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DYNAMIC PULLOUT RESISTANCE OF SOIL REINFORCEMENTS USING STRESS CONTROL APPARATUS

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SUMMARY

Heavy structures on weak soils may cause failures. Some modern heavy structures may warrant soil improvement measures even for strong soils. Reinforcing earth increases strength, elastic moduli, and range of stresses with elastic behaviour and reduces strains. Tensile failure of geotextile reinforcements leads to catastrophic failures, especially under dynamic loads, which may be avoided if ultimate pullout resistance of geotextiles is less than its tensile strength. It makes pullout resistance an important design data. Geotextiles under pullout forces exhibit ductility, which is important in earthquake engineering. Equipment cited in present day state of the art to determine pullout resistance of geotextiles is of strain control type, which overestimates pullout resistance. This is unsafe. Stress control apparatus are superior and have not been reported in the state of the art. This presentation deals with a stress control apparatus to obtain pullout resistance of geotextiles embedded in sand placed in a 300 mm x 300 mm direct shear box. Sustained pullout force is applied by suspending dead weights to a string attached to geotextile. Dynamic pullout forces are created by exciting test box with an eccentric drive powered by a DC motor-speed control unit. The apparatus can control frequency and amplitude of vibrations, apply desired normal stress, measure pullout forces, displacements and accelerations using suitable transducers and data acquisition system. Results indicate that for a given displacement amplitude of test box, pullout displacement increases nonlinearly with reducing normal stress, reducing sustained pullout stress, increasing frequency of excitation, increasing dynamic pullout stress and increasing number of cycles of dynamic pullout force, which are expected. Angle of mobilized dynamic pullout resistance is significantly lower than angle of shearing resistance of soil from direct shear tests. Pullout displacement dependent data obtained this way has important applications in designs of reinforced earth structures under static and dynamic loads.

INTRODUCTION

Soil withstands compressive stresses but is weak in tension. When soil is reinforced with geotextiles with good tensile strength, it acquires tensile strength, which is an advantage if loads are dynamic. Reinforced
earth has benefit of higher capacity to take loads, higher elastic moduli, larger range of stresses with elastic behaviour and undergoes smaller strains for a given loading compared to plain soil. Other advantages of

