STUDY OF THE SOIL-REINFORCEMENT FRICTION COEFFICIENT.

by

KHATTRI MOHAMMED SOOMAR, B.E.

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Department of Civil Engineering

University of Glasgow

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J. S. HERON LTD
5 QUEENS CRESCENT
ST. GEORGES CROSS
GLASGOW 041 332 1883

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NOTATION

γd	-	Dry Density.
σn	-	Normal pressure.
ϕ	-	Angle of internal friction.
Ψ	-	Angle of skin friction measured from shear box.
δ	-	Angle of skin friction measured from Pull-out test.
f^*	-	Apparent friction coefficient.

SUMMARY

This research study has been carried out to gain further insight into existing available testing methods for measuring a soil-reinforcement friction coefficient.

Previous research work pertaining to soil-reinforcement friction mobilization, including testing methods and the relative influences of different factors affecting the value of the soil-reinforcement friction coefficient has been reviewed.

Actual site material, strip and soil has been employed in this investigation. Shear tests on soil samples compacted at various densities using both direct shear and triaxial tests were carried out in order to develop a relationship between dry density and angle of internal friction. The relationships obtained using both testing methods were linear.

Friction tests on both smooth and ribbed reinforcing strip samples at varying density were performed using a shear box. The results indicated a linear relationship between dry density and angle of skin friction for both types of reinforcement. On comparing the results of smooth and ribbed strips, it appeared that ribbed strip yielded a greater value of skin friction coefficient than smooth strip, both being lower at all densities than the coefficient internal friction of the soil alone. It was also noted that density had very little effect on the soil-reinforcement friction coefficient in the case of the smooth strip where as it had a significant influence in the case of the ribbed strip.

The main part of the present investigation was a study of pull-out testing methods. For this purpose, an apparatus, at large scale, was constructed in which three series of tests were conducted. The first series of tests consisted of pulling the strip out and calculating the apparent friction coefficient. In the second series of tests the strip together with the facing plate was pulled out at the same normal pressure range, as in the first series, in order to determine the effect of the testing method. The results showed that both pull-out testing methods in loose and dense soil gave higher value of apparent friction coefficient compared to the direct shear method and indicated a trend of decreasing apparent friction coefficient-with-increasing normal pressure. The dense soil yielded higher value of apparent friction coefficient than the loose soil. A decrease of 3.5° and 4° in the values of angle of skin friction in the case of the dense and loose soil respectively was noticed when the facing plate was pulled out with the strip. The third series of tests was carried out using both testing methods and with density varying along the length of the strip in order to investigate the effect of density variation on the value of skin friction angle. The results showed that the apparent friction coefficient decreased with decreasing density along the length of the strip.

Besides the other researcher's conclusions that the direct shear method gives conservative values of soil-reinforcement friction coefficient and the pull-out test yields extremely high values which are believed to be due to dilatancy, arching, and undulations in the strip, the author has concluded that the testing/

method and variation of density along the length of the strip have also an influence on the value of the soil-reinforcement friction coefficient. If all these factors were taken into account the angle of skin friction would be almost equal to the value of the angle of internal friction of soil, thus the author believes that the use of a high value of soil-reinforcement friction coefficient in design would be misleading. A further insight could be gained into the pull-out testing method by measuring the tensile force distribution and normal pressure distribution along the length of the strip.

CHAPTER 1

INTRODUCTION

Reinforced earth, as introduced by M.H. Vidal (57) is the incorporation of earth and reinforcing strips in such a way as to enhance the strength of a soil mass by the mobilization of friction between soil and reinforcement.

Reinforced earth has been used, since its innovation, in a variety of structures such as industrial structures (material processing and storage facilities, containment dykes for crude oil, liquefied natural gas storage and foundation slabs), hydraulic structures (sea walls, dams, tunnels, flood protection structures and sedimentation basins) and various forms of earth retaining structures. It is in this latter role that reinforced earth has been most widely applied, as McKittrick, D.P. (42) reported that over 3000 structures have been completed.

The construction of a reinforced earth retaining wall, fig.1.1,consists of alternating layers of compacted granular soil and reinforcing strips which are distributed at suitable horizontal and vertical intervals, with one end of the strips attached to the facing element.

General design procedures for earth retaining walls include the checking of interal and external stability. External stability of a reinforced earth wall is checked using conventional procedures. Internal stability requires checking against tension failure and adhesion failure. To design a reinforced earth retaining wall against the latter type of failure, a/

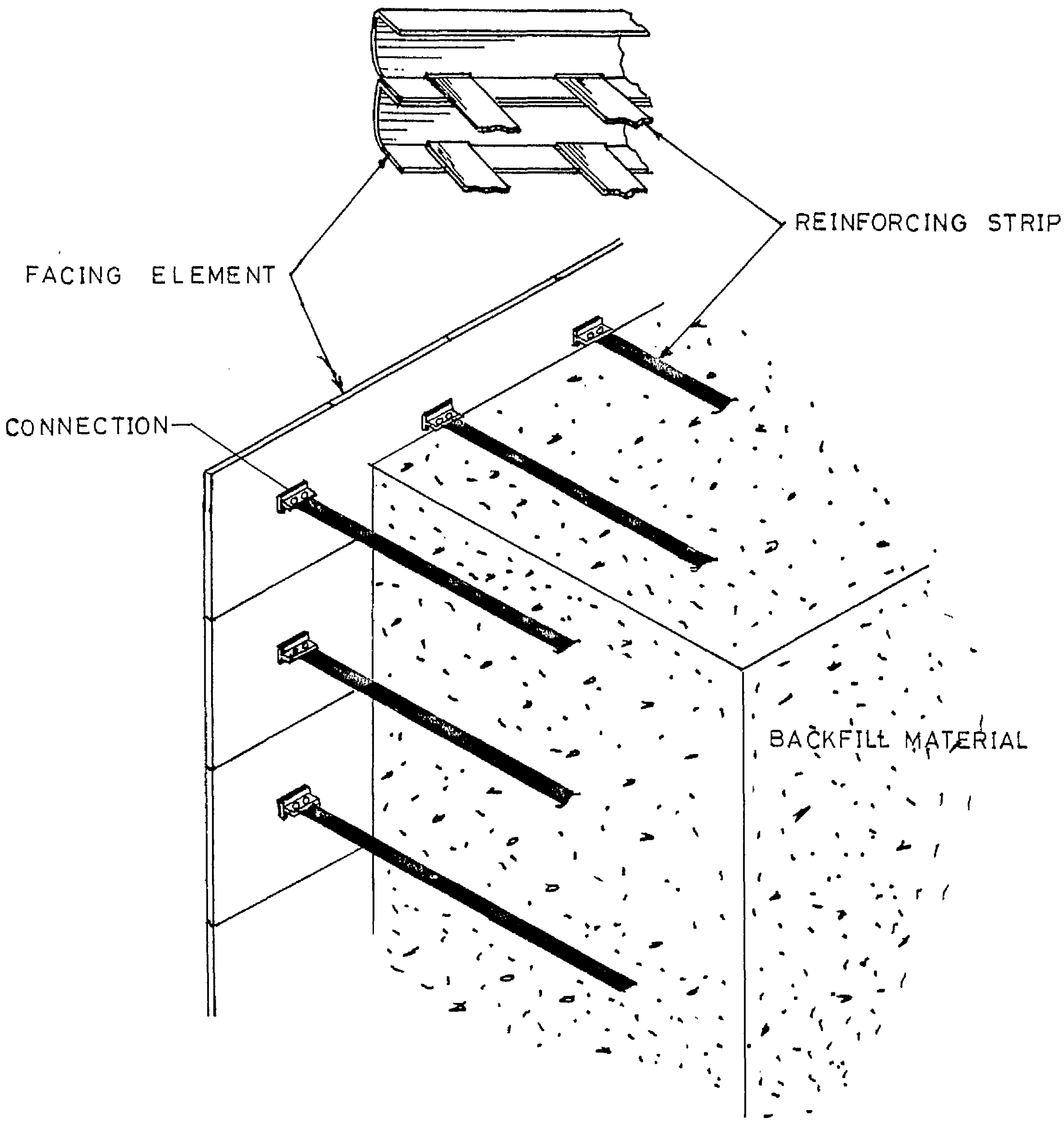


Fig.1.1. Schematic representation of major elements of reinforced earth wall.

knowledge of appropriate friction coefficient values between the reinforcement strip and the fill material is required.

The various ways in which different investigators have attempted to obtain these values are outlined below and cover the range from laboratory to full-scale testing.

Direct Shear test:

This test, fig. 1.2, consists of a shear box, one half of which is fitted with a sample of the reinforcement in such a way that the sample is flush with the top edges while the other half is filled with the soil. By shearing in a conventional manner, the peak shear is measured and the ratio of peak shear stress to applied normal stress is taken to be the value of skin friction coefficient.

Pull-out test

This test consists of withdrawing reinforcement from a soil mass and recording the pull-out force-displacement curve from which the peak pull-out force is taken as a measure of the skin friction coefficient. This test has been carried out by different investigators using several methods, e.g. pull-out test from shear box, model pull-out test, pull-out test on actual structure and pull-out test by rotation, as shown in fig. 1.3.

Model tests

From model tests to failure by reinforcement slippage, the soil-reinforcement friction coefficient has also been/

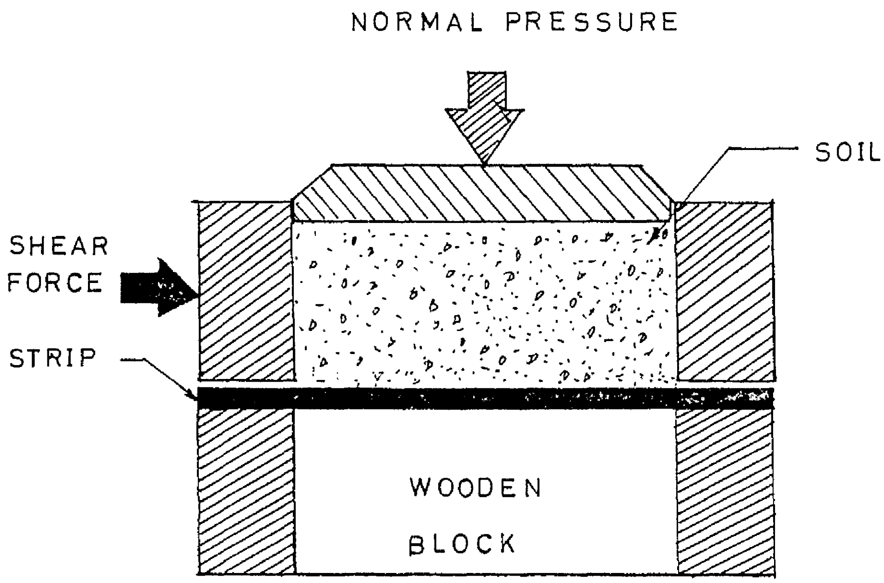
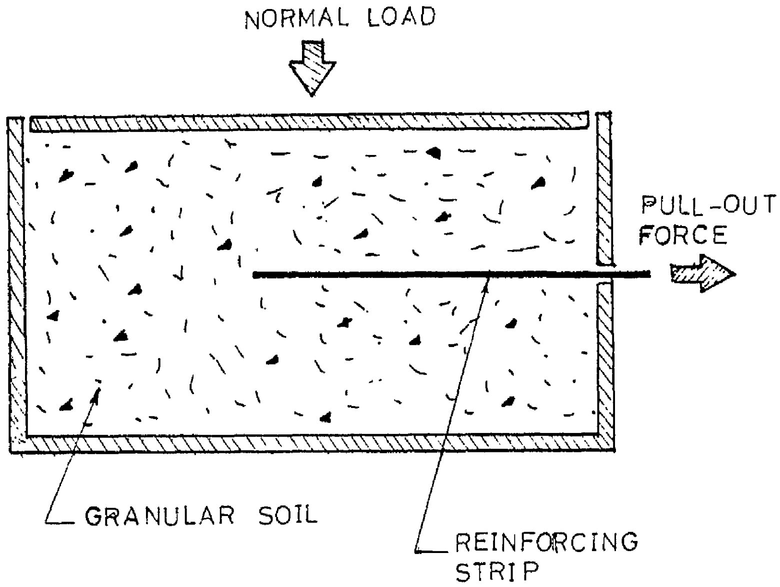
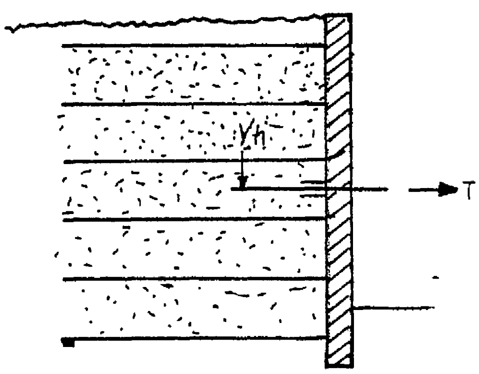


Fig. 1.2. DIRECT SHEAR TEST.



Model Pull-out Test (Schlosser & Elias)



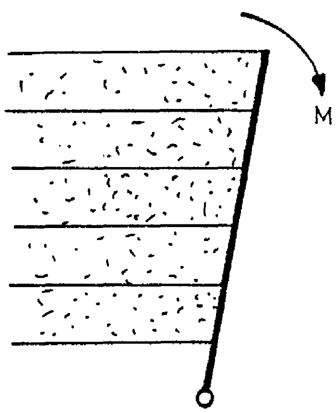


Fig. 1.3. Pull-Out test on actual structure (Chang).

Full-Scale Pull-out Test by rotation. (Hausman & Lee) calculated by taking the maximum strip tension as a maximum pull-out resistance.

Over the past few years, besides other aspects of reinforced earth, extensive research work on the complex mechanism of soil-reinforcement interaction has been carried out by investigators in various countries. This research has included the study of mobilization of friction and the relative influence of various factors affecting the value of soil-reinforcement friction coefficient.

The present investigation was aimed at gaining further insight into testing methods available for measuring the soil-reinforcement friction coefficient.

Scope of thesis

The findings into soil-reinforcement frictional behaviour reported from tests performed by different investigators using all existing available testing methods and the discussions on them held in various conferences have been reviewed.

The author has determined the strength of a fill material over a range of densities using both direct shear and triaxial tests. Friction tests on both ribbed and smooth steel reinforcement strips have been conducted in a shear box using fill material at varying densities. Pull-out tests were carried out using two different methods, strip pull-out (a conventional testing method) and strip-with-facing plate pull-out. The results obtained from these two testing methods were then compared in/

order to observe the influence of the test method on the measured value of skin friction coefficient.

One series of tests was conducted in which the fill density was varied along the length of the strip and both methods of pull-out were used in order to determine the effect of density variation along the length of the strip on the skin friction coefficient.

Finally, the results are discussed in general, conclusions drawn, and future recommendations are presented.

CHAPTER 2

REVIEW OF INVESTIGATIONS INTO THE SOIL-REINFORCEMENT FRICTION BEHAVIOUR OF REINFORCED EARTH SYSTEMS.

2.1 Introduction

Since the introduction of reinforced earth techniques, a great emphasis has been placed on the methods from which a realistic value of angle of skin friction can be measured.

Two types of test have normally been used in measuring the angle of skin friction, viz:

- Direct shear test
- Pull-out test

Model test results at failure have also been used by several investigators to measure an angle of skin friction.

The pull-out test is carried out under different conditions, as follows:

- Reinforcing strip pull-out tests from rig or shear box.
- Reinforcing strip pull-out tests from model, prototype and full scale reinforced earth wall and embankments.
- Reinforcing strip pull-out test from a rigid moving model wall.
- Reinforcing strip pull-out tests during vibrations - model and prototype.

In the following sections, the work pertaining to determination of friction angle between soil and reinforcement from both testing methods and from model tests carried out by different investigators will be reviewed.

2.2. Direct shear tests

Potyondy (45) first used the direct shear box to measure the angle of skin friction between various construction materials such as steel, wood and concrete and different type of soils.

When Vidal introduced the technique of reinforced earth, this method was proposed for measuring the angle of friction between soil and reinforcement and since then many investigators including Shen et al (53), Jones and Smith (32), Bacot et al (5), Al-Hussani and Perry (2), Ingold and Templeman (28) and Osman (44) have carried out tests on different strip materials, metallic and non-metallic to measure the angle of skin friction either for the use of design or for the comparison with pull-out test results.

Besides the general use of the shear box to derive a design parameter, some of the investigators have reported a large number of tests in which the influence of some factors, such as roughness of strip, density, supporting medium to the strip, and testing method, on the magnitude of angle of skin friction, and the strain pattern in the direct shear test have been investigated.

Schlosser and Vidal (52) performed a series of tests on samples of calcareous and leucate sand with smooth and roughened/

reinforcements. The results of these tests are shown in fig.2.1. They concluded that the grooved strip gave higher values of angle of skin friction (close to the angle of internal friction of soil) than the smooth strip. Examination of the strips after shearing showed some striation marks on the smooth strip oriented in the direction of the displacement, evidence that sliding of soil particles along the strip had occurred. Examination of the roughened strip did not show such striations, evidence that sliding of soil particles had taken place along a soil-soil interface.

In addition to conventional testing methods Soydemir and Espinosa (55) performed tests using another testing method in which instead of shearing the sand at the strip surface, the strip was sandwiched at the level of the controlled shearing plane. They found that this method gave an angle of skin friction 10° higher than the conventional method.

Lee K.L. (34) conducted a series of tests on samples of sand at various densities sheared along and in contact with a sheet of aluminium foil in order to measure the angle of skin friction. He discovered that density has no effect on the value of angle of skin friction, and has suggested that the angle of skin friction should be expressed as a ratio of the angle of internal friction of soil ($k_u = \delta / \phi$) which varies between the limits of approximately zero for frictionless surface to a maximum of 1.0. The ratio of 0.66 is normally accepted in design.

Friction tests were carried out by Delmas et al (22) to study the soil-fabric friction in the direct shear box. He used many types of soil as a supporting medium to the strip and various type of fabrics. He has reported test results which show the effect of the particle size distribution, shape of soil particles, the nature of the fabric and the normal pressure,and concluded that supporting gravel yields greater values of angle of skin friction than supporting sand and that the apparent angle of skin friction increases with increasing normal pressure.

Very important work was carried out by Jewell (30) to study the patterns of strain which result from the interaction between sand and reinforcement in the direct shear box test. He believes that reinforcement imposes constraint on the way that the sand may strain; due to this constraint the new patterns of strain occur. To study this he performed a set of tests in a large shear box in which the reinforcement was embedded within dense sand across the central plane.

He observed two important features in the shear box test. (i) a new well defined zone of strain patterns and(ii) strip force-displacement relationship, as shown in fig.2.2 which were then compared with pull-out tests carried out using the same material subject to the same stress level.

2.2.1. DISCUSSIONS

The use of the direct shear box for measuring an angle of friction between soil and reinforcement remains a controversial topic among different researchers.

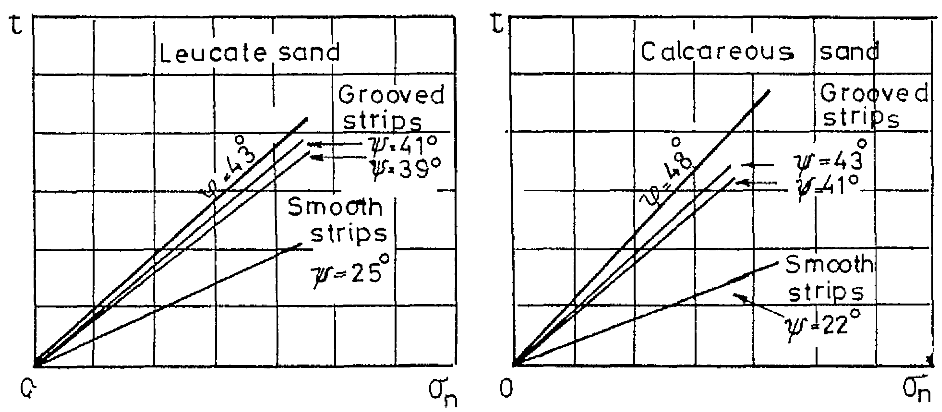


Fig. 2.1. Coefficient of soil-strip friction (After Schlosser & Vidal)

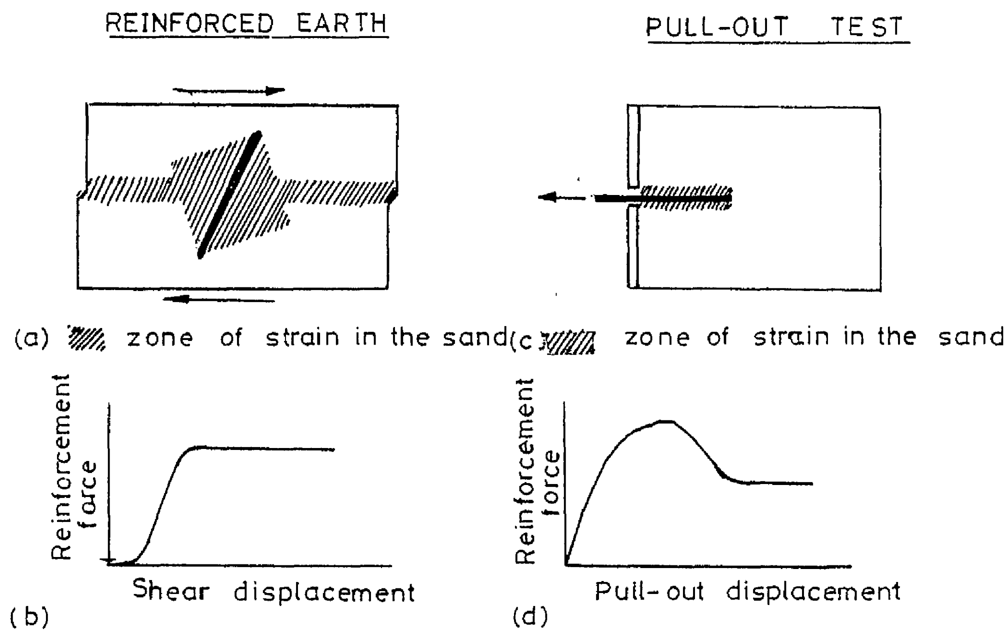


Fig.2.2. A comparision of the strained zone in the sand and the reinforcement force-displacement relationship, for reinforced sand loaded in shear and a pull-out test (After Jewell).

McKittrick (42) noted in particular, following the work carried out by Schlosser, that an appropriately roughened strip surface gave a value of angle of skin friction approximately equal to the angle of internal friction of soil, and suggested that the values of friction obtained from either a plane compression test adjusted for the effects of dilatancy, or from a direct shear test in the case of a non-dilatant soil could be used in design. He further argued that the shear box testing method was readily available to designers to measure the angle of skin friction ; unlike other testing procedures which required more specialized apparatus.

Additional support for its use comes from the work performed indirectly by different investigators.

Osman (44) carried out direct shear tests employing a plain strip and sand. The value of angle of skin friction obtained was compared with the value which was back-calculated from the results of model tests carried out to investigate the pull-out failure mode. The same value was found in both cases.

Masaru Hoshiya (27) also reported the same value of angle of skin friction both by the direct shear test and by a prediction from model test results, using plain brass strip as a reinforcement.

Chapuis (18), used the results of model tests carried out by Bacot (5) and Lee (34) and presented in the form of failure height, H_f, versus length of strip, L_a, to determine f from the equation for R_t, the tensile strength of the strip:

$$R_t = 2b\, L_a\, f\, \gamma_d\, H_f$$

where b is the strip width, and γ_d is the soil unit weight. He found approximately the same value of f as determined by the direct shear test. From this discussion it seems that the direct shear testing method in the case of the smooth strip measures a quite realistic value of angle of skin friction but this is not the case with ribbed strip for which no such comparison between model and laboratory test results has been made.

On the other hand, most of researchers argue that this method does not model the behaviour of a strip subject to tensile force ; in the field it is not certain whether the strip slides over the sand surface or is pulled out from the layers of soil. This method measures dynamic coefficient of skin friction, but in design a static coefficient of skin friction is required (Al-Yassin et). McGown (41) and other investigators consider that the direct shear test probably represents the lower limit of soil-reinforcement frictional interaction.

2.3. PULL-OUT TEST

An alternative method for measuring an angle of skin friction is naturally a pull-out test which consists of withdrawing a reinforcing strip from the reinforced earth mass and recording the pull-out force-displacement curve. This test represents adequately the conditions which actually occur in reinforced earth structures. The values of soil-reinforcement friction coefficient measured from this testing method are used in designing structures, when considering failure by lack of bond. However, because of the dilatancy effect the normal pressure exterted on the strip is unknown. Hence this test gives only an/

average apparent friction coefficient, f*, which is derived from a knowledge of the pull-out force, p, the embedded length, 1, overburden pressure, γH, and strip width, w.

$$f^* = \frac{p}{2wl\gamma H}$$

In the following section, the conditions under which pull-out tests have been carried out by different investigators will be reviewed under their separate headings.

2.3.1 Reinforcing strip pull-out tests from rig or shear box

Shen and Mitchell (53) performed a series of pull-out tests on steel strips of various lengths and widths in apparatus especially constructed for this purpose. The values of angle of skin friction obtained are shown in table 2.1. After noting the random variation of angle of skin friction with strip size, which was thought to be due to the presence of waves in the backfill strip, a few tests on a undulating strip were carried out. The results showed quite large differences in δ values compared to those obtained with a plane strip, as shown in fig. 2.3. Shen and Mitchell suggested that the apparent angle of skin friction would be affected not only by the testing method but also by soil arching, dilation, boundary conditions, soil compaction, strip geometry (length and width) and undulations in the strip.

P.D. Walter (58) conducted a series of pull-out tests to compare the performance of ribbed and smooth reinforcing strips in various types of soil compacted at different moisture contents. The results are shown in fig. 2.4. He concluded that ribbed strip/

Length (cm) \ Width (cm)	1·27	2·54	5·08
39·12	11·9	16·5	15·7
31·50	12·4	14·2	16·2
23·88	12·6	14·1	15·5
16·26	13·0	14·1	14·1

Table 2.1. Angle of skin friction from pull-out tests (after Shen et al)

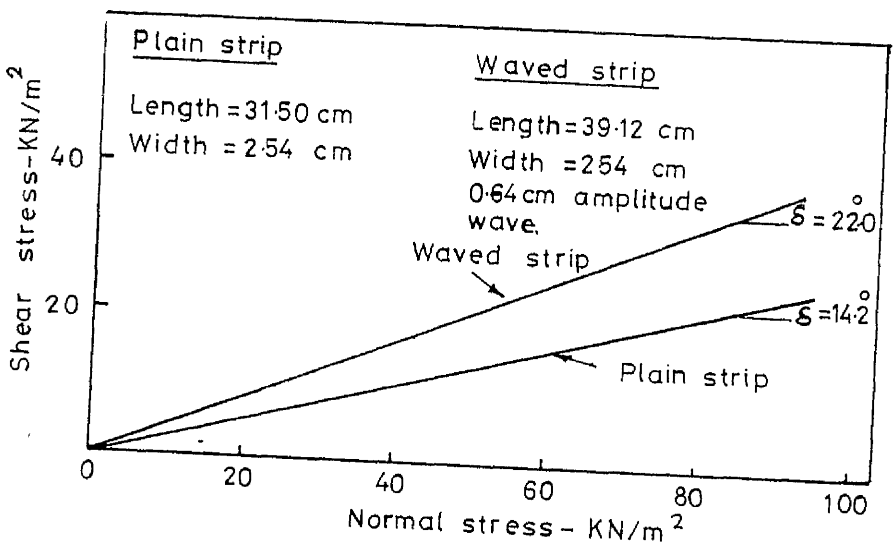
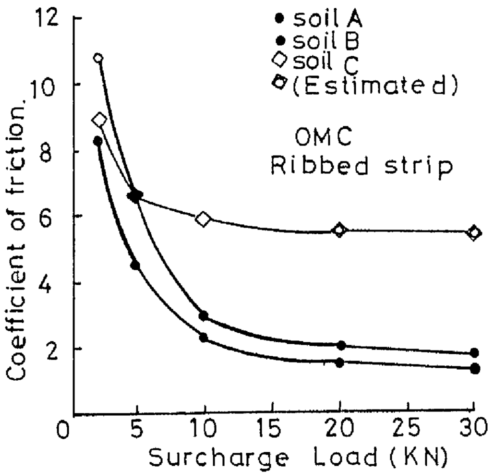
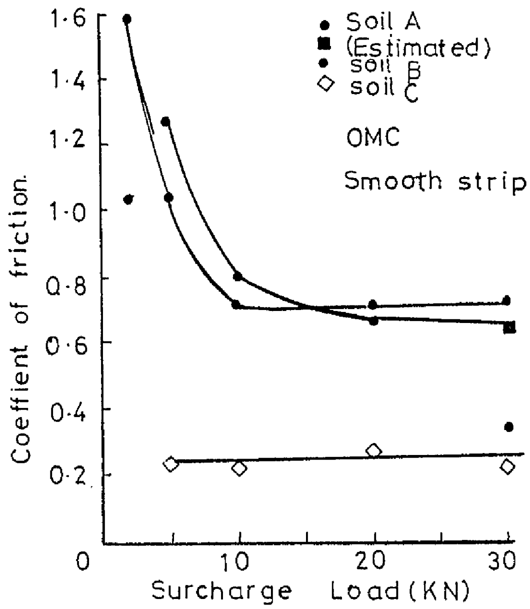


Fig. 2.3. Effect of undulations in the strip (After Shen et al)



Coefficient of earth-strip friction versus surcharge load for ribbed strip.



Coefficient of earth-strip friction versus surcharge load for smooth strip.

Type of Reinforcement	Soil Type	Soil A			Soil B		Soil C
Ribbed strip	Moisture content	OMC (10·5%)	8·9%	11·3%	OMC (7·6%)	5·5%	OMC (9·8%)
	Tangent of the angle of earth-strip friction.	0·68	0·19	0·68	0·82	0·84	5·09
Smooth strip	Tangent of the angle of earth-strip friction.	0·56	0·26	0·52	0·64	0·28	0·23

Fig. 2.4. Summary of test results (After Walter)

performed better than smooth strip at the optimum moisture content, and that the soil-reinforcement friction coefficient decreased with increasing surcharge load.

Some pull-out tests were conducted by the Reinforced Earth Company, U.S.A. (42) on both smooth and ribbed strips using a special large shear box under the maximum normal pressure of 200 kN/m^2. Five type of soil such as Ottawa sand,Coal refuse, a decomposed phillite gravel, a bank run gravel and a river sand were used. The results from two types of soil are shown in fig.2.5.

The conclusions drawn from this are that the apparent friction coefficient decreases with increasing value of average normal pressure, and that the high values of apparent friction coefficient, greater than tan ϕ in the case of ribbed sand and higher than tan ψ in the case of the smooth strip, were thought to be due to the dilatancy of soil.

Jewell R.A.(30) carried out a series of pull-out tests, in addition to the direct shear tests already mentioned in the previous section, in studying the strain pattern.

The results presented showed a limited zone of straining sand developed between an unyielding mass of sand and the surface of the reinforcement, and well defined peak and residual points on the load-displacement curve (Fig. 2.2).

Some investigators have used various types of net structures and fabrics in place of metallic reinforcement.

Ingold and Templeman (28), in their comparative performance/

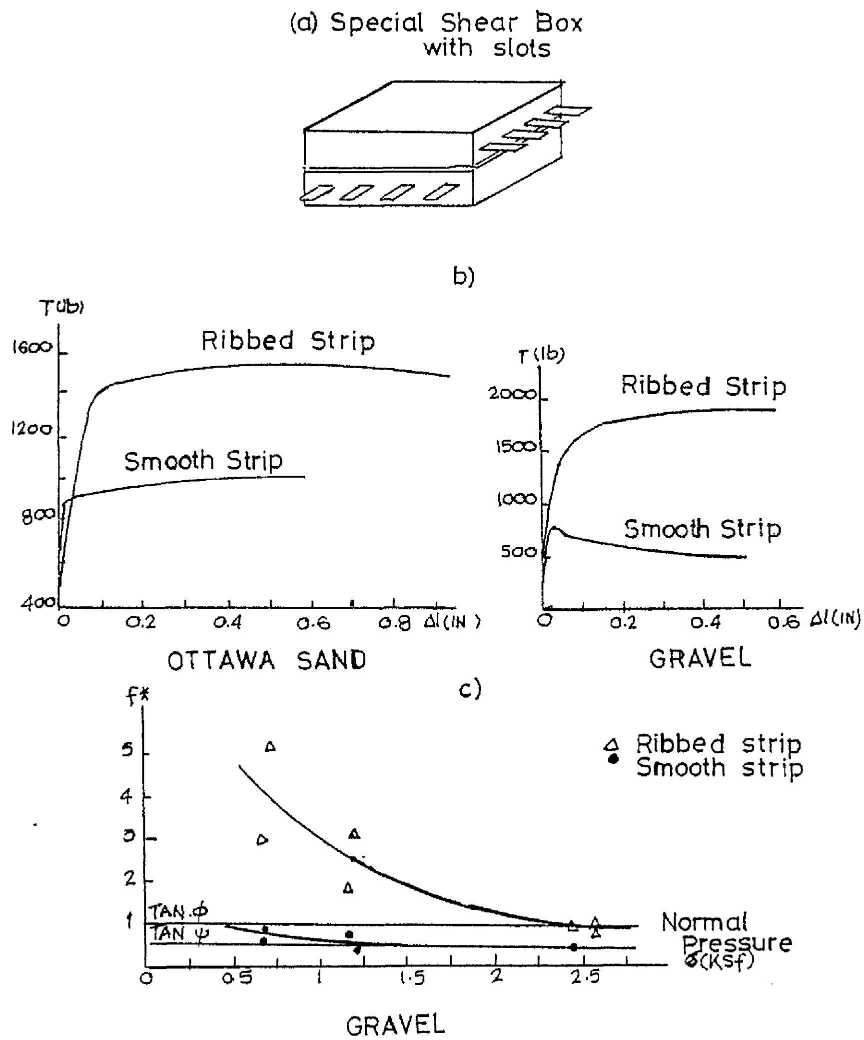


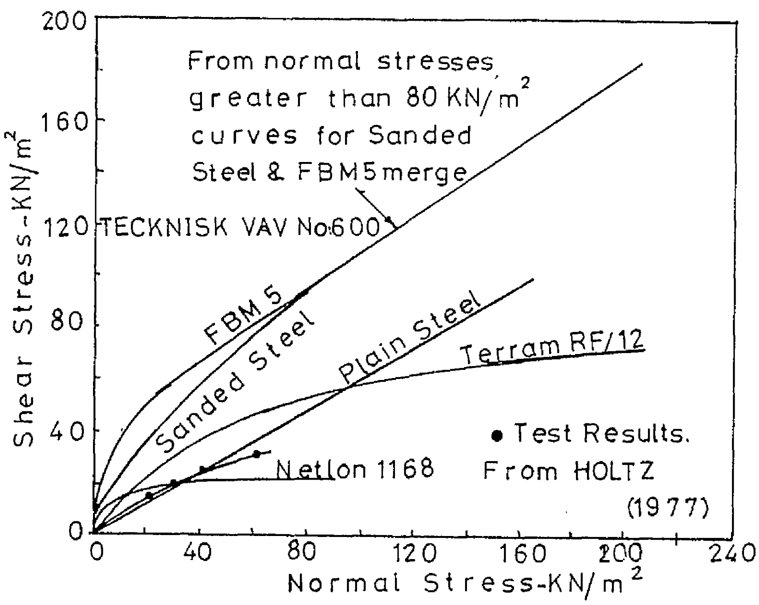
Fig. 2.5. Pull-out tests on a large direct shear box (After Schlosser).

study of polymer reinforcement, performed a series of pull-out tests from the rig described in reference (28), on five different type of samples including plain steel, sand coated steel, two net structures (Netlon 1168 and FBM5) and Woven fabric (Terram RF/12).

