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Effect of Soil Parameters on the Friction Coefficient in Reinforced Earth

by

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Introduction

Architects, engineers designers and researchers throughout the world are showing keen interest in the use of reinforced earth technique which Vidal (1968) has postulated. New knowledge, techniques, hypotheses and theories are continuously being added to the basic concepts which were pioneered and promoted by Vidal.

Reinforced earth is a construction material composed of soil fill, strengthened by the inclusion of rods, bars fibres or nets which interact with the soil by means of frictional resistance and act as a coherent mass. A broader definition could also include the use of rock bolts as earth anchors, sand, lime or stone columns to improve the qualities of natural deposits. The concept of strengthening soil with added rods or fibres is not new. Throughout the ages, attempts have been made to improve the quality of brick by adding straw. Preliminary access roads through swampy areas are often constructed on a foundation of small tree trunks and branches (Lee *et al.*, 1973).

The main applications of reinforced earth are: the earth retaining walls, embankments used in highways, railways, bypasses and bridge abutments. Also, the other fields where reinforced earth technique is adopted are reinforced earth slabs/beds, industrial projects like rock crushers, dams coal slot storage, etc. The reinforced earth is a good solution for marine projects and hillside construction of houses at various levels. In spite of its wide usage, number of aspects require detailed investigation such that the use of this technique becomes rational. The most fundamental, the most critical and the least understood aspect of reinforced earth in any form is the mechanics of sliding shear resistance

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between soil backfill and the tensile reinforcing elements and the factors affecting the same.

From a study of literature (Potyondy 1961, Ramnathan and Aiyer 1970, Bacot *et al.*, 1978, Schlosser and Elias 1978, Ingold 1981) it can be seen that the friction between the reinforcing material and the soil plays an important role and is always less than the soil-soil friction. The investigations which have been carried out by many researchers could be grouped basically into three. They are:

(*i*) Experiments in box shear apparatus with soil on one half and the reinforcing material in another half (Potyondy 1961, Panchanathan & Ramaswamy 1964, Bacot *et al.*, 1978, Dash 1978, Ingold 1981, Yoshimi and Kishida 1981, Koivumaki 1983).

(*ii*) With reinforcing material inside the soil medium the test being pull-out test (pulling out of the reinforcement (Ramnathan and Aiyer 1970, Richardson and Lee 1975, Bacot *et al.*, 1978, Schlosser and Elias 1978, Dash 1978, Walter 1978, Sridharan and Hans Raj Singh, 1984, 1986).

(*iii*) The reinforcing material being uniformly mixed with the soil (Verma and Char 1978, Long *et al.*, 1983, Hoshiya and Mandal 1984).

Considering the reinforced earth problem, the second group of experiments are relatively more appropriate. Although other two groups namely (*i*) and (*iii*) may qualitatively give an insight into the behaviour, theyare not the appropriate tests which can be directly compared with the field conditions of the reinforced earth technique.

It is also seen from the literature survey that the number of investigations of group (*ii*) are meagre and not sufficient enough to clearly bring out the factors involved in realizing the friction coefficient between soil and the reinforcement. Hence in this investigation the friction coefficient between the soil and the reinforcing material has been studied in detail by means of pull-out test, with particular reference to the changes in soil type, density and moisture content. The effect of pullout speed has also been brought out.

The Apparatus

A newly designed apparatus for this purpose was used in this study (Sridharan and Hans Raj Singh, 1984, 1986). The principle of the pullout test is shown schematically in Fig. 1. The apparatus consists of a box (made out of 6 mm thick mild steel plate) of size 305 mm × 76 mm × 102 mm with the top platen of size 303 mm × 74 mm (Figure 2). The cover plate is provided with a rigid beam to insure the uniform distribution of

