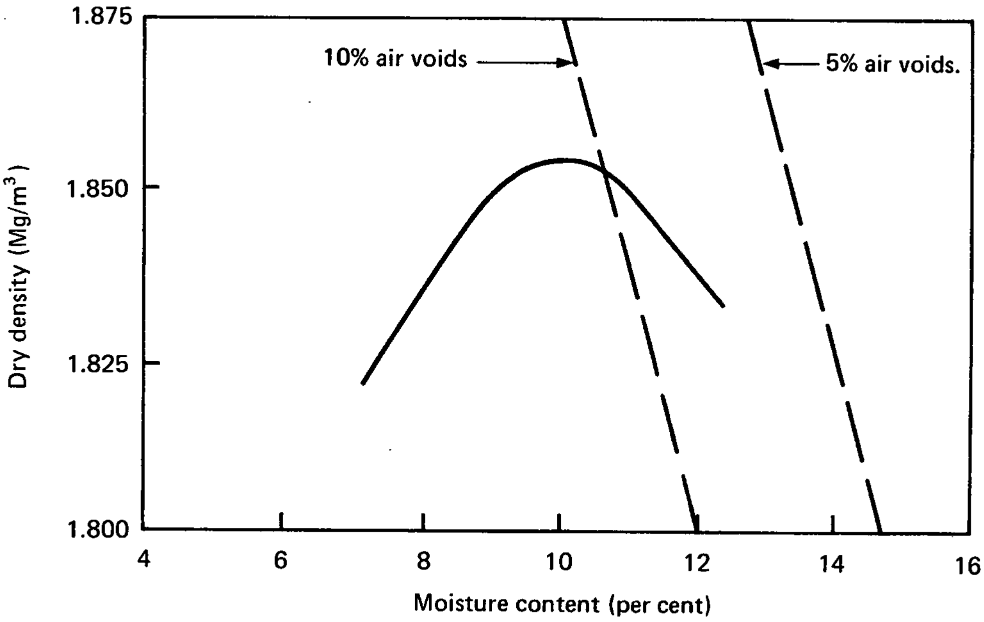


Fig. 3 RELATION BETWEEN DRY DENSITY AND MOISTURE CONTENT FOR WASHED SAND (VIBRATING HAMMER METHOD).

