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Walls reinforced by fabrics - Results of model tests
Murs renforcés par des tissus - Résultats d'essais sur modèles

RÉSUMÉ. Le comportement de murs renforcés par un tissu polyester est décrit. Le tissu a été placé en couches horizontales et fixé à un mur de 1,5 m de haut et construit d'éléments préfabriqués larges de 240 mm. L'espacement et la longueur du renfort de tissu ont été variés, et la pression latérale ainsi exercée sur le mur a été mesurée. Les murs renforcés de tissu, même soumis à des charges assez importantes, se sont révélés étonamment forts. Les essais montrent que la longueur optimum du renfort de tissu correspond à moins de la moitié de la hauteur du mur; de plus, la longueur du tissu doit être à peu près la meme pour toutes les couches.

INTRODUCTION. Woven polyester fabric has been used to increase the bearing capacity of road embankments at three construction sites in Sweden (Holtz, 1975; Holtz and Massarsch, 1976). The sucess of these first field installations led the manufacturer of the fabric, AB Fodervävnader of Borås, Sweden, to sponsor some fundamental laboratory tests at the Swedish Geotechnical Institute (SGI) (Holtz, 1973). These studies and the performance of the fabric in the field suggested that the fabric could be used as reinforcement for earth retaining structures as well as for embankments on soft foundations.

Some pilot studies were performed on earth retaining structures at the SGI using a 672 mm high model wall reinforced with fabric (Lindskog, Bergdahl and Holm, 1975). Additional investigations have been conducted at the Royal Institute of Technology (KTH) in Stockholm (Broms, 1975; Davidson and Ekroth, 1975) using a Taylor-Schneebeli "pin" model. The results of these initial studies were encouraging, and they provided the preliminary data as to configurations of reinforcement, spacing of layers, etc., for the large-scale model tests reported herein.

MODEL TESTS. Sand:--The sand used in the model tests was a washed uniform medium-fine sand from the Island of Bornholm, Denmark (Silver Sand No. 55). Its classification and strength properties are shown in Table I.

Fabric Reinforcement:--The fabric used in the tests was an industrial grade woven polyester ("Teknisk väv No. 600"). It was woven by AB Fodervävnader of Borås, Sweden, from fibers manufactured either by Hoechst (Trevira No. 710) or ICI (Terelin). The basic fiber is a 1100 dtex (990 denier) polyester with a 20/Z60 yarn structure. Its tensile strength is about 900 MPa at a failure strain of 15%. It has excellent creep resistance. Tests indicated that the extrapolated creep strength after more than one year is 700 MPa. The creep was found to increase per log cycle of time about 0.18% at 700 MPa. The corresponding increase at 600 MPa was about 0.14%. Data obtained from the manufacturers indicated that the fiber has good to excellent resistance to ageing, light, weathering, rotting, bacteria, and rodents. It is very resistant to acids, relatively resistant to bases, and it is in general insoluble in most organic solvents. Theoretical tensile strength based on the fiber properties is 70 kN/m of width while grab tensile tests indicated a strength of 43 kN/m at 12% strain. Results from a biaxial tensile test on the fabric is shown in Fig. 1.

TABLE I.
PROPERTIES OF SILVER SAND NO. 55

D_{10}	0.32
C_u	1.58
e_{max}	0.87
e_{min}	0.59
ϕ_{triax}	37^o at $D_r = 70\%$

Model Wall:--The tests were carried out in a 1.9 m wide test pit in the Soil and Rock Mechanics Laboratories at KTH. The retaining wall was constructed of six elements each 240 mm high, 45 mm wide and 1.8 m long. The total height of the wall was 1.44 m. The elements were made of wood, planks to simulate a reinforced wall made of precast concrete elements. The fabric which was placed in layers in the backfill was anchored to the wall

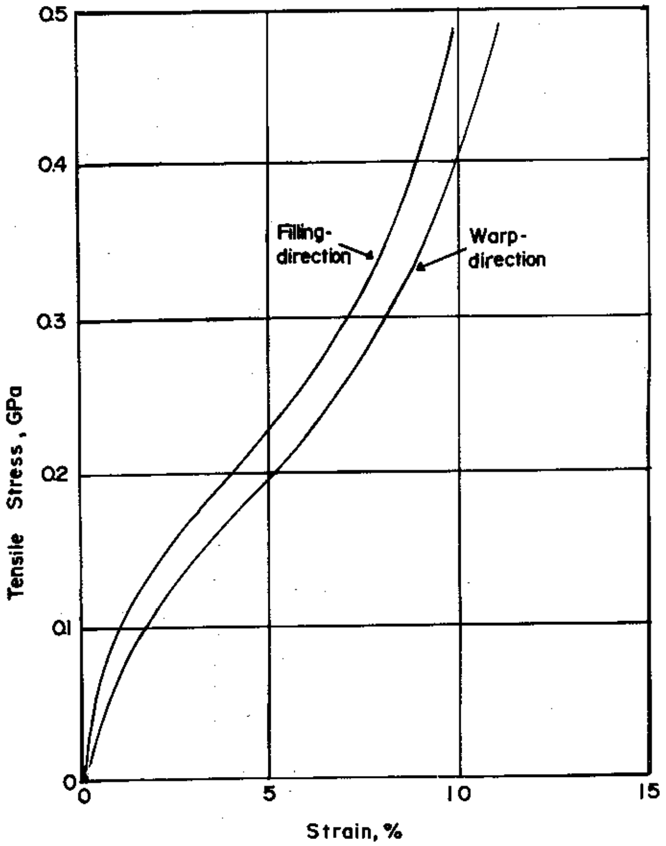

FIGURE 1. BIAXIAL STRESS-STRAIN CURVES FOR THE FABRIC.

between the elements. Translation of the elements was prevented through a system of cleats, but the elements were free to rotate about 20° with respect to each other. The bottom element was securely fastened to the test pit floor to prevent horizontal slippage. Thus the effective height of the wall was 1.20 m. Two adjustable jacks at approximately the third points of the wall width supported the wall during construction (Fig. 2). The wall could either (1) rotate outward about the base, or (2) translate outward parallel to the floor. Polyethylene sheets were placed on the test pit walls and attached to the inside of the wooden wall elements (Fig. 2) to reduce side friction. This arrangement also prevented leakage of sand from the edge of the wall.

The wall was constructed and backfilled in layers to simulate construction in the field. A flexible hose 50 mm diameter attached to the bottom of a barrel suspended by an overhead crane was used to place the sand. As the sand ran out of the barrel, it was scattered by a small plate attached about 50 mm below the end of the hose. A constant height of fall of 0.5 m was maintained. With this procedure the unit weight of the sand could be rather closely controlled to a relative density of about 70%. At the conclusion of each test, the sand was removed by an air operated suction device. Since the total volume of the sand in the pit exceeded 5 m^3, only the sand next to the wall was removed. The sand located behind the failure surface in the fill was not exchanged before the next test.

Surcharge was applied to the backfill by means of an air compressor-regulator system and three air mattresses in series. After construction and backfilling was completed, the mattresses were confined by a wooden frame and a reaction beam arrangement. In this way, the wall could be forced outwards even when the wall was stable.

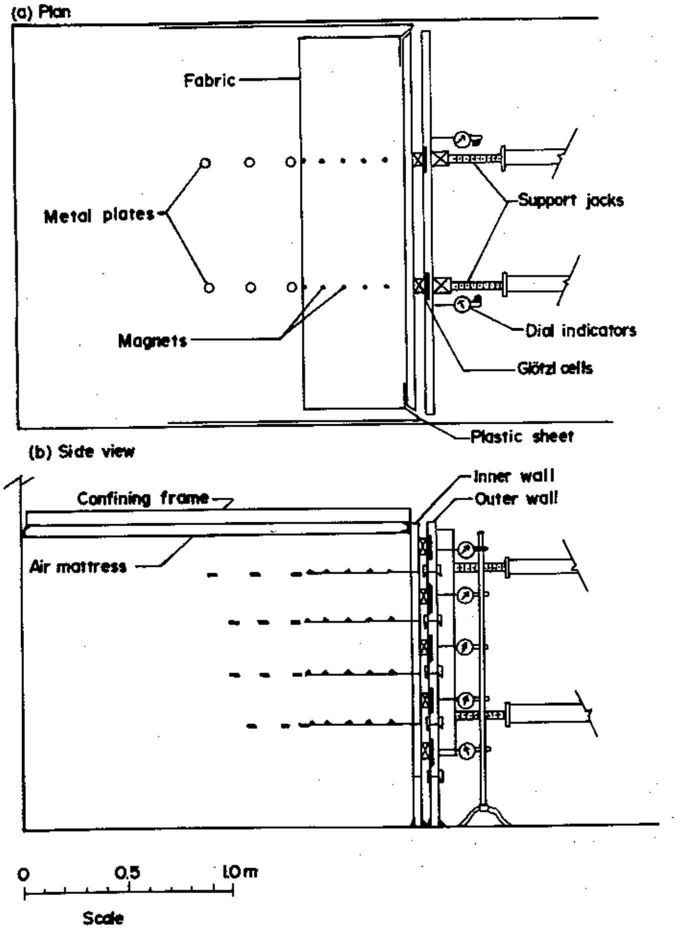

FIGURE 2. SCHEMATIC DIAGRAM OF MODEL WALL AND INSTRUMENTATION.

Instrumentation:--The lateral earth pressures against the wall elements were measured approximately at the third points of each active wall element with two 400 kPa Glötzl earth pressure cells (Fig. 2).

An initial pilot test showed that the earth pressures only slighly exceeded the sensitivity of the cells (about 1 kPa). The pilot test also showed that relatively large outward deformation and bending of the wooden planks occurred, especially at the center of the wall. This must have affected the stress distribution on the wall. Truly plane strain conditions probably did not exist as assumed, in spite of attempts to reduce the pit wall friction.

An identical inner wall was constructed which was laterally supported by 10 wood blocks acting directly on the Glötzl cells in order to increase the accuracy of the readings. The cells responded satisfactorily to a concentrated load on the surface as long as the load was applied in the central portion of the cell; the registered pressure was essentially independent of the loaded area.

Two vertical rows of five dial indicators (Fig. 2) were used to measure the lateral deformation of each wall element as the supports were adjusted. The dial indicators were mounted close to the support jacks so that the readings would be least affected by the outward bending of the wall elements.

It was also of interest to measure the stretch or deformation in the fabric during a test. Small magnets, spaced about 100 mm apart, were glued to the fabric (Fig. 2), and a 10 mm diameter plastic tube was buried in the sand under each row of magnets. A sensor attached to a millimeter tape was inserted in the tubing during a test to detect the location of each magnet. The accuracy of the readings was about 0.5 mm. The same system had been successfully used in other laboratory tests on the fabric (Holtz, 1973).

In an attempt to locate the failure zone behind the wall, six steel plates were buried behind the fabric layers at four different levels (Fig. 2). During the filling phase, and after each test during excavation of the sand, their positions, both vertically and horizontally, were carefully measured to an accuracy of about ± 5 mm.

Tests:--The spacing and length of the reinforcement and other test details of the five tests of this investigation are presented in Table II. Essentially the same procedure was used for all tests. After the wall was backfilled, a surcharge of 50 kPa was applied through the air mattress system. The wall was then allowed to move outwards from the top (Stage I) by successively releasing the top supports until the earth pressure cells no longer indicated any further decrease of lateral earth pressure. If the wall was still stable (e.g., in Tests B, C and E), the lower supports were also released (Stage II) which allowed the bottom of the wall to move outward. If the wall was still stable, the surcharge load was further increased (Stage III, Tests B and E). Lateral displacement of the wall elements and the fabric were also recorded with each successive release of the support jacks.

The loading and the movements of each test are also shown in Table II. Test A was an unreinforced control test. No surcharge was needed since the wall easily moved outward when the top support was released. When the average tilt (δ/H) reached 0.037, the lateral earth pressure did not change, and the test was terminated. The results of the measurements will be discussed in the next section.

Four layers of fabric extending 50 cm back of the wall ($L/H = 0.42$) were used in Test B. After a surcharge of 50 kPa had been applied and the top released, the average tilt was 0.014. When the bottom was released, it moved out about 5 mm while the top moved back, and the average tilt decreased slightly (0.013). Since the wall was apparently stable and showed no tendency to creep, the surcharge was increased to 70 kPa. (A 70 kPa surcharge load is equivalent to approximately a 4.5 m high earth embankment). This resulted in an additional outward movement, and the average tilt was 0.015. The surcharge load was not increased further.

Because Test B performed so well, it was decided to decrease the length of the reinforcement to 40 cm ($L/H = 0.33$) for Test C. A surcharge of 50 kPa was applied. The wall was stable even when the top was released. The resulting average tilt was only 0.013. When the bottom was released, one of the air mattresses sprang a leak and the surcharge pressure was lost before any measurements could be taken. It was observed that the wall was stable.

For Test D the length of the reinforcing was varied according to Fig. 3. The fabric extended only about 150 mm behind the theoretical Rankine failure line ($\theta_f = 45^\circ + \phi'/2$). After a surcharge was applied and the top had been released, the average tilt was about 0.015 and the wall was stable. When the bottom support was released, the second and fourth layers suddenly slid outwards about 50 mm against the supports which were positioned near the wall to prevent catastrophic collapse. The mode of failure in this test was apparently similar to the "ties pull out" mode postulated by Lee, et al (1973) for the Vidal reinforcing system.

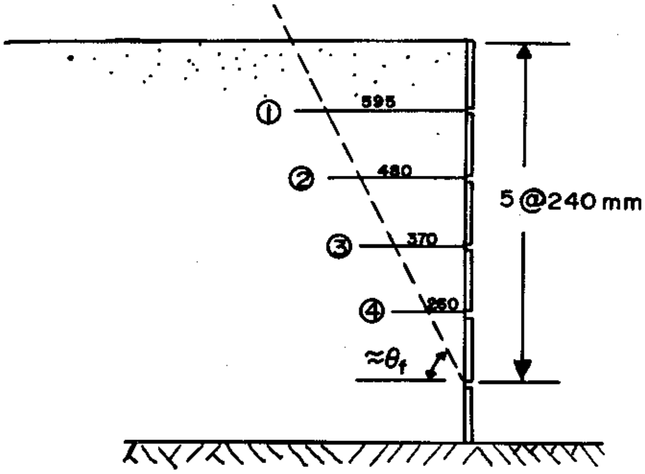

FIGURE 3. VARIABLE LENGTH REINFORCEMENT CONFIGURATION FOR TEST D. LENGTHS SHOWN ARE IN mm.

In Test E the effect of fewer but longer layers of reinforcing was investigated. Two 800 mm long layers of fabric were used ($L/H = 0.67$). After the wall was surcharged and the top released, the average tilt was 0.023. When the bottom was released, the wall moved outwards about 6 mm, and the tilt decreased to about 0.020. The wall was still stable and did not show any tendency to creep. When the surcharge was increased to 70 kPa, the air mattresses ruptured and the surcharge load was lost. However, just before this occurred, it was noted that the top of the wall had moved out about 44 mm.

ANALYSIS OF RESULTS. Earth Pressure Distributions and Wall Movements:--Fig. 4 shows the measured earth pressure distributions after backfilling but before the surcharge was applied or the supports were released. The average earth pressure for two cells at each level is shown as well as the theoretical earth pressure for "at rest" (K_o) and Rankine failure conditions (K_a). Only near the top of the wall did the horizontal stress approach K_o conditions. Apparently the deflection of the lower wooden wall elements was sufficient to reduce the earth pressure to essentially active conditions. Only a qualitative analysis of the horizontal earth pressure measurements is possible because of local effects around the earth pressure cells and the nature of the inner wall system which was designed to concentrate the horizontal pressure directly on the Glötzl cells. The reinforcement did reduce somewhat the earth pressure at rest. Reducing the amount of reinforcement (Tests D and E) seemed to increase

TABLE II.
DETAILS OF REINFORCEMENT GEOMETRY AND HISTORY OF EACH TEST
See text for description of test stages.

Test	L, mm	L/H	No. of Layers	Layer Spacing, mm	Surcharge kPa	Tilt (δ/H) and horizontal movement δ, for each test stage I	II	III
A	Unreinforced				None	0.037	-	-
B	500	0.42	4	240	50 → 70	0.014	0.013 δ=5 mm	0.015 δ=7mm
C	400	0.33	4	240	50	0.013	Unknown (lost surcharge)	
D	Var	Var	4	240	50	0.015	Layers 2 & 4 failed	-
E	800	0.67	2	480	50 → 70	0.023	0.020 δ=6 mm	Lost surcharge

the earth pressure at rest, especially for Test E.

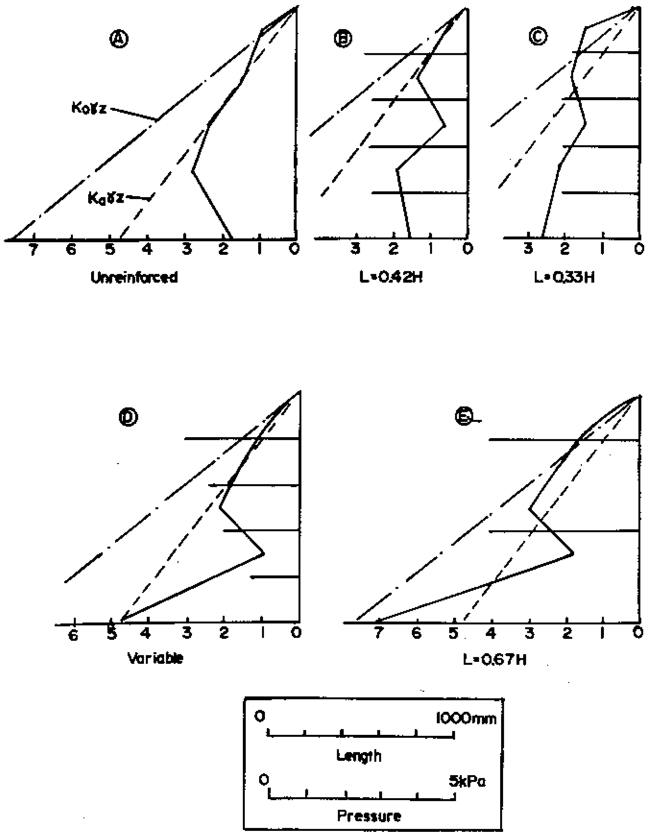

FIGURE 4. MEASURED EARTH PRESSURE AT REST BEFORE APPLICATION OF ANY SURCHARGE. THEORETICAL LATERAL PRESSURE DISTRIBUTIONS ARE BASED ON $\phi = 37^{o}$.

The earth pressure distribution and the horizontal movement at the final stage of each test is shown in Fig. 5. In general, the reinforcement reduced the lateral earth pressures. As the wall moved outward under the surcharge and the supports were released, the earth pressure decreased. The geometry of the reinforcement affected the pressure distribution as well as the magnitude of deformation. The earth pressure was in general less for Test B than for Test C. The earth pressure distribution of Test D, where the length of the reinforcement was varied, was significantly greater at the bottom of the wall where the length of the reinforcement was short. When Tests B, C, and E are compared, it seems that the length of reinforcement back of the wall has a greater effect on the lateral earth pressure than the number of layers.

Strain in the Fabric:--The movements of the magnets which were glued to the fabric were unfortunately too small for accurate calculations of the strain distribution in the fabric. However, overall average strains could be calculated.

For Tests B and C, maximum deformation was between 2 and 4 mm over the entire length of fabric. Average strain thus was less than 1%. Test D, which had the variable reinforcing lengths and which failed when two layers of fabric slipped or pulled out, had average strains of about 1 to 1.5%. Test E, which had only two long layers of reinforcing, also had larger maximum strains than the walls with four equal layers. Total stretch was between 6 and 11 mm, which corresponded to an average overall strain of about 1%.

The maximum observed stretch in the fabric nearly occurred in all tests when the 50 kPa surcharge was applied. The additional deformation in the fabric after that was small. Therefore, only a small deformation was apparently required to develop the full frictional resistance of the fabric. A similar conclusion based on laboratory pull out tests on the same fabric was advanced by Holtz (1973).

Location of the Failure Surface:--Small metal plates were placed behind the reinforcing to detect the location of the failure surface. Preliminary results of the laboratory tests with the Taylor-Schneebeli ("pin") models (Broms, 1975; Davidson and Ekroth, 1975) showed that the failure surface at large wall deformations was located behind the end of the reinforcement and at about the theoretical Rankine failure line ($45^o + \phi'/2$). Although there was some difficulty in precisely locating the plates during the excavation of the sand, the conclusions of the pin model tests were verified in general.

Test A (with unreinforced soil) failed along a surface that was located somewhat behind the Rankine theoretical surface, but the observations were complicated by the possibility that a composite failure surface developed. The movements of the plates in Tests B and C were inconclusive, while for Test D, where the length at the fabric was varied, the failure surface passed just behind the fabric reinforcement.

CONCLUSIONS. The feasibility of using a woven polyester fabric as reinforcement behind an earth retaining structure has been demonstrated. Not only were the earth pressures against the wall and the deformations reduced, but the reinforced walls could support relatively large surcharge loads without excessive deformation or tendency to creep. The properties of the woven polyester fabric used in these tests suggest also that the problem of corrosion can be substantially reduced by using woven fabrics as reinforcement.

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REFERENCES.

Broms, B. B. (1975). "Armerad jord: Försök med pinnmodell," ("Reinforced earth:Tests with a pin model"), Royal Institute of Technology, Stockholm, unpublished report, 26 pp.

Davidson, S., and Ekroth, N. (1975). "Försök med vävförankrad stödmur," ("Tests with retaining walls reinforced with fabric"). Royal Institute of Technology, Stockholm, unpublished thesis, 43 pp.

Holtz, R. D. (1975). "Recent developments in reinforced earth", Proceedings of the 7th Scandinavian Geotechnical Meeting, Copenhagen, Polyteknisk forlag, pp. 281-291.

Holtz, R. D. (1973). "Laboratory studies of reinforced earth using a woven polyester fabric", Report to A B Fodervävnader, Swedish Geotechnical Institute, Stockholm.

Holtz, R. D., and Massarsch, K. R. (1976) "Improvement of the stability of an embankment by piling and reinforced earth", Proceedings of the 6th European Conference on Soil Mechanics and Foundation Engineering, Vienna, Vol. 2.1, pp. 473-478.

Lee, K. L., Adams, B. D., and Vagneron, J. M. J. (1973), "Reinforced Earth Retaining Walls," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 99, No. SM10, pp. 745-764.

Lindskog, G., Bergdahl, U., and Holm, G. (1975). "Rapport över laboratorieförsök med vävförankrad stödmur," ("Report on laboratory tests of retaining walls reinforced with fabric"), Swedish Geotechnical Institute, Stockholm, unpublished report. 40 pp.

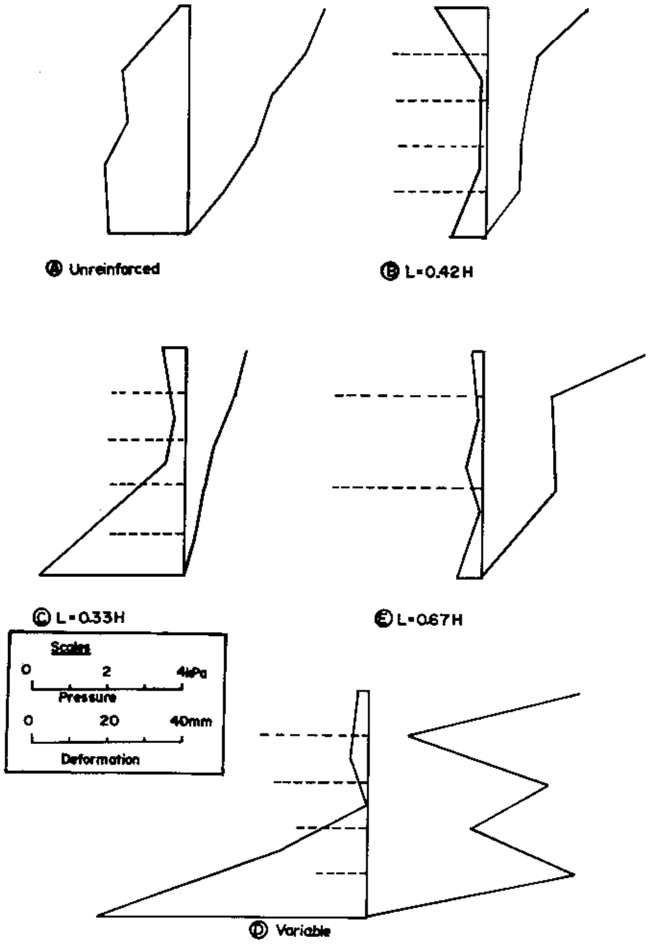

FIGURE 5. EARTH PRESSURES (LEFT SIDE) AND DEFORMATIONS (RIGHT SIDE) ON THE WALL AT THE FINAL STAGE OF EACH TEST. DASHED LINES INDICATE THE FABRIC REINFORCEMENT.