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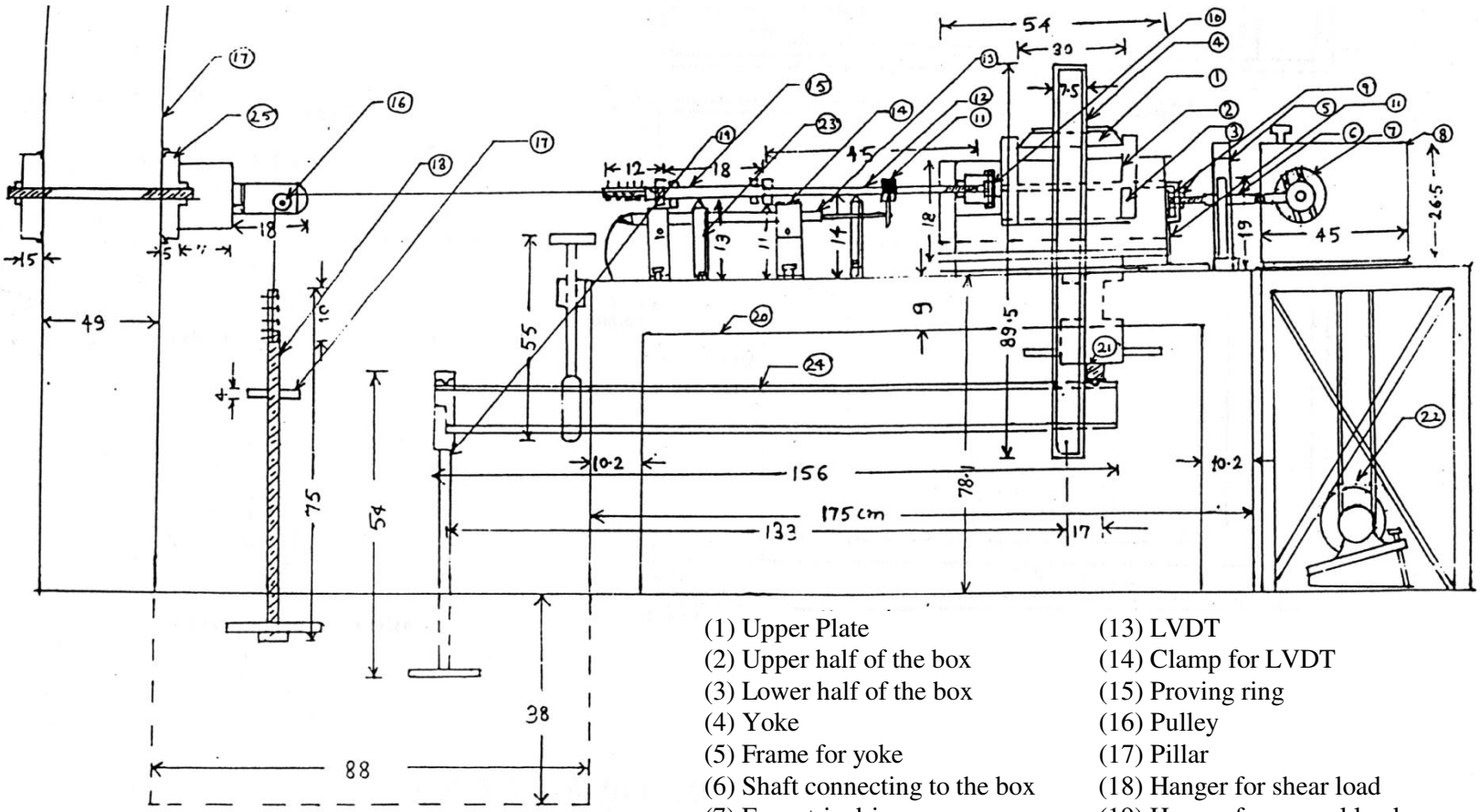


Fig. 1 Experimental Setup

(1) Upper Plate
(2) Upper half of the box
(3) Lower half of the box
(4) Yoke
(5) Frame for yoke
(6) Shaft connecting to the box
(7) Eccentric drive
(8) Gear system
(9) Check nuts
(10) Grip head
(11) Clamp connected to LVDT
(12) Connecting rod
(13) LVDT
(14) Clamp for LVDT
(15) Proving ring
(16) Pulley
(17) Pillar
(18) Hanger for shear load
(19) Hanger for normal load
(20) Workbench
(21) Hydraulic jack
(22) DC Motor
(23) Frame to keep proving ring horizontal
(24) Reaction beam
(25) Frame for pulley