The results presented in the form of σ_n vs τ and σ_n vs f* are reproduced here in fig.2.6. They state in their concluding remarks that the apparent angle of skin friction decreases with increasing normal pressure, and that the extremely high value of apparent angle of skin friction obtained is not simply because of dilatancy but postulate that some additional mechanism is acting. A good bond can be achieved between soil and reinforcement by using fabrics or nets instead of steel or aluminium.

Pull-out tests employing fabric reinforcing strip (NT400) in a direct shear box were carried out by Delmas et al(21). An attempt was also made to interpret a pull-out test theoretically by using elastic theory in which the deformations of the fabric and of the soil were incorporated. It was concluded that the fabric maintained a relatively plane shape and that the results were close to those obtained with a smooth support in the friction tests. The importance of fabric length was also noted ; for a long strip a large displacement was needed at the fixed end to mobilize friction at the free end. The experimental results were in partial agreement with the theoretical.

The possibility of constructing reinforced earth structures with in-situ fine-grained soils instead of imported coarse-grained/



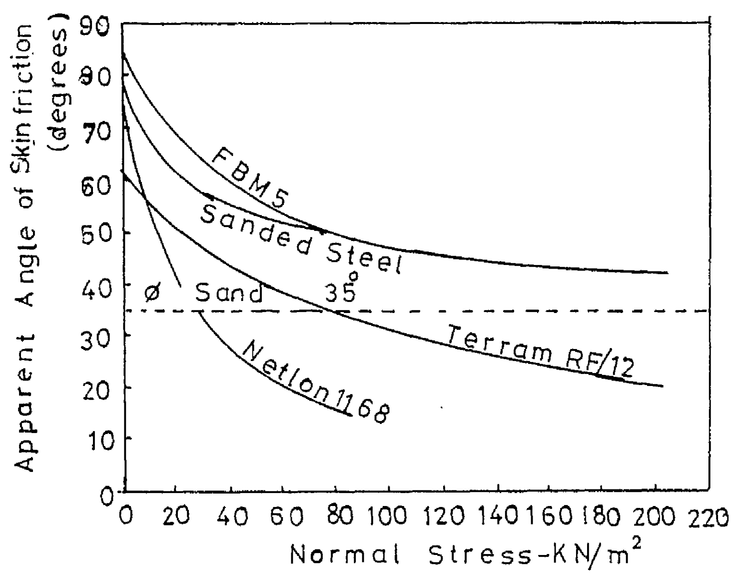


Fig. 2.6. Comparison of pull-out test results (After Ingold & Templeman).

materials has led to the investigation of the friction characteristics of fine-grained soils.

Elias V. (23) performed a series of pull-out tests in a large direct shear box, using various type of soils (fine sand, silt and clay) and ribbed strip of the type which is presently used by the Reinforced Earth Company. The results were presented in the form of load-displacement curves from which the f* values were calculated. The conclusions drawn by the author are that the apparent friction coefficient decreased with increasing normal stress, as in the case of cohesionless soil, and that the f* values for fine-grained soil appeared to be considerably less than for coarse-grained soil. He suggested that for all normal pressures greater than 47.9 to 71.8 kN/m^2, the value of f* equal to 1/2 to 2/3 of the drained angle of friction could be used and for lower normal pressure, it is justified to use an f* value equal to the drained angle of friction, and that the soil should be compacted dry of optimum. Elias does not mention the fact that the angle of friction has been found to depend on the normal pressure at testing, and is not, therefore, unique.

2.3.2. Reinforcing strip pull-out tests from model, prototype and full scale reinforced earth walls and embankments.

Tumay et al (56) carried out, on model walls, a comparative study which was designed to evaluate the efficiency in mobilizing soil-reinforcement interaction of both non-woven fibre fabric and metal reinforcement, and also to study the effect of relative density of the sand backfill and length of reinforcement. The equipment, testing procedure and results are described in/

reference (56). He drew the following conclusions from his work.

- The effectiveness in mobilizing sand-reinforcement interaction for fibre fabric is three times higher than that of metal, because of the grabbing effect of fibre fabric. The frictional resistance of fibre fabric reinforcement increases with increasing relative density of sand ; whereas in the case of metallic reinforcement the relative density has very little effect in improving friction capacity.

- Increasing length increases the efficiency in mobilizing soil-strip interaction for both types of reinforcement.

- A great improvement can be achieved by using fibre fabric at low densities of sand.

To study the effect of density and width of reinforcement, pull-out tests on a reduced scale model of sand embankment were carried out by Alimi and Schlosser (3).

The results, fig. 2.7a, showed that at low density the peak value of tension was achieved at a small displacement of 2mm, whereas at high density it was obtained at greater displacement of 160 mm. The high density of soil yielded a greatly enhanced value of f* increasing from 0.3 at a dry density of 1.56 Mg/m^3 to 2.5 at a density of 1.76 Mg/m^3, due to the dilatancy of the granular soil at high density.

The effect of reinforcement width was observed by testing three widths of reinforcement (1.5 cm, 3cm and 4.5 cm) and the results presented are shown in fig. 2.7b.

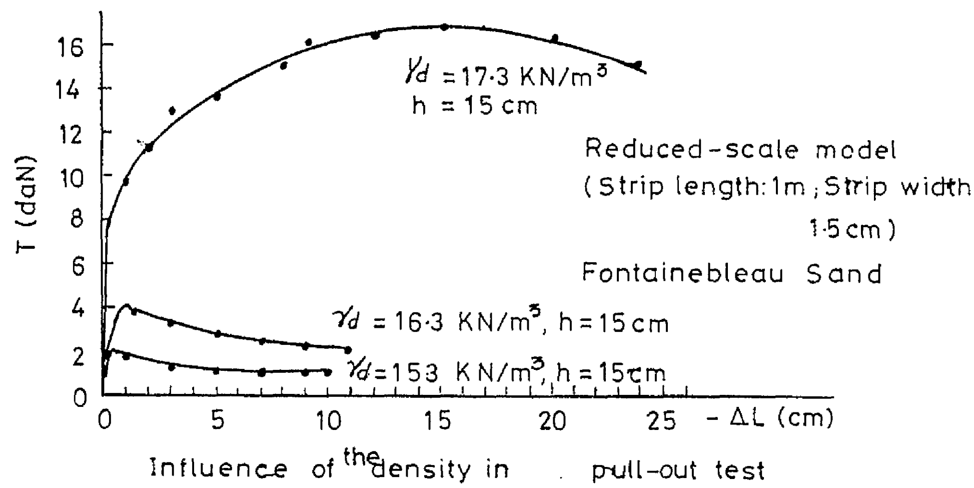


Fig.2.7a;

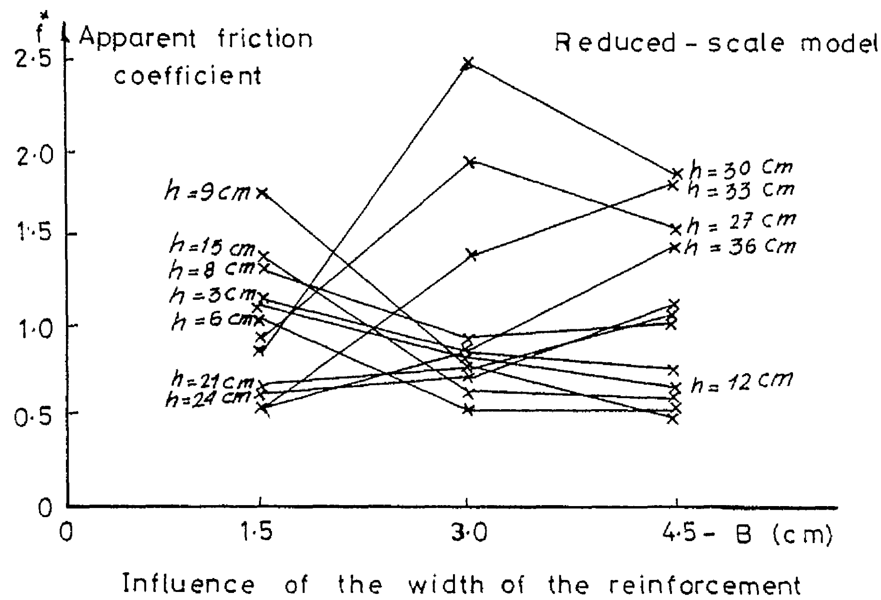


Fig.2.7b. Pull-out tests on reduced scale model (After Schlosser)

For an overburden height, h, less than 18 cm. the f* values decreased with increasing width but for h greater than 18 cm, no definite trend appeared. The author further stated that the width of reinforcement indirectly influences the f* values, e.g. by decreasing the deformability of the strip with increasing width and by decreasing the dilatancy effect beyond a critical value of the width the f* values decrease.

A great number of pull-outtests at full-scale to investigate the effects of embedded length, overburden and strip roughness have been carried out by different investigators.

Chang (13) performed the first full scale field pull-out tests during the construction of a reinforced earth wall at Highway 39, California, U.S.A. The results were obtained in the form of load-displacement curves with yielding, peak and residual points clearly defined (Fig. 2.8). These points correspond to three loads which are : the yield load, representing maximum possible frictional grip of the compacted soil without introduction of strain of the soil ; the peak load which represents the maximum mobile pulling resistance of the composite material of the soil and reinforcement ; residual load, representing the load which occurs after peak load when the strip becomes partially loose and the whole length of the strip starts sliding. Fig. 2.8 shows the relationships between these three pulling loads and the overburden height, overburden load and strip length.

Chang concluded that the angle of skin friction decreases with increasing overburden height and increases with the length of/

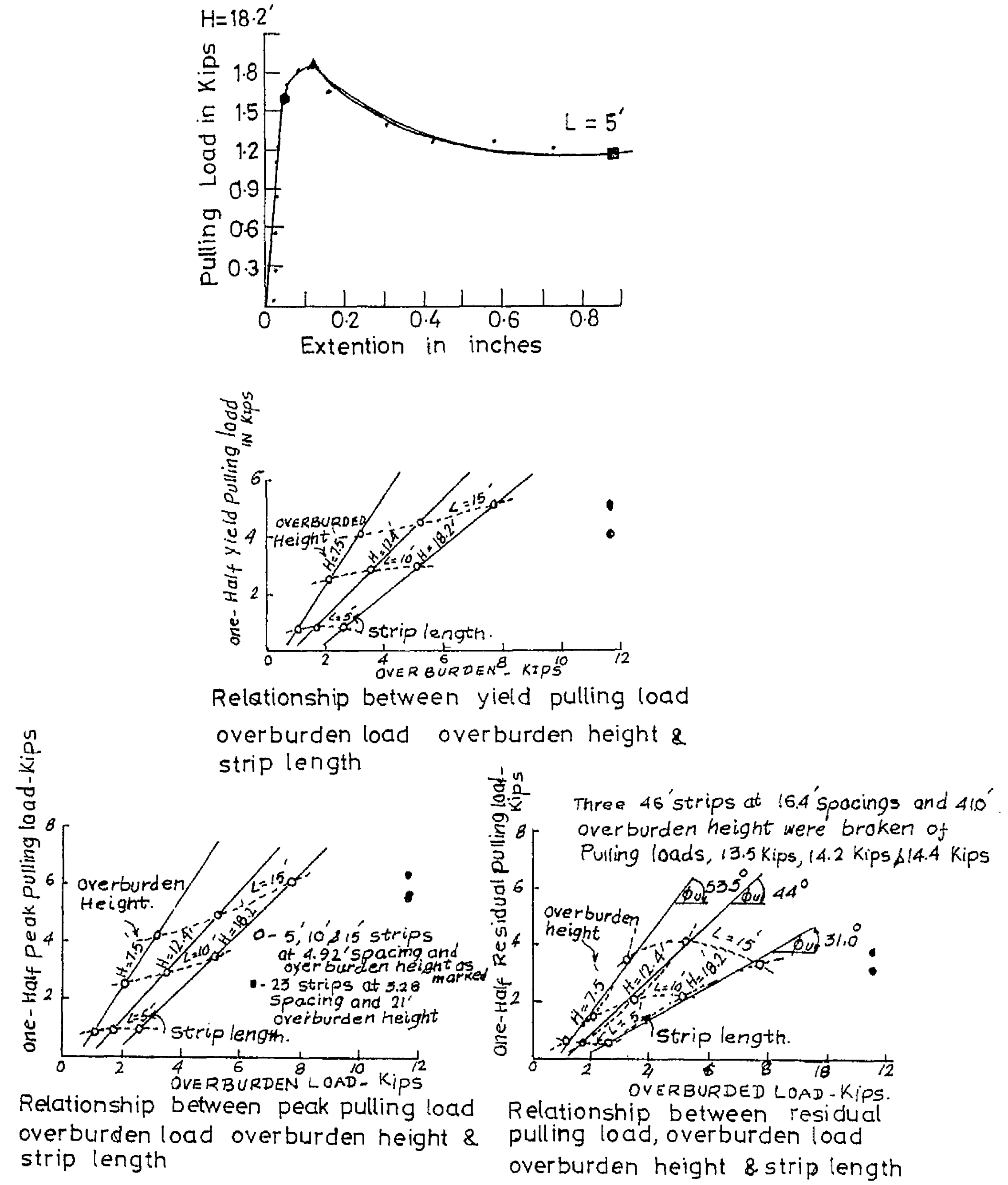


Fig. 2.8. Typical load-displacement curve & Relationships between pulling load, overburden load, overburden height and strip length (After Chang).

the reinforcement (Fig. 2.9.).

The effects of strip length on the apparent friction coefficient are also reported by other investigators, viz. Schlosser& Elias(47), as shown in fig. 2.9. and Alimi and Bacot (5).

Some 500 field pull-out tests, using two types of reinforcements, plain and ribbed galvanised steel strip, in granular fill material have been performed by the Reinforced Earth Company to study the effect of strip roughness. Typical load-displacement curves, fig. 2.10, show that the peak resistance for ribbed strip is greater than for smooth strip, occurring at a displacement of approximately 50 mm and 5 mm with the ribbed strip and the smooth strip respectively. The value of f* for both types of reinforcement was greater than tan ψ measured using a direct shear box.

The influence of overburden pressure from full-scale pull-out tests on both ribbed and smooth reinforcement reported by Schlosser and Elias (47), Fig. 2.11 shows extremely high values of f* at low overburden pressures, particularly for the ribbed strip, which decrease with increasing overburden pressure, and appear to remain constant after reaching an overburden pressure of approximately 100 kN/m^2. The same author presented another two series of tests on ribbed and smooth strip, Fig. 2.13, which show the same trend, i.e. a decrease of f* with increasing overburden pressure, and it appears that f* values are higher than unity for a ribbed strip. The extremely high value of f*

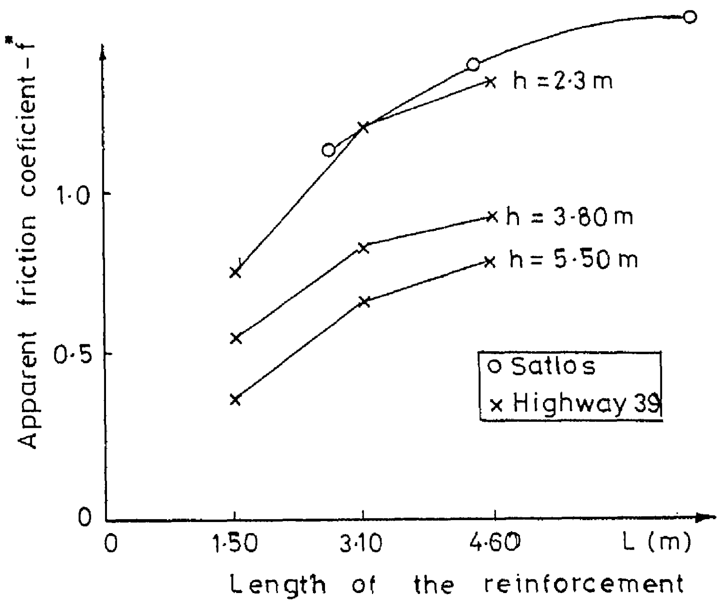


Fig. 2.9. Influence of the length of the strip (After Chang & Schlosser).

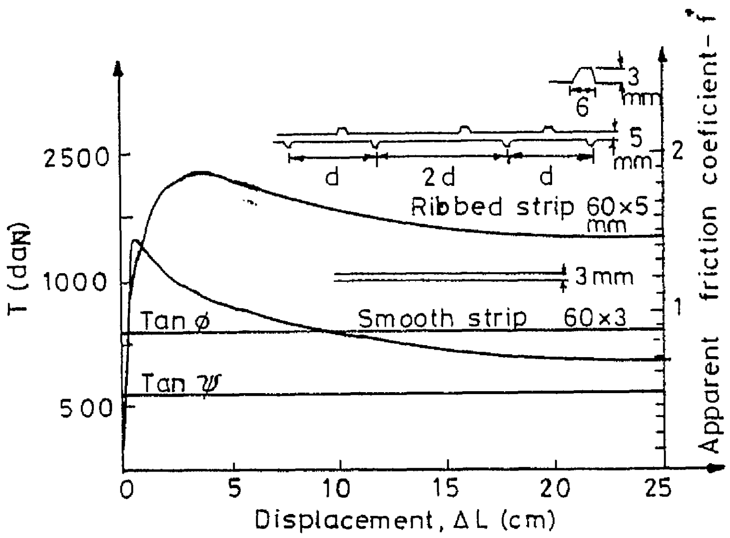


Fig. 2.10. Influence of the nature of the strip surface Pull-out tests (After Schlosser).

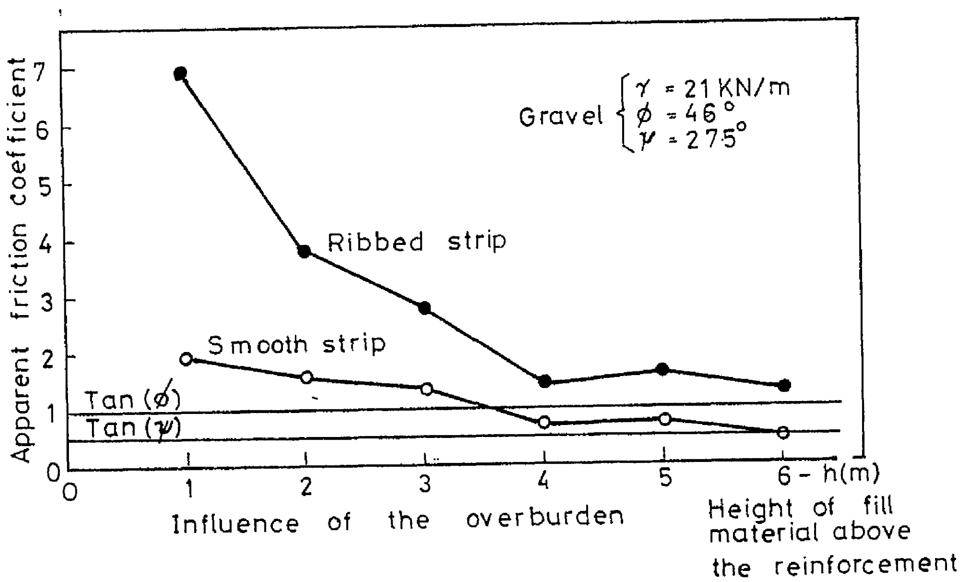


Fig. 2.11. Pull-out tests (After Schlosser).

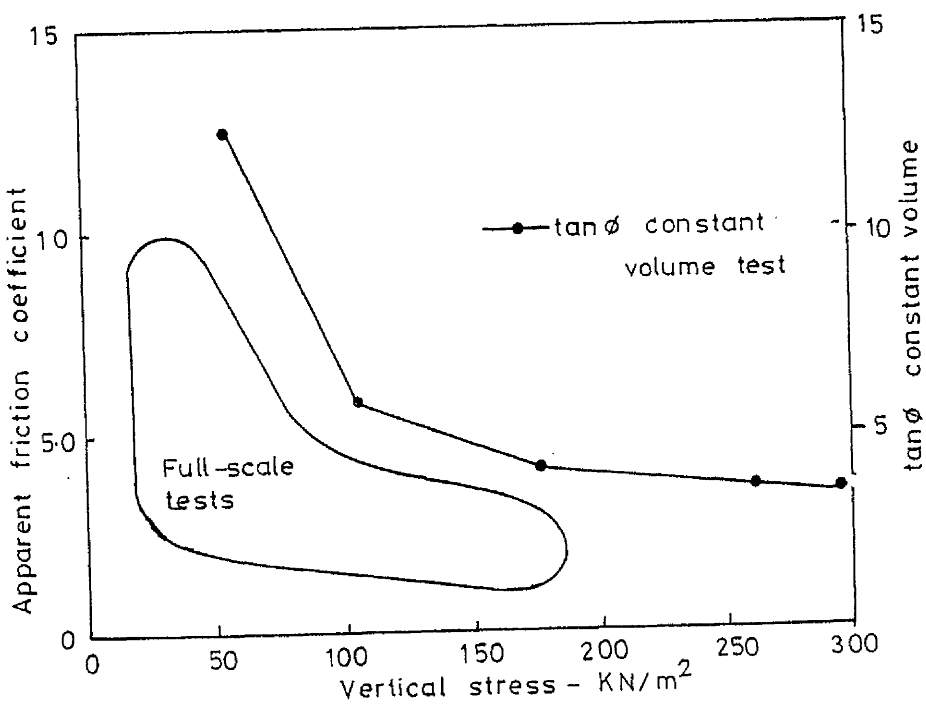


Fig. 2.12. Comparison of full-scale and laboratory test results (After Guilloux et al).

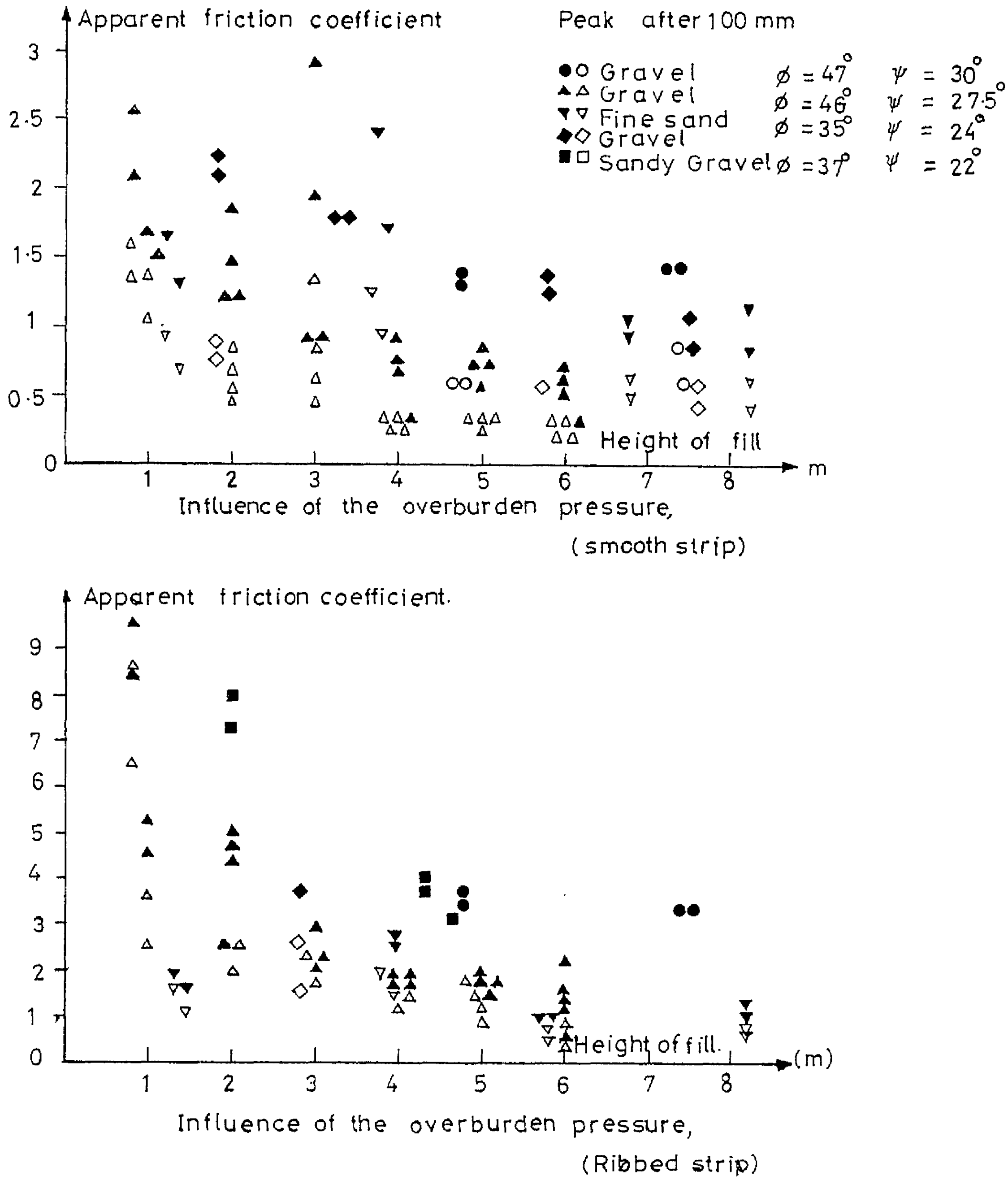


Fig. 2.13. Apparent friction coefficient (Pull-out tests) (After Schlosser).

at low normal pressure is attributed by McKittrick (42) to dilatancy.

Ingold (29) discussed the dilatancy effect, which he believes, cannot completely account for the 36° increase in δ value recorded for ribbed strip, but which may account for the 17° increase for the smooth strip.

To further explain this behaviour, Guilloux (24) carried out shear tests on highly compacted samples of sand under constant volume conditions. The results of these tests and the envelope of full-scale pull-out test results are shown in fig.2.12. He suggested that dilatancy, which occurs in the immediate vicinity of the reinforcement, is restrained during pull-out which, in turn, increases the normal pressure acting on the strip. This increased normal pressure, therefore, results in high values of apparent friction coefficient f^*.

2.3.3. Reinforcing strip pull-out test from a rigid moving model wall.

Lee and Hausman (25) conducted tests in which a rigid model wall was used in place of a conventional element wall to determine the actual soil-reinforcement friction coefficient.

Rotating the model wall about a knife edge support attached to the base of the box containing sand backfill, the curve of the applied moment-versus the rotation angle was recorded. The authors/

indicated that results are believed to be relevant to Reinforced earth design, because the overall deformation pattern reported for experimental walls is essentially that of rotation rather than translation.

They concluded that soil-reinforcement friction mobilization is a function of the overall deformation of the reinforced earth mass and that frictional resistance is not fully mobilized, even at the point of failure, when compared with direct shear test results.

2.3.4. Reinforcing stip pull-out tests during vibration - model and Prototype.

In the design of seismically stable reinforced earth structures it was felt necessary to evaluate the effect of vibration on the soil-strip friction angle. Richardson and Lee (47) performed pull-out tests at various stages such as initially after construction of the wall, during 0.05 g acceleration and statically after the acceleration was removed, from the model walls. A pull-out device constructed in the laboratory was used to measure the force-displacement characteristics, and peak values were used for calculating the angle of skin friction. The summary of their results is shown in fig.2.14.

They found a considerable reduction in values of skin friction angle from peak to residual. The most surprising observation was that the peak soil-strip friction angle was higher during vibration and after vibration than under static conditions (pre vibration).

To determine if surface vibrations such as produced by traffic can affect the adherence resistance of reinforced earth structures, Murray and Carder (39) carried out pull-out tests on metal and fiber reinforced plastic reinforcement embedded in an experimental reinforced earth wall, at full-scale, using uniformly graded sand. The tests were done under both dynamic and static conditions. The results are given in fig. 2.15 & 2.16. They found that the apparent friction coefficient measured from dynamic tests was approximately 25 percent lower than that obtained from static tests. They also concluded that the measured values of skin friction angle were greater than those obtained from shear box tests. This effect was attributed to dilatancy of the soil and undulations in the strip.

2.4. Estimation of the friction coefficient from model wall test results.

A few investigators have attempted to calculate the soil-reinforcement friction coefficient from the results of tests conducted on model walls failed by lack of adherence. Some researchers have compared the calculated f^* values from the failure tests of models with those obtained from existing available laboratory methods in order to check the reliability of the testing method.

Shen and Mitchell (53) performed a series of tests on a model with rigid and flexible facings to measure the tensile strain distribution along the length of the reinforcement, from which the angle of skin friction was back-calculated. After/

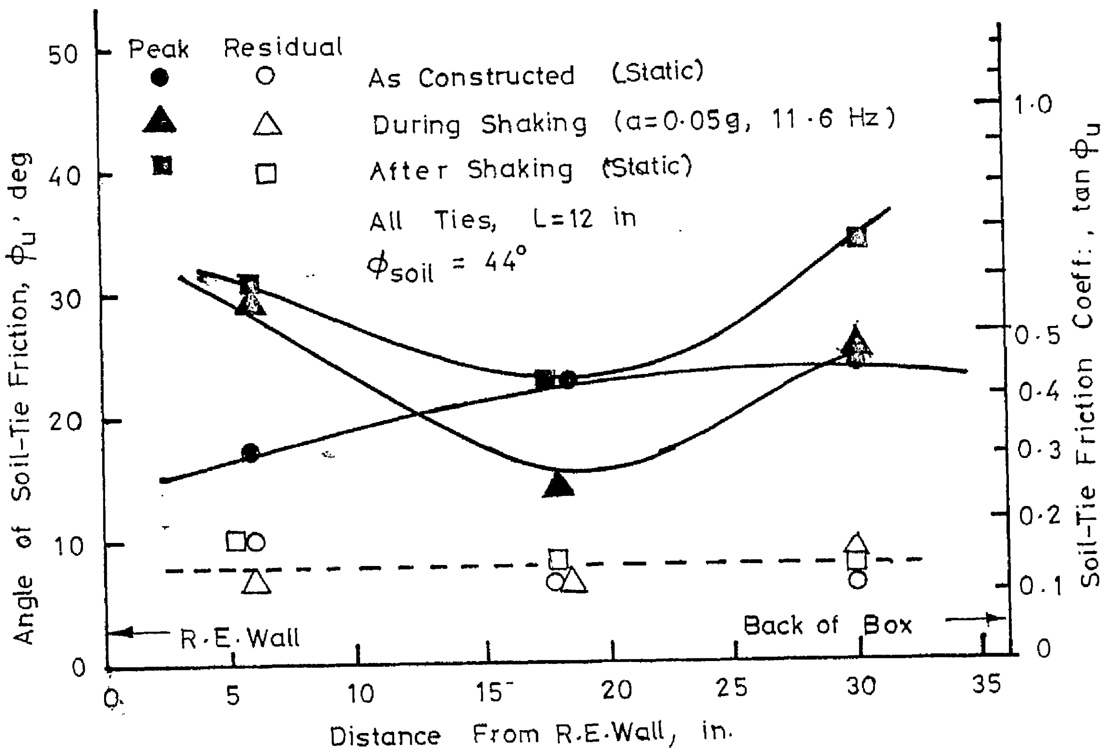


Fig. 2.14. Summary of soil-strip friction data (After Richardson & Lee).