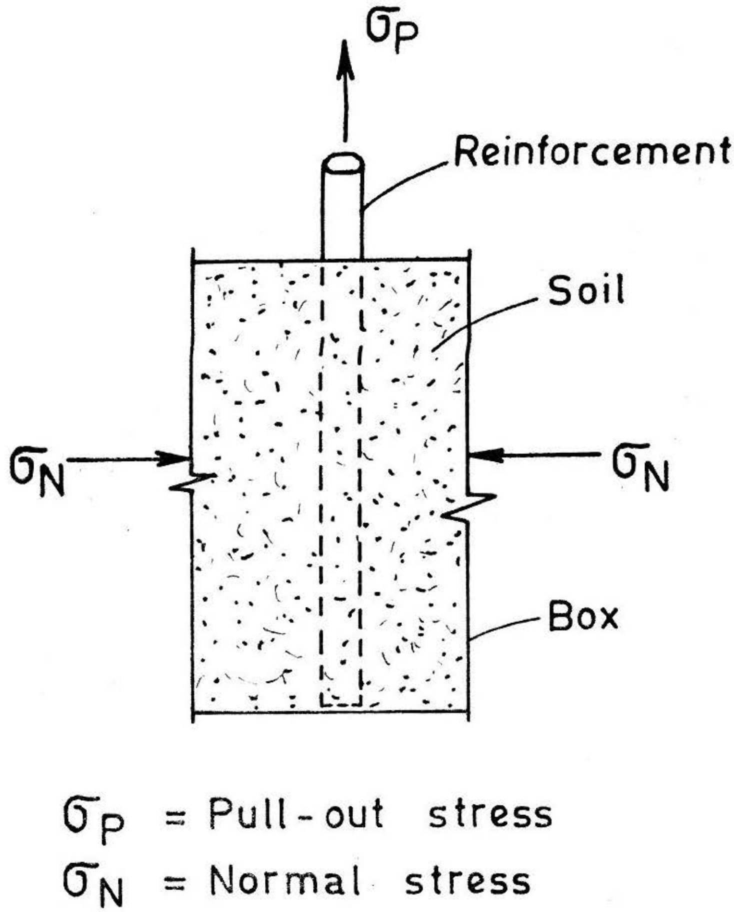

FIGURE 1 Principle of Pull out Tests

the normal load. The box had a side hole of dia. 40 mm (on the side 76 mm × 102 mm) through which the reinforcing material could be inserted. The required soil is compacted to the bottom half of the box, the reinforcement is placed carefully and the top half of the box is compacted with soil. After placing the cover plate the required normal load can be applied on the cover plate by a self straining loading frame with a screw jack. The normal load can be measured by means of a proving ring. The whole box with self straining loading frame and proving ring snugly fits onto the conventional triaxial loading frame. The reinforcing material in vertical position can be pulled out at required speed and the pull-out length can be measured by means of another proving ring. The pull out length can be measured by a dial guage with a sensitivity of 0.025 mm.

The reinforcement can be suitably connected to a vertical proving ring which measures the pull out strength to a maximum value of 500 kgs.

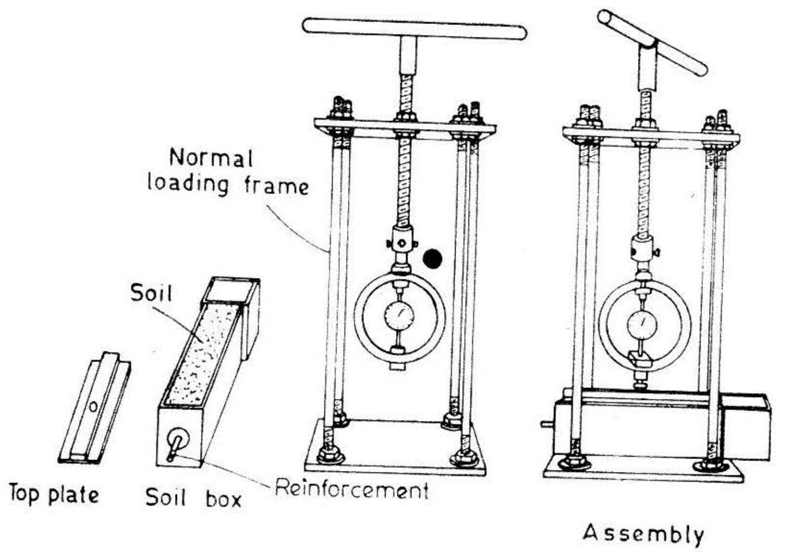

FIGURE 2 Experimental Set up

Soils Used

Four different soils were used; three of them are sands (designated as Soil *A*—passing IS 2.36 mm sieve and retained on IS 212 micron; Soil *B*—passing IS 2.36 mm and retained on IS 75 micron; Soil *C*—passing IS 150 micron and retained on IS 75 micron) and the fourth one (designated as Soil—*D*) being a locally available red earth which is a sandy silty clay of medium plasticity (liquid limit = 38% and plastic limit = 18%). Figure 3 gives the grain size distribution curves.