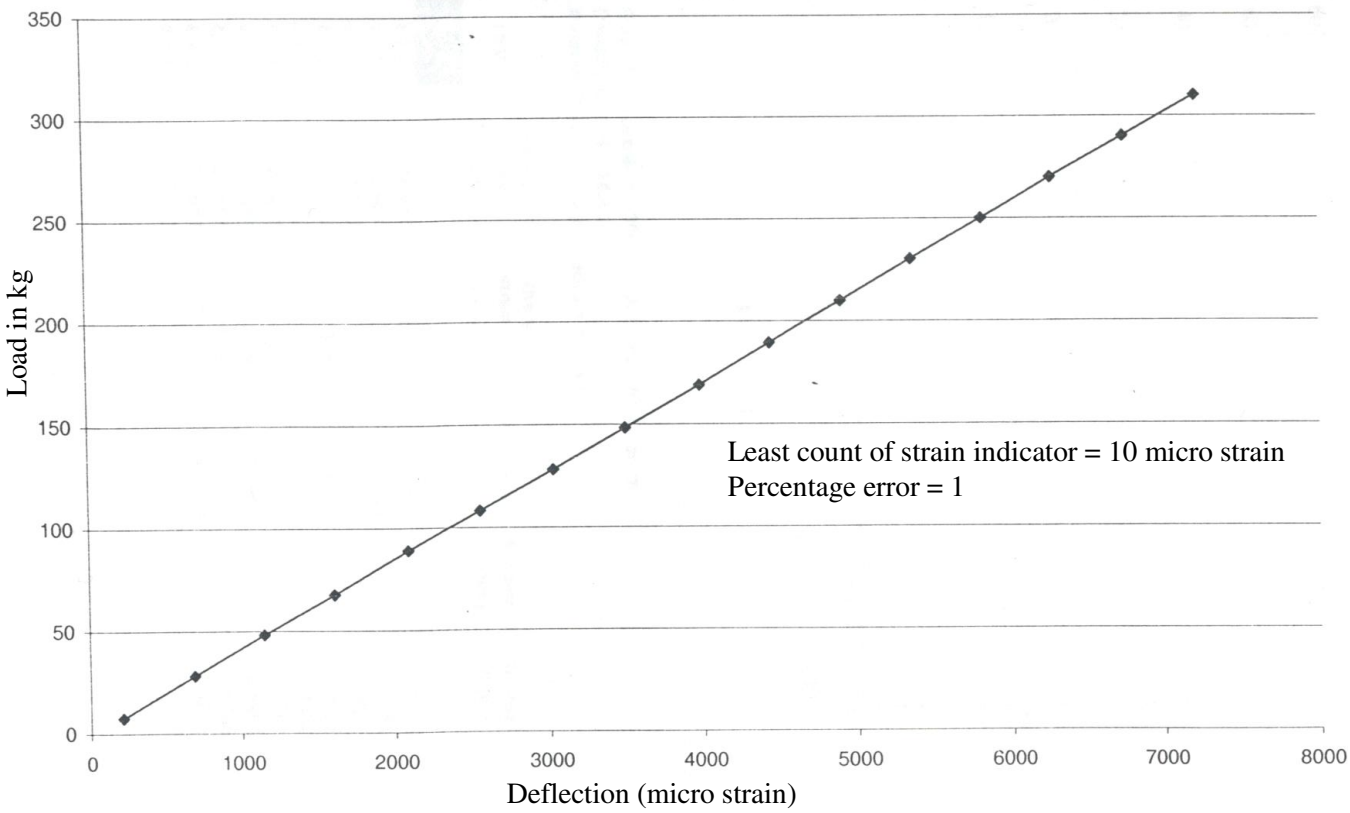


Fig.2 Calibration curve for proving ring

MATERIALS USED IN THE INVESTIGATION

Geotextile and sand used

Woven geotextile (100% polypropylene, Quality No. PD 380/B) was tested for which specifications are given in Table 1. Soil used in this study is air dry, clean and uniformly grained fine Solani river sand of Roorkee classified as SP as per Indian Standard codes of practice. Gupta [7] based on microscopic examination reported it as angular sand. Angle of shearing resistance, ϕ, is 42° at relative density, D_r, of 46% and 44.44^o at D_r of 70%. Its particle size D_{10} is 0.15 mm, specific gravity is 2.67, minimum void ratio is 0.532, maximum void ratio is 1.04768, minimum density is 1.3 t/m^3 and maximum density is 1.74 t/m^3.

TEST PROCEDURE FOR STATIC PULLOUT RESISTANCE

Preparation of geotextile sample

Geotextile specimen, 100 mm, 200 mm and 290 mm wide were tested. For some static tests, 295 mm long specimen and for other static and dynamic tests, 400-450 mm long test specimen were used, which were longer than the test box (300 mm) so that effective length of the geotextile specimen is always maintained as 300 mm. This provision eliminates possibility of continuous reduction in the effective length of the test specimen due to pullout displacements. The free edges of the geotextile specimen are properly stitched using fine fish-net thread to preclude loosening and separation of its individual threads along edges.