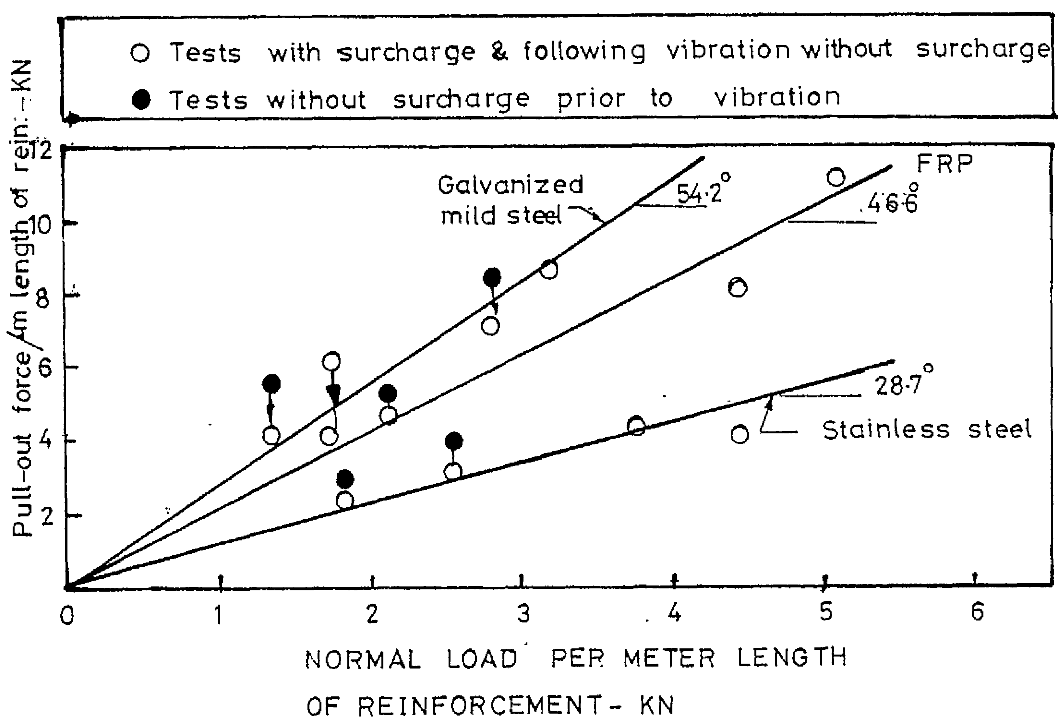
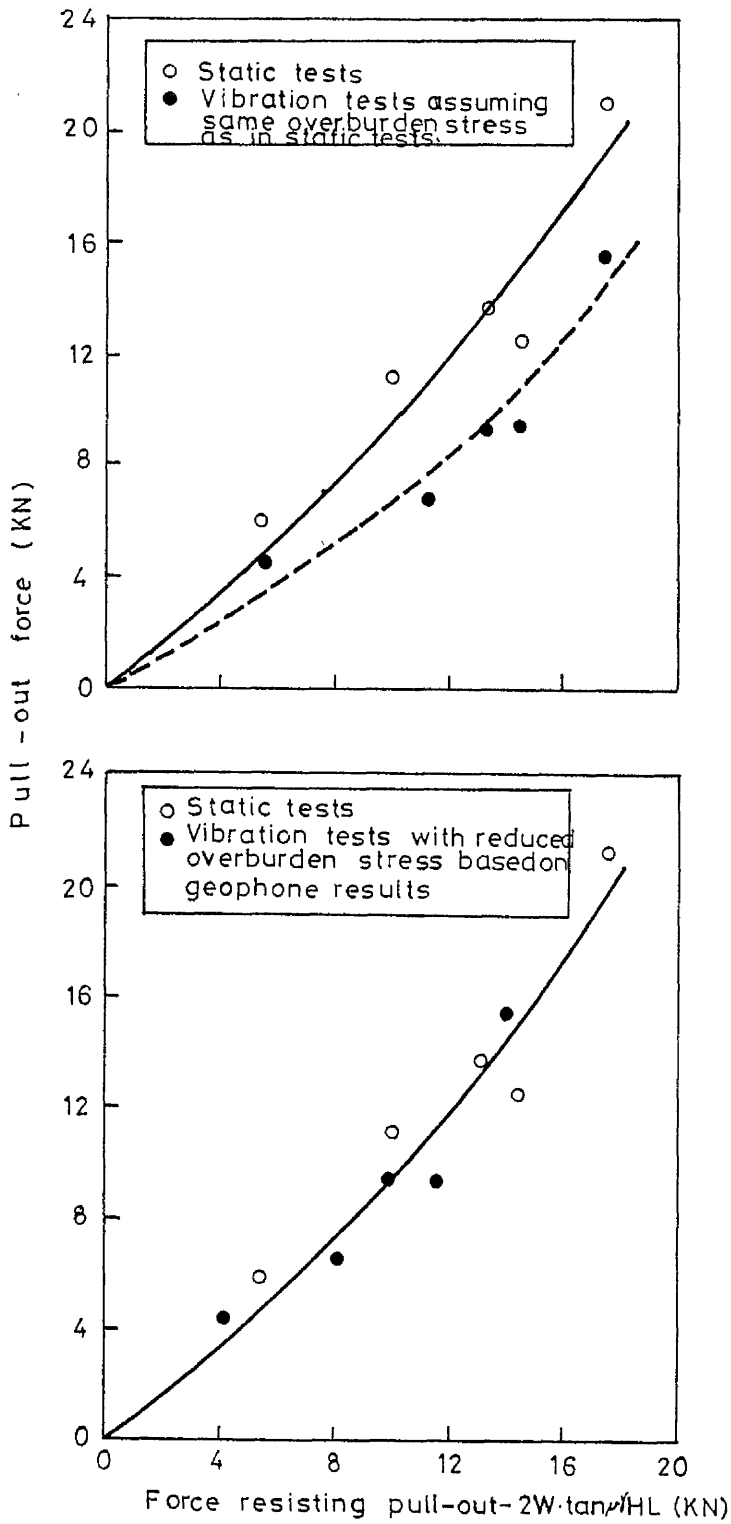


Fig. 2.15. Pull-out tests under static load (After Murray & Carder).



For. 2.16 Results of pull-out tests with both static and dynamic conditions showing the effect of vibration in reducing overburden stress (After Murray & Carder).

noticing the resemblance between the mobilization of friction along the length of strip in model test and friction forces which are developed in a pull-out test, the authors suggested that the pull-out test should be used to determine the frictional behaviour of the soil-strip interaction.

Osman (44) also calculated the apparent friction coefficient by assuming the maximum tie tension, measured from the reinforced earth retaining wall model at the moment of failure, equal to the pull-out resistance.

Comparing these values with those obtained from shear box tests using the same strip material and soil, he found a good agreement between them.

Bacot (5) carried out failure tests on a reduced-scale tridemensional model. Considering a broken strip and its breaking point represented by H_a (auto-destruction height)and L_a (adherence length to this height) he calculated the experimental lower and upper bounds of f* values using the equation:

$$RT = 2\gamma_d H_a L_a f^*$$

which exists when the friction mobilization along a strip reaches its tensile strength. The effect of geometry of the strip (length and width) on f* was also determined. He concluded that the friction coefficient is always greater than that obtained with the shear box, and that f* varies inversely with width and directly with length.

This approach was also followed by Chapuis (18). Using experimental values of L_a and H_a, the curves (H,L) were plotted to provide a possible check on the laboratory methods normally used to measure f* values. For this purpose, two sets of model wall tests, carried out by Lee (34) and Bacot (5), in which the two different methods were used to measure f* value, were selected. Chapuis concluded that the shear box test gives a good evaluation of the friction coefficient but the pull-out test yields an overvaluation.

2.5. DISCUSSIONS

A study has been made of a large number of papers by many investigators on the subject of pull-out tests on full-scale and model-scale reinforced earth walls under different conditions. It is concluded that a pull-out testing method gives a high value of the apparent friction coefficient, which is influenced by numerous factors such as dilatancy, overburden pressure, density, undulations in the strip, deformability, surface conditions and geometry of the reinforcement.

The use of this high value in design has been debated by various researchers. Most of them believe that a pull-out test represents a frictional behaviour which exists in actual reinforced earth structures, and that the use of a high value would permit economy in design.

Shen et (53) suggested that pull-out test should be used for measuring an angle of skin friction, because the results of this testing method agree with those of the model tests.

Al-Yassin (4) further supported his opinion. He analysed the rigid facing model using a finite element technique, and found very good agreement between the model test data and the analytical test results when the angle of skin friction as determined by pull-out testing was used.

A significant discussion on the use of the pull-out test was presented in the Seventh European Conference on Soil Mechanics and Foundation Engineering. Schlosser considered that it was advantageous to use the pull-out test for measuring an angle of skin friction, because the various factors could be included in it. Such factors are difficult to analyse otherwise. The apparent friction coeffient takes into consideration the effects of dilatancy and compaction, which are difficult to include separately in a calculation.

On the contrary, some investigators, e.g McGown (41) and Jewell (30), have criticized this testing method. They believe that a pull-out test does not model the behaviour which actually occurs in the reinforced earth system. McGown has discussed the fact that the shear stress distribution is not the same as that in a reinforced earth system, and that in the case of deformable reinforcement the distribution of stresses and strains is not uniform, which affects the measured value of f^*. He also pointed out that the pull-out test is influenced by various factors such as overburden pressure and its distribution and the edge effect in the vicinity of the facing.

Similar comments have been made by Jewell (30), more particularly, he states that values of f^* greater than $\tan \phi$ in reinforced earth are far from reality, and that these values reflect only the particular conditions of the pull-out test.

CHAPTER 3

TEST EQUIPMENT AND MATERIALS

3. In this chapter the equipment which was constructed to investigate the pull-out testing methods and the materials, strip and soil, will be described.

3.1. Test equipment

The testing equipment Fig.3.1 and 3.2 mainly consisted of a steel box, facing plates and a pulling arrangement. Each will be described under their separate headings.

3.1.1. Box

The planned tests were to consist of (a) pulling a reinforcing strip out of a mass of soil through a slit in a facing plate, and (b) pulling the facing plate with the reinforcing strip attached away from the soil mass. In view of this, and the fact that a full-size reinforcing strip was to be used embedded in fill material with a large particle size, a relatively large box was required. In addition edge effects had to be minimised. Previous investigators making tests on full size strips (23) had used 0.91 x 0.9 x 45 mm size of box.

In the present test series the width upon height ratio of the box was kept to 1.9. In a further attempt to cut down the effects of side friction, the box was lined with thin plastic sheet.

A steel box with internal dimensions 2000 mm long. 420 mm wide and 229 mm high was constructed. The drawing of this is shown in fig. 3.3.

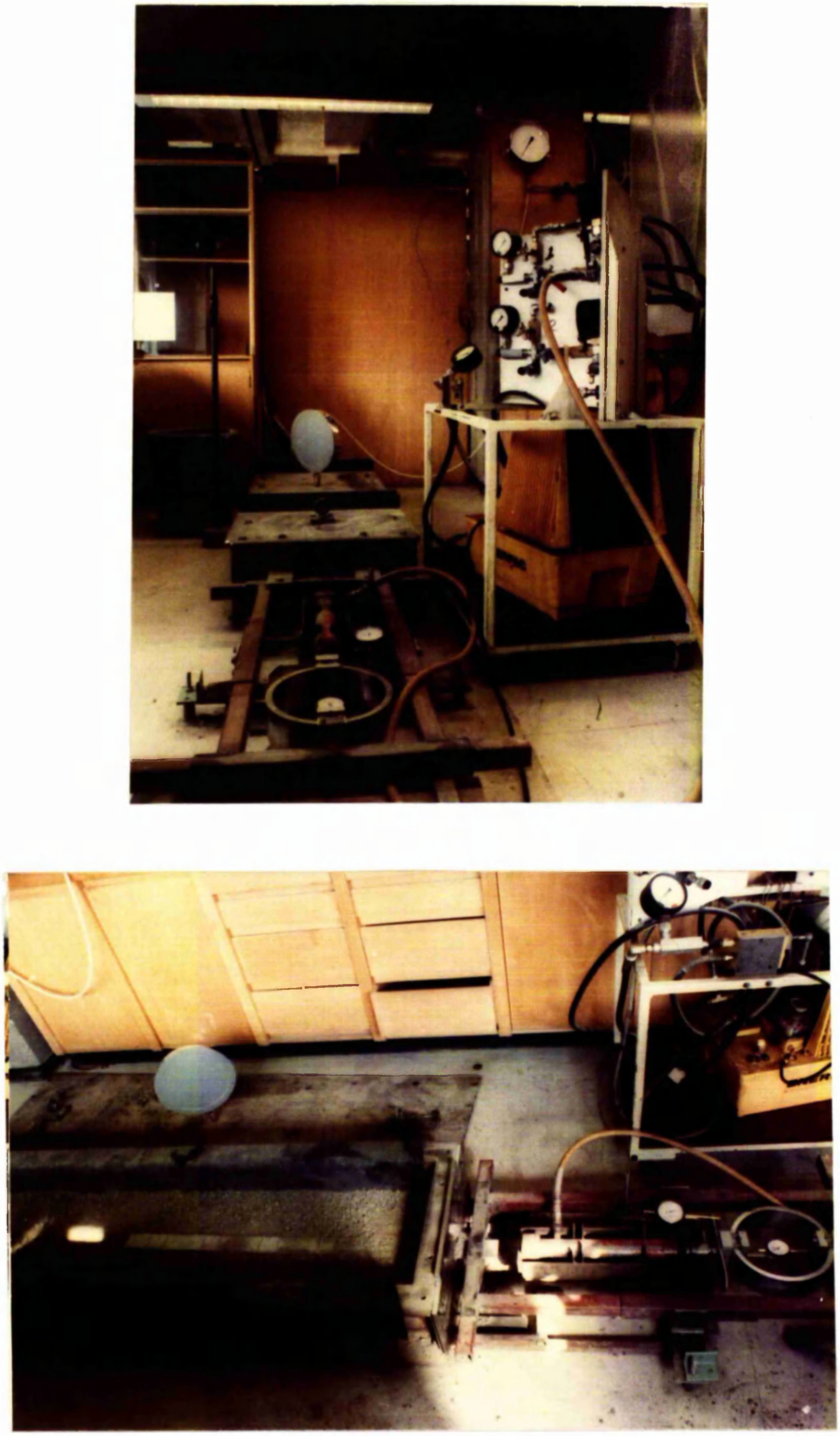


Fig. 3.1. General view of pull-out apparatus.

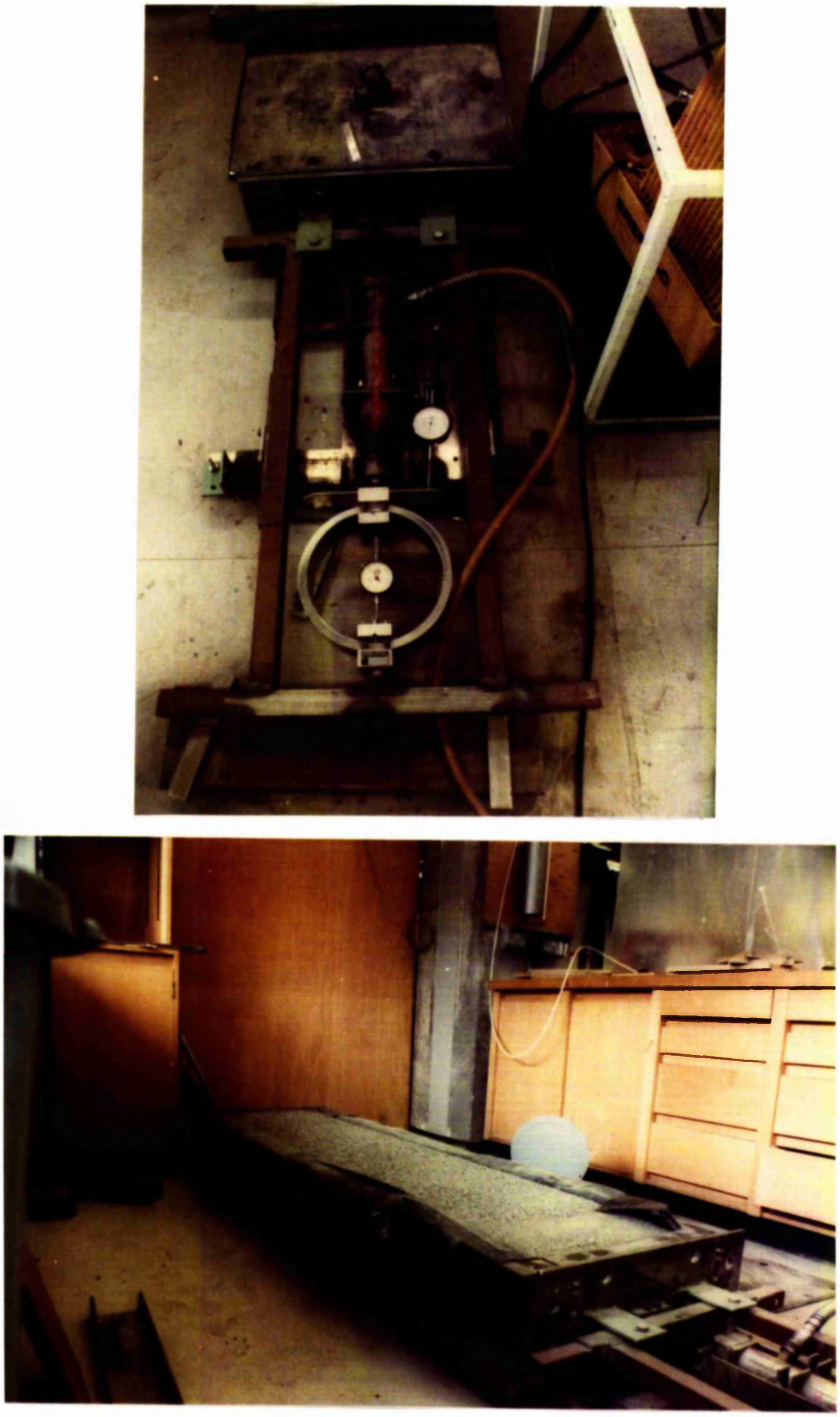


Fig. 3.2. General View of pull-out apparatus.

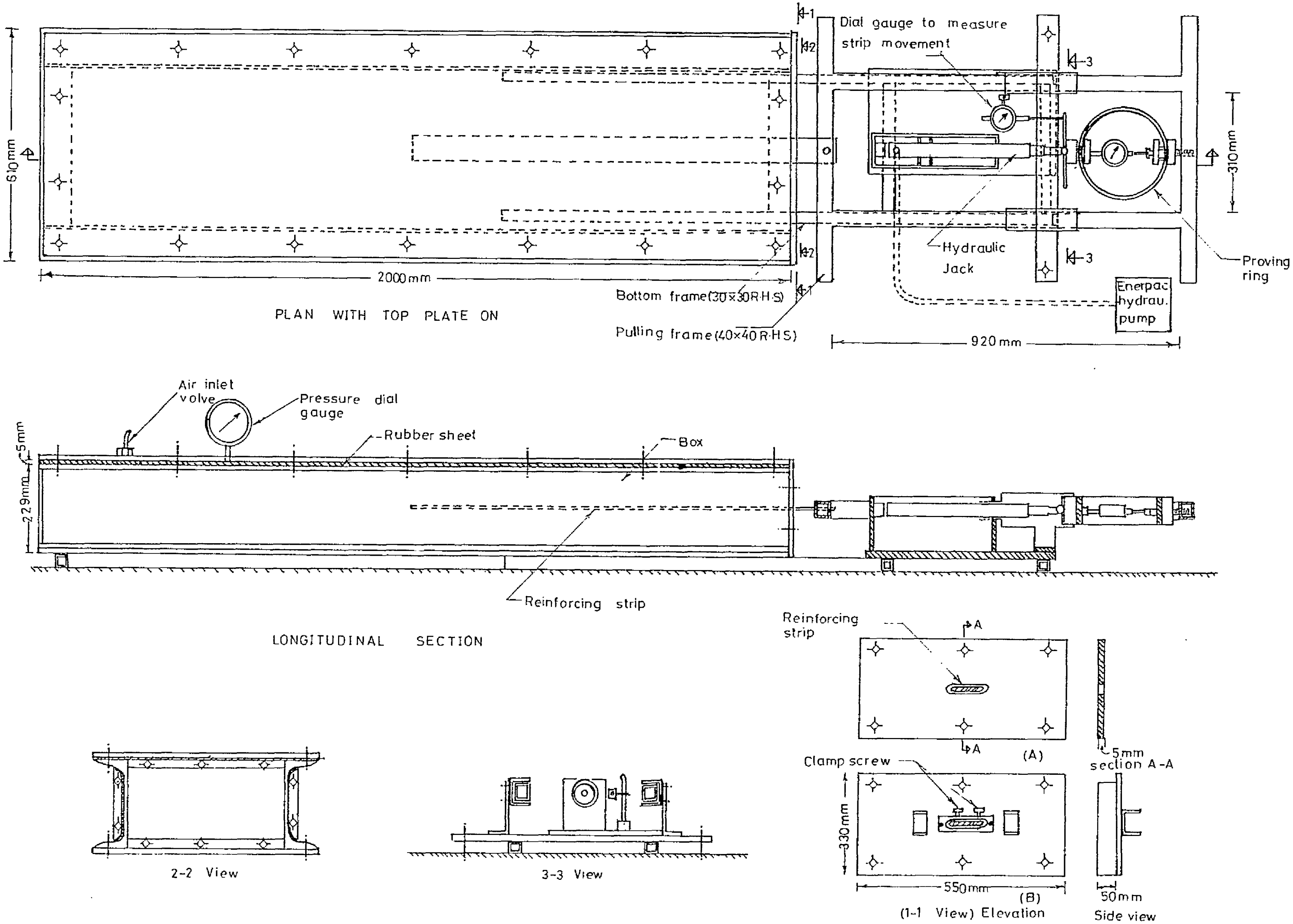


Fig 3.3 TEST SETUP

3.1.2. Facing Plates

Two separate facing plates were made from 12.7 mm thick steel plate for strip pull-out and strip with facing plate pull-out and a slot (80 x 30 mm) was cut in the middle of the plate. One facing plate had bolt holes to fix it to the front of the box for use in the pull-out test. The other had an arrangement, as shown in Fig.3.3 to fasten the strip at the middle of the plate and to attach the facing plate to the pulling frame in order to pull the strip and facing plate together for use in the strip-with-facing pull-out test.

3.1.3. Pulling arrangement

To withdraw the strip from the box, a steel frame, as shown in fig.3.3 was used. To keep the frame in position and to fix the hydraulic jack at the strip level, a bottom frame (reaction frame) with jack box bolted on the top of it was used. The front end of this frame was bolted down to the floor to prevent it from lifting up while pulling the strip out, and the opposite end was welded to the underside of the box.

Two guides for each arm of the pulling frame were provided in order to keep the pulling frame at the strip level and to restrict the sideways movement. These guides were fixed to the bottom frame.

The jack was fixed in the jack box and connected to an "Enerpac hydraulic pump" in order to apply a steady pulling load to the strip.

To measure the pulling load, a 5-ton proving ring was/

fitted between the hydraulic jack and the pulling frame end. The contact between the ram of the hydraulic jack and the proving ring was made through a steel ball.

While carrying out the tests, the strip, the hydraulic jack and the centre of the pulling frame were all placed in line.

3.2. Normal Pressure

A simulated overburden pressure was applied to the level, surface of soil filling the box by means of air pressure acting on a rubber membrane fixed under the steel top plate of the box.

3.3. Materials

The reinforcing strip and soil employed in this investigation were brought from a site at Maryhill in Glasgow. It was believed that these materials had been selected according to specification of the Reinforced Earth Company. The properties of the materials will be described in the following section.

3.3.1. Strips

The galvanised steel ribbed reinforcing strips used had a geometric configuration is shown in fig.3.4.

A piece of strip 1-m long was cut from a long strip for use in the tests. The tensile strength of the strip material measured in the laboratory was 355 N/mm^2.

3.3.2. Soil

The air-dried soil used in this investigation was 10 mm/

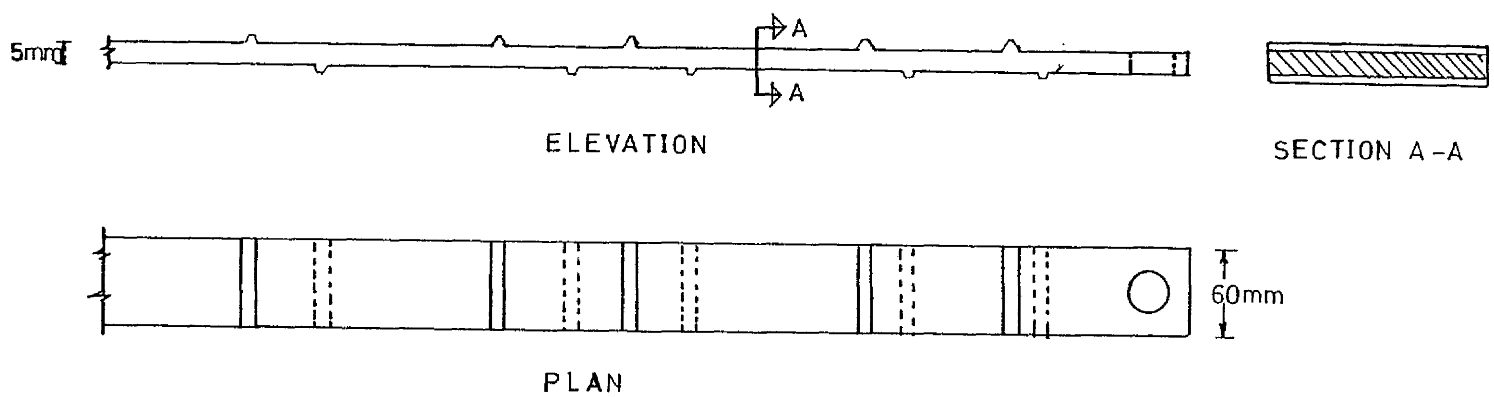


Fig.3.4. Ribbed strip.

down sandy gravel. The particle size distribution is shown in fig. 3.5. Tests to obtain the shear strength characteristics of the soil are fully described in Chapter 4 together with the detailed results over a range of densities. The pull-out tests were carried out at two different density values viz. 1.76 Mg/m^3 and 2.05 Mg/m^3. The term loose soil and dense soil as used herein refer to these two density conditions.

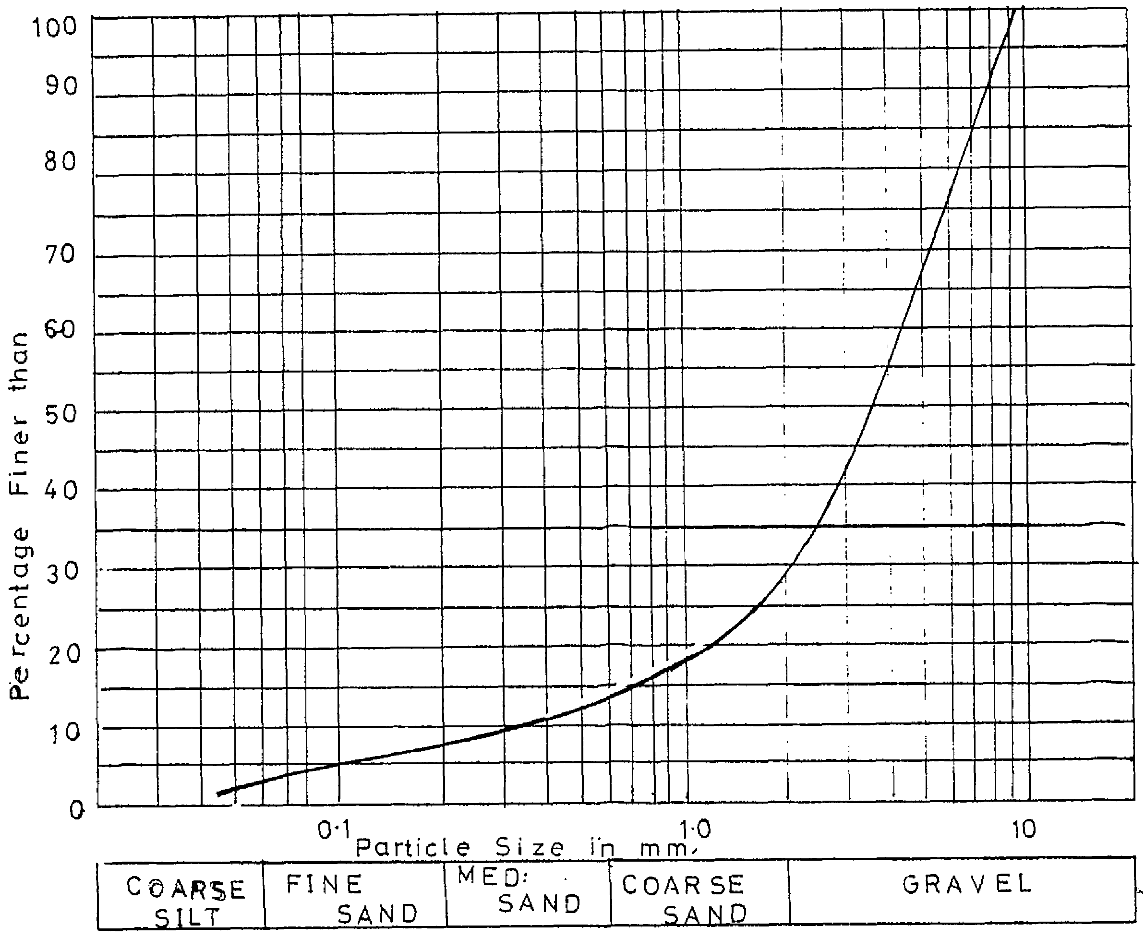


Fig. 3.5.Particle Size distribution of the soil.

CHAPTER 4

SHEAR TESTS ON FILL MATERIAL AND FRICTION TESTS ON SMOOTH AND RIBBED REINFORCING STRIPS USING SHEAR BOX

4.1. SHEAR TESTS

4.1.1. Introduction

The conventional constant rate of strain shear box apparatus (10.16 x 10.16 x 4.8 cm) was used to measure the internal friction of the fill material.

The fill material used in these tests has already been described in Chapter 3.

In the following section, the test procedure and the results will be presented.

4.1.2. Test Procedure

4.1.2.1. Preparation of soil sample.

The normal procedure for preparing a sample in direct shear test was used, i.e. the soil was filled in the box in layers and each layer was compacted before placing the next layer, this procedure being continued until the soil was flush with the top of the box.

4.1.2.2. Compaction

Insitu density measurements made in the field (by the Civil Engineering Department) on the reinforced earth retaining wall at Maryhill produced the results shown in fig. 4.1. An attempt/

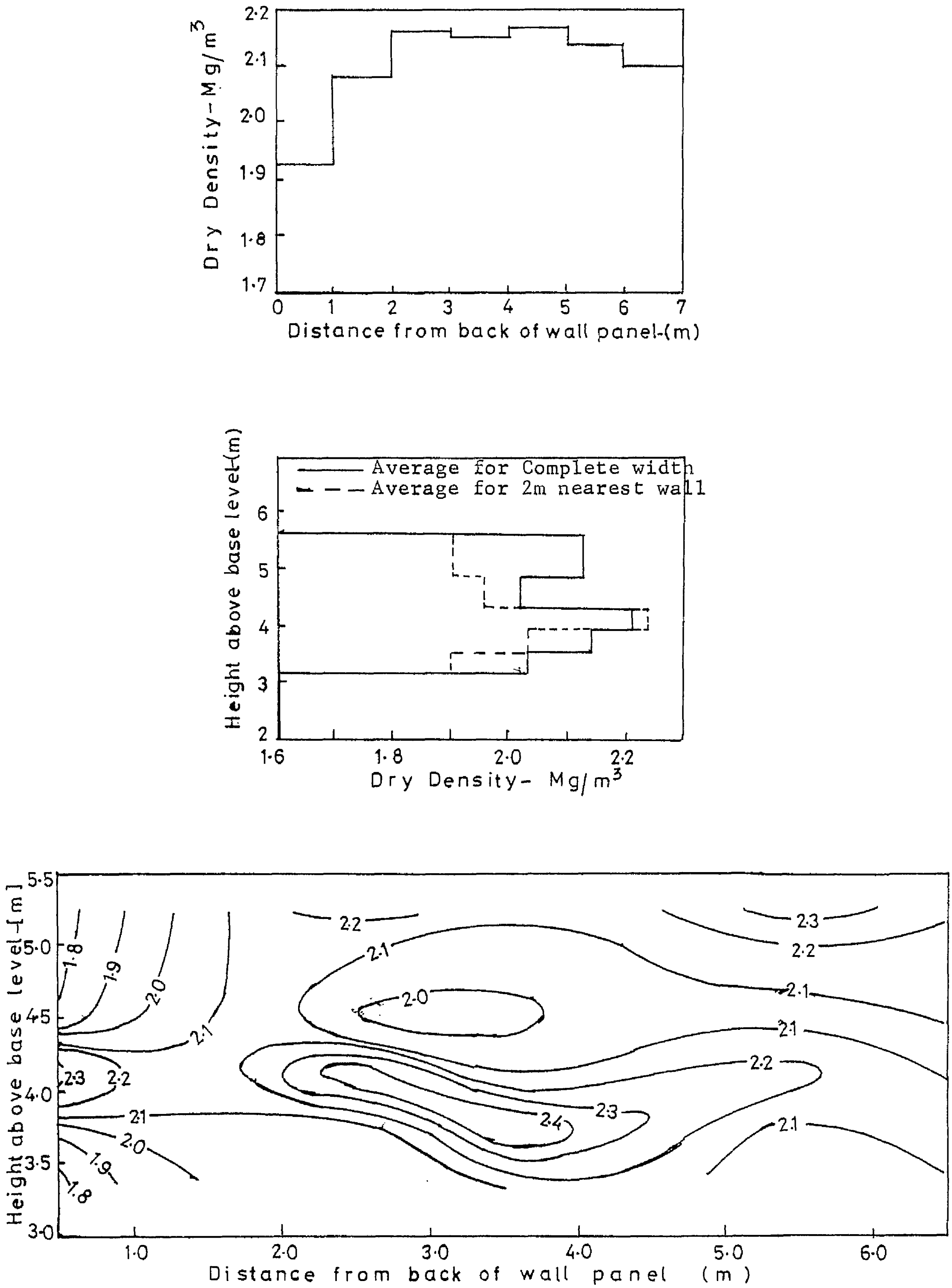
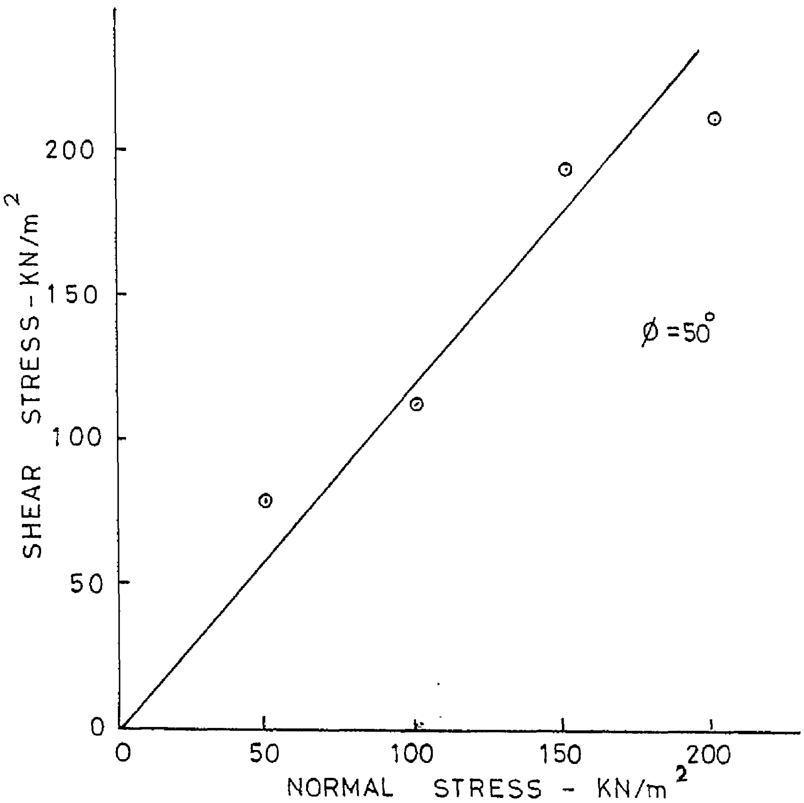


Fig. 4.1 Insitu dry density test results. (After departmental report)

was made to carry out the laboratory direct shear tests at the same average dry density of 2.1 g/cm^3 as obtained from the field tests. To obtain this density and to control it at each normal pressure in the direct shear tests, the standard compaction techniques tamping and vibrating, were employed. Initially, a tamping method was tried in which the soil was placed in layers and each layer was compacted by tamping with a light steel rod. The tests were carried out, for each normal pressure, on samples compacted at the same number of blows. The σ-τ relationship and the actual densities at which the tests were carried out are shown in fig. 4.2. The density variation and the scattered points on the σ-τ plot which resulted may havebeen due to the method of compaction. In view of this , another method, vibrating, was tried in which each layer of the soil in the box was compacted by vibration.