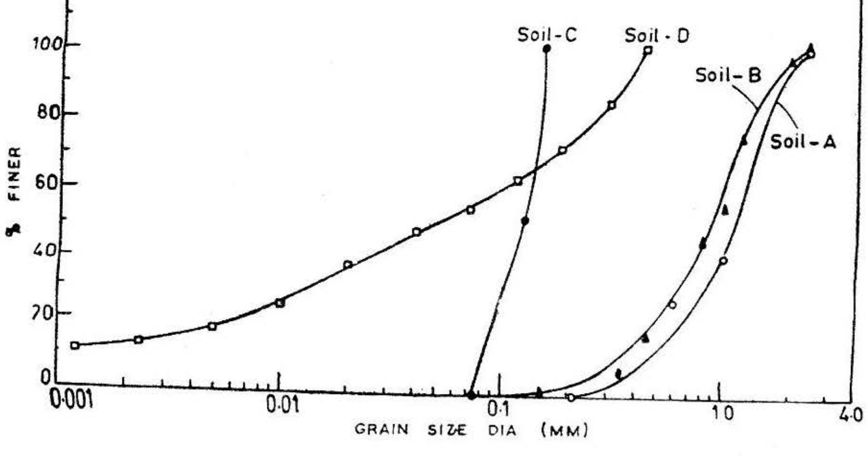

FIGURE 3 Grain Size Distribution Curves of Soils Used

To bring out the effect of soil density, three different densities have been used for the sand (soil—B) in the investigation presented here. They are : 1.34 gm/cm^3, 1.40 gm/cm^3 and 1.59 gm/cm^3, the corresponding relative densities are 15%, 31% and 71%. For soils A, C and D the bulk density used is 1.40 gm/cm^3. For soil A and soil C the respective relative densities are34% and 41%. The Proctor's maximum dry density for soil D is 1.85 gm/cm^3 and O.M.C is 16%.

The density of 1.34 gm/cm^3 was obtained just by pouring the sand freely while the density of 1.40 gm/cm^3 was obtained by pouring the soil and giving small vibration manually. To achieve the density of 1.59 gm/cm^3, the soil was subjected to vibration for about 1.5 minutes. Care was taken not to spill the soil from the hole, while filling thesand, placing the rod and while applying the normal load. It was assumed that with the provision of the rigid top plate the normal load was uniformily distributed. During the test care was taken to see that the rod is positioned at the centre as well as in its vertical position.

In case of moist sand, known quantity of water was added to the sand and the exact moisture content was determined after the test was over.

In case of red earth with moisture, known quantity of water was added to the red earth, mixed throughout, cured and the desired density was achieved by static compaction. At the end of the pull out test, the exact water content was measured.

For testing under nearly saturated conditions with sand as the fill material, continuous flow of water with very low head was maintained in order to obtain near saturation.

For the different soils, at different conditions, drained angle of shearing resistance (ϕ_d) and cohesion (c_d) have been found out using box shear apparatus.

Reinforcements Used

Two types of reinforcements have been used in this investigation. A circular mild steel smooth 12 mm dia. bar has been used for most of the tests, while a 12.5 mm dia. ordinary tor steel has been used to a limited extent with three sands (A, B and C) in dry conditions to bring out the performances of tor steel in reinforced earth.

Calculation of Pull Out Test Results and Friction Coefficient

Suitable normal loads which are usually encountered in the field were chosen. The respective pull out stress (σ_P) were found experimentally. From the normal stress (σ_N) vs pull out stress (σ_P) relationship, friction angle (ϕ_μ) and adhesion (c_a) between soil and reinforcement were evaluated.

In general, the tangent of the angle of friction ($\tan\phi_\mu$) is defined as friction coefficient (f^*) between soil and reinforcement. But this definition of friction coefficient does not take into consideration the adhesion value if it exists. Hence, in the case where adhesion value has been found, the friction coefficient has been evaluated as shown below.

The modified friction coefficient is defined as:

$$f^* = (c_a/\sigma_N) + \tan\,\phi_\mu \text{ (soil-reinforcement)}^* \quad ...(1)$$

$$\text{and } f = (c_d/\sigma_N) + \tan\,\phi_d \text{ (Soil-soil)}^* \quad ...(2)$$

In all the experiments more than four normal loads were used to obtain ϕ_μ and c_a. For purposes of comparison and to obtain f^* and f values, a normal load of 1.5 kg/cm^2, generally encountered in the field was used.

Average pull out length (ΔL) was obtained by summing up the pull out length (at failure) for all the normal loads and dividing by the total number of normal loads used.

Pull Out Test Results and Analysis

Effect of Pull Out Speed

To study the effect of pull out speed on the friction angle between soil and the reinforcement (ϕ_μ), tests were conducted at three different pull out speeds viz : 0.1219 mm/min, 0.3048 mm/min and 3.048 mm/min. The fill material selected for this series was soil *B* and the reinforcement used was 12 mm dia. smooth M.S. bar. The density of the airdried sand was maintained at 1.40 gm/cm^3. The pull out test results are presented in Table 1 and Fig. 4.

The effect of pull out speed on the friction coefficient f^* is quite significant whereas on the angle of shearing resistance of sand it is marginal. The value of ϕ_μ is increased from 14.5° to 22.5° when the pull out speed is increased from 0.1219 mm/min to 3.048 mm/min. Under similar conditions the soil friction angle increased from 40.5° to 44.5° only. From Fig. 4, it can be seen that irrespective of the pull out speed, the shape of the curve is quite similar. Since the normal load was applied through a screw jack and since the load was measured by a proving ring, it was not possible to keep the normal load exactly same in all the cases. The exact normal load realised in the test has been reported in all the cases. Perhaps it is preferable to carry out the tests at slow speed which is more representative of field conditions. The ratio of $\tan\phi_\mu/\tan\phi_d$ is less than 0.5 for all the cases but more than 0.3.

Effect of Soil Type

The tests have been carried out in two series, in series I, 12mm dia. bar

TABLE 1

Effect of Pull Out Speed on Friction Coefficient Soil-B, Reinforcement—12 mm dia. smooth M.S. Bar Length of Reinforcement, L=305 mm Soil Density—1.40 gm/cm^3, Moisture Content—Airdried

Sl No	Pull Out Speed/ Strain Rate mm/min.	ϕ_d degrees	c_d kg/cm^2	tanϕ_d	f (Eqn. 2)	ϕ_μ Degrees	c_a kg/cm^2	tan ϕ_μ	f* (Eqn. 1)	ϕ_μ/ϕ_d	f*/f	ΔL mm	ΔL (%)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.122	40.5	0.00	0.854	0.854	14.5	0.00	0.259	0.259	0.358	0.303	1.47	0.48
2	0.305	42.0	0.00	0.900	0.900	19.0	0.00	3.344	0.344	0.452	0.382	2.39	2.78
3	3.048	44.5	0.00	0.983	0.983	22.5	0.00	0.414	0.414	0.506	0.421	1.27	0.42

Note : ΔL=average pull out length for all the normal loads

γ_b=airdried density/bulk density, ϕ_d=angle of shearing resistance of soil c_d=cohesion of soil

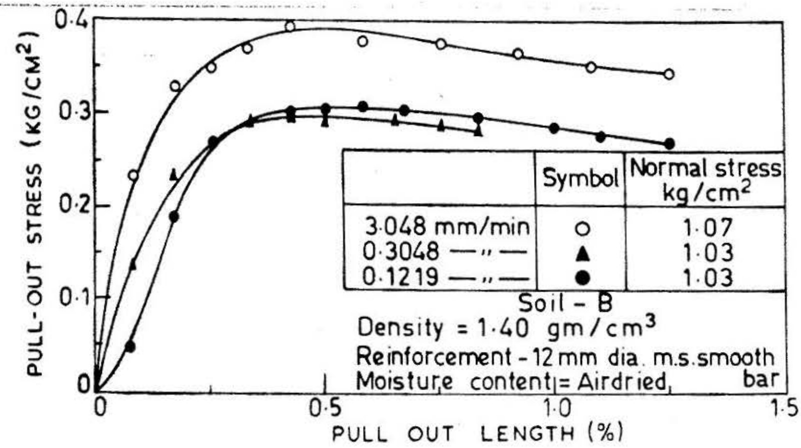

FIGURE 4 Effect of Pull out Speed on Pull out Length vs Pull out Stress

was used as reinforcement and in series II, 12.5 mm dia. tor steel was used. In case of smooth bar, the density was kept at 1.40 gm/cm³ while in case of tor steel, two densities of 1.34 gm/cm³ and 1.40 gm/cm³ have been used with three different sands. Reinforcements were pulled out at a constant strain rate of 0.3048 mm/min in all the cases. The pull out test results have been presented in Figs 5 and 6 and Table 2.

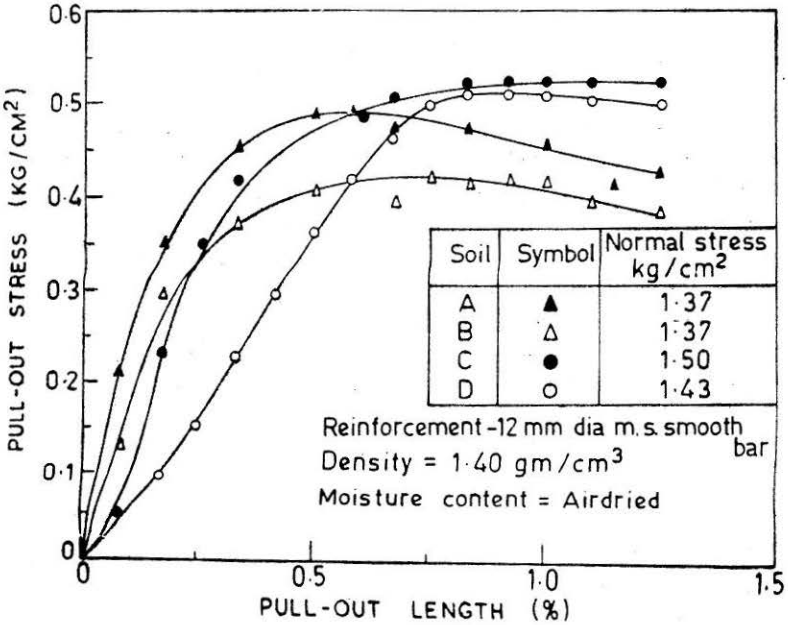

FIGURE 5 Effect of Soil Type on Pull out Length vs Pull out Stress for M.S. Smooth Bar

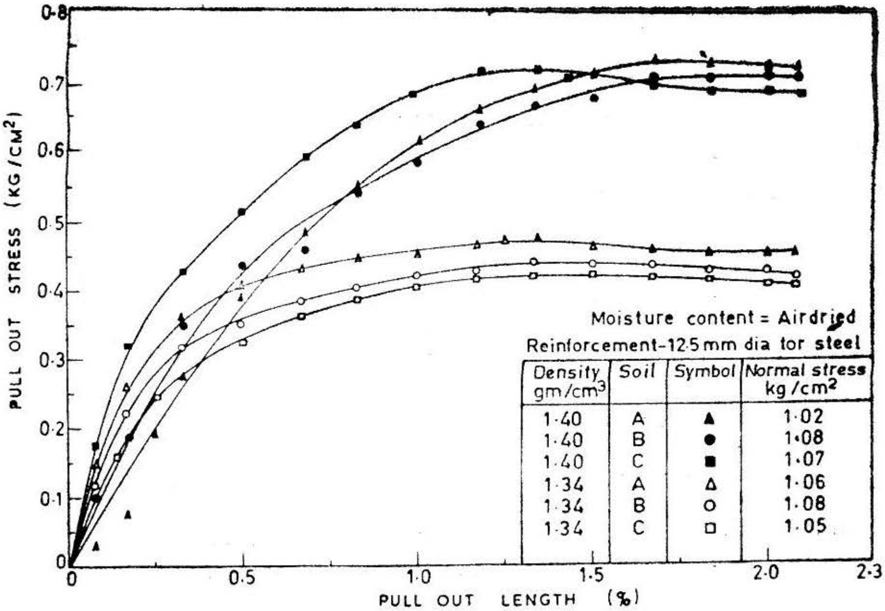

FIGURE 6 Effect of Soil Type on Pull out Length vs Pull out Stress for Tor Steel

Figure 5 shows the relation between pull out length and pull out stress for the four different soils used with smooth bar (12 mm dia.) as reinforcement. It can be seen that there is no significant difference in the shape of the curve except that the pull out length increases as the material becomes more finer (Table 2).

Figure 6 shows the effect of soil type on the pull out length vs pull out stress for two densities for tor steel as reinforcing bar. It is clear that as density increases, the pull out stress increases. The effect of soil type on the shape of the curve is similar to what has been noticed for smooth bar (Fig 5). The effect of soil type is marginal at lower density, whereas it is significant at higher density. The coarser the soil, higher the pull out stress realized at the same pull out length. The more noteworthy feature is that the pull out length at failure is more for tor steel when compared with that of smooth bar (Fig 5) especially at medium density. However for the same pull out stress, the tor steel gives lesser pull out length when compared to smooth bars (Figs 4 and 6).

It can be seen from Table 2 that irrespective of sand type, the angle of shearing resistance is essentially same varying between 41° and 44°. The variation in the angle of friction between soil and reinforcement is marginal. However, there is a clear decrease in the friction angle. The same trend is reflected in the ratio of ϕ_μ/ϕ_d and the friction coefficient. The pull out length or percent deformation increases as the sand becomes finer though the difference is not much.

TABLE 2

Effect of Soil Type on Friction Coefficient, Moisture Content—Airdried, Length of Reinforcement, L=305 mm Pull out speed—0.3048 mm/min

Sl No	Soil	γ_b gm/cm^3	ϕ_d degrees	c_d kg/cm^2	tanϕ_d	f (Eqn. 2)	ϕ_μ degrees	c_a kg/cm^2	tanϕ_μ	f* (Eqn. 1)	ϕ_μ/ϕ_d	f*/f	ΔL mm	ΔL (%)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Reinforcement : 12 mm dia. smooth M.S. bar														
1	A	1.40	44.0	0.00	0.966	0.966	20.5	0.00	0.374	0.374	0.466	0.387	2.13	0.70
2	B	1.40	42.0	0.00	0.900	0.900	19.0	0.00	0.344	0.344	0.452	0.382	2.39	0.78
3	C	1.40	43.0	0.00	0.869	0.869	18.5	0.00	0.335	0.335	0.451	0.386	2.85	0.93
4	D	1.40	41.0	0.26	0.869	1.043	18.0	0.04	0.325	0.439	0.439	0.338	2.08	0.68
Reinforcement : 12.5 mm dia tor steel														
5	A	1.34	42.5	0.00	0.916	0.916	25.5	0.02	0.477	0.490	0.600	0.535	5.27	1.73
6	B	1.34	42.0	0.00	0.885	0.885	24.0	0.02	0.445	0.458	0.578	0.518	4.37	1.43
7	C	1.34	40.0	40.0	0.839	0.839	21.0	0.06	0.384	0.424	0.525	0.505	3.30	1.08
8	A	1.40	44.0	0.00	0.966	0.966	35.0	0.08	0.700	0.753	0.796	0.780	5.99	1.97
9	B	1.40	42.0	0.00	0.900	0.900	30.5	0.08	0.589	0.642	0.726	0.713	5.33	1.75
10	C	1.40	43.0	0.00	0.869	0.869	28.5	0.08	0.543	0.596	0.695	0.686	3.39	1.11

In the case of red earth, the friction angle between soil and the reinforcement has further reduced which can be expected because the red earth has more fine material when compared with sand. It should be mentioned here that the red earth has shown small cohesion intercept of 0.04 kg/cm^2.

Further, Table 2 presents results obtained on tor steel with different soils. The angle of friction between soil and reinforcement obtained is more than that of smooth bar. This is especially so, for higher density. The ratio of $\phi u/\phi d$ is as high as 0.796 (Sl No. 8, Table 2) as against 0.466 obtained for smooth bar. The significant increase is primarily due to surface condition of the reinforcement. Contrary to what has been noticed for smooth bar, the pull out length is more for the coarse grained material for tor steel. There is a general increase in the percent of pull out length (more than 100% increase) for tor steel when compared to smooth bar at failure. This shows that rough surface could be preferable to smooth surface from pull out strain consideration also.

Effect of Moisture Content

Figures 7 and 8 and Table 3 bring out the effect of moisture content on the friction coefficient. In these tests, fully drained condition was maintained. For sand (Fig 7), it is seen that there is increase in the pull out stress/angles of friction for higher moisture content. With increase in moisture content some cohesion intercept was also obtained. The increase in friction angle between soil and the reinforcement possibly be attributed to more and more sand particles adhering to the reinforcement (because of the moisture) resulting in higher friction angle. The maximum cohesion intercept obtained for moisture content of 70% can be attributed to the capillary pressure. As the moisture increases, capillary pressure decreases and hence reduction in c_a. Potyondy (1961) reports similar results in box shear apparatus.

Table 3 lists the values of ϕ_d, ϕ_μ, c_d, c_a, f^*/f ratio and pull out length etc. It is clear that because of capillary pressure, higher friction coefficient has been obtained for moisture content = 7%. It is also noticed that the pull out length is maximum for the same.

For red earth also, the effect of moisture content is significant on pull out length vs pull put stress relationship. The sample with moisture content as 10% resulted in highest friction coefficient (Table 3). This has been attributed to the capillary pressure that exists in partially saturated soils.

Rao and Sridharan (1976) have brought out that the shear strength increases as moisure content increases from dry condition, reaches a maximum and then decreases with further increase in moisture content. It has been reasoned out that the capillary pressure is maximum at an intermediate

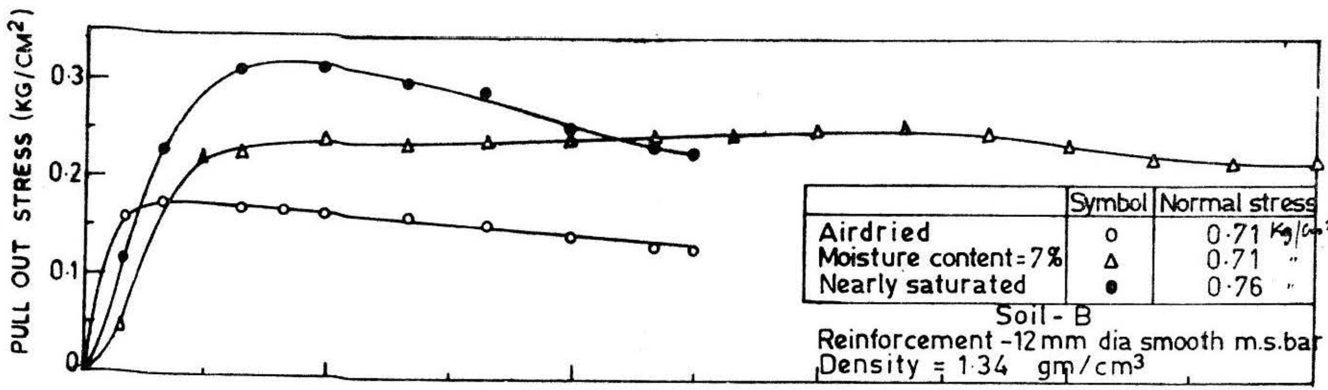

FIGURE 7 Effect of Moisture content on Pull out Length vs Pull out Stress for Sand

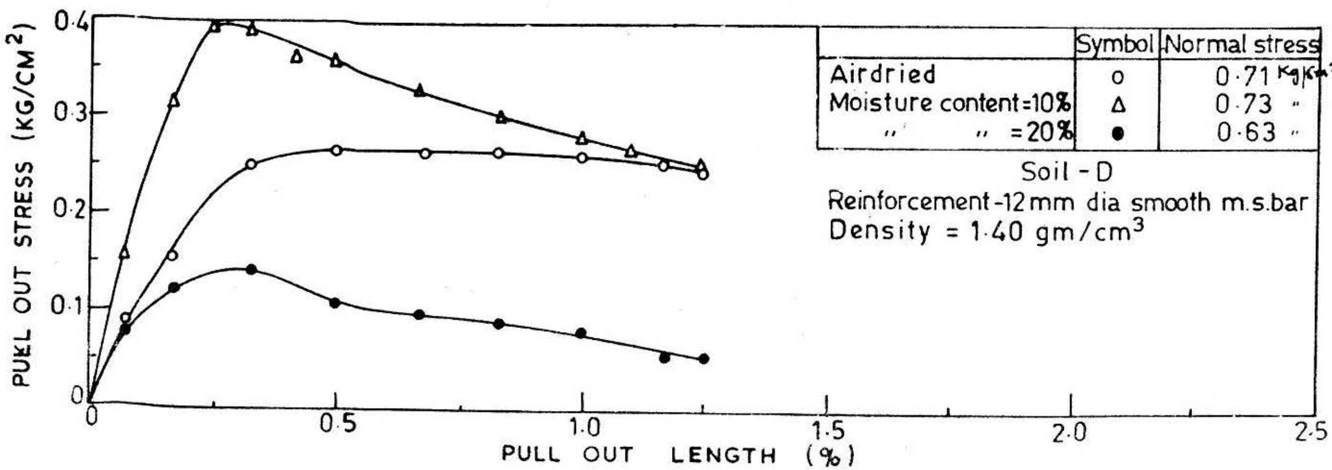

FIGURE 8 Effect of Moisture Content on Pull out Length vs Pull out Stress for Red Earth

TABLE 3

Effect of Moisture Content on Friction Coefficient, Reinforcement—12 mm dia. msooth M.S. Bar Pull Out Sppeed—0.3048 mm/min. Length of the Reinforcement, L=305 mm

Sl No	Moisture content	γ_b gm/cm^3	ϕ_d degrees	c_d kg/cm^2	tanϕ_d	f (Eqn. 2)	ϕ_μ degrees	c_a kg/cm^2	tanϕ_μ	f* (Eqn. 1)	ϕ_μ/ϕ_d	f*/f	ΔL mm	ΔL (%)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Soil-B														
1	Airdried	1.34	42.0	0.00	0.885	0.885	13.5	0.00	0.240	0.240	0.325	0.271	1.74	2.24
2	7%	1.34	37.0	0.08	0.754	0.807	14.5	0.08	0.259	0.312	0.392	0.387	3.37	1.10
3	nearly saturated	1.34	38.0	0.02	0.781	0.795	22.5	0.01	0.414	0.421	0.592	0.530	1.52	0.50
Soil-D														
4	Airdried	1.30	41.0	0.26	0.869	1.043	17.5	0.04	0.315	0.342	0.427	0.328	2.08	0.68
5	10%	1.40	39.5	0.72	0.824	1.304	25.0	0.06	0.466	0.506	0.633	0.388	0.92	0.30
6	20%	1.40	30.0	0.20	0.577	0.710	12.0	0.00	0.213	0.213	0.400	0.300	1.23	0.40

moisture content. This has been further verified by Krishnamurthy *et al.*, (1987) for four different soils.

It is interesting to note from Fig. 8 that for red earth, with moisture content = 10%, the pull out length vs pull out stress relationship showed a pronounced peak. This aspect becomes important when the deformation behaviour of reinforced earth retaining walls is also taken into consideration in the design. The percent pull out length obtained (Table 3) does not bear any trend with moisture content.

Effect of Soil Density

Figure 9 and Table 4 present the test resuls obtained to bring out the effect of density on the friction coefficient. From Fig 9, it is clear that the increase in density has pronounced effect on the pull out length vs pull out stress characteristics. As density increases both the pull out stress and the pull out length at failure increases. For the same pull out stress, the pull out length is less for soils with higher density except at low stress levels. This brings out the distinct advantages of using higher density in the field. It can be seen that for the highest density used in the test, apart from the significant increase in ϕ_μ the marked cohesion intercept is also obtained (Table 4). The effect of density is more pronounced in ϕ_μ than ϕ_d resulting significant increase in f^*/f ratio with ncrease in density.

Taking into consideration the cohesion intercept, the value of friction coefficient, f^* (Eqn. 1) at normal stress of 1.5 kg/cm^2 for the highest density is 0.934. Schlosser and Elias (1978) have also reported the significant effect of density on friction coefficient.

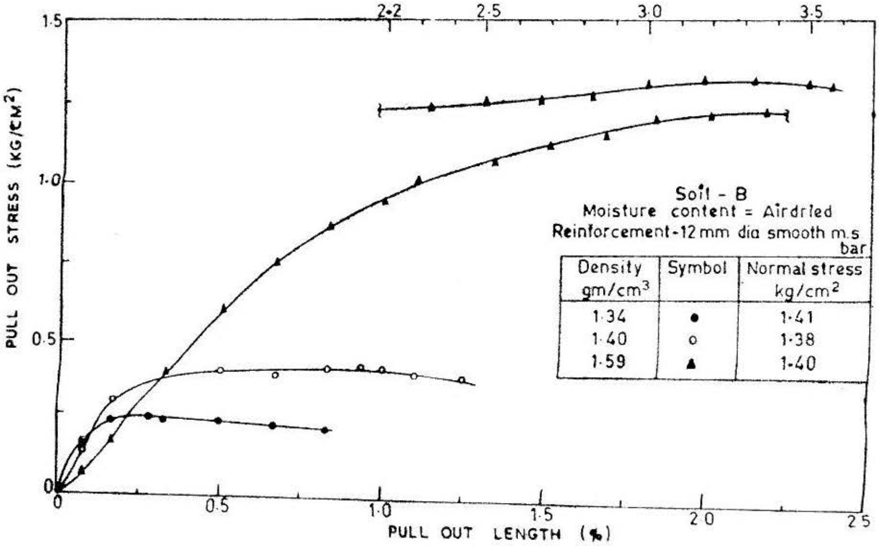

FIGURE 9 Effect of Soil Density on Pull out Length vs Pull out stress

TABLE 4

Effect of Soil Density on Friction Coefficient Soil-B, Reinforcement—12 mm dia. smooth M.S. Bar Moisture Content—Airdried, Pull Out Speed 0.3048 mm/min. Length of the Reinforcement, L=305 mm

Sl No	γ_b gm/cm^3	ϕ_d Degrees	c_d kg/cm^2	$\tan\phi_d$	f (Eqn .2)	ϕ_u Degrees	c_a kg/cm^2	$\tan\phi_u$	f* (Eqn. 1)	ϕ_u/ϕ_d	f*/f	ΔL mm	ΔL (%)
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1.34	42.0	0.00	0.885	0.885	13.5	0.00	0.240	0.240	0.325	0.271	0.74	0.24
2	1.40	42.0	0.00	0.900	0.900	19.0	0.00	0.344	0.344	0.452	0.382	2.39	0.78
3	1.59	46.5	0.13	1.053	1.140	27.5	0.62	0.521	0.934	0.591	0.819	11.33	3.71

Conclusions

Based on the above experimental study, the following conclusions can be drawn:

It has been brought out that the definition of friction co-efficient cannot be limited to the tangent of the friction angle between soil and reinforcement alone. A new definition for friction coefficient has been suggested which takes into account the cohesion intercept also (Eqn. 1).

It has been found that the density has a significant effect not only on the friction coefficient between soil and the reinforcement f^* but also on the ratio of the friction coefficient between soil and the reinforcement to the friction coefficient of soil, f^*/f. This value of f^*/f varied from 0.271 to 0.819 for sand for a density variation of 1.34 to 1.59 gm/cm^3 respectively. Hence attempt should be made to obtain higher density in the field to have an economical design.

The effect of moisture content is significant on friction coefficient f^*, while it is marginal for the friction coefficient between soil-soil itself, f especially for sand. Partially saturated soils can result in higher friction coefficient f^*, because of adhesion component due to capillary pressures.

The pull out length generally increases with increase in pull out strength. Comparison between tor steel and smooth mild steel bar as reinforcements showed the former to yield more pull out stress and length at failure. For the same pull out strength, tor steel yielded lesser pull out length. In other words the deformation of the structure will be less for reinforcing element of higher friction coefficient.

Similarly, reinforced earth structures with soils of higher density deform less, but at the same time behave more flexible.

With respect to frictional coefficient, the grain size of the sand is not important but from the view point of the rate of mobilization of friction and drainage conditions, coarse grained sand should be preferred.

The pull out length vs the pull out stress relationship obtained from number of tests has clearly indicated that substantial pull out length required for the mobilization of required pull out stress. This suggests that in the design, enough consideration should be given to permit deformation for the mobilization of required pull out stress.

It has been noticed that the friction coefficient, increased with increase in the pull out speed. Proper rate of strain should be chosen taking into consideration the field conditions while determining the friction coefficient experimentally.

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