Preparation of test specimen of reinforced earth for static pullout resistance

Sand sample of desired density was prepared in lower half of the box by sand rain method. After gently leveling the surface, geotextile sample (with loading edge properly gripped by grip head) is placed gently

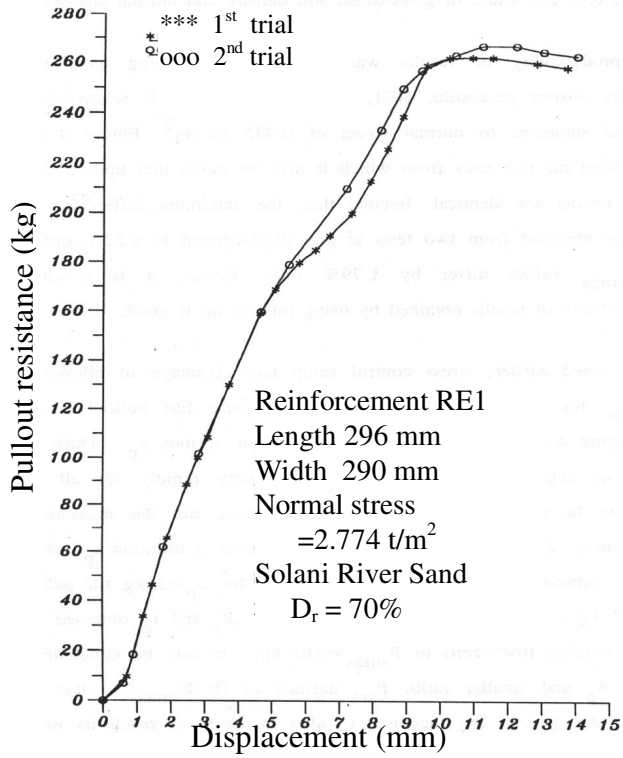


Fig. 3 Reproducibility of test results

TABLE 1 MATERIAL PROPERTIES OF WOVEN GEOTEXTILE

S. No.	Quality No. Specifications	PD 380/B
1.	Specific gravity	0.91
2.	Weight per square meter in grams	276
3.	Thickness, mm	0.68
4.	Breaking strength (5 x 20 cm) (IS-1969-1963): Warpway (kg)	245.70
	Weftway (kg)	182.00
5.	Elongation at break percentage (IS-1969-1963) Warpway	46.90
	Weftway	27.80
6.	Grab strength test (3" x 1" strip) (ASTM-D-1682) Warpway (kg)	214.80
	Weftway (kg)	152.80
7.	Elongation % (Grab test) (ASTM-D-1682) Warpway	45.30
	Weftway	30.30
8.	Tear strength (single strip) (ASTM-D-2261) Warpway (kg)	21.20
	Weftway (kg)	18.00
9.	Water permeability (litres/sec/metre) at 10m mm water head	4.20
10.	Pore size in microns Mean	25
	Maximum	69

over soil. After placing metal strips on longitudinal walls of the lower half of box to create clearance between two halves, upper half was positioned properly and secured tightly to lower half by clamping

screws. Sand is then rained in upper half to desired thickness, leveled gently and ribbed top plate of box was placed on top of the soil and leveled by using a spirit level. After placing two ball trains in V-grooves, the loading yoke is placed on them. Desired normal load is applied by placing required weights on hanger. Outer box was now rigidly clamped to work bench to keep it stationary through out the test.

A screwed rod connected proving ring (supported on knife edges) and grip head. Clutch wires attached to other end of ring pass over a pulley and get connected to a hanger to receive weights to apply desired pullout force measured by proving ring, a strain indicator. Pullout displacements were measures using LVDT. Pullout force was applied in steps not greater than 20% of estimated ultimate pullout resistance of fabric. At each applied load, pullout displacements were measured at different time intervals till maximum pullout displacement occurs. Near ultimate pullout resistance, load increments were kept small. Using test data, pullout force–pullout displacement relationship may be plotted from which pullout resistance may be obtained. The test may be repeated with different normal stresses, widths of geotextiles etc.

TEST PROCEDURE FOR DYNAMIC PULLOUT RESISTANCE

Sample preparation, placement of geotextile and application of normal load are explained earlier. Amplitude of displacement and frequency of vibrations of box were predetermined and preset by adjusting eccentric drive. Displacement was measured by precision dial gauge. Power axis of eccentric drive driven by a DC motor-speed control unit was connected to eccentric drive through a gear box with reduction ratios of 1:1, 1:10, 1:100 and 1:1000. This is useful in obtaining desired speeds. Ram of eccentric drive moving sinusoidally was connected to outer box to vibrate it sinusoidally. Using a trial run, setting on speed control unit was marked before start of actual test. Though frequency control is approximate, precise frequency and acceleration were measured by using acceleration pickup (fixed to outer box) and data acquisition system. The DC LVDT of ± 50 mm measured dynamic pullout displacements. For all tests, single amplitude of ± 3.73 mm (eccentricity of 1.243%) and D_r of 46% (medium dense sand) were employed.