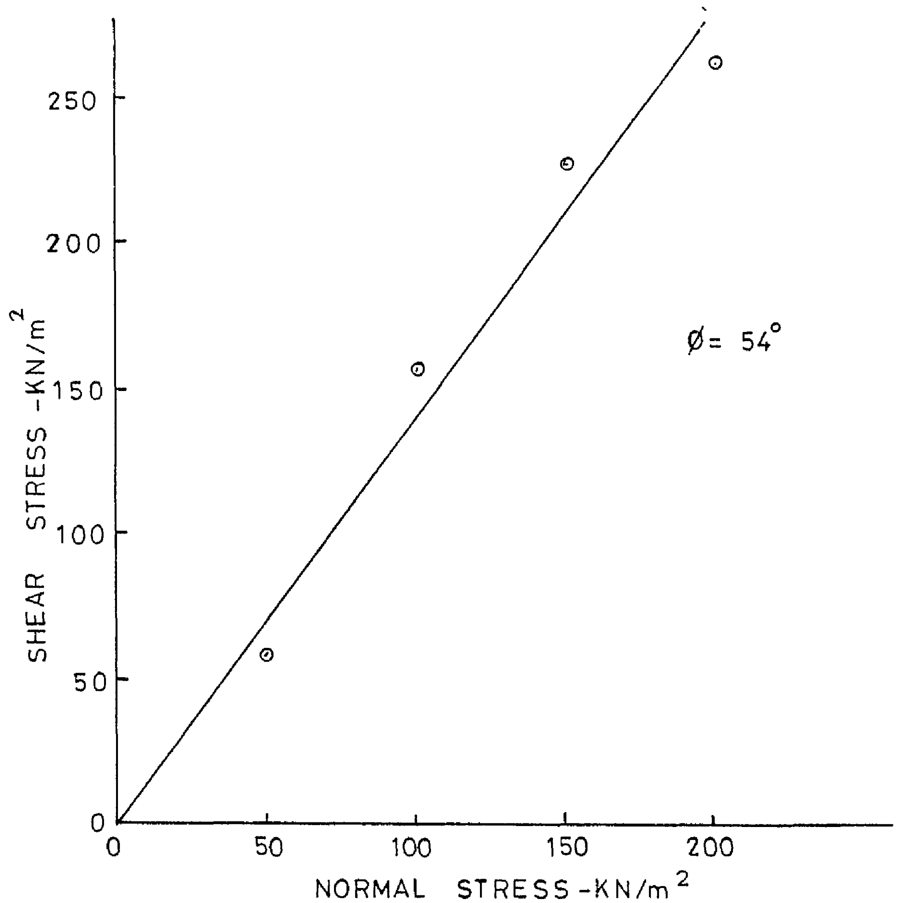
To vibrate the box, initially, a 'kango hammer' was used but later the box was placed on a 'vibrating table'. The box, with one layer of the soil , was allowed to vibrate for a certain period and then the next layer of the soil was placed and vibrated for the same time period. This procedure was continued until the soil was flush with the top edge of the box. For this method the σ-τ relationship and the sample densities are given in fig.4.3. The scatter of the data on the σ-τ plot also appeared using this method of compaction.

This problem was overcome by carrying out direct shear tests at the same normal pressure using samples of different density and then repeating for different normal stresses to obtain/



NORMAL PRESSURE KN/m^2	DRY DÊNSITY g/cm^3	AVERAGE DRY DENSITY g/cm^3	STD· DEVIATION g/cm^3
50	2·06	2·04	0·036
100	2·02		
150	2·08		
200	2·00		

Fig.4.2 Soil-soil friction by direct shear tests using a tamping method of compaction.



NORMAL PRESSURE KN/m^2	DRY DENSITY g/cm^3	AVERAGE DRY DENSITY g/cm^3	STD. DEVIATION g/cm^3
50	2·08	2·09	0·02
100	2·10		
150	2·12		
200	2·07		

Fig. 4.3 Soil-soil friction by direct shear tests using a vibrating method of compaction.

relationships between dry density and shear stress for each normal stress, figs. 4.4. From these the shear stress vs normal stress at particular values of density were picked out by interpolation, figs. 4.5 and 4.6. The establishment of the γd-τ relationship was used to establish the influence of density on the angle of internal friction, fig.4.7. Later, in developing the γd-τ relationships, the vibrating method of compaction was preferred to the tamping method, because it gave reasonably uniform values of density and it was also possible to obtain some intermediate densities between maximum and minimum which was difficult using the tamping method.

4.2. TRIAXIAL TESTS

4.2.1. Introduction

A series of cylindrical compression tests on the soil were carried out in order to measure the angle of internal friction, to develop the relationship between dry density and angle of internal friction, and to compare the values of angle of internal friction from the triaxial test with those obtained by direct shear tests on the same soil.

In the following section, the testing procedure will be described, the results presented and the discussions on them will be given together with direct shear test results.

4.2.2. Testing procedure

4.2.2.1. Triaxial apparatus/-

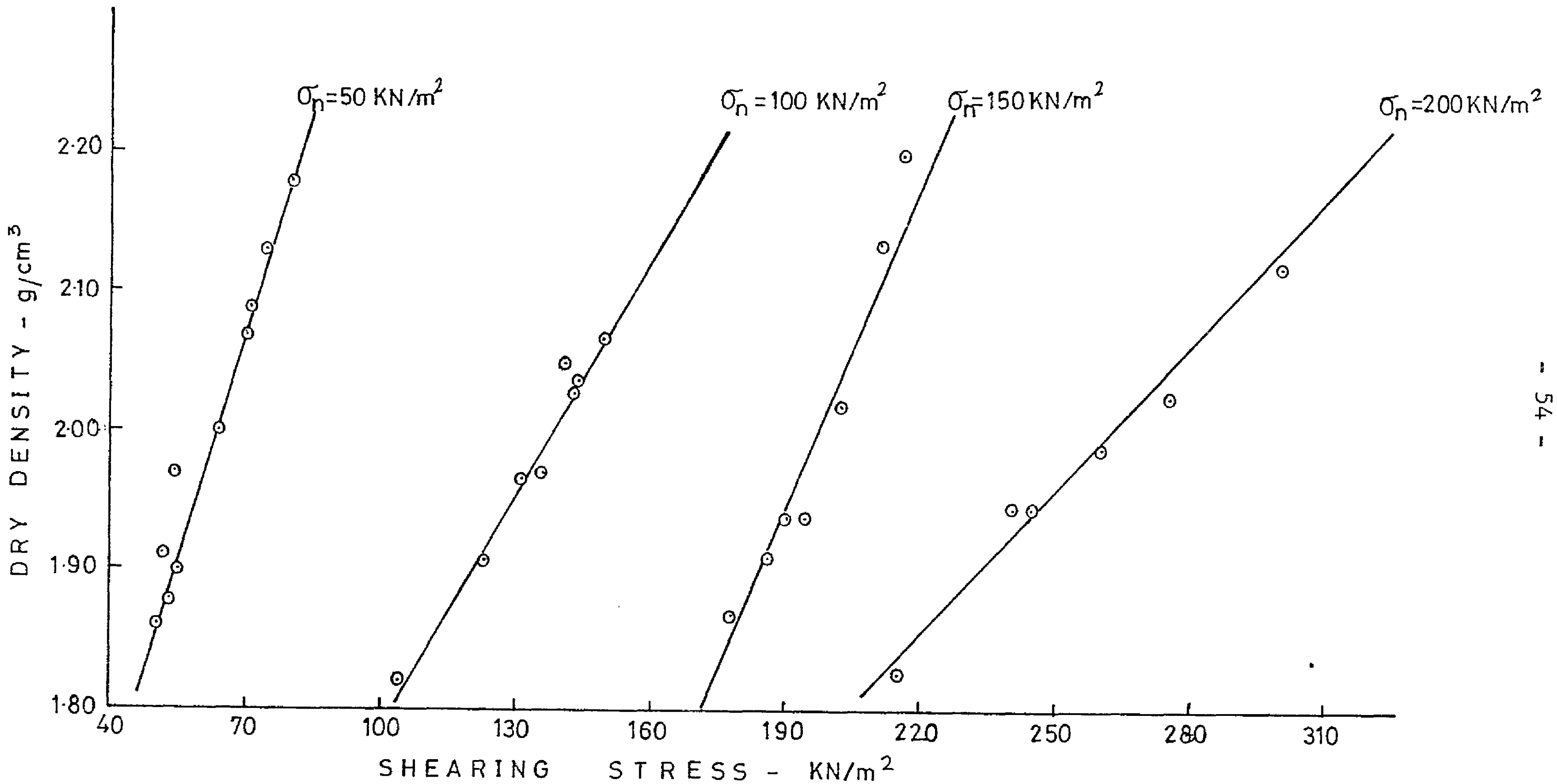


Fig.4.4 Dry density - Shearing stress relationsip (Soil-Soil) from direct shear tests.

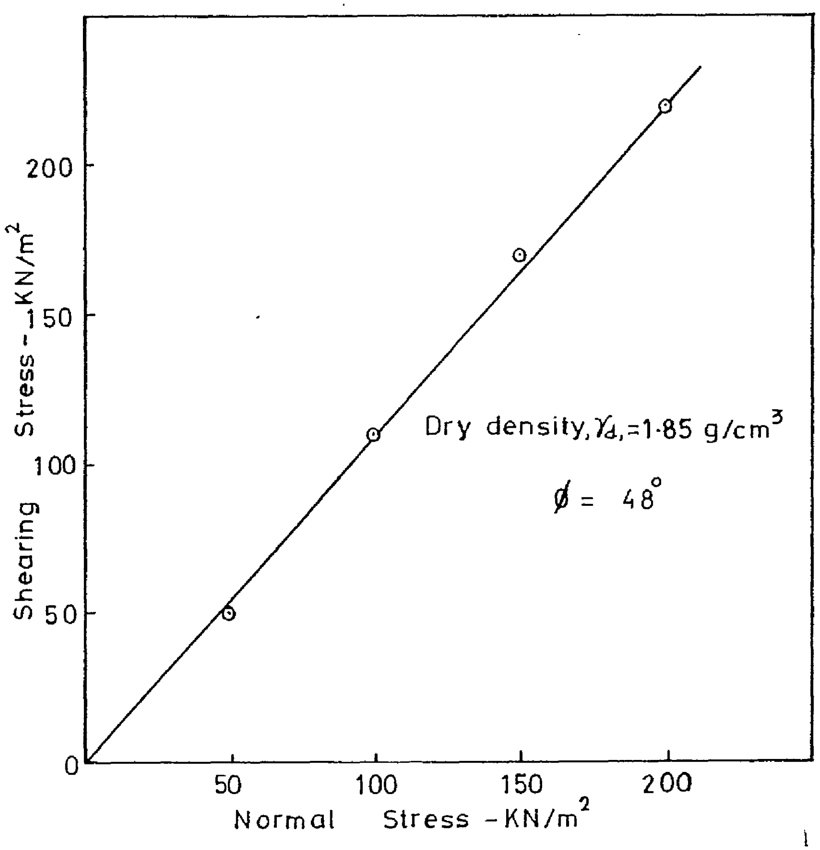


Fig.4.5 Soil-Soil friction by direct shear tests.

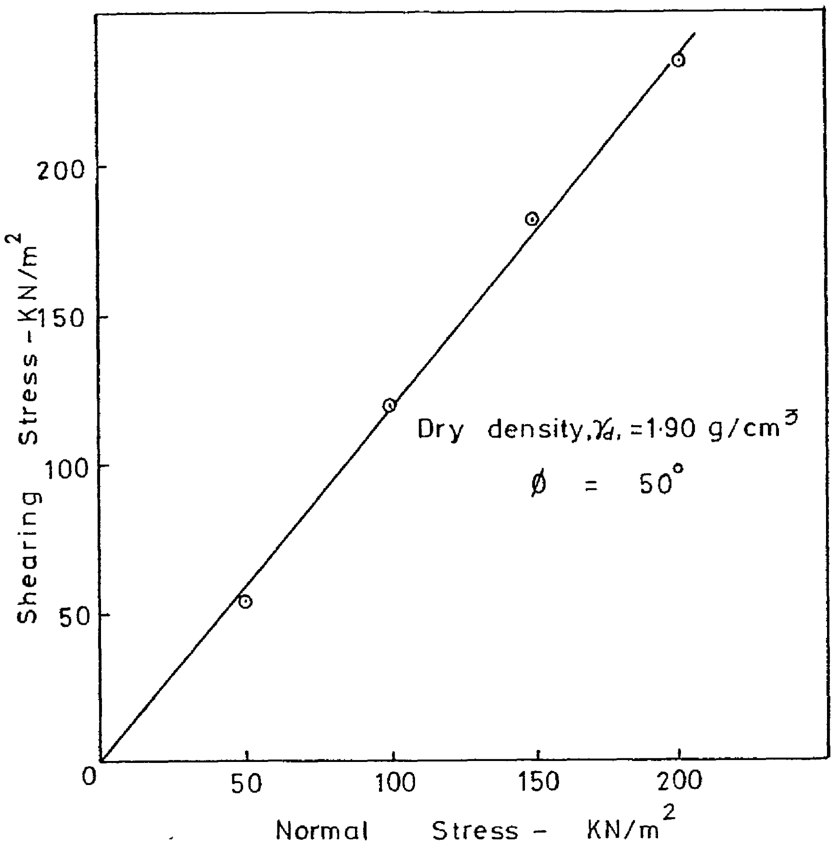


Fig. 4.5 Soil-Soil friction by direct shear tests.

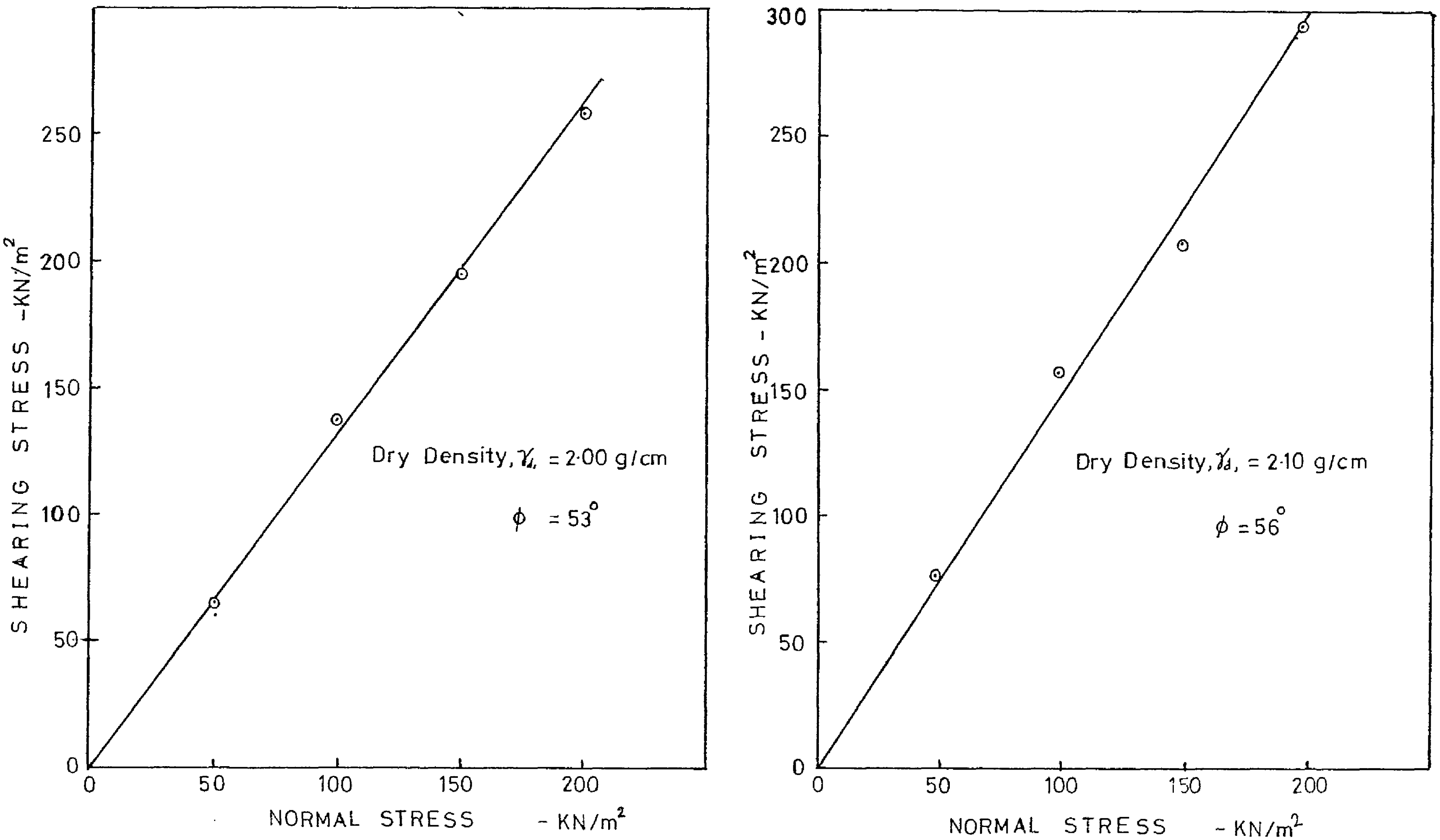


Fig. 4.6. Soil-Soil friction by direct shear tests.

DRY DENSITY - g/cm^3	ANGLE OF INTERNAL FRICTION (degrees)
1·85	48
1·90	50
2·00	53
2·10	56

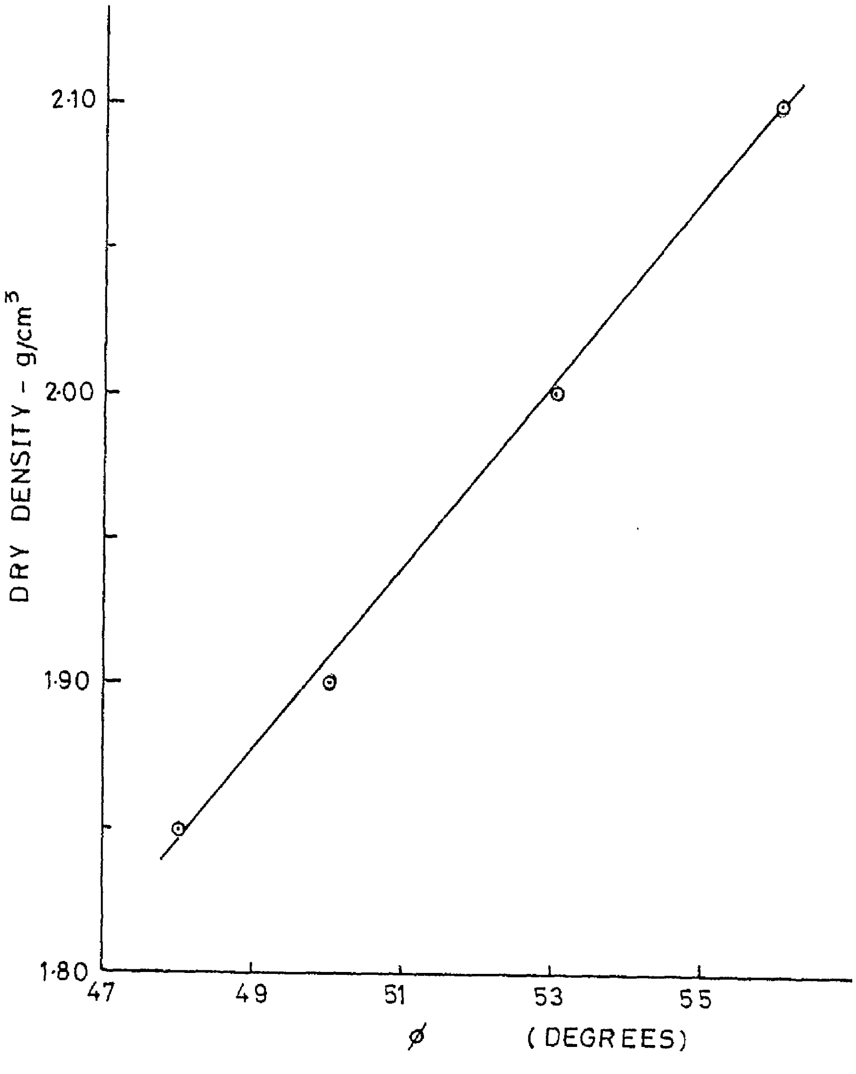


Fig.4.7. Dry density - angle of internal friction relationship by direct shear tests. (soil-soil)

4.2.2.1. Triaxial apparatus

A conventional triaxial apparatus was employed in this testing programme. A triaxial cell recommended for a compacted 101.6 mm diameter sample (Bishop and Henkel, 1962) was used. To prepare the sample, a 101.6 mm former was used. The cell pressure was applied through a compressed air/water system and a strain controlled loading system was adopted in shearing the sample.

4.2.2.2. Preparation of sample

The 101.6 mm diameter, 203.2 mm high sample was prepared using the former. A rubber membrane, 0.9 mm thick, 101.6 mm diameter and 304.8 mm high was used to enclose the sample. Compaction was done by tamping the soil in layers with a steel rod. As a preliminary, a few samples were compacted with a varying number of blows in order to note the range between maximum and minimum dry density within which the tests were to be carried out. Maintaining the same density at different confining pressures was difficult. Therefore, the relationship between deviator stress at failure and dry density for each confining pressure (20, 40, 50,60 kN/m^2) was established, fig. 4.8. From these curves the deviator stress values at the same density were picked out to obtain the angle of internal friction of the soil, fig. 4.9.

4.3. DISCUSSION OF RESULTS

In this section, the results obtained from the direct shear and triaxial tests are discussed.

The average angle of internal friction of the soil measured was 54.7^{o} and 46.7^{o} from direct shear and triaxial tests/

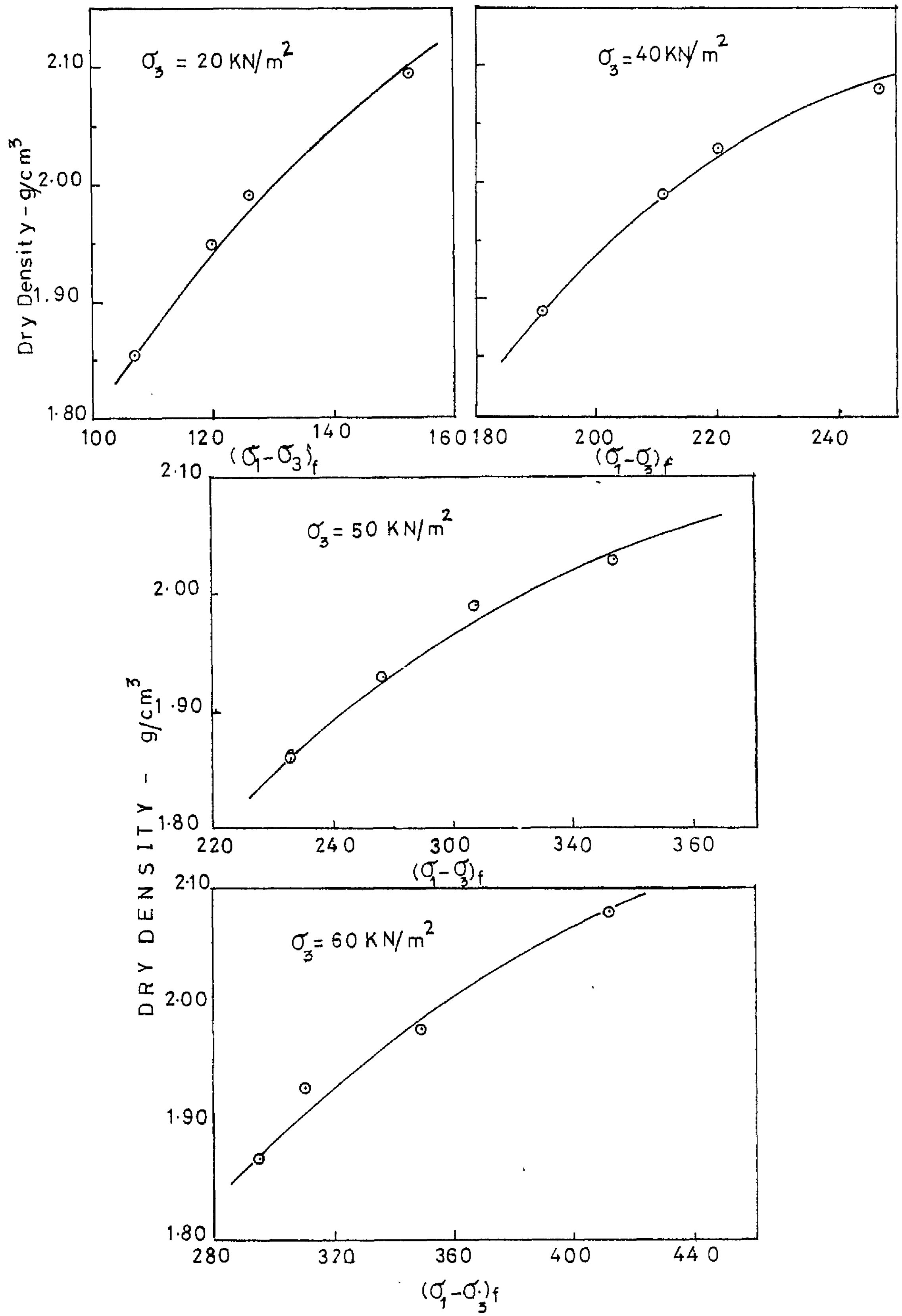


Fig. 4.8. Dry density - $(\sigma_1-\sigma_3)_f$ relationships from triaxial tests.

TEST	DRY DENSITY g/cm^3	ANGLE OF INTERNAL FRICTION (DEGREES)
DIRECT SHEAR	1·85	48
	1·90	50
	2·00	53
	2·10	56
TRIAXIAL	1·85	43·5
	1·90	45
	1·95	46·5
	2·00	48
	2·10	51

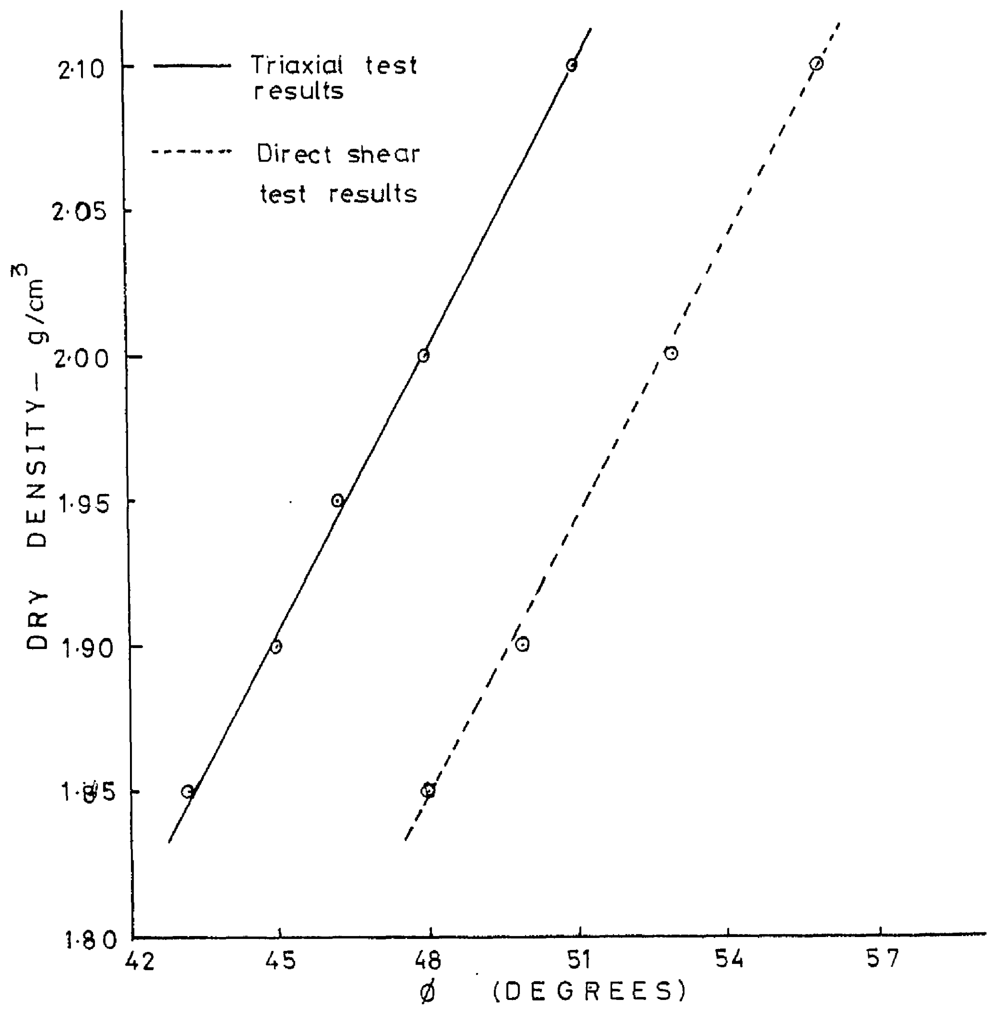


Fig. 4.9 Relationship between angle of internal friction and dry density (triaxial tests).

respectively within the density range of 1.85 g/cm^3 to 2.1 g/cm^3.

The difference was about 5° larger from direct shear tests as compared to the triaxial tests. This agrees with the results reported by Lee(37) Bishop (8) Comforth (20) and others who have reported the differences about 1° to 4° larger for direct shear tests. The probable factors which cause this difference are:

Strain conditions: In triaxial test a sample is tested under symmetric strain conditions which mobilize the minimum shearing resistance whereas in direct shear test the non-uniform strain conditions occur which mobilize the maximum shearing resistance.

Dilatancy: In triaxial tests the soil particles strain equally in the direction of equal stress under the symmetric external stress. On the contrary, in direct shear test the soil particles are least free to move in a random direction and the particles in the line of shear are obstructed by neighbouring particles which sets up a high normal pressure and results in increased angle of internal friction.

4.4. TESTS TO DETERMINE FRICTION BETWEEN REINFORCING STRIP AND FILL MATERIAL USING DIRECT SHEAR BOX

4.4.1. Preparation of soil-reinforcement sample

To prepare a soil-reinforcement sample, a perspex block, size 10 x 10 x 1.5 cm, was cut to fit inside the lower half of the shear box to give a rigid support to the strip in the box.

For the soil-ribbed sample, two pieces of strip of the same size as the block were cut from the original strip. The ribs on the strip were not equally spaced, so the sample pieces were cut in such a way that two ribs could be included in the required pieces of the strip. The perspex block was fitted in the lower part of the box and then pieces of the strips were mounted on it so that the strip surface was flush with the top of the lower part of the box. After that, the soil was filled and compacted in layers in the upper part of the box. In the case of the soil-smooth strip, the same strip was used, only the ribs and zinc coating were machined off so as to make the surface smooth. The rest of the procedure in preparing the sample was the same as that adopted in the above case.

4.4.2. Test Results

4.4.2.1. Soil-smooth strip

In the case of the smooth strip, the relationships between γd and τ for the normal pressure range of 50-200 kN/m^2 were found and are shown in fig. 4.10.

Fig. 4.11 shows the normal stress/shear stress relationships for the density range of 1.85 to 2.1 g/cm^3 from which the angles of skin friction were calculated and shown in table 4.1 . The relationship between the angles of skin friction and dry density is plotted in fig. 4.12.

4.4.2.2. Soil-ribbed strip

Using a similar procedure to that for soil-soil tests/

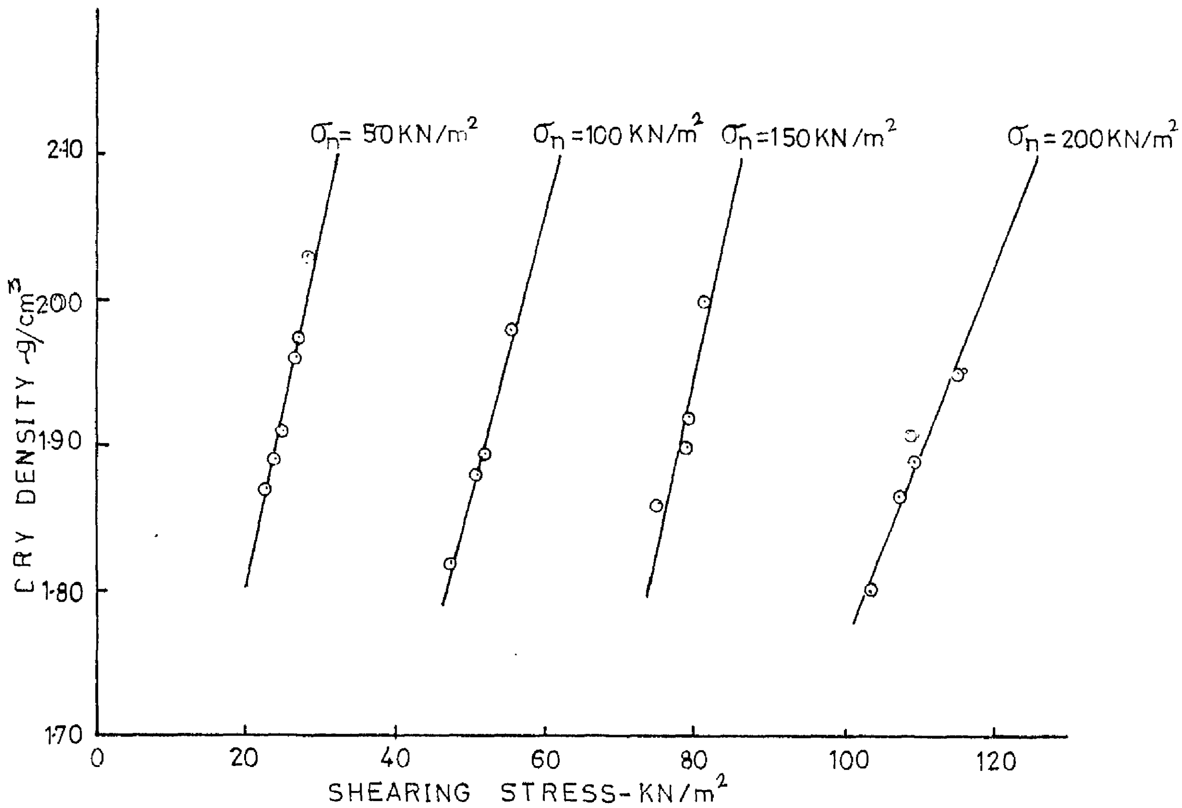


Fig. 4.10. Dry density-shearing stress relationship (soil-smooth strip).

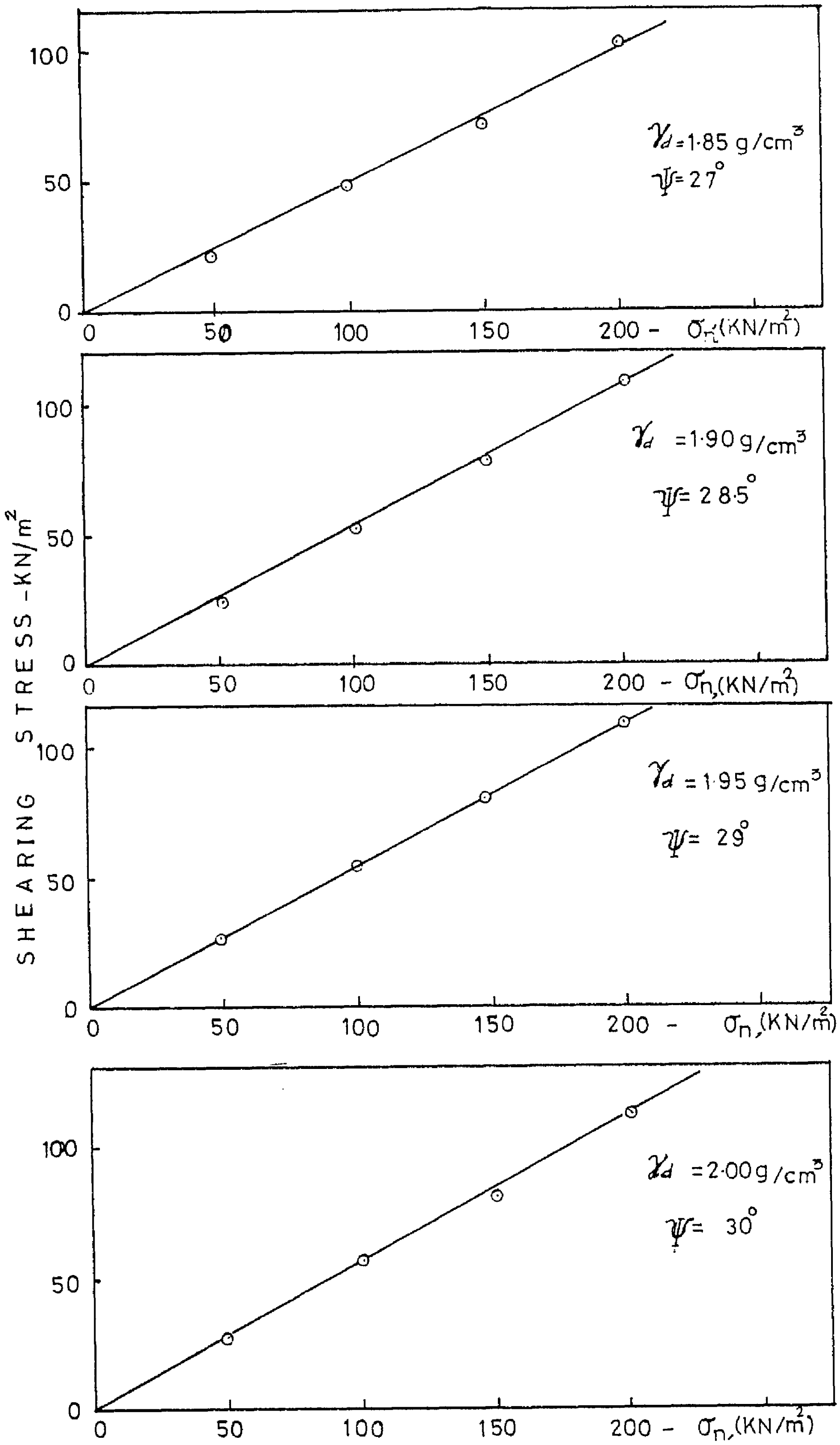


Fig. 4.11.. Soil-smooth strip friction by Direct Shear tests.

Table 4.1.

DRY DENSITY-g/cm^3	ANGLE OF SKIN FRICTION (degrees)
1·85	27
1·90	28·5
1·95	29
2·00	30

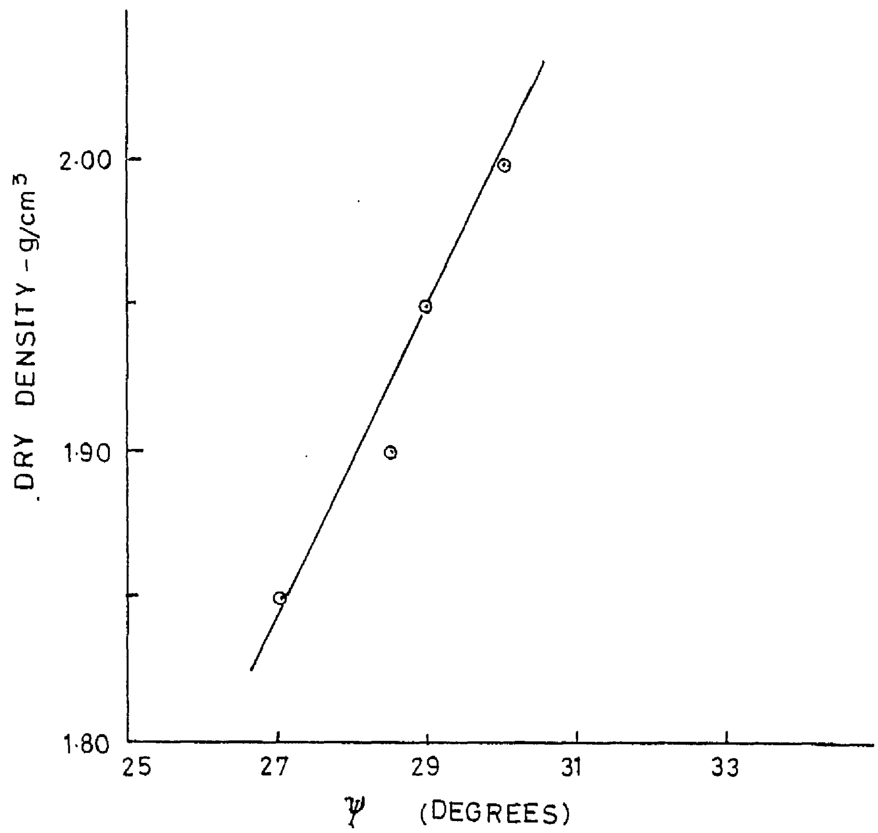


Fig. 4.12. Dry density - angle of skin friction relationship (Soil-smooth strip).

the dry density-shearing stress relationships for a normal pressure range of 50-200 kN/m^2 were obtained for the soil-ribbed strip and are shown in fig. 4.13. The normal stress versus shear stress plots were obtained at four density values, ranging from 1.85 - 2.1 g/cm^3, figs. 4.14 and 4.15.

The values of shear stress corresponding to desired density, which was the same at each normal pressure, were taken from the $\gamma d/\tau$ curves. Table 4.2 shows the values of angle of skin friction measured from σ_n/τ plots. These values are plotted against dry density and the relationship obtained between them is shown in fig. 4.16.

4.4.3. Discussions on experimental results

Fig. 4.17 and table 4.3 show the relationships between γd vs ψ and γd vs ϕ derived from the tests, soil-soil (Direct shear), soil-soil (Triaxial), soil-smooth strip and soil-ribbed strip. From the shearing stress/displacement curves, a typical curve at a normal pressure of 200 kN/m^2 at a dry density of 2.1 g/cm^3 obtained from these three types of tests is presented here in fig. 4.18.

It can be seen that the values of angle of skin friction obtained were higher for the ribbed reinforcement than the smooth strip. A probably reason for these lower values in the case of smooth strip is that the contact planes are parallel to the strip surface so that particles slide easily on the strip surface and therefore less dilatancy occurs.

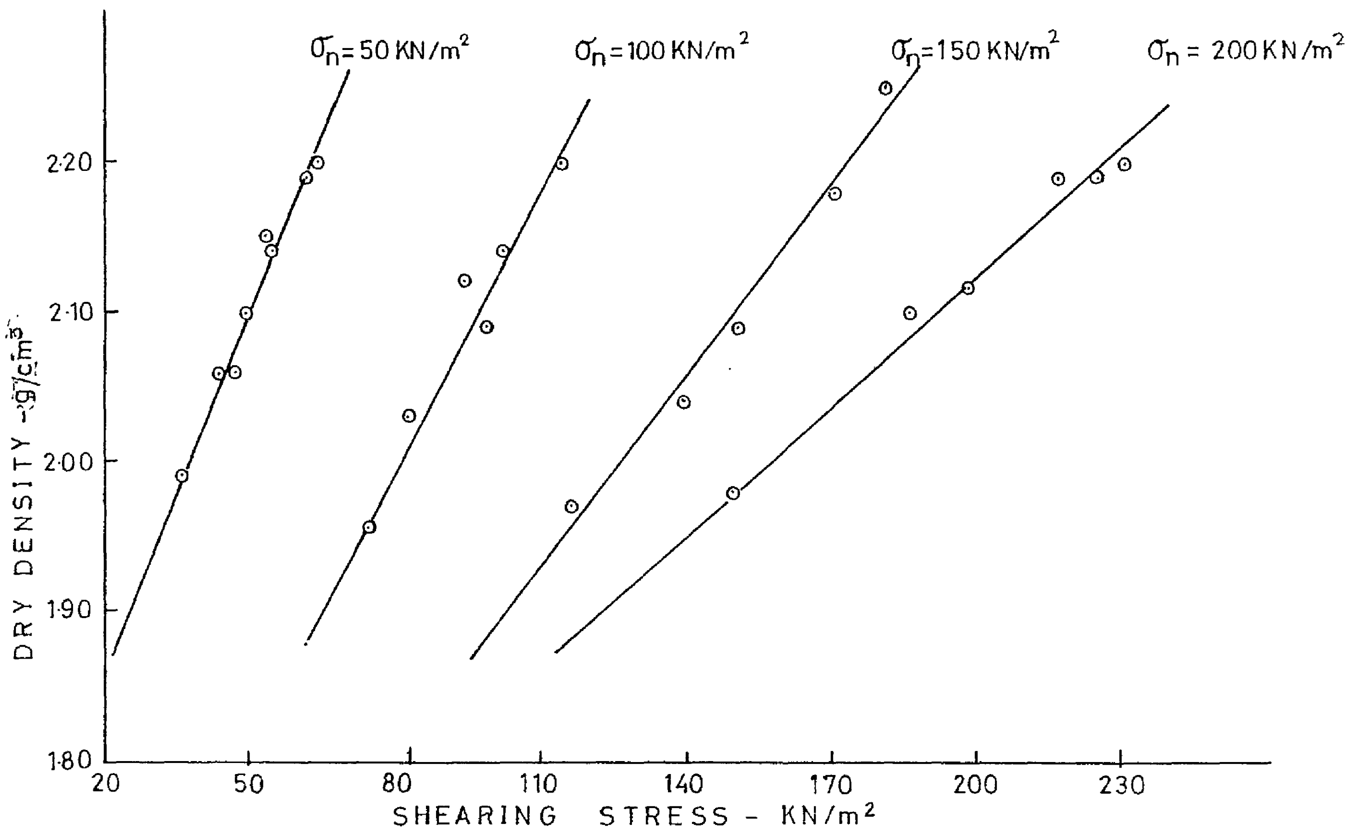
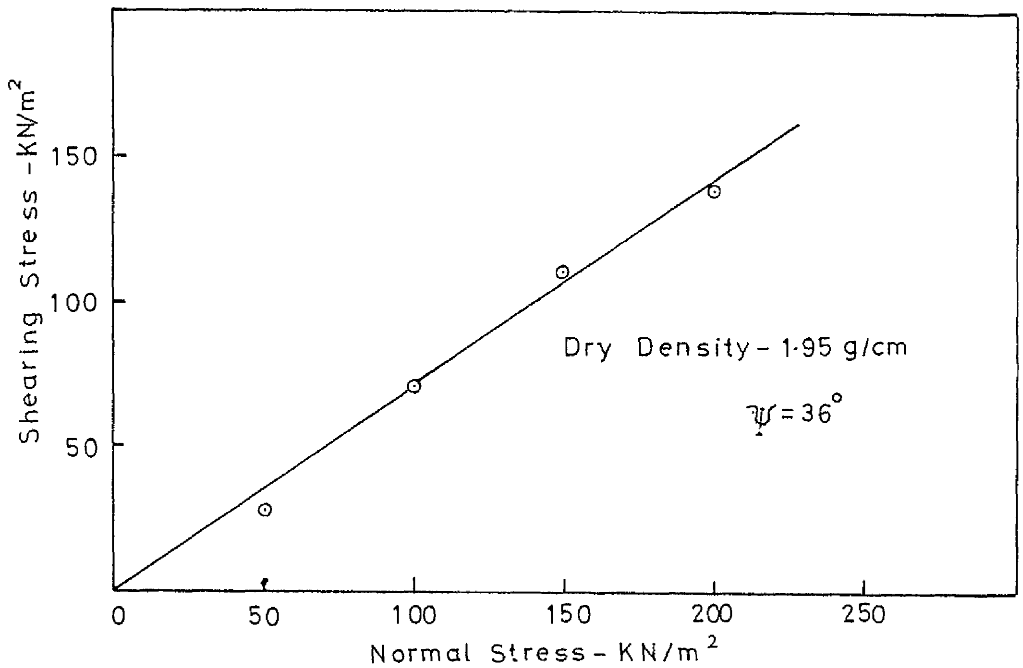


Fig. 4.13. Relationship between dry density and shearing stress (soil-ribbed strip).



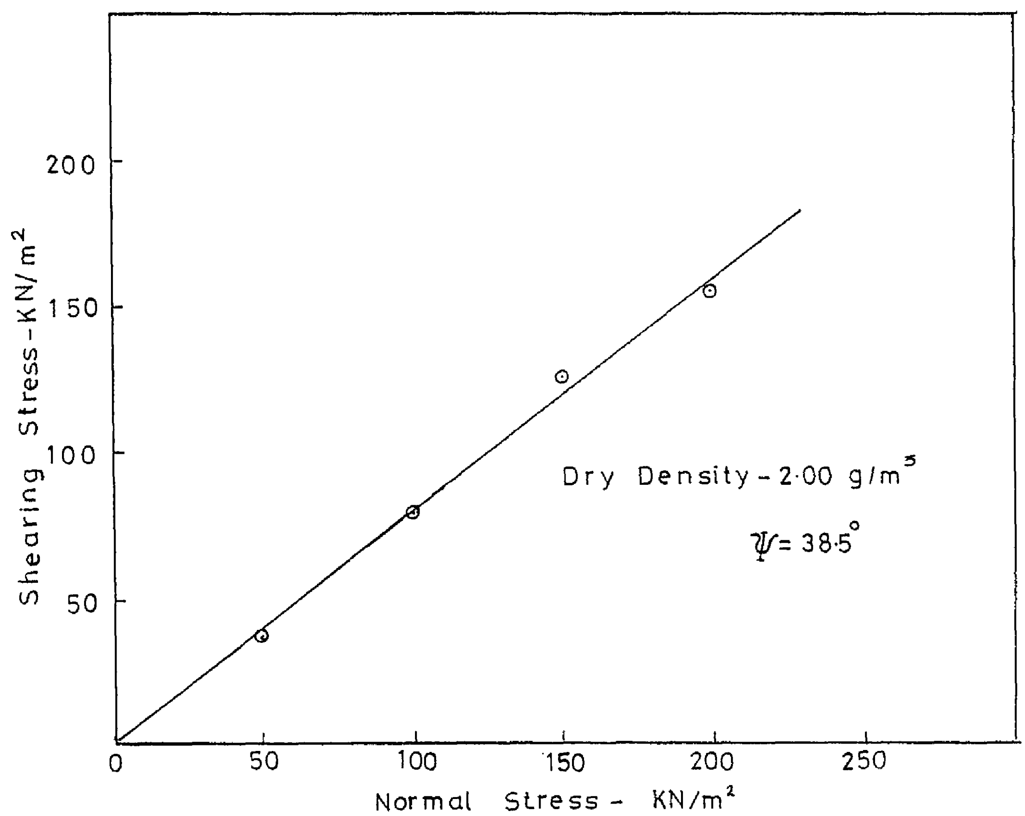
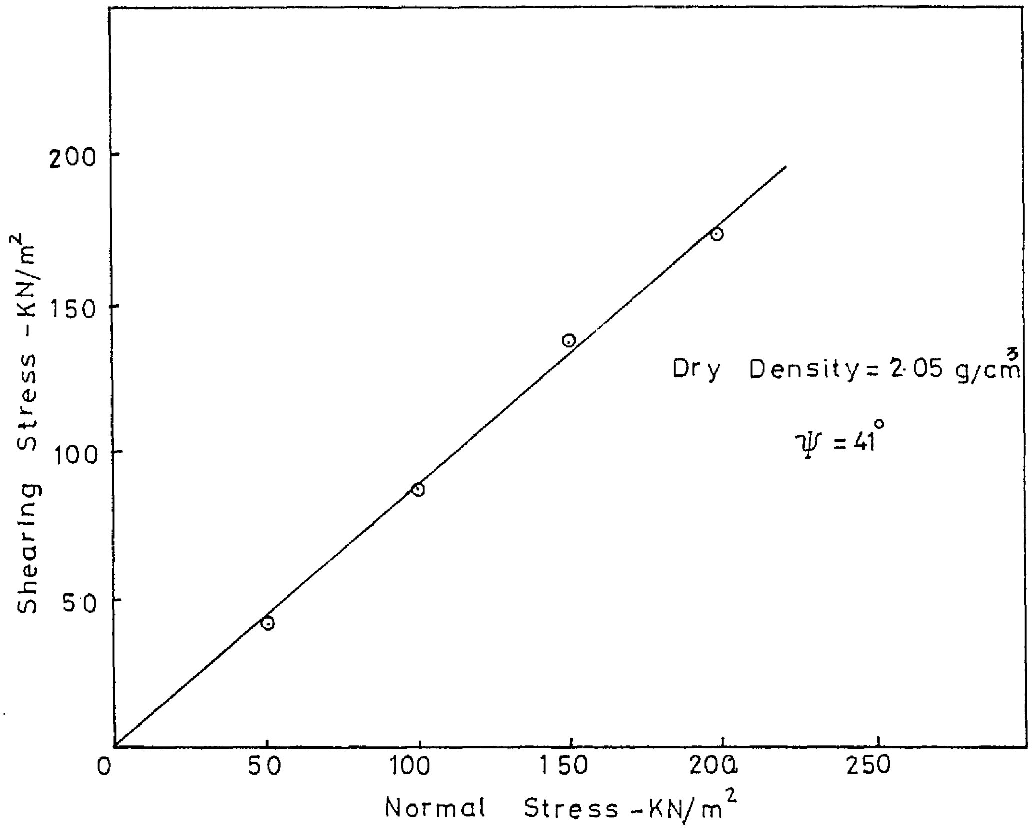


Fig. 4.14. Soil-ribbed strip friction by direct shear tests.



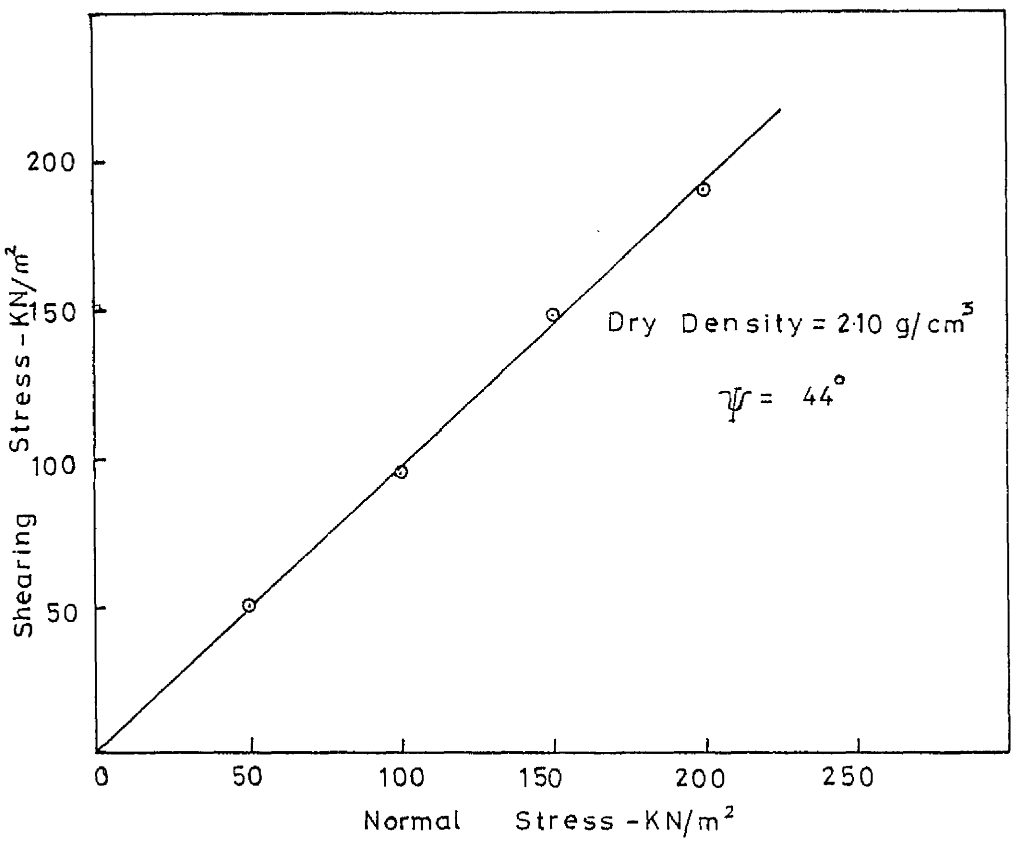


Fig. 4.15. Soil-ribbed strip friction by direct shear tests.

Table 4.2.

Dry density - g/cm^3	Angle of skin friction (degrees)
1·95	36
2·00	38·5
2·05	41
2·10	44

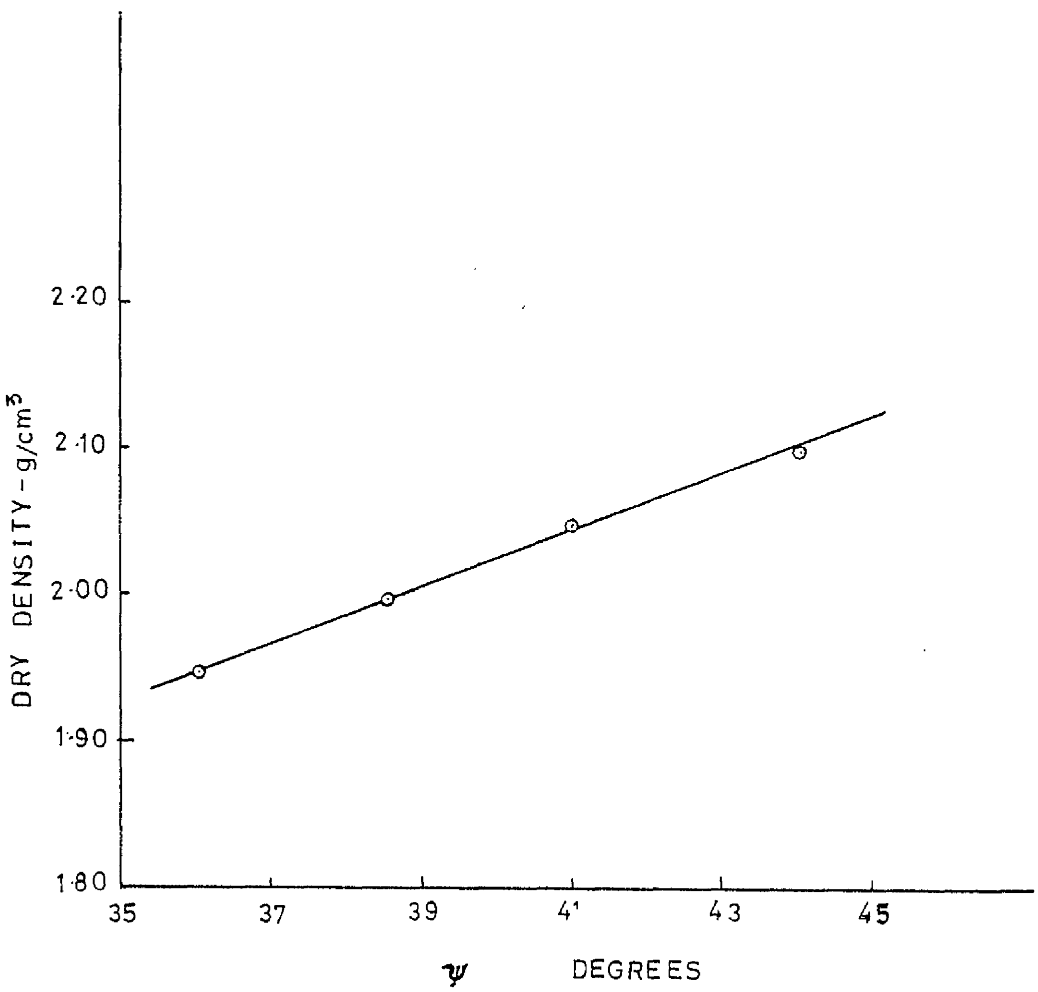


Fig. 4.16. Dry-density - angle of skin friction relationship (soil-ribbed strip).

Table 4.3

SAMPLE	TEST	DRY DENSITY-g/cm^3	ϕ_{av} or ψ_{av}
SOIL-SOIL	DIRECT SHEAR	1·85 - 2·10	51·7°
SOIL-SOIL	TRIAXIAL	1·85-2·10	46·7°
SOIL-RIBBED STRIP	DIRECT SHEAR	1·95-2·10	39·8°
SOIL-SMOOTH STRIP	DIRECT SHEAR	1·85-2·10	28·6°

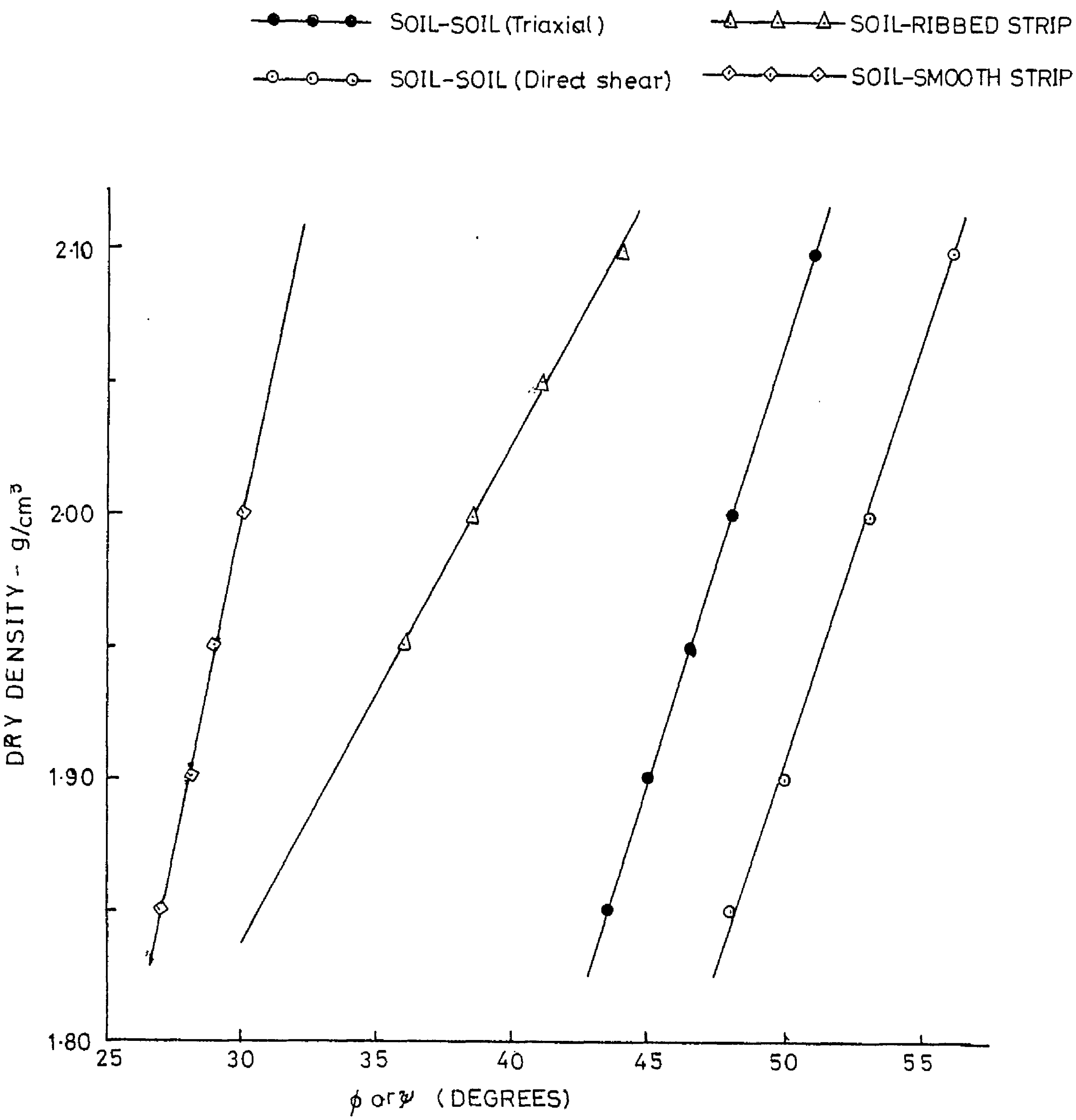


Fig.4.17. Comparison of dry density-angle of friction relationships.

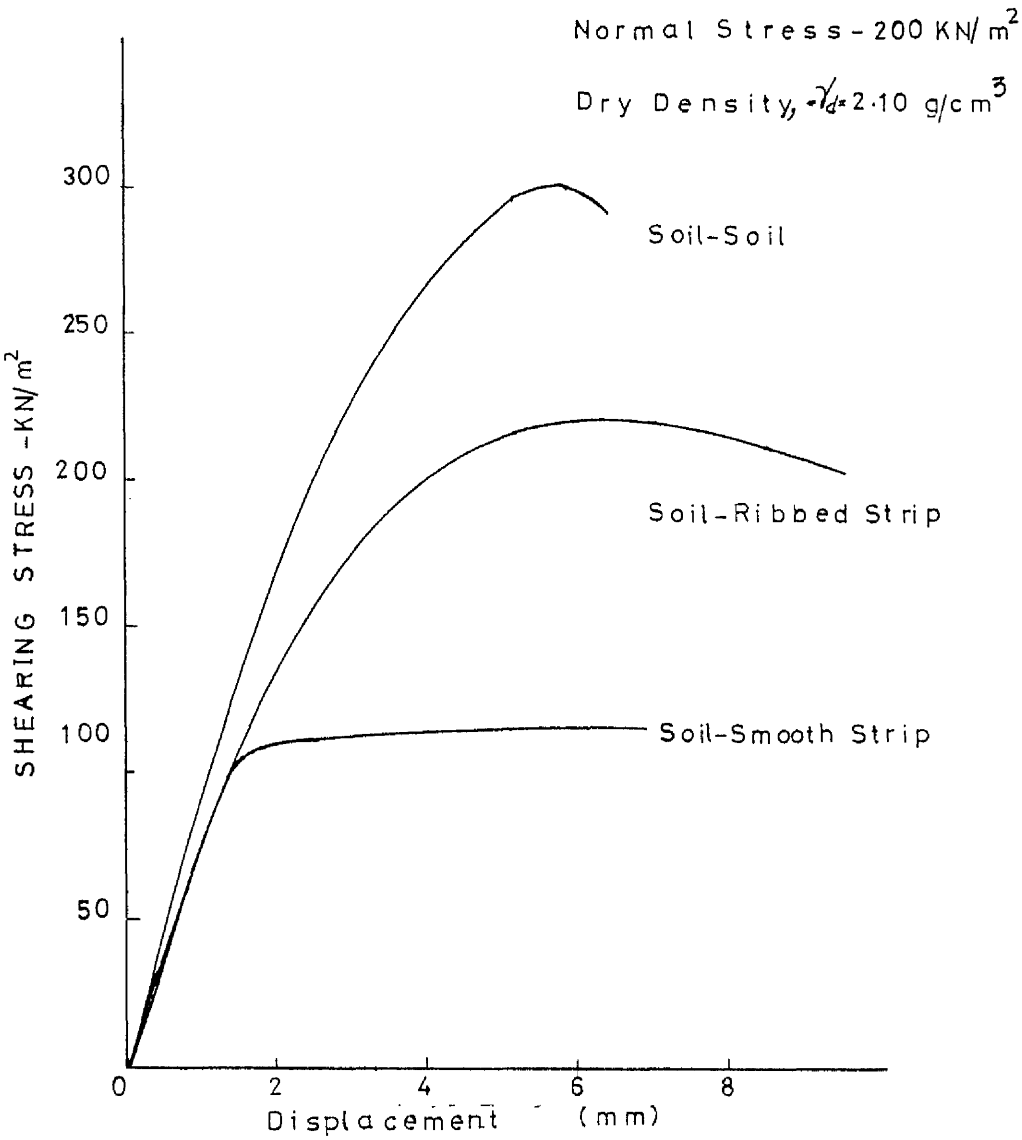


Fig. 4.18. Comparison of shearing stress-displacement curves obtained from direct shear tests.

Upon close examination of the strip surface after shearing in the case of the soil-smooth strip, some striation marks oriented in the direction of displacement were observed which reveals that sliding of soil particles along the strip surface occurs. On the contrary, the soil-ribbed strip tests did not show any striation marks. This indicates that sliding of soil particles did not occur along the strip surface, but that shearing took place along the soil-soil interface parallel to the longitudinal axis of the strip. The same striation marks on the strip surface after shearing have been noted by other investigators. (48).

It has been argued by different researchers, Schlosser (52) Mackittrick (42), that in the case of the smooth strip, the frictional behaviour depends on the soil-to-reinforcement interaction and in the case of the ribbed strip the soil-to-soil interaction controls the friction. If, in the case of the ribbed strip, the friction depends on the frictional behaviour of soil alone, then the values of the angle of skin friction, Ψ, would have been expected to correspond to the angle of internal friction of the soil. It was found, however, that the average value of angle of internal friction ($\phi = 51.7^{o}$) measured from direct shear test was 12^{o} higher than the average value of angle of skin friction ($\Psi = 39.8^{o}$) for the ribbed strip. This shows that simple soil-soil characteristic does not control the friction between soil and reinforcement, but it is also possible that shearing takes place on the strip surface and the soil-soil interface as well.

The relationships, γd vs Ψ, for soil-smooth strip and soil-ribbed strip found are linear. It appears that in the/

soil-smooth strip case, increasing density from 1.85 to 2.00 g/cm^3 gives 1° average increase in ψ value, this shows that density has very little influence on the magnitude of ψ value. This agrees with the results of Lee (34) in which he used aluminium foil with sand and found that density had no effect on the angle of skin friction.

In the case of soil-ribbed strip, however, the value is increased by 8° as the density increased from 1.85 to 2.0 g/cm^3.

Fig. 4.18 shows the general form of shearing stress/ displacement curves obtained from each test. In the case of soil-smooth strip, the maximum shearing stress value was obtained at a small displacement, 2 mm, as compared to the soil-ribbed strip where the maximum shearing stress value was attained at a large displacement, 6.25 mm. The soil-smooth strip case showed no well defined peak, on the contrary, the soil-ribbed strip case showed a broad zone peak value. The soil-soil case showed a clear peak which was attained at almost the same displacement as in soil-ribbed strip case. This also supports the idea of soil-soil friction controlling the behaviour in the case of soil-ribbed strip.

The results obtained with soil-ribbed strip will be compared with pull-out test results in the next Chapter.

CHAPTER 5

PULL-OUT TESTS

5.1. Summary of test programme

The present test programme consisted of two test series, viz.

1. strip pull-out.
2. strip with facing plate pull-out.

A summary of these test series will be given in this section. The materials and apparatus used in these test series have been described in Chapter 3. All the tests used ribbed strip.

5.1.1. Strip pull-out

This is a conventional method to study the friction between soil and reinforcement, which has been used by different researchers. This testing method was adopted in the present test series in order to determine the angle of skin friction at different normal pressures and to compare the results with those of the other method.

The tests were carried out at normal pressures, ranging from 25 kN/m^2 to 105 kN/m^2 in both loose and dense soil, corresponding to densities of 1.76 g/cm^3 and 2.05 g/cm^3 respectively.

The test results were compared with those of the second test series and the direct shear test results.

5.1.2. Strip with facing plate pull-out

It was thought that the action of pulling a strip through a slot in a rigid facing plate as used in the test just described/

would result in setting up higher lateral pressures and therefore higher vertical or normal pressures on the strip than would be the case in the field. This, in turn, would lead to an increase in the angle of skin friction.

This test series was intended to determine the influence of the testing method on the magnitude of angle of skin friction. For this purpose a strip was pulled out together with the facing plate instead of pulling out the strip alone.

The tests were carried out within the same normal pressure range at the same densities as in the previous tests. The results were compared with those of the previous test results.

5.2. STRIP PULL-OUT

5.2.1 Introduction

Since the actual site materials were available for testing, it was decided to carry out the pull-out tests at a reasonably large scale to obtain the angle of skin friction and its variation with normal stress and to compare these results with the other testing method in which the strip and facing plate would be pulled out together.

For this purpose, a pull-out rig was constructed in which the tests were carried out in the conventional manner at normal pressures, ranging from 25 kN/m^2 to 105 kN/m^2 on both loose and dense soil.

The testing procedure adopted and the results in the/

form of $\sigma n/\tau$, $\delta/\sigma n$ and $f^*/\sigma n$ will be given in the following section.

5.2.2. Testing Procedures

The apparatus, the steel box, pulling arrangement ; normal pressure applying technique and the materials (soil and strip) are fully described in Chapter 3. Here, the test procedure will be explained.

5.2.2.1. Sample preparation

An air-dried soil sample was placed in layers into the box, and in every test the weight of soil used to fill the box was noted for density measurements. Prior to soil placement, a thin plastic liner was placed in the box to reduce friction along the sides. The soil was placed at two density conditions, loose and dense. In the case of the dense sample, each layer of soil was compacted by tamping it thoroughly with an 11 kg hammer. The density measurements were made knowing the volume of soil from the measured dimensions of the box and the weight of soil used to fill the box. The densities obtained were within the range of 2.00 g/cm^3 to 2.05 g/cm^3. In the case of the loose sample, the soil was simply placed in the box without any compaction, and densities were achieved within the range of 1.75 to 1.76 g/cm^3. After placing the first two layers, the reinforcing strip, 112 cm long and 6 cm wide, was positioned. This put the strip at the mid height of the box and in line with the horizontal slit at the facing plate. Some 12 cm of test piece was left projecting out of this slit for connection to the pull-out frame. The embedded length, 100 cm, was kept constant throughout all tests. After that, the remaining layers of soil were placed in order to flush the soil with the edges of the box, the excess soil was trimmed off, subsequently, a rubber sheet, 1.6 mm thick, was laid on the top of the soil filled open box, and a rubber gasket was also fitted around the edges to stop leakage. A thick steel plate was then positioned on top and bolted down at the edges of the box.

5.2.2.2. Testing

The pulling out steel frame, described in Chapter 3, was moved towards the box so that the projected piece of the strip could be pinned down at the centre of the frame. The pulling load was applied by a hydraulic jack mounted on the thick steel plate located within the frame. The jack, strip and axis of the proving ring were in line. The jack, in turn was connected to an "Enerpac hydraulic pump" to apply a steady load. The load measurements were made by a standard proving ring placed between the hydraulic jack and the frame used to pull the strip.

A 50-mm travel dial gauge was attached to the box in order to record the relative horizontal movement of the strip. Normal pressure was applied through the air pressure system, described in Chapter 3. The range of normal pressure from 5 to 105 kN/m^2 was selected on the basis of Schlosser's findings (48): "the value of apparent angle of skin friction remains approximately constant after a normal pressure of 100 kN/m^2". Normal pressure used in calculating the apparent angle of skin friction was the sum of applied normal pressure and overburden weight of soil, γh, on the strip. A series of tests at each normal pressure, ranging from 5 to 105 kN/m^2 and 2.41 to 102.41 kN/m^2 in case of the dense and loose sample respectively, were carried out. After applying normal pressure, the strips were pulled out until either sliding occurred or there was no further increase in tensile resistance. The pulling loads and the relative movements of the strip were recorded and plotted to obtain peak loads at each normal pressure for loose and dense soil.

5.2.3. Presentation of results

Taking the maximum loads from the pull-out load-displacement curves drawn for each normal pressure, the shear stresses were calculated. It was assumed that the shear stress was uniformly mobilized on both sides of the strip and over the full embedded length and the edge friction ignored. On this basis, the shear stresses were calculated by using the formula:

$$\tau = \frac{P}{2b}$$

where P = Pulling load

b = width of strip

l = length of strip

These shear stresses were plotted against the normal stresses to obtain the relationship between them for loose and dense soil. This relationship is shown in fig. (5.1). Fig.5.2. shows the relationship between apparent angle of skin friction, δ, and normal stress, σn, for both dense and loose soil. The values of τ and σn taken from the $\tau / \sigma n$ relationship in fig. 5.1 were used/

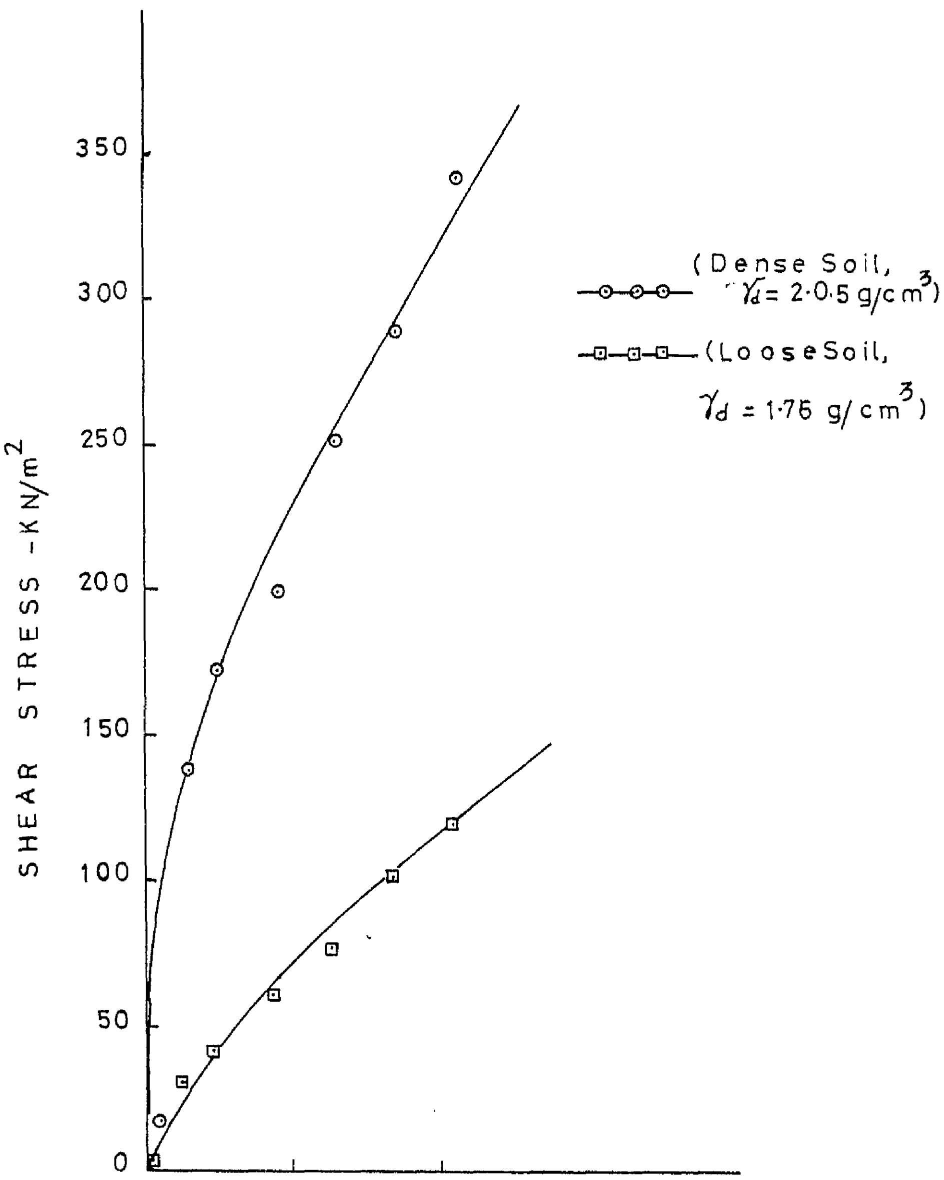


Fig. 5.1. Normal stress-shear stress relationship (strip pull-out).

	NORMAL PRESSURE KN/m^2	APPARENT ANGLE OF SKIN FRICTION, δ (DEGREES)
LOOSE SOIL =1·76 g/cm^3	2·41	64·7
	12·41	68·3
	22·41	62·6
	42·41	56·1
	62·41	51·6
	82·41	50·9
	102·41	49·5
DENSE SOIL = 2·05 g/cm^3	5	74·3
	15	83·8
	25	81·7
	45	77·3
	65	75·8
	85	73·6
	105	72·8

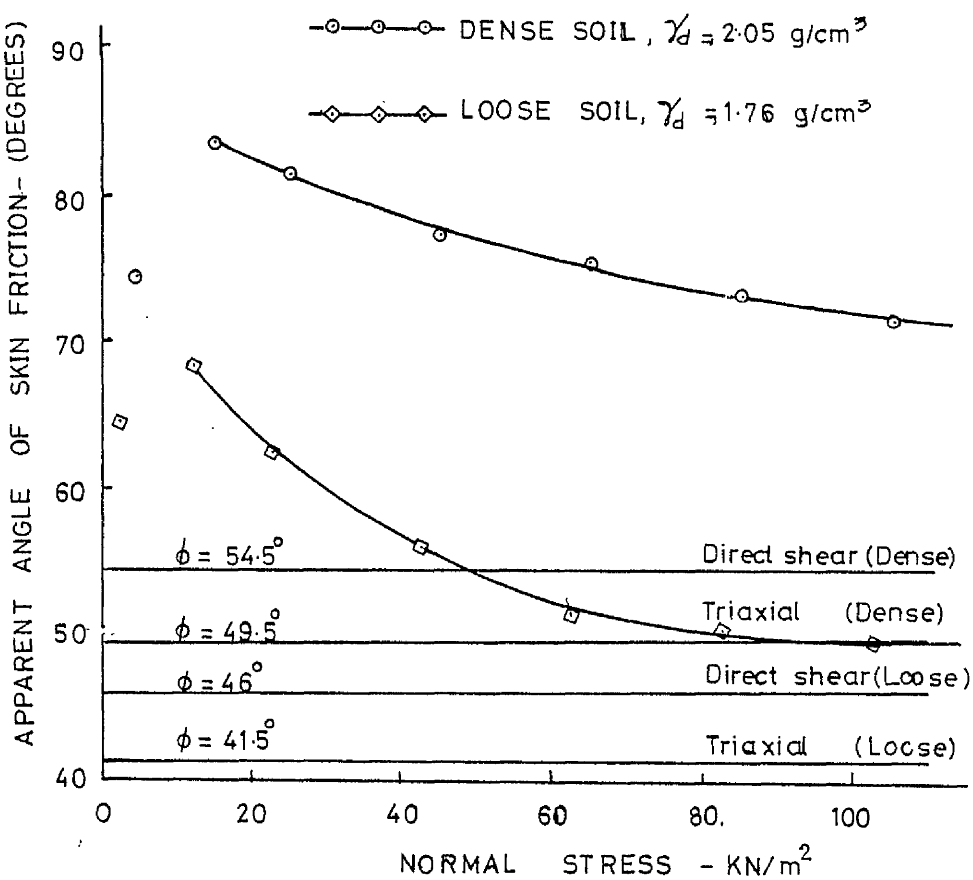


Fig. 5.2. Variation of apparent angle of skin friction with normal stress. (strip pull-out).

to calculate the apparent angle of skin friction, δ, which is equal to $\tan^{-1}\tau/\sigma n$.

Fig.5.3 shows also the relationship between normal stress, σn, and apparent coefficient of friction ($f^* = \tan\delta$).

Fig.5.4 shows the comparision between the results obtained from the present test series and direct shear.

Fig.5.5 shows the typical pulling force displacement curves obtained at normal pressure of 105 kN/m^2 and 102.41 kN/m^2 for dense and loose soil respectively, which were selected from all pulling force-displacement curves for each normal pressure to present here.

These results will be discussed in the following section.

5.2.4. Discussions on experimental results

Fig.5.2 shows that the apparent angle of skin friction decreases with increasing normal pressure. This is also confirmed by Schlosser and others(47,28)from field and model pull-out tests. At low normal pressure levels the value of δ reaches 70^o for loose soil and 83^o for dense soil as compared to the values of ϕ which are 54.5^o and 46.0^o ; 54.5^o and 41.5^o (Dense, loose) measured from direct shear and triaxial tests respectively.

The 83^o value of δ, in the case of dense soil agrees well with the values reported, by Schlosser and Elias (47) who measured 82^o for ribbed strip pull-out under a normal pressure of 100 kN/m^2. The soil used was gravel with ϕ values of 46^o,

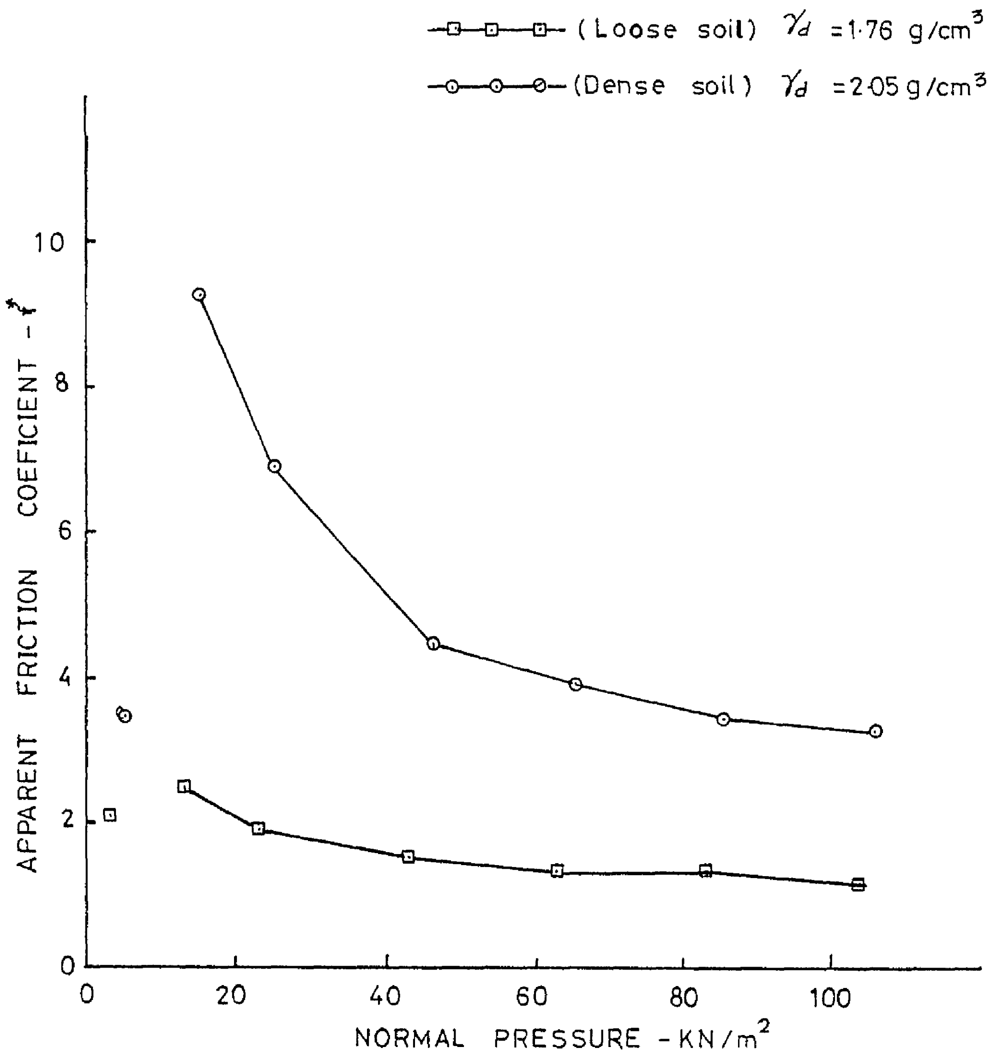


Fig. 5.3. Variation of apparent friction coefficient with normal stress (strip pull-out).

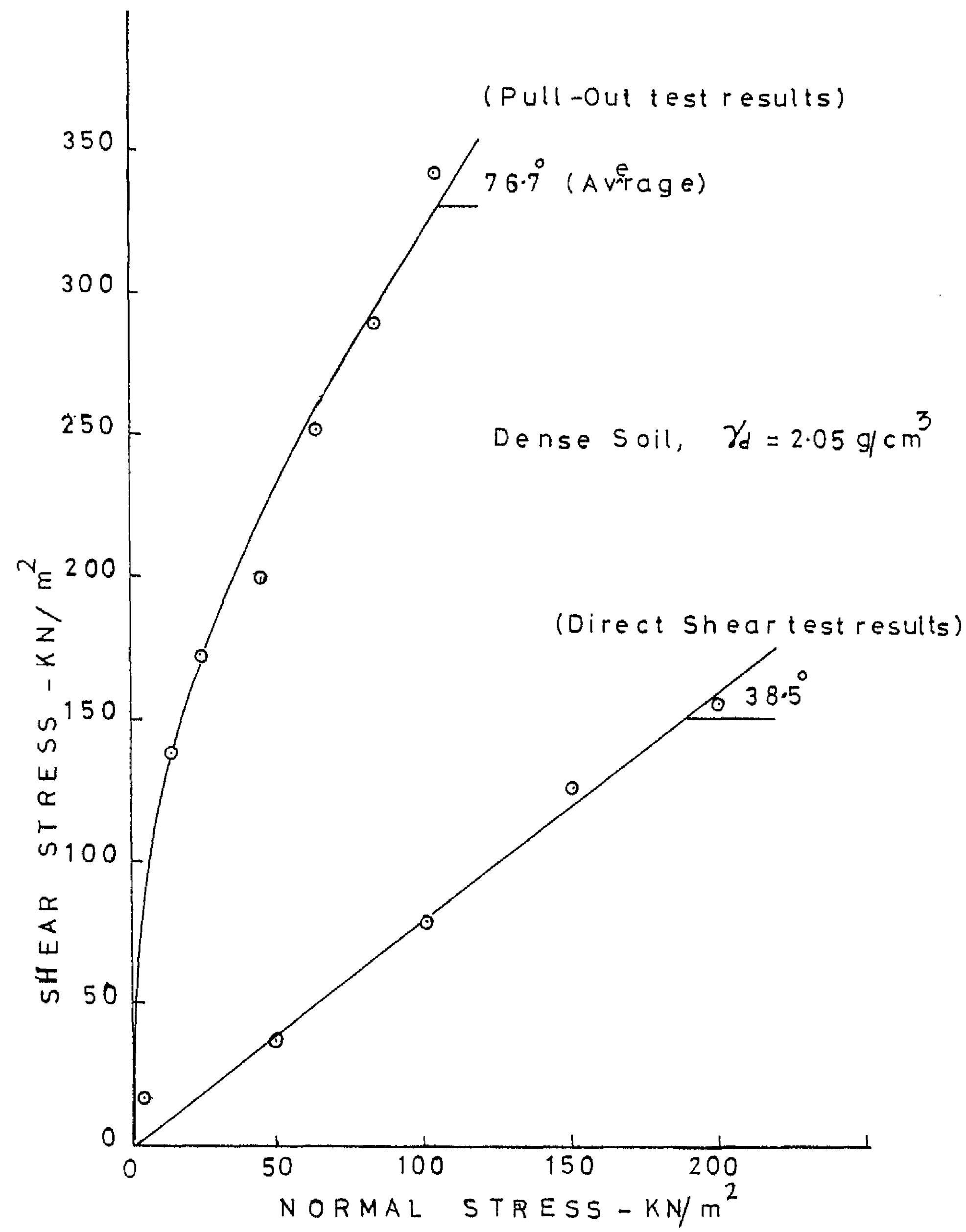


Fig. 5.4. Comparis on of direct shear and strip pull-out test results.

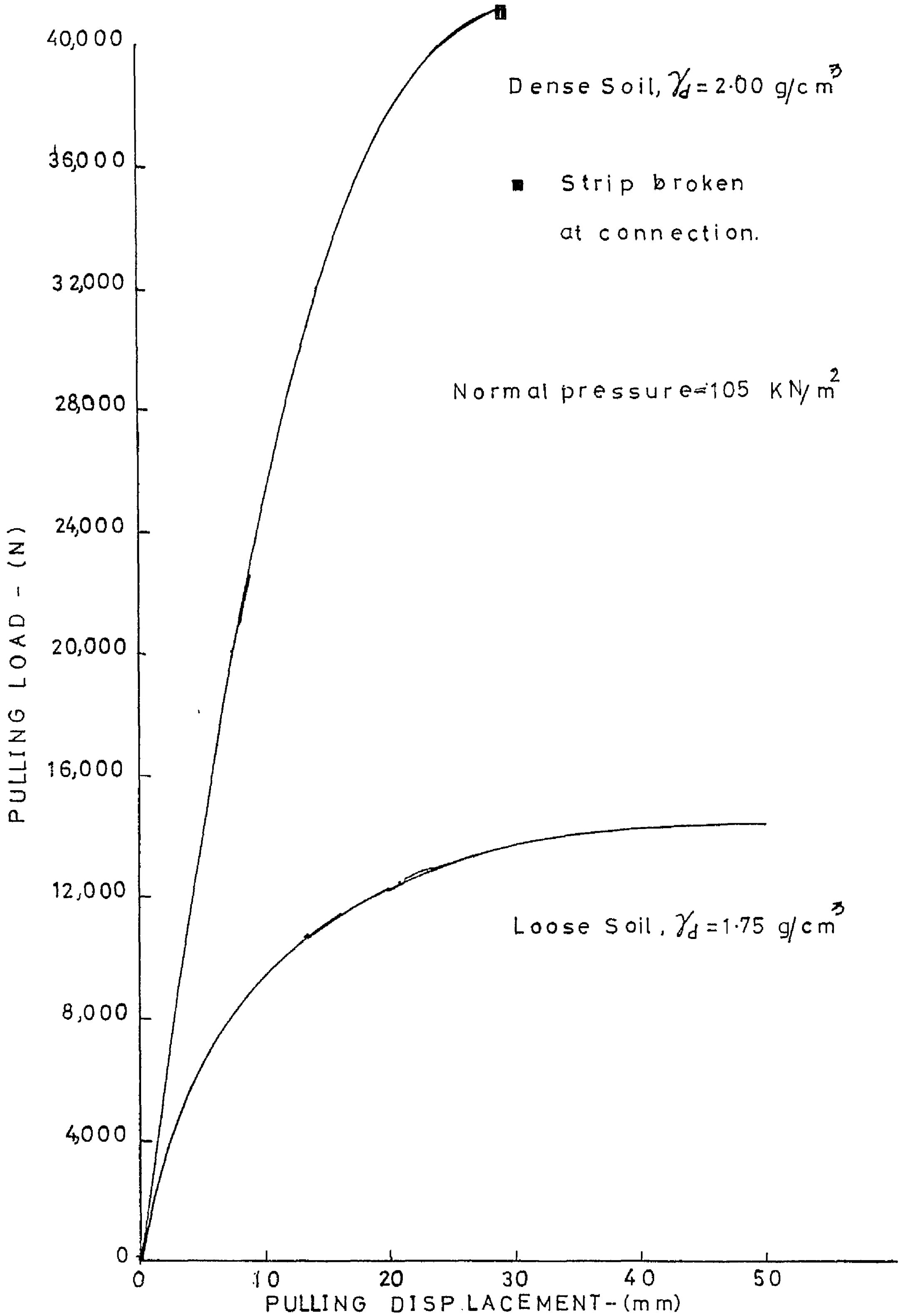


Fig. 5.5. Relationship between pulling force and pulling displacement for loose and dense soil. (strip pull-out test)

measured from direct shear test.

The extremely high values of apparent coefficient of friction at low normal pressures are mainly attributed to the dilatancy which is experienced in pull-out and which in turn increases the normal pressure acting on the strip surface. This hypothesis is borne out by Guilloux (24). He carried out shear tests under constant volume conditions on highly compacted sand and found very large increases in the normal pressure values.

At a high normal pressure level, in the case of loose soil, the angle of skin friction, δ, nearly approaches the value of ϕ, whereas in case of the dense soil it is much higher than ϕ.

From the relationship between normal pressure and apparent friction coefficient, it can be seen that, in case of dense soil, the magnitude of apparent friction coefficient, f^*, does not vary much above a normal pressure of 80 kN/m^2 and, in the case of the loose soil, it remains almost constant after a normal pressure of 40 kN/m^2.

Fig.5.2. shows the influence of density on the magnitude of δ value. The dense soil gave higher values of δ as compared to the loose soil. This has also been reported by other researchers (48). Later, the effect of varying density along the length of strip on the magnitude of δ was also investigated. This will be presented and discussed in the next chapter.

Just as striation marks were observed on the strip surface in the direct shear test, the same marks were also observed in the pull-out tests. It is interesting to note that/

the ribbed strip in dense soil in the direct shear test did not show any striation marks but it did appear in the pull-out tests. This supports the idea that the pattern of strain in the soil is not the same in the two testing methods, direct shear and pull-out, Jewell (30).

The present test results were also compared with the direct shear test results. It appears that the direct shear method gives lower or conservative values of angle of skin friction than the pull-out method. This phenomenon has been noted by others (28,30,41,48).

The pulling force/displacement curves obtained for loose and dense soil show that in case of the dense soil, the strip had broken at the connection when the load reached the yield strength of the strip. After breaking of the strip, there was no peak or residual load. This point indicates that design of the connection between strip and facing element needs careful attention.

It is concluded from the above discussions that the behaviour during pull-out testing observed in the present study is the same as that reported by others. The factors, dilatancy, arching, boundary conditions, geometry of the strip and undulations in the strip, are believed to be responsible for yielding high values of coefficient of strip friction. Besides these factors, it was also thought that the rigid facing plate enhances the lateral pressure while the strip is pulled out, which, in turn, increases applied normal pressure on the strip and results in high values of coefficient of skin friction. To investigate this/

point, some changes were made to the conventional testing method. These will be described and their results will be presented and discussed in the following section.

5.3. STRIP WITH FACING PLATE PULL-OUT

5.3.1. Introduction

It is thought that in the case of the strip pull-out test where the facing plate is integral with the box, lateral pressure develops on the back of the facing plate while the strip is being withdrawn. This, in turn, increases the normal pressure acting on the strip surface, resulting in high values of apparent angle of skin friction.

To investigate this effect, the facing plate in the pull-out rig was replaced with one which had an arrangement to allow the facing plate and the strip to be pulled together.

The tests were carried out within the same normal pressure range as in the previous strip pull-out tests, on both loose and dense soil.

The results were compared with the previous ones.

The testing procedure, results and dicussions on them will be presented in the following section.

5.3.2. Testing procedure

The same box used in the previous tests was modified by removing the facing plate and replacing it with another facing plate which had an arrangement to fix the strip at the centre and/

connect it to the pull-out frame. This is clearly described in Chapter 3.

The testing procedure: sample preparation (Placement of soil, compaction and density measurements), normal pressure applying technique and pulling arrangement adopted was the same as in the previous test series. A series of tests at normal pressures, ranging from 5 to 105 kN/m^2 on both loose and dense soil were carried out. Pulling loads corresponding to relative displacements were recorded and plotted in the form of load versus displacement for each normal pressure. The peak loads as maximum loads were taken from these curves to calculate the apparent angle of skin friction.

5.3.3. Presentation of results

Fig. 5.6 shows the relationships between normal stress and shear stress for loose and dense soil.

Fig.5.7 shows the relationship between normal stress and apparent angle of skin friction ($\delta = \tan^{-1}\tau/\sigma_n$) which were calculated by taking the values of τ and σ_n from the normal stress/shear stress curves.

The values of ϕ determined by direct shear and triaxial tests are plotted in the same graph for comparison purpose.

5.3.4. Comparision between previous and present test results

In this section, the results obtained in the previous test series will be compared with present test results.

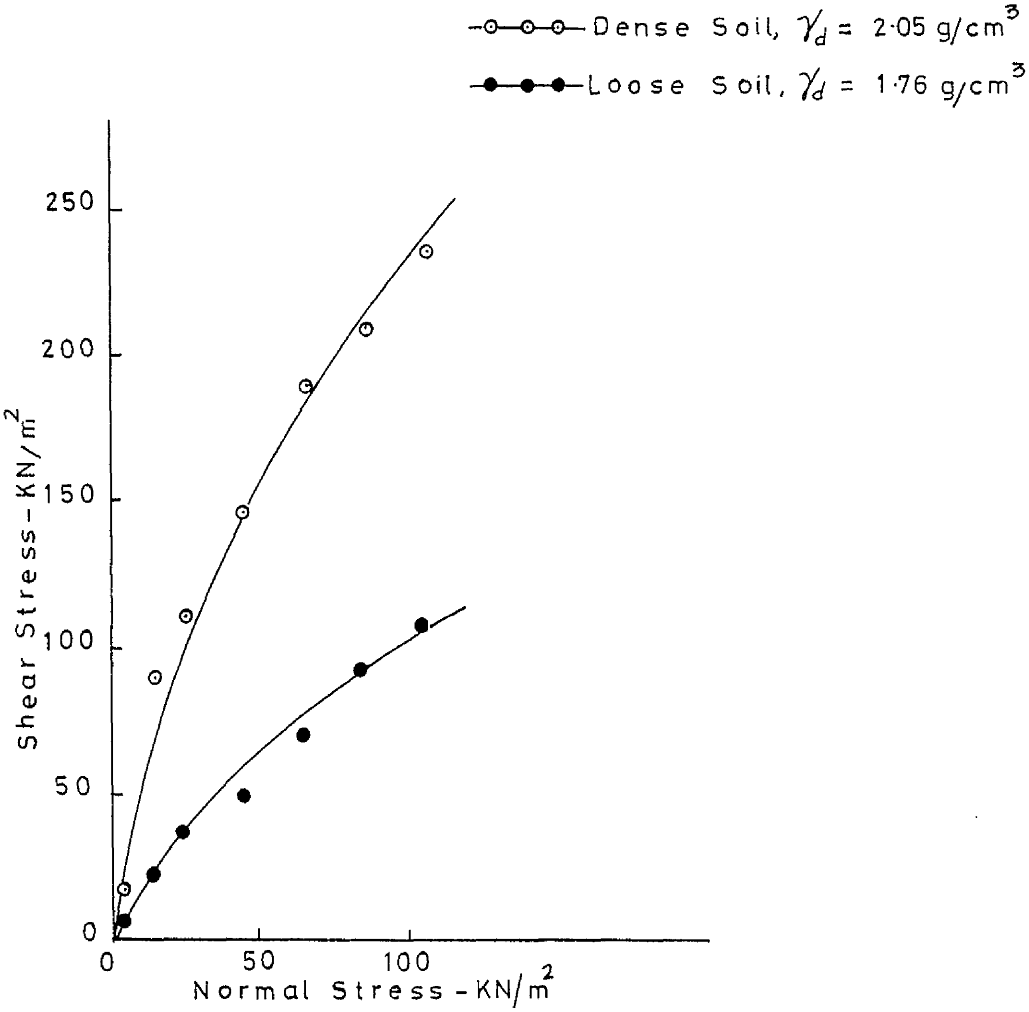


Fig. 5.6. Normal stress- shear stress relationship (strip with facing plate pull-out).

	NORMAL PRESSURE KN/m²	δ APPARENT ANGLE OF SKIN FRICTION (degrees)
LOOSE SOIL = 1·76 g/cm³	2·41	68·2
	12·41	62·3
	22·41	58·8
	42·41	49·5
	62·41	48·1
	82·41	48·2
	102·41	46·8
DENSE SOIL = 2·05 g/cm³	5	74
	15	80·8
	25	77·3
	45	72·8
	65	72·1
	85	68·0
	105	66·0

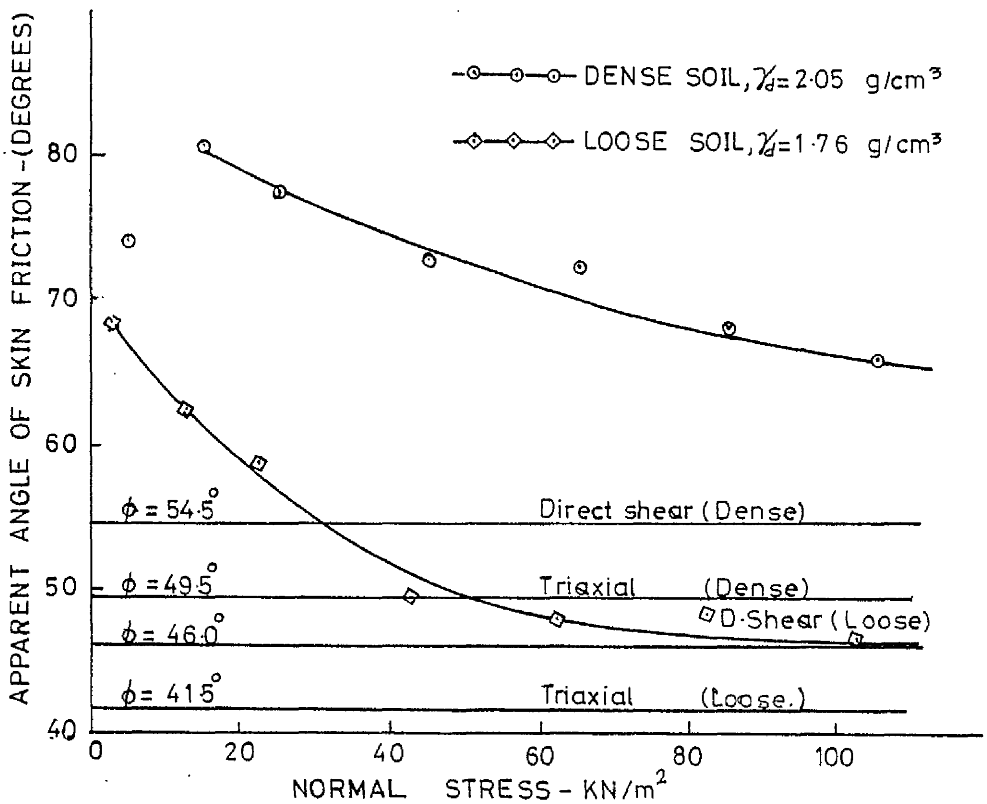


Fig. 5.7. Variation of apparent angle of skin friction with normal stress. (strip with facing plate pull-out).

Fig. 5.8 shows the comparison of relationships between normal stress and shear stress obtained from both testing methods for loose and dense soil.

Fig. 5.9 shows the comparison of σ_n - δ relationships obtained from both testing methods for loose and dense soil.

Fig. 5.10 shows the comparison of σn - f* relationships obtained from both testing methods for loose and dense soil.

Fig. 5.11 shows the typical pulling force-displacement curves obtained for loose and dense soil.

To compare the load/displacement behaviour of these two testing methods, the curves obtained at 85 kN/m^2 were selected, because a similar pattern observed at each normal pressure, which is shown in fig.5.12.

Fig. 5.13 shows the pulling force-displacement behaviour of both pull-out tests and direct shear test. The displacements corresponding to the maximum pulling loads for each normal pressure are given in table 5.1.

5.3.5. Discussions on experimental results

From the present test results it can be seen that the trend of relationships, $\sigma n - \tau$, σn - δ, σn - f*, obtained is the same as in the previous method, but the magnitude of δ is different. In the case of the dense soil, after comparing the values, the skin friction angle values, δ, are 3^o to 7^o, lower within a normal pressure range of 5 kN/m^2 to 105 kN/m^2, than the values obtained/

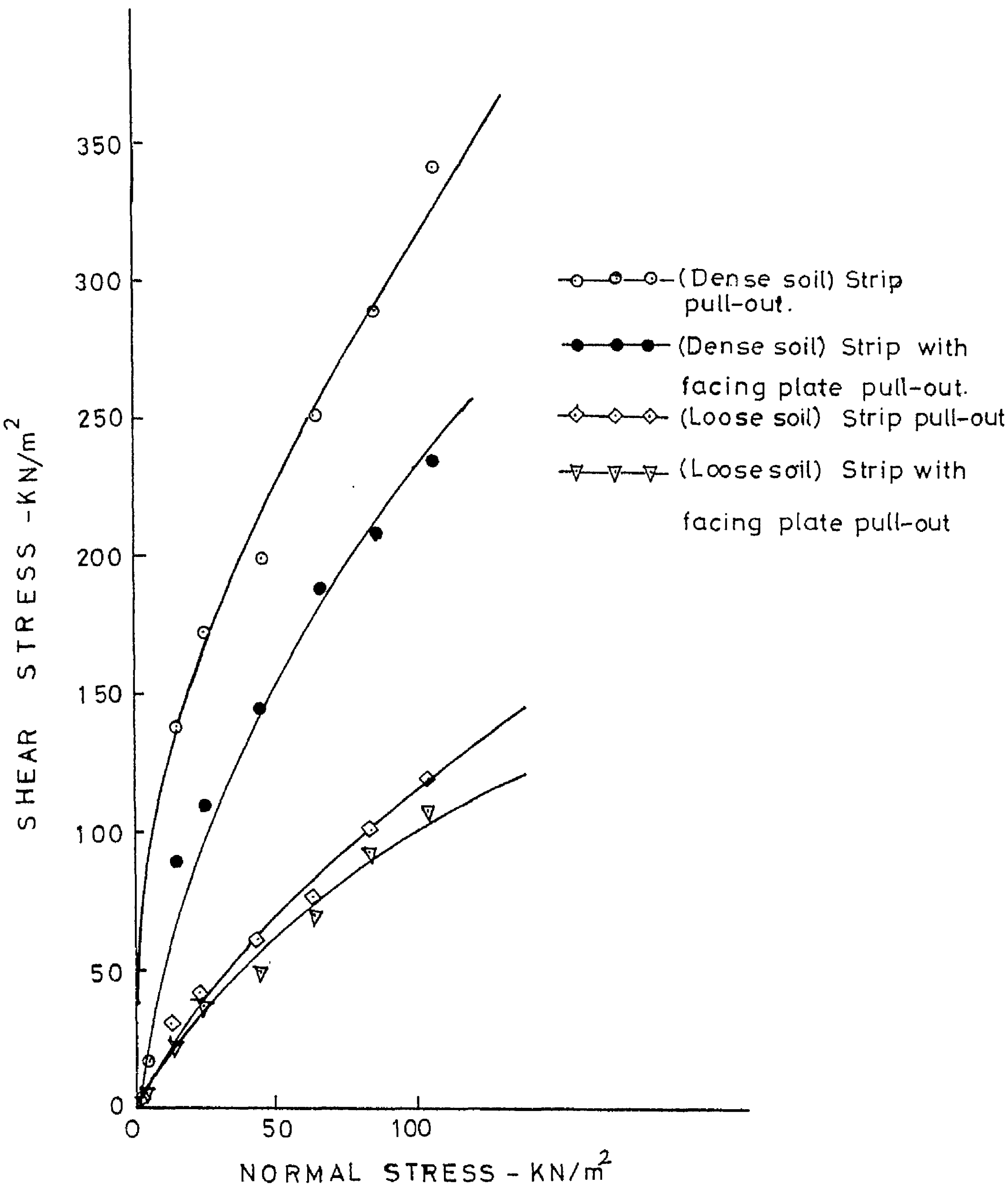


Fig. 5.8. Comparison of normal stress-shear stress relationships.

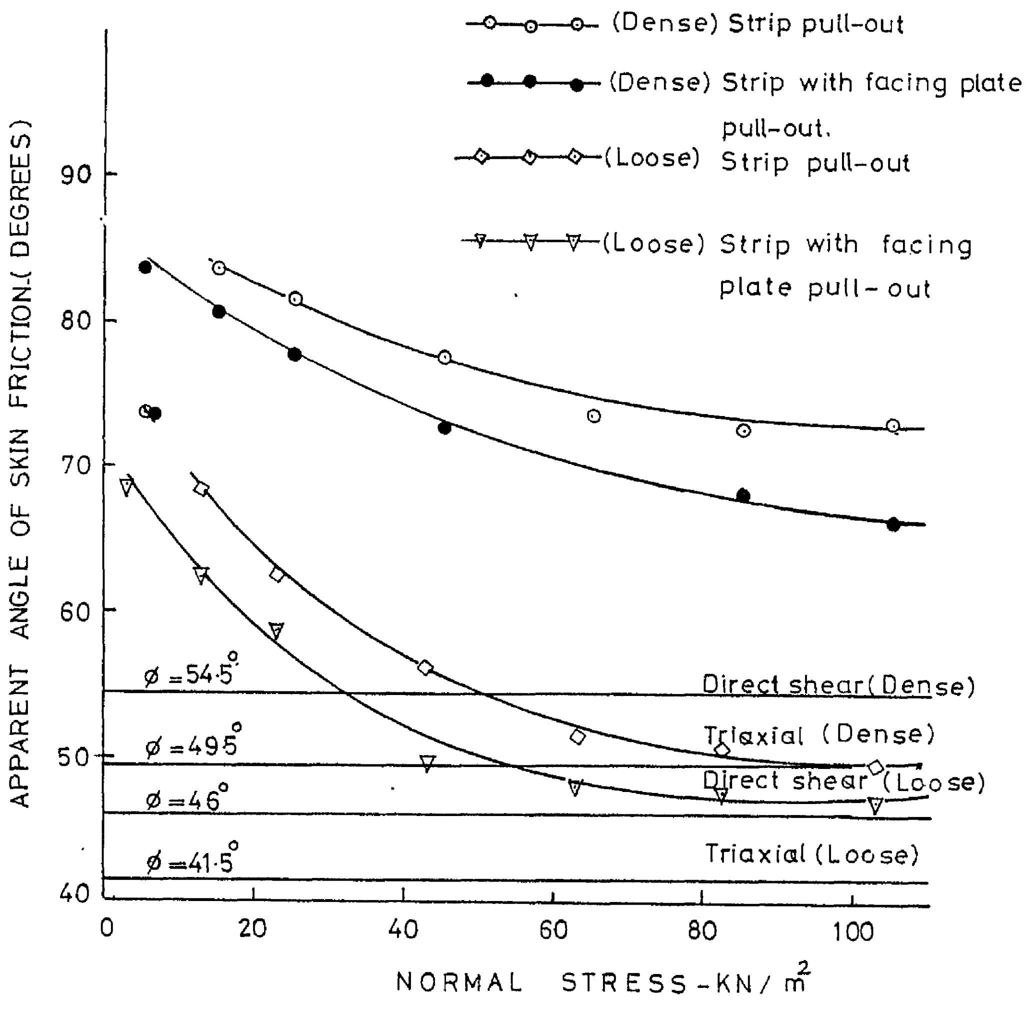


Fig. 5.9. Comparison of test results.

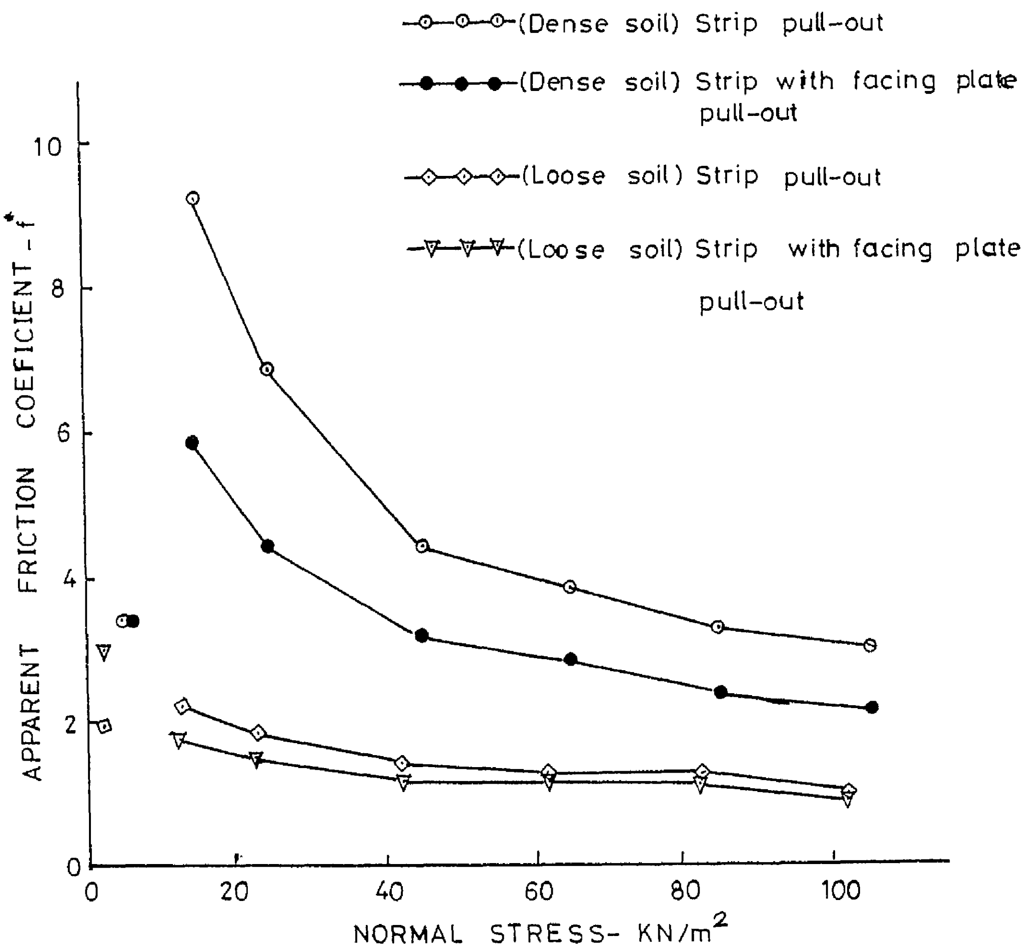


Fig. 5.10. Comparison of test results.

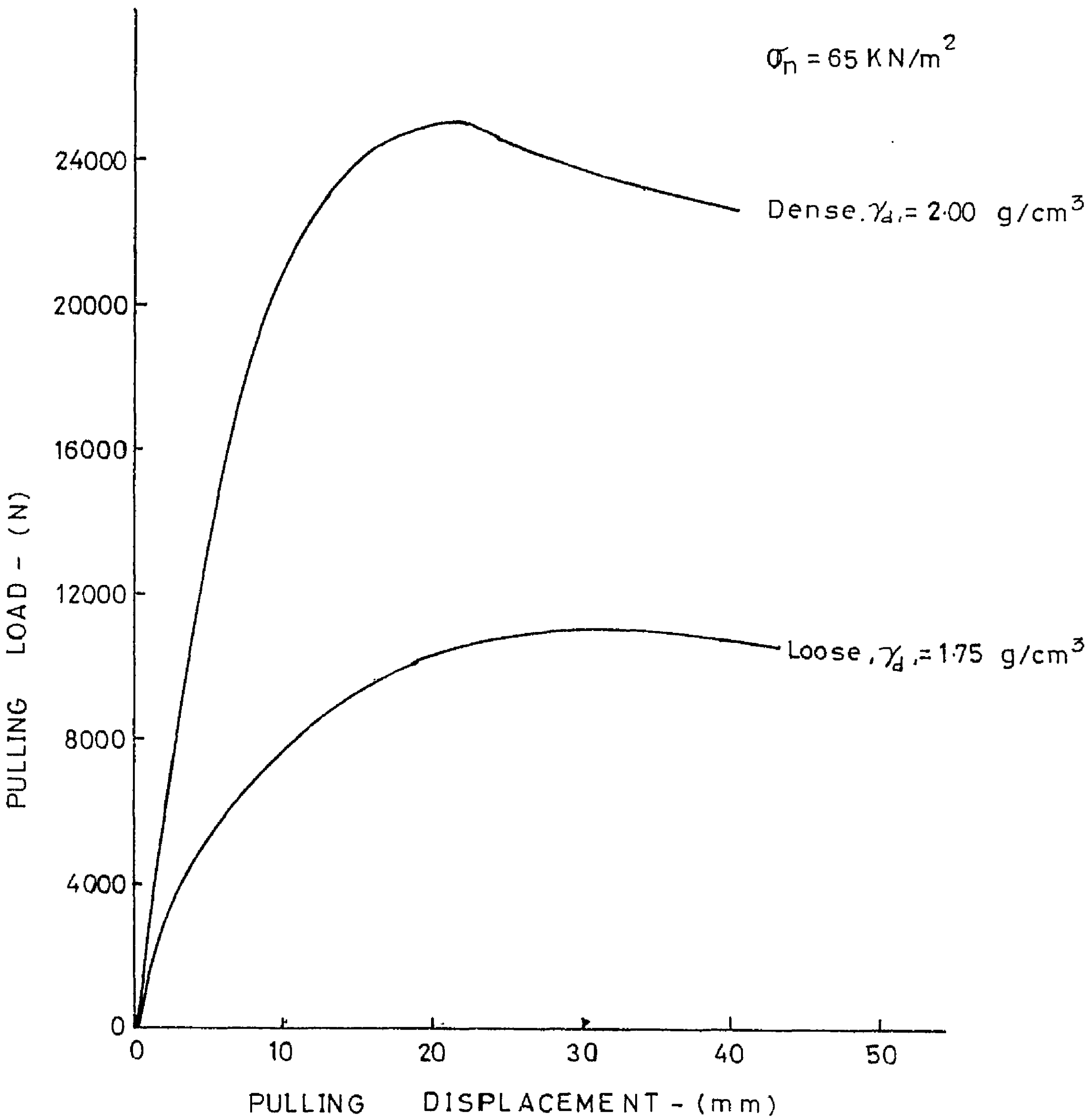


Fig. 5.11. Relationship between pulling force and pulling displacement for loose and dense soil (strip with facing plate pull-out).

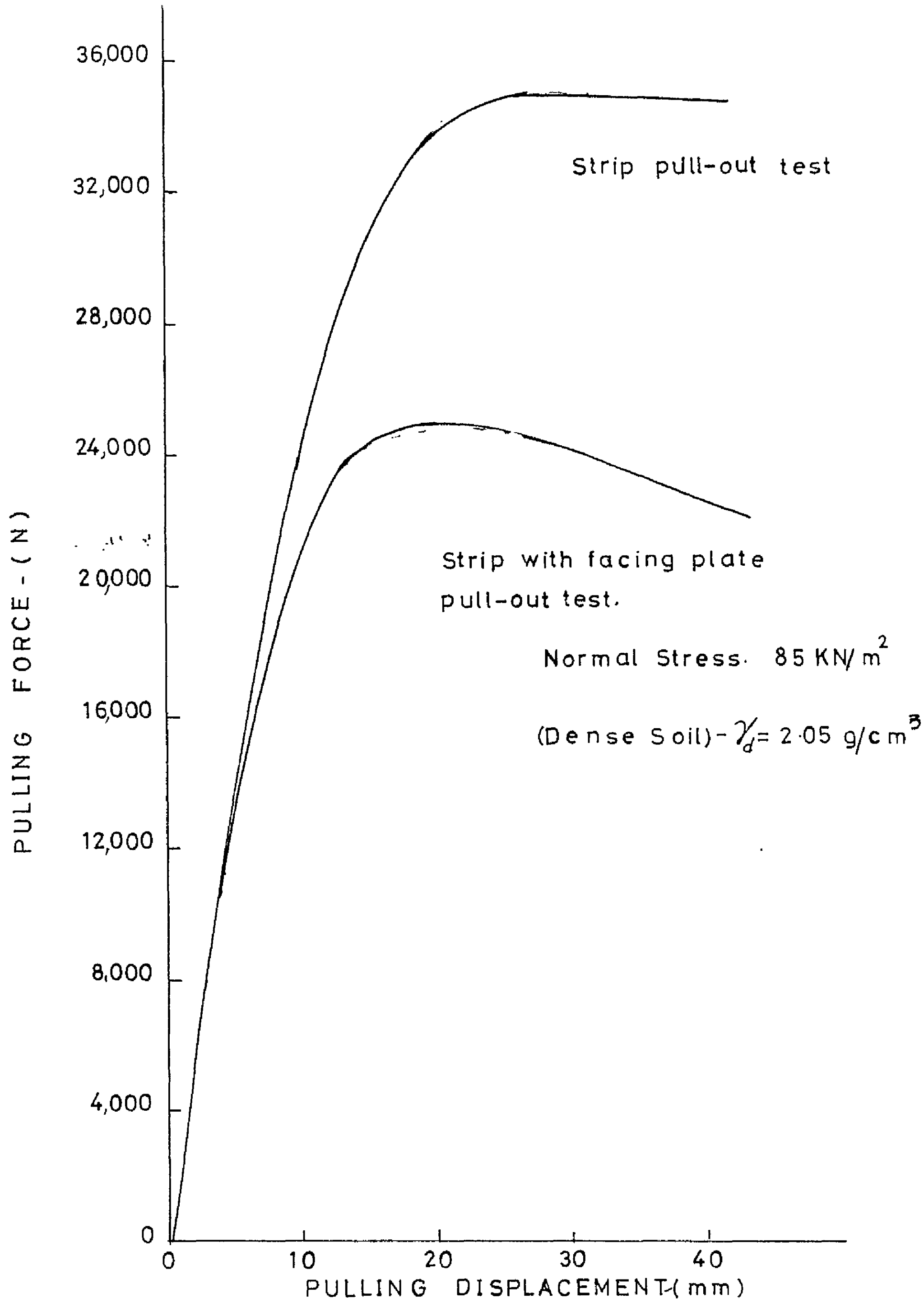


Fig. 5.12.. Comparison of pulling load-displacement curves.

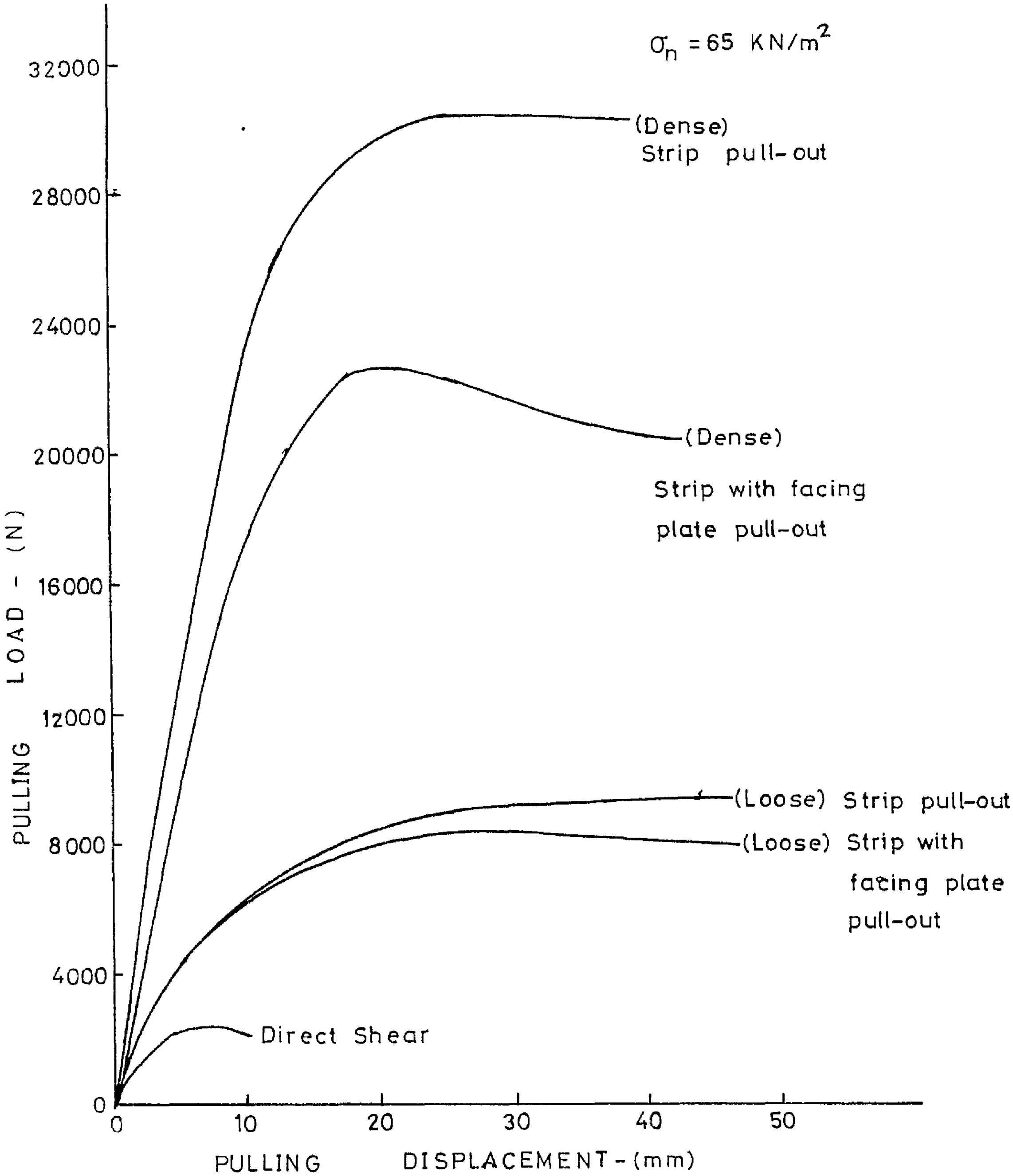


Fig. 5.13. Comparison of pulling force-displacement curves.

DENSE

NORMAL PRESSURE KN/m	MAXIMUM LOAD (N)		DISPLACEMENT AT MAX: LOAD (mm)	
	STRIP PULL-OUT	STRIP WITH FACING PLATE PULL-OUT	STRIP PULL-OUT	STRIP WITH FACING PLATE PULL-OUT
15	17·8	10·7	31	18
25	20·4	13·3	30	16
45	24·0	17·4	16	20
65	30·4	23·7	23	20
85	34·8	24·8	25	19

LOOSE

NORMAL PRESSURE KN/m	MAXIMUM LOAD (N)		DISPLACEMENT AT MAX: LOAD (mm)	
	STRIP PULL-OUT	STRIP WITH FACING PLATE PULL-OUT	STRIP PULL-OUT	STRIP WITH FACING PLATE PULL-OUT
12·4	3·9	2·9	22	15
22·4	5·6	4·0	31	23
42·4	7·6	6·0	31	28
62·4	9·5	8·4	47	26
82·4	12·2	11·2	38	29

Table 5.1. Displacements at maximum load in both strip pull-out test and strip with facing plate pull-out test.

from the strip pull-out testing method. In the case of the loose soil, δ is decreased by 3^{o} to 4^{o} within a normal pressure range of 2.41 kN/m^2 to 102.41 kN/m^2.In the case of the loose soil, the differences in δ values between the two testing methods appear to be the same at each normal pressure. On the contrary, in the case of the dense soil, the differences in δ values seem to increase as the normal pressure increases.

All results from both testing methods for loose and dense soil are given in fig. 5.8, but these are shown in a more meaningful manner in fig.5.9. It can be seen that, in the case of the loose soil, the value of the angle of skin friction decreases with increasing normal pressure and almost approaches the angle of internal friction of the soil, measured from the triaxial test, after a normal pressure of 80 kN/m^2. On the contrary, in case of the dense soil, the values of δ do not appear to vary much and remain higher than the angle of internal friction of soil, ϕ. The $\sigma n/f^*$ relationships from both testing methods for loose and dense soil show that these all follow the same trend of decreased f*-with-increasing normal pressure.

The effect of facing plate on the apparent angle of skin friction has been reported directly or indirectly by different investigators. Shen and Mitchell (53) reported differences in δ values of about 1^{o} when the tests were conducted with rigid and flexible facing plates and Tumay (56) measured the lateral reaction on a facing plate when the strip was pulled out.

The high values of δ, particularly in the dense soil/

are often entirely attributed to dilatancy, but the present test results show that dilatancy is not entirely responsible for the high values of friction coefficient, testing method also having an influence on the δ value.

Fig. 5.11 shows clear peak and residual points on the curve for dense soil. The maximum load was attained at a displacement of 20 mm in the case of dense soil and 30 mm in the case of loose soil.

A comparison of pulling force-displacement behaviour of these two testing methods is given in fig. 5.12. It appears that in the case of strip-with-facing plate pull-out test the ultimate, peak and residual points on the curve are clearly defined, but in the case of strip pull-out, the peak and residual points did not appear. The pulling load-displacement behaviour from this latter method agreed well with that of reported by Chang (13) from field pull-out tests. This also resembles the curves obtained by Guilloux (24) on high compacted sand from constant volume shear tests.

It can be seen in fig. 5.13 and table 5.1 that the displacement at maximum load in the two pull-out testing methods and in the direct shear test differs in magnitude. In the strip pull-out test the maximum load was reached at a longer displacement compared to that in the strip with facing plate pull-out test. Normal load-displacement curve for a cohesionless soil indicates that as the normal pressure increasing so the maximum load and the displacement at maximum load also increase.

It has been assumed as stated previously that the normal pressure increases locally on a strip being pulled through the facing plate, and does not increase when a strip moves with the facing plate. This increase in normal pressure should obviously result in the observed phenomenon viz: strip pull-out giving a higher load at a larger displacement than strip with facing plate pull-out.

The differences in maximum load between these two types of test is smaller in the case of loose soil compared to the dense soil. The probable reason for this is that in the loose state the passive resistance of the soil particles is lower, resulting in a smaller increase in normal pressure on the strip.

The direct shear test indicates a maximum load at a smaller displacement than either of the pull-out tests. This is probably a reflection of the different testing method in which only one side of the strip is in contact with the soil.

All those points will be referred to and discussed in Chapter 7.

CHAPTER 6

PULL-OUT TESTS WITH VARYING DENSITY ALONG THE LENGTH OF STRIP

6.1. Summary of testing programme

The object of this test series was to determine the effect of variation of density along the length of strip on the apparent angle of skin friction.

This test series was decided on after observing the density variation which occurred in an actual reinforced earth retaining wall.

In this series, using the same pull-out apparatus, tests were carried out under a normal pressure of 25 kN/m^2 and 105 kN/m^2 with 25 percent and 50 percent of the strip length in dense soil and the remainder in loose soil. Both testing methods strip pull-out and strip with facing plate pull-out, were used with ribbed strip.

The variation in apparent angle of skin friction with percentage of strip length in dense soil was observed.

6.2. Introduction

After reporting on the insitu field densities from the backfill of a reinforced earth retaining wall at Maryhill in Glasgow, as referred to at the beginning of Chapter 4, the effect of density variation along the length of strip on the magnitude of δ was thought to be worthy of investigation. Thus, a series of 4 tests each at normal pressure of 25 kN/m^2 and 105 kN/m^2, representing low and high normal pressure respectively, was carried out.

The same test rig was used with a temporary barrier plate placed across the box at distances of 0.25 m in one test and 0.5 m in the other from the back of the facing plate in order to compact the rear zone first and then to fill the soil loose in the front zone.

The testing procedure adopted in this series and presentation of results and discussions on them will be given in the following section.

6.3. Testing procedure

The testing procedure adopted in this series of tests was the same as was adopted in the previous test series except for the preparation of the sample when the soil was placed in two zones ; one compacted and the other loose.

A series of four tests were carried out in which the first two tests had a loose zone, 0.25 m and 0.5 m respectively from the back of the facing plate, at a normal pressure of 105 kN/m^2, and the other two tests had the same loose zone areas at a normal pressure of 25 kN/m^2.

In order to compact the rear zone and leaving the front zone uncompacted, a temporary steel plate, 11 cm x 40 cm, was used. This plate was placed vertically across the box at the distance of 0.25 m in the first test and 0.5 m in the second test from the back of the facing plate and then temporarily propped up so that it could not move forward while compacting the soil. Having temporarily fixed the plate, the rear part of the box was filled/

with soil in layers and was compacted by the same method as was used in the previous best series. The front part was filled with loose soil without any compaction. This was done up to the mid height of the box. After that the plate and supports were removed from the box. Then, the reinforcing strip was placed flat on the soil surface ; with one end through the facing plate attached to the pulling frame. The plate was again positioned at the same distances and was temporarily supported, repeating the same procedure in placing and compating the remaining layers of the soil. After removing the plate and supports, the excess soil was trimmed off so as to flush the soil with the top edge of the box. The rubber sheet with gasket were laid on the soil surface and the steel plate bolted down at the edges of the box. After applying normal pressure, the pulling load was applied through the hydraulic jack. The pulling loads were recorded on the proving ring dial gauge corresponding to the horizontal movement recorded on the dial gauge.

Plotting these pulling loads versus horizontal displacement values, the pulling load/displacement relationships were established from which the peak pulling loads were taken for calculating the apparent angle of skin friction, δ.

6.4. Presentation of test results

Table 6.1 shows the values of apparent skin friction angles obtained with both methods of testing and the values calculated by using the following equation.

$$X \tan \delta_D + Y \tan \delta_L = 100 \tan \delta_C$$

where X = Percentage of strip length in Dense soil.

Y = Percentage of strip length in loose soil.

δ_D = Measured apparent skin friction angle at 100% compaction.

δ_L = Measured apparent skin friction angle at 0% compaction.

δ_C = Calculated apparent skin friction angle at varying density along the length of the strip.

Fig. 6.1 shows the relationship between apparent angle of skin friction and percentage of strip length in the dense soil.

The pulling load/displacement curves obtained from the present test series were plotted together with those obtained from both fully compacted and loose soil from both testing methods, and are shown in figs. 6.2 to 6.5.

6.5. Discussions on experimental results

A considerable change in the values of δ was found when the density was varied along the length of the strip. Using the strip pull-out method, in the first case where 25% of the strip length was embedded in the loose soil, the δ value was decreased by a constant 5.5° and in the second case with 50% of the strip/

length embedded in the loose soil, the value was decreased by 8.2^{o} and 11.6^{o} under normal pressures of 25 kN/m^2 and 105 kN/m^2 respectively. A decrease in δ values was also obtained using strip-with-facing plate pull-out method. This decrease was a constant 2.7^{o} in the case of 25% of the strip length embedded in loose soil and 5.3^{o} and 4.4^{o} for 25 kN/m^2 and 105 kN/m^2 respectively in the case of 50% of the strip length embedded in loose soil.

Fig. 6.1 and table 6.1 show that the calculated values of apparent angle of skin friction compare reasonably well with the measured values in the case of strip-with-facing plate pull-out test but this is not so in the case of strip pull-out test which shows slightly greater values than the measured values.

Fig. 6.1 clearly shows that the apparent angle of skin friction, δ, decreases with decreasing density along the length of strip, particularly when the strip pull-out method was used.

It is generally assumed that the apparent angle of skin friction remains constant along the whole length of strip. In actual field conditions, because of the specified compaction method used, the density is lower within the 2 m of backfill adjacent to the wall facing than in the rest of the fill. Because of this, the apparent angle of skin friction will not be the same along the whole length of strip.

Schlosser and Guilloux (48) conducted some pull-out tests from which the tensile forces and their distribution along the length of strip have been reported. The significant effect/

DENSITY VARIATION	TEST	APPARENT ANGLE OF SKIN FRICTION(DEGREES)			
		MEASURED		CALCULATED	
		$\sigma_n = 25$ KN/m^2	$\sigma_n = 105$ KN/m^2	$\sigma_n = 25$ KN/m^2	$\sigma_n = 105$ KN/m^2
100% Compaction	STRIP PULL-OUT	81·7	73	–	–
75% 〃		76·2	67·7	79·9	70
50% 〃		73·5	62·4	77·2	65·8
25% 〃		–	–	72·4	59·5
0% 〃		62·6	49·5	–	–
100% Compaction	STRIP WITH FACING PLATE PULL-OUT	77·3	66	–	–
75% 〃		74·6	63·2	75·0	62·8
50% 〃		72·0	61·6	71·8	58·8
25% 〃		–	–	66·9	53·6
0% 〃		58·8	46·8	–	–

Table 6.1

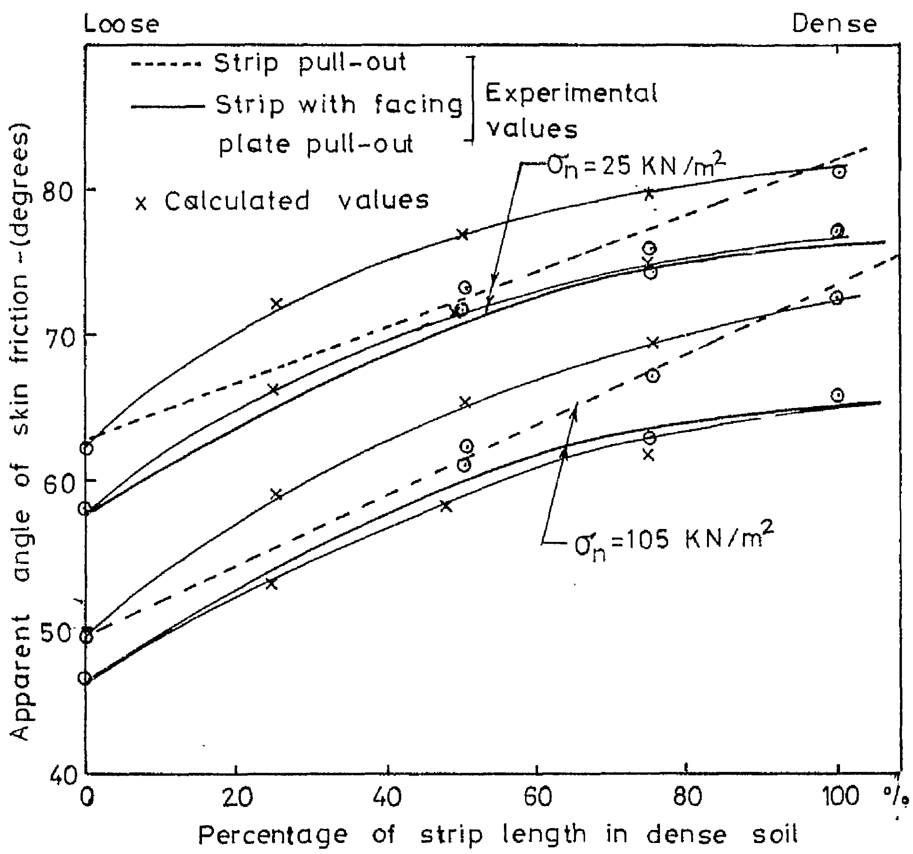


Fig. 6.1 Variation of apparent angle of skin friction with percentage of strip length in dense soil.

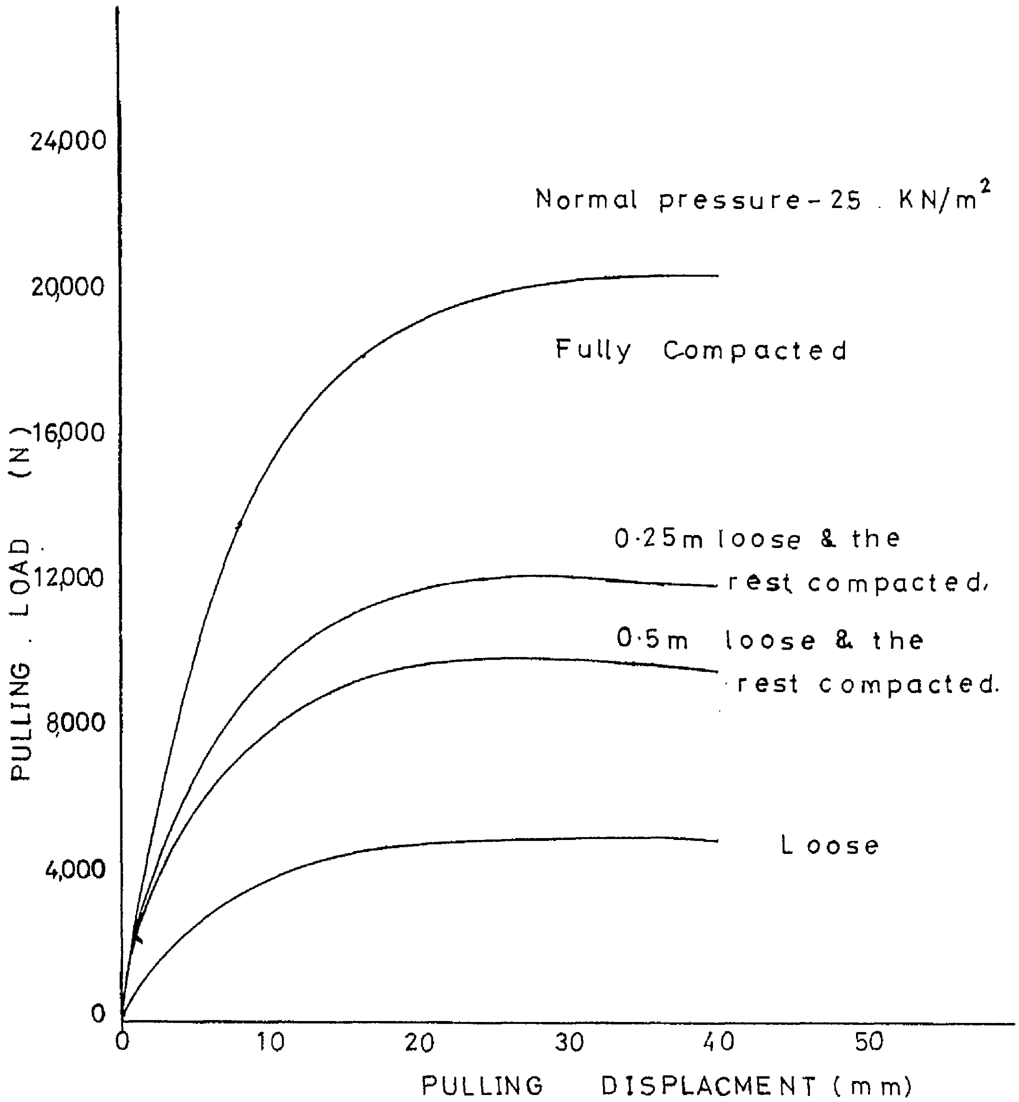


Fig. 6.2. Pulling load-displacement curves. (strip pull-out)

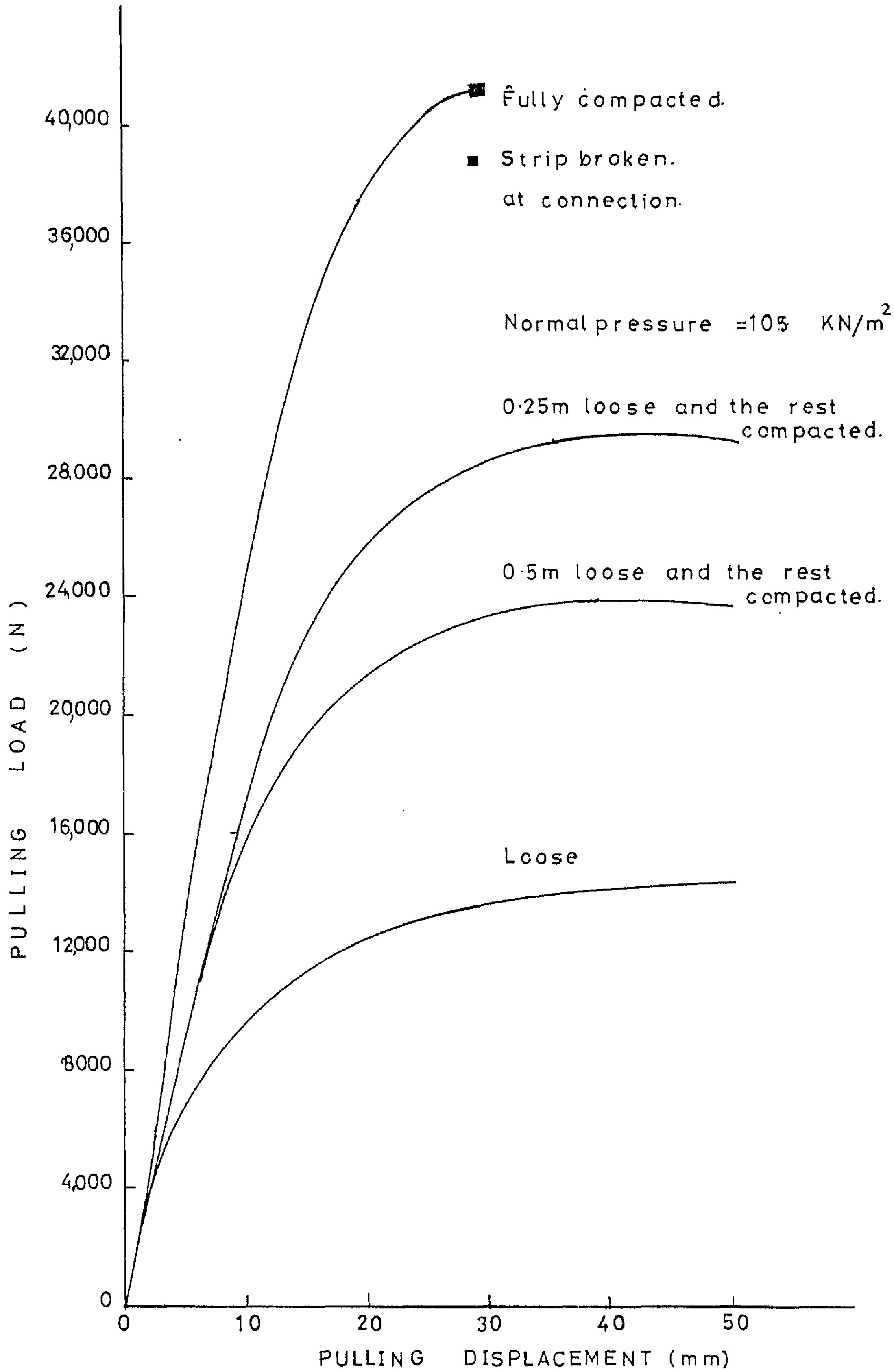


Fig. 6.3. Pulling load-Displacement Curves.
(strip pull-out)

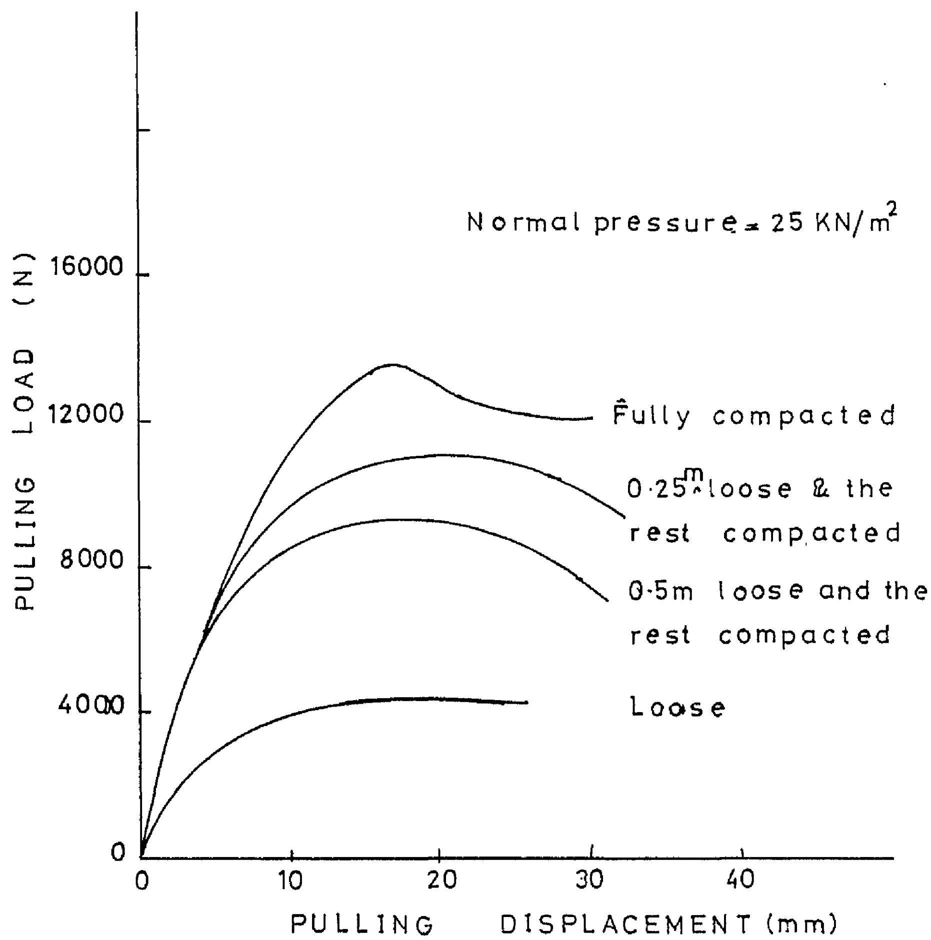


Fig. 6.4. Pulling load-displacement curves.
(strip with facing plate pull-out)

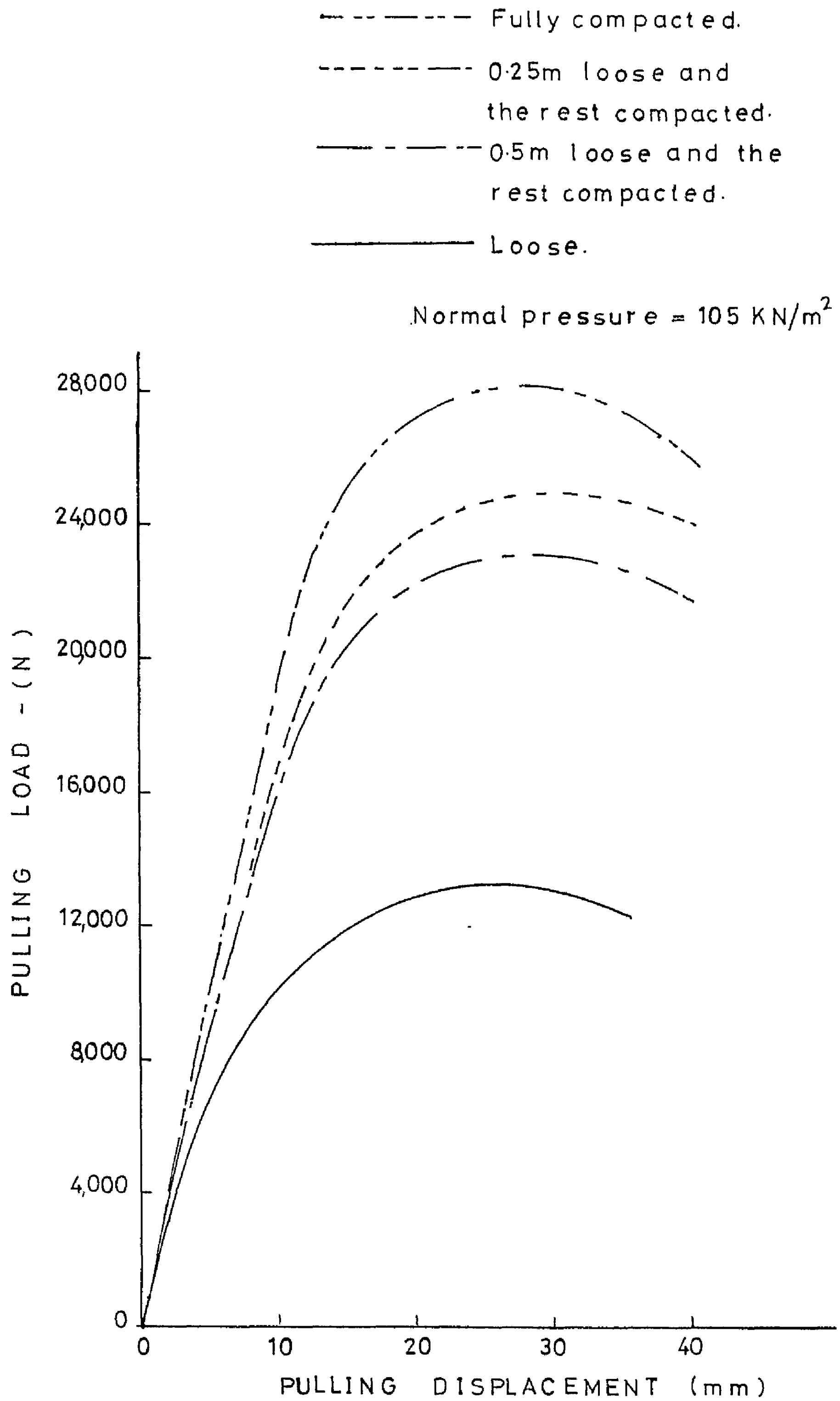


Fig. 6.5. Pulling load-displacement curves.
(strip with facing plate pull-out)

of density on the mobilization of friction has been noticed. It is hypothesised that, in the case of the dense soil, the reinforcement acts as a deformable element and the mobilized friction is more important at the fixed end of the strip than near its free end. As has already been pointed out the front part of the strip is embedded within loose soil, and this may have an influence on the tensile force distribution and mobilization of friction. If the tensile forces and their distribution along the length of strip were determined under these conditions, the effect of variation of density on the mobilization of friction could have been observed.

From a comparison of pulling force-displacement relationships of each case it can be seen that a general form of all curves is somewhat the same and the maximum pulling loads are obtained at nearly the same displacement.

The present test results will further be discussed in the next Chapter.

CHAPTER 7

GENERAL DISCUSSIONS, CONCLUSIONS AND FUTURE RECOMMENDATION.

Discussions on the results obtained from each series of tests have been presented at the end of each section. Here, all the results will be discussed in more detail.

In designing a reinforced earth wall against bond failure, there are Reinforced Earth Company, Rankine, Columb force, Columb moment methods in which the factor of safety depends on the friction coefficient between soil and reinforcement. This soil-reinforcement friction coefficient will significantly influence both the stability and economy of the final design. For determining this important design parameter, the existing available methods are direct shear and pull-out.

Different investigators have concluded from a large number of tests using both methods, that a direct shear method gives conservative or low values of soil-reinforcement friction coefficient while a pull-out method gives very high values of soil-reinforcement friction coefficient, even greater than the soil alone, particularly at low normal pressure. The use of high values of skin friction coefficient from pull-out method in design is a controversial subject among most researchers. Thus, different investigators have been involved in the study of pull-out tests on model, prototype actual field walls and embankments. They have reported that dilatancy, arching, geometry of the strip, boundary conditions and compaction of soil may cause an increased coefficient of friction.

To gáin further insight into this, the present/

investigation was planned in which pull-out tests, employing actual site material, at large scale were carried out in order to see the effect of testing method, fill density and its variation along the length of strip on the soil-reinforcement friction coefficient. In addition to this, direct shear and triaxial tests on the same material were also performed.

Direct shear test results, in general, have shown a similar trend as has been reported by others. Both direct shear and triaxial tests were conducted on the soil sample at several densities to measure the angle of internal friction, the former method gave 5^{o} higher value than the latter method. This difference agrees with that reported by other investigators. In a similar way direct shear tests on the soil-smooth strip and the soil-ribbed strip at the same densities were carried out in order to measure the angle of skin friction. From the results it appeared that the soil-smooth strip yields lower values of angle of skin friction compared with the values for the soil-ribbed strip. The values of angle of skin friction from both these samples are lower than the angle of internal friction of the soil. The ratio of average values of tan ϕ to tan ψ is 0.55 and 0.77 for soil-smooth strip and soil-ribbed strip respectively. From the γd vs ϕ relationships it can be seen that, in the case of soil-smooth strip, density has a negligible effect on the ψ values, on the contrary, in the soil-ribbed strip case the ψ value is greatly influenced by the density.

A study of the pull-out testing method was the main/

part of the present investigation in which three series of tests were carried out. A first series consisted of strip pull-out tests which have normally been used in measuring coefficient of friction between soil and reinforcement.

These tests were conducted at normal pressures, ranging from 5 to 105 kN/m^2 on both loose and dense soil. The results obtained indicate the extremely high values of apparent angle of skin friction at low normal pressure and the decrease in it with increased normal pressure. A similar behaviour has been reported by other investigators. One reason for the high values of apparent friction coefficient may be dilatancy, i.e. while the strip is pulling out, arching occurs across the strip by which the ambient soil supresses the volumetric expansion which, in turn, increases the applied normal pressure and results in enhanced apparent angle of skin friction. If we take into account a dilatancy effect, e.g. following Cornforth (20) and Ponce and Bell (46) who attributed an increase over ϕ_{cv} of 17° due to dilatancy in dense sand, the value of δ still remains high. This shows that there is some mechanism involved in addition to dilatancy.

Another probable reason is that the action of pulling a strip through a slot in a rigid facing plate results in developing high lateral pressure which, in turn, enhances applied normal pressure on the strip. This leads to an increase in the angle of skin friction. To investigate this point, a second series of tests at the same normal pressures and in both loose and dense soil was carried out. In this testing method the strip and facing/

plate were pulled out together. The results obtained show that the testing method has a considerable effect on the δ value. A large reduction in the δ value is obtained by using this method. The results, in the case of loose soil, show that the apparent angle of skin friction approaches the value of angle of internal friction of soil at high normal pressure, but this was not so in the case of dense soil in which the values remained high.

This much higher value of apparent angle of skin friction in the case of dense soil may be due to the fact that a wedge of soil adjacent to the back of the facing plate is formed due to the action of pulling the strip. In addition the facing plate moves downwards, causing a bend in strip. This bending of the strip possibly increases the normal pressure acting on the strip and results in an enhanced apparent angle of skin friction.

After noting the variation of density along the length of strip in the backfill of a full-scale reinforced earth wall, the third series of tests was carried out in order to observe the effect of density variation on the δ value. The tests were performed with both methods of pull-out. The results show a decrease of δ value with decreased percentage of strip length in dense soil in both methods of pull-out. It seems that the latter method, strip with facing plate pull-out, with 75 percent of the strip length in dense soil reflects the condition which normally occurs in the field. The value of δ achieved in this case is 63° at a normal pressure of 106 kN/m^2. If the δ value is adjusted for the effects of dilatancy, it would be reduced to 46° which is equivalent to the angle of internal friction of the soil. This/

shows that if the pull-out test is conducted under the conditions normally occurring in the field, the angle of skin friction would probably not be greater than the angle of internal friction, particularly at high normal pressure.

From the tests just discussed above, a further insight could be gained if the tensile force distribution along the length of strip was measured by instrumenting the strips with strain gauges. A more realistic value of angle of skin friction could be found if the stresses and strains in the proximity of a strip undergoing pull-out were determined. It is, however, difficult to place pressure cells in the vicinity of a strip for measuring stresses, without affecting the results.

It is postulated that if the distribution of normal pressure along the strip length is determined the angle of skin friction can be calculated by incremental treatment, i.e. the $f^* \left(\frac{L}{\gamma H}\right)$ values are calculated at predetermined intervals along the strip, taking corresponding values of normal stresses and measured shearing stress. All f^* values are then summed to obtain the true value of coefficient of skin friction.

Finally, it is concluded that the pull-out testing method is over-sensitive to the different factors such as testing method, fill density and its variation along strip length. So, at this stage, the author agrees withother investigators that, from the safety point of view, the values of coefficient of friction used in design should not be greater than the values of coefficient of internal friction of the soil.

CONCLUSIONS

From direct shear test results:

1. The relationships, γd vs ϕ and γd vs ψ, obtained from the soil-soil, soil-smooth strip and soil-ribbed strip were linear.

2. The ribbed strip gave higher values of coefficient of friction than the smooth strip.

3. In the case of the soil-ribbed strip the magnitude of ψ was much influenced by the density, but, in the case of the soil-smooth strip the density had very little influence on the ψ value.

4. The magnitude of ψ values with the ribbed strip at all densities were lower than the angle of internal friction of the soil alone measured from triaxial and direct shear tests.

From Pull-out test results:

1. In general, the magnitude of the δ value was considerably influenced by the testing method, density and its variation along the length of strip.

2. The apparent coefficient of friction decreased with increasing normal pressure in both loose and dense soil. This trend was obtained from both testing methods, strip pull-out and strip with facing plate pull-out.

3. The density had considerable effect on the magnitude of δ value in both testing methods ; the dense soil gave higher values of apparent coefficient of friction than the loose soil at each normal pressure.

4. The strip-with-facing plate pull-out testing method yielded lower values of apparent angle of skin friction by 3.5^{o} and 4^{o} in case of the dense and loose soil respectively than those obtained from the strip pull-out testing method. In this testing method, the value of apparent angle of skin friction approached the value of angle of internal friction of the soil measured from the triaxial test, particularly at high normal pressure. In the case of dense soil the values did not vary much with normal pressure but remained high.

5. Both methods of pull-out gave high values of apparent angle of skin friction as compared to the direct shear method.

6. The apparent angle of skin friction decreased with varying density along the length of strip.

FUTURE RECOMMENDATION

1. In order to see how friction is mobilized along the strip the tensile forces and their distribution along the length of the strip can be measured by putting strain gauges at suitable intervals on the strip surface. This can be/

done in both testing methods and with varying density along the length of the strip.

2. The influence of geometry of the strip (length, width) on the apparent friction coefficient can be observed by using both methods of testing and with varying density along the length of the strip.

3. The effect of vibrations on the apparent friction coefficient can be studied by carrying out tests with the same methods of pull-out as mentioned above.

4. Using both methods of pull-out, the apparent friction coefficient can be measured by employing other materials : coarse grained soil with different grain size distribution and silty or clayey soils ; fabric or plastic as a reinforcement instead of aluminium or steel.

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