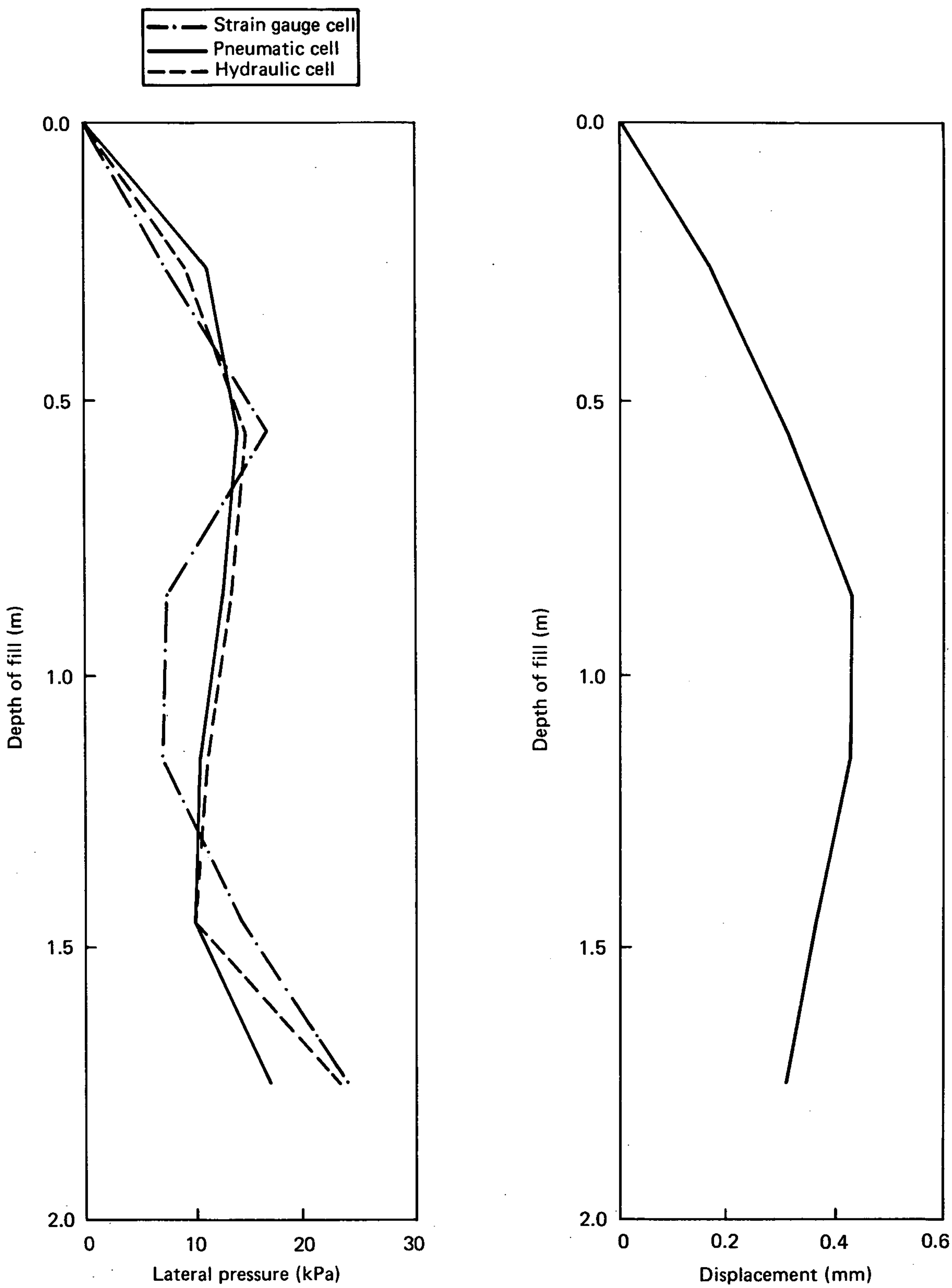


Fig. 4 COMPACTION OF SAND AGAINST WALL

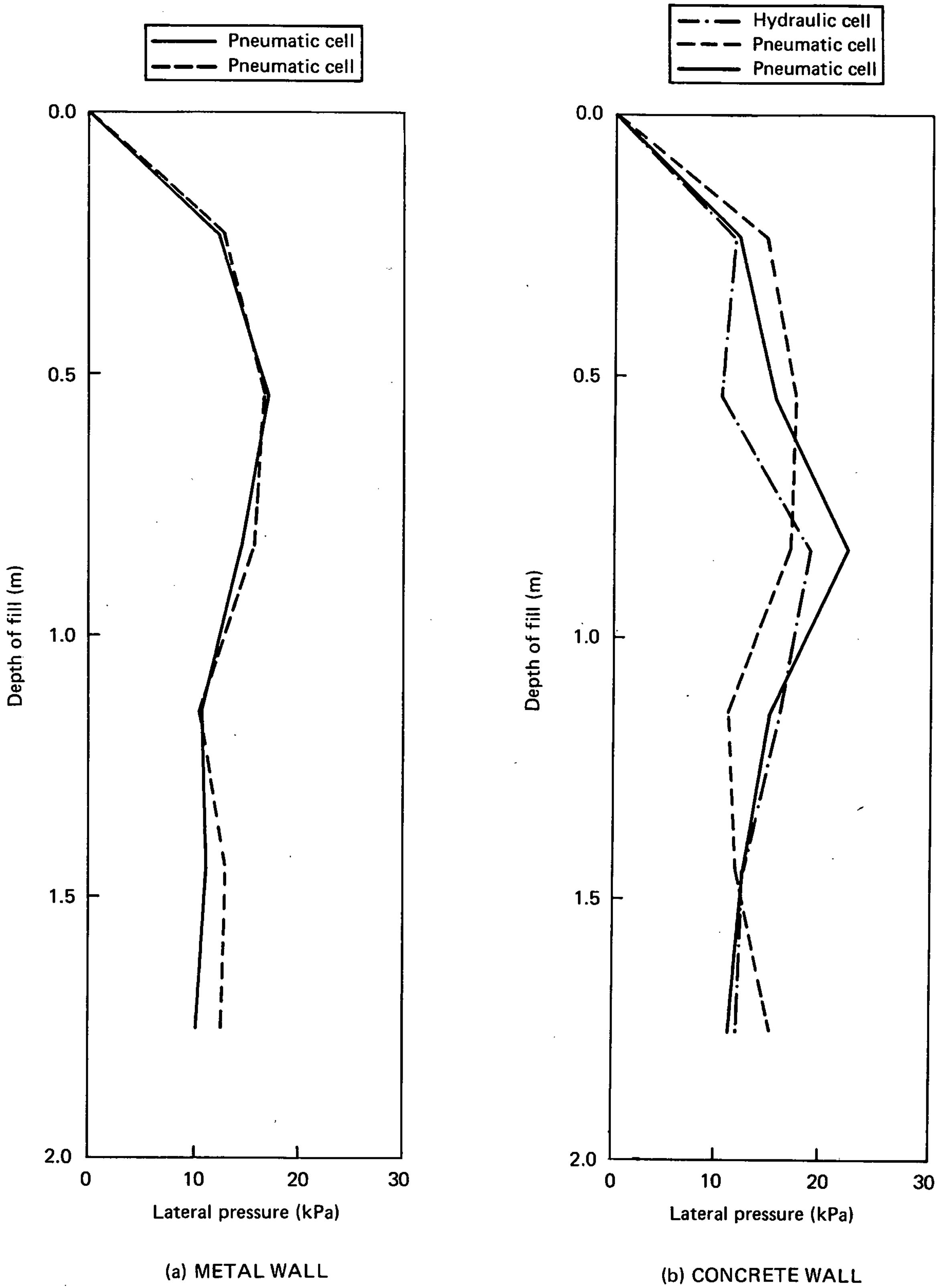


Fig. 5 COMPACTION OF SAND

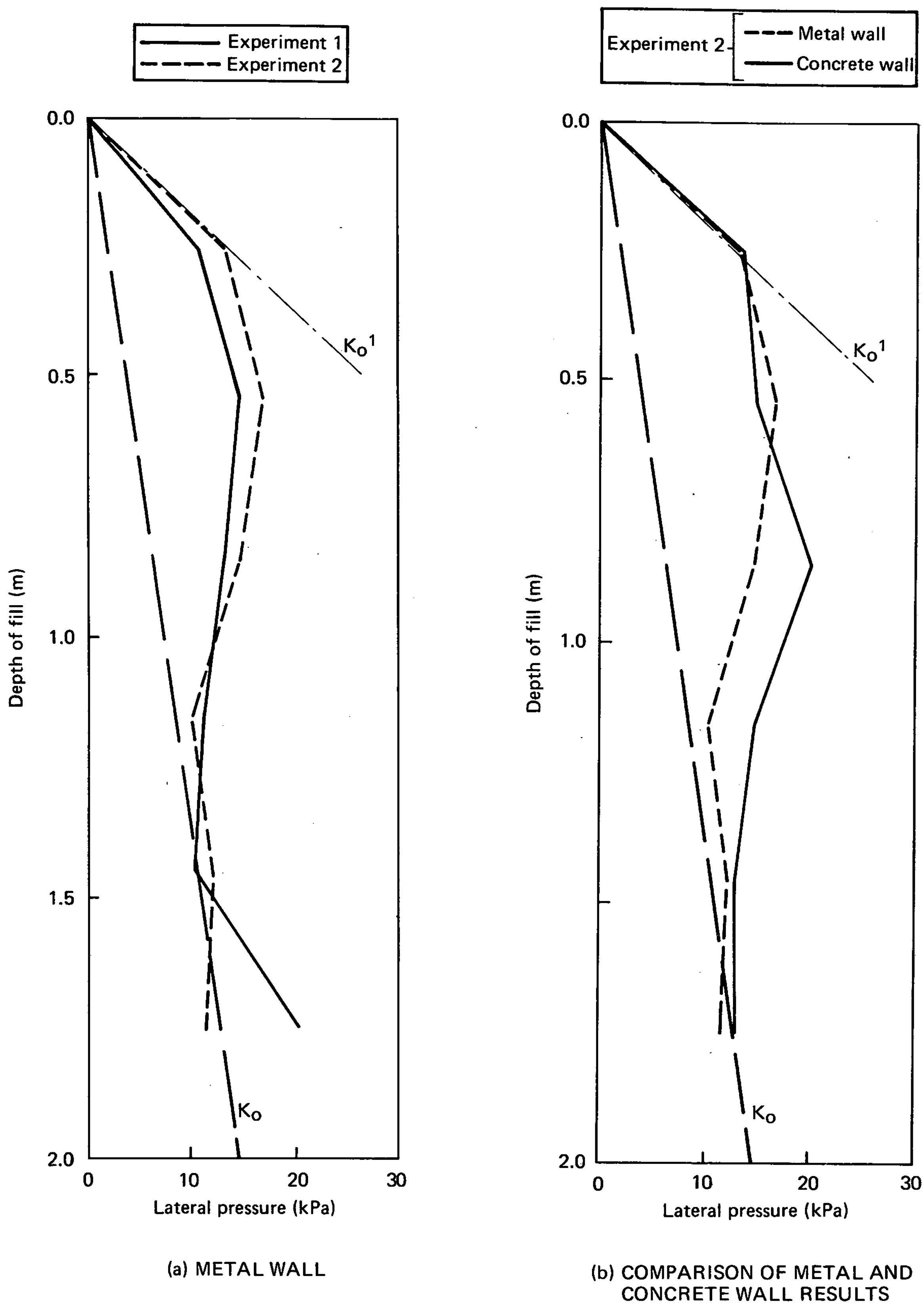


Fig. 6 COMPACTION OF SAND

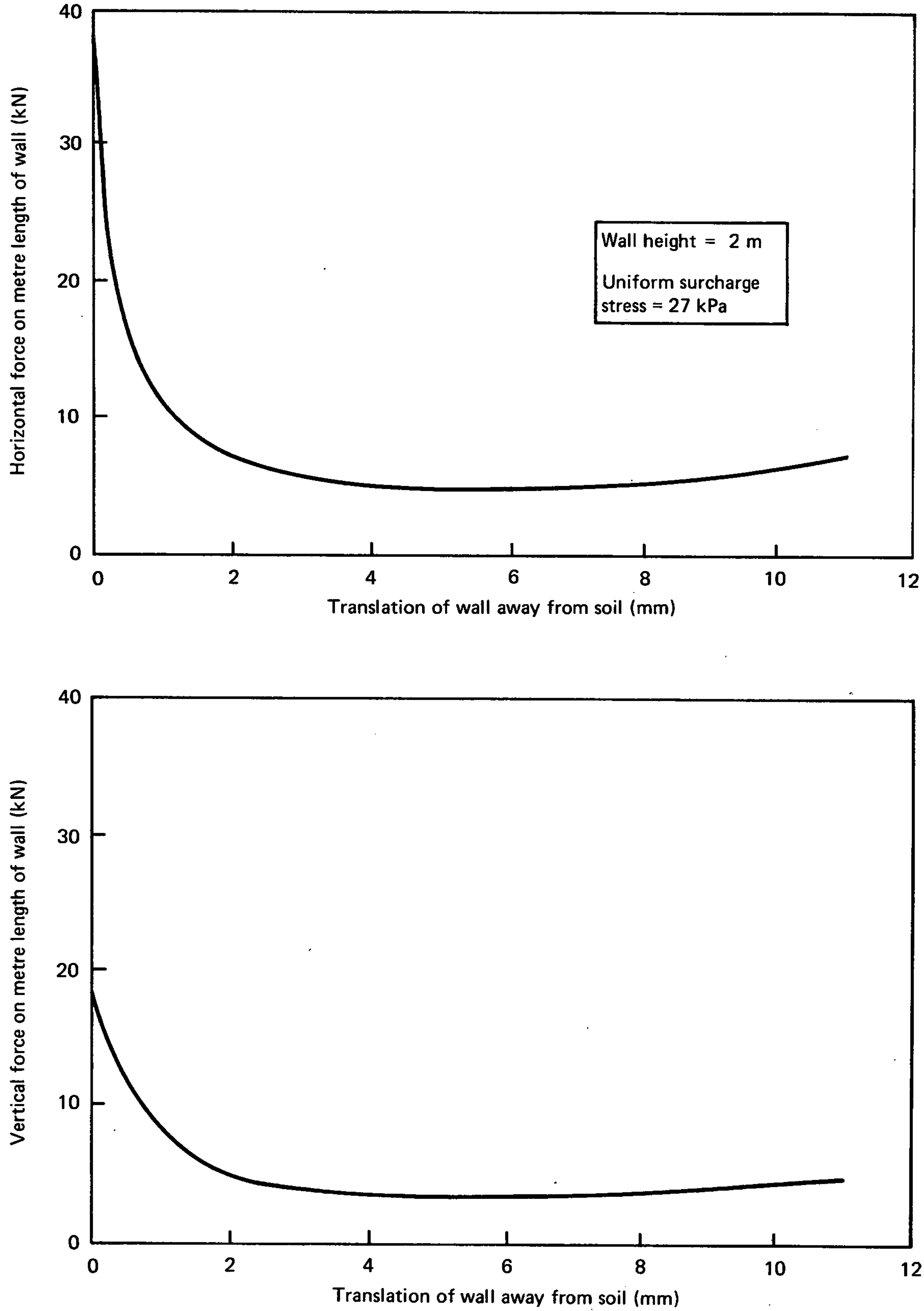


Fig. 7 THE ACTIVE CONDITION

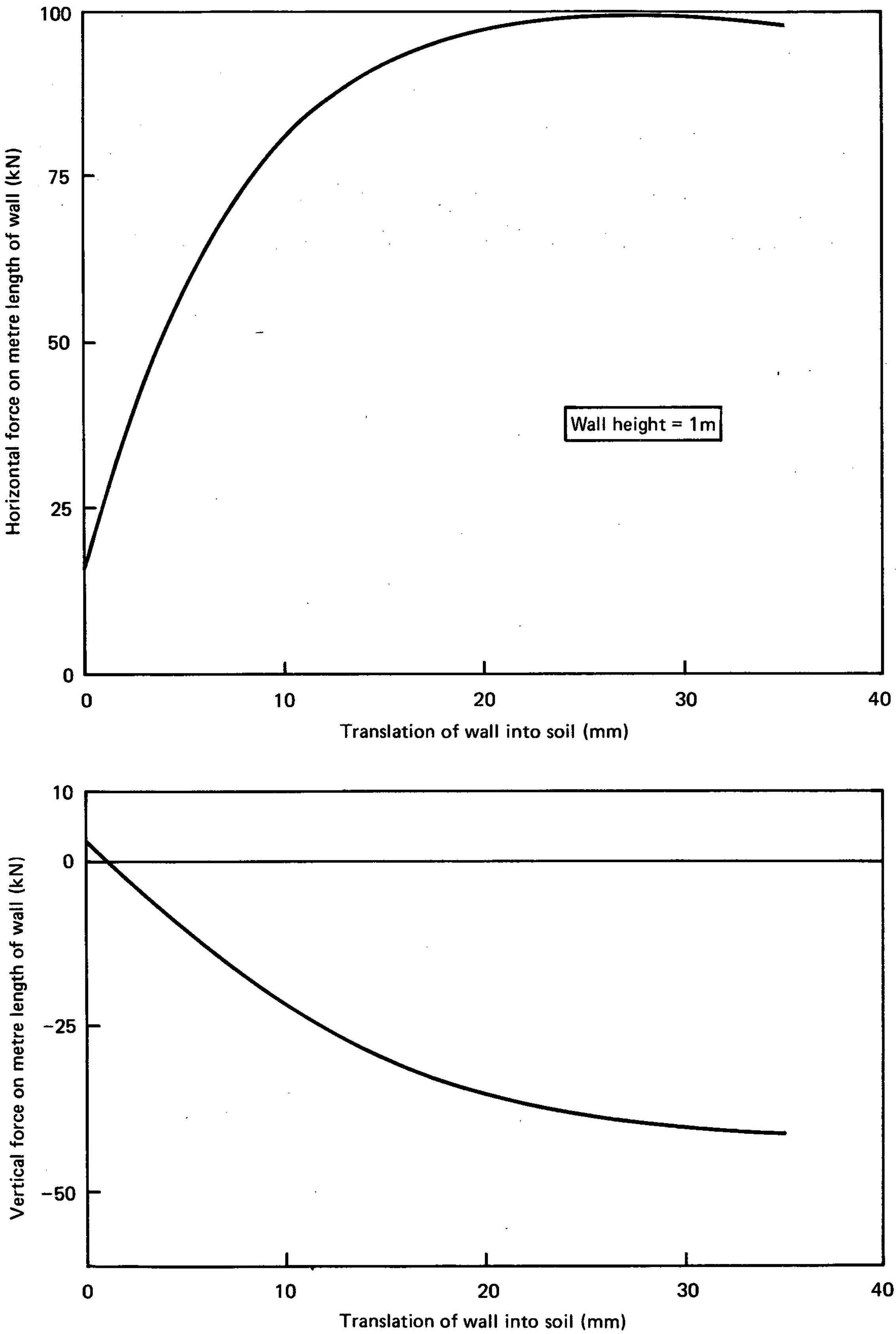
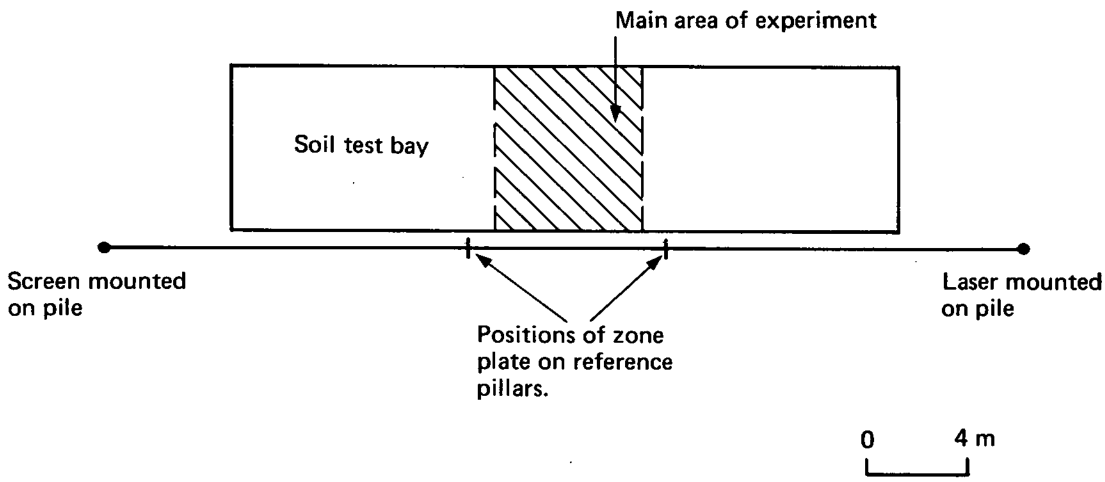
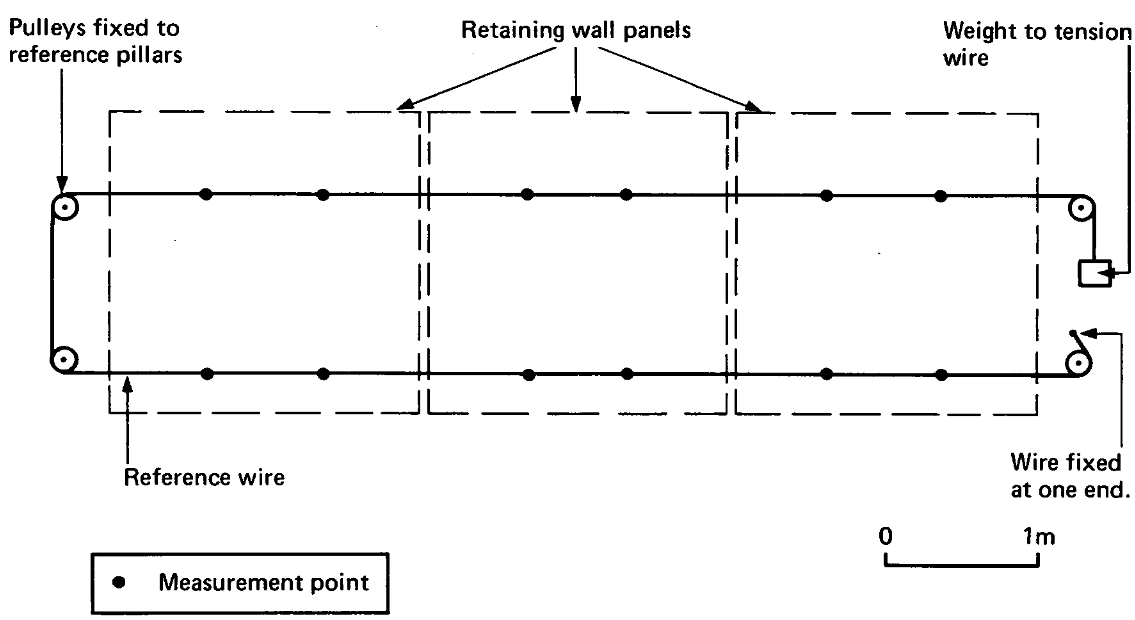


Fig. 8 THE PASSIVE CONDITION



(a) THE LASER SYSTEM



(b) POSITION OF MEASUREMENT POINTS

Fig. 9 MEASUREMENT OF WALL MOVEMENTS.

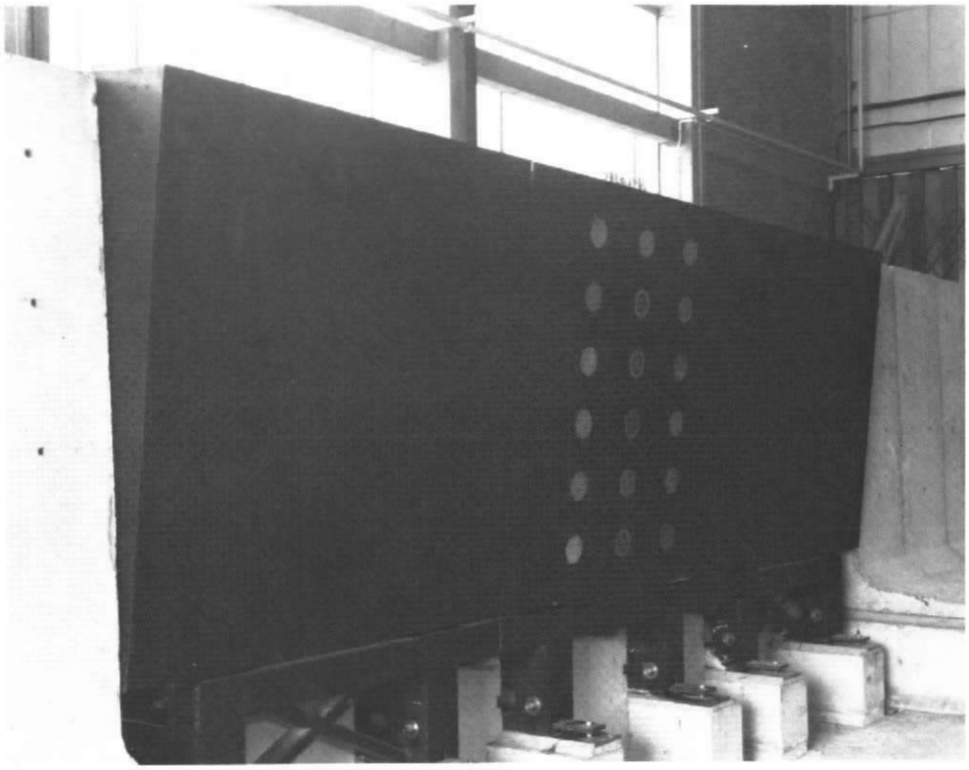


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Plate 1 THE EXPERIMENTAL RETAINING WALL

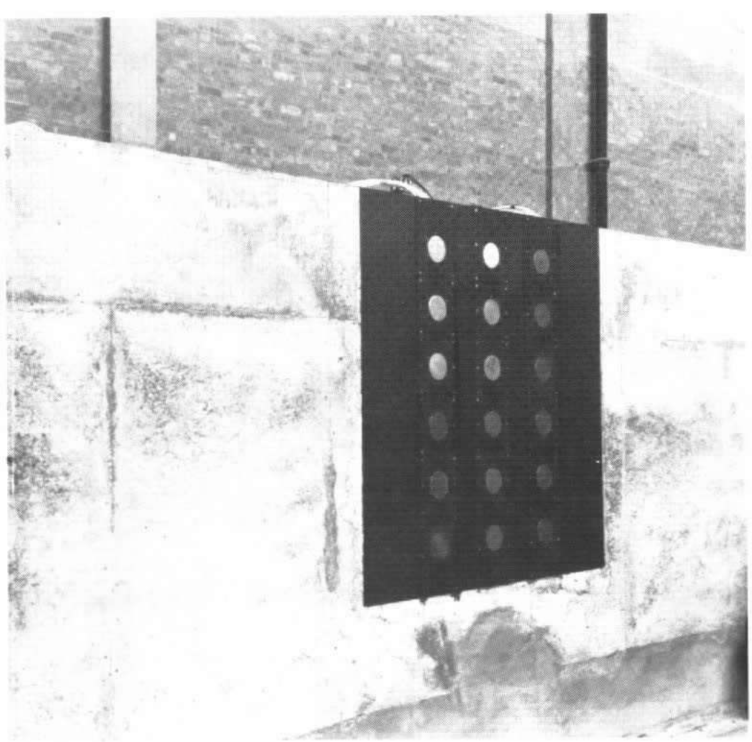

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Plate 2 THE REINFORCED CONCRETE WALL

Neg no B817/74/6

Plate 3 COMPACTING THE SAND AGAINST THE WALL

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