For dynamic tests, it is required to specify sustained pullout stress and amplitude of dynamic pullout force (as percentages of ultimate static pullout resistance). Usually sustained pullout force ranges from 30 to 50% and dynamic pullout force from 5 to 25% of ultimate static pullout resistance. Sum of sustained pullout force and dynamic pullout force should not exceed ultimate static pullout resistance for a given test. Tests were performed this way with different sustained pullout forces and frequencies.

PRESENTATION OF RESULTS FROM STATIC TESTS

Presentation of results is made as far as possible by using dimensionless parameters, because, it is advantageous and desirable to do so. It makes results independent of units of measurement.

Reproducibility of test results

Static test results for pullout resistance of geotextile with σ_v of 2.774t/m^2 shown in Fig.3 show excellent reproducibility under identical conditions with error of only 2.5% in pullout resistance and about 5% error on pullout displacement at failure, which is considered as good performance of apparatus developed.

Results of Static Pullout Resistance Tests

Tests were performed at normal stress, σ_v, of 27.962 kN/m^2, 32.962 kN/m^2 and 37.936 kN/m^2 with D_r of 46% to get pullout stress-pullout strain curves (Fig. 4). Pullout stress ratio is pullout stresses normalized with respect to corresponding σ_v and pullout displacement ratio is pullout displacement normalized with

respect to length of box (300 mm). These two dimensionless terms for three σ_v plotted in Fig. 5 merge data of above 3 tests into one design curve, which is advantageous. At any displacement ratio, the stress ratio is tangent of angle, ϕ_p, of mobilized pullout resistance, which is useful in understanding pullout displacement dependent mobilization of pullout resistance. Stress ratio increases almost linearly with displacement ratio up to displacement ratio of 0.04 to 0.05 and beyond that nonlinear behaviour dominates. Maximum stress ratio mobilized at failure remains the same for displacement ratios larger than that at failure.

Ductility of materials is usually discussed with respect to its behaviour in tensile or compressive forces. A material is ductile if its strength at failure strain remains substantially the same at strains significantly larger than failure strain. If this is discussed with respect to pullout behaviour of fabric embedded in soil, it may be noted that reinforced earth exhibits ductile behaviour since ultimate pullout strength substantially remains the same at pullout displacements are larger than that at failure. This ductile behaviour of reinforced earth makes it an ideal material for application in geotechnical earthquake engineering. This is of help in limiting plastic displacements at failure to relatively reasonably small values.

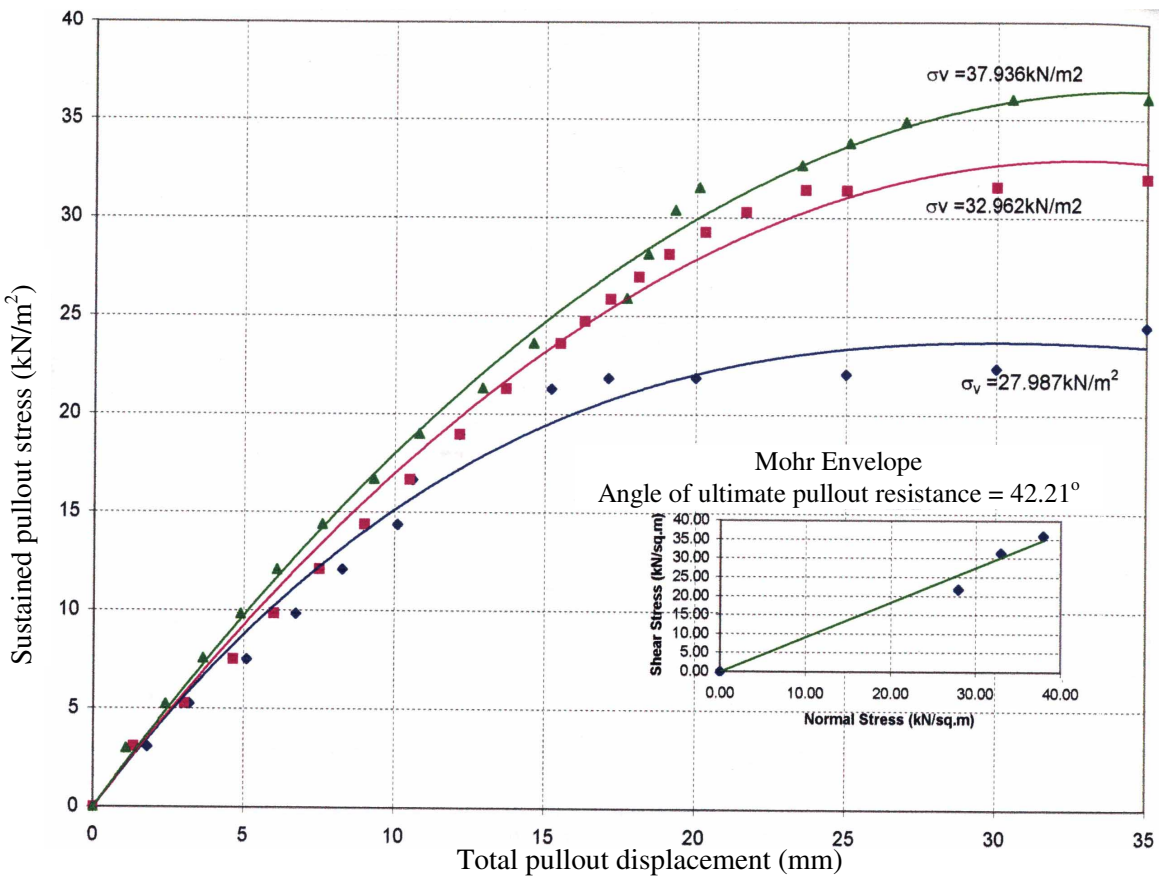


Fig. 4 Variation of sustained pullout stress with total pullout displacement for various normal stresses.

Influence of time on pullout displacements

Stress control apparatus permits study of influence of time on pullout displacements for a given pullout force. It is impossible with strain control tests, because, at every time instant pullout displacement and corresponding pullout force keep increasing. Hence, before full influence of applied load corresponding to any pullout displacement is realized, higher pullout force comes into play. This tends to under-

realization of pullout displacement at any applied pullout force, which is unsafe and undesirable. To study influence of time, geotextile was subjected to static pullout forces in steps. Pullout force at each stage was allowed to stay for sufficiently long time so that pullout displacements get stabilized. Pullout displacements were measured at intervals of time after applying pullout force increment, Δp. Typical results are shown in the

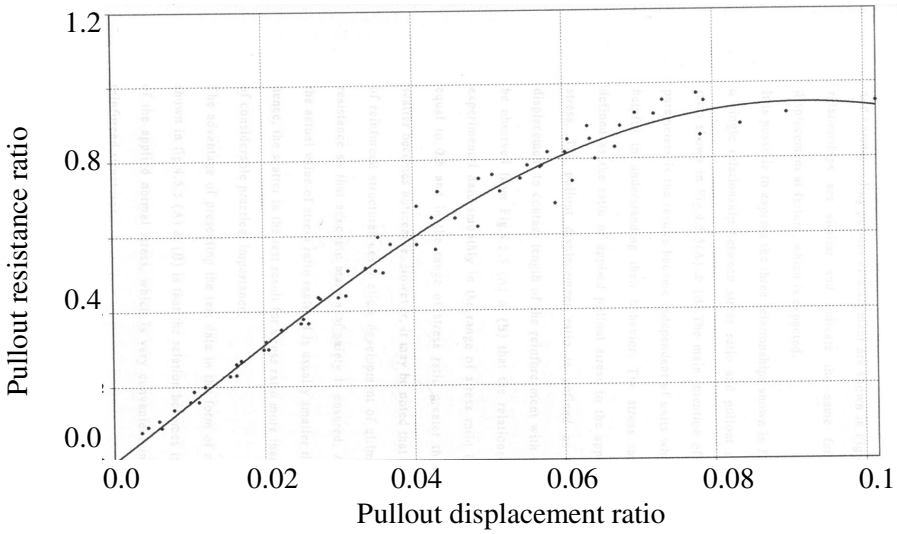
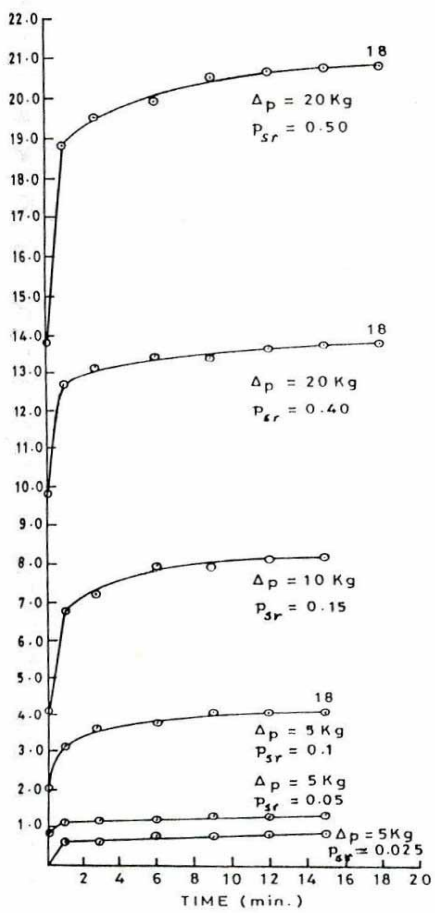


Fig. 5 Variation of pullout resistance in terms of dimensionless parameters



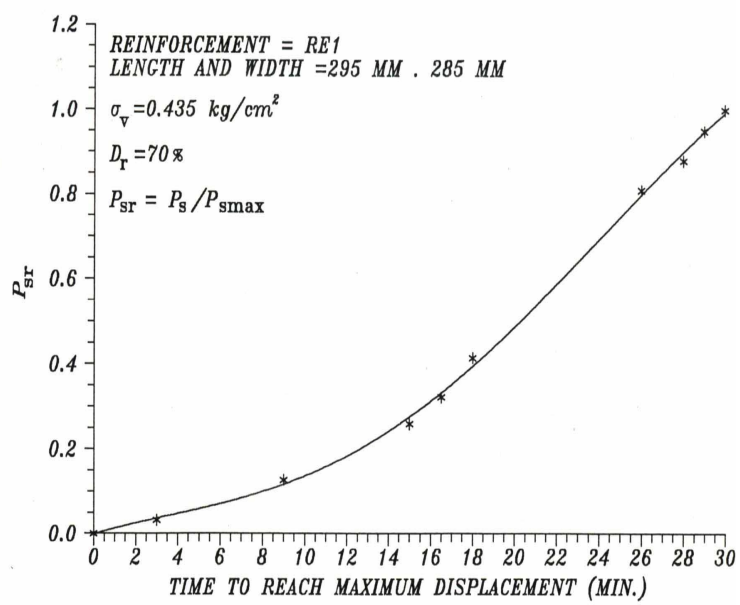


Fig. 6 Influence of time on pullout displacement

Fig. 7 Effect of ratio of pullout force, P_{sr}, on time for reaching maximum pullout displacement, d_p.

Fig. 6 from which it may be observed that with increasing time interval the pullout displacement also increases. However, the rate of increase of pullout displacement with time reduces sharply with increase in time and then ultimately stop. Time duration to realize the maximum pullout displacement increases with increasing Δp and reducing normal stress as well as D_r, which is expected. Ratio $P_{sr,}$ may be defined as (P_s/P_{smax}) where P_s is pullout force under consideration and P_{smax} is the maximum pullout force at failure. For a given Δp, time required to reach maximum displacement is small when P_{sr} is small. As P_{sr} increases, for same Δp time required to reach maximum pullout displacement also increases. Variation of time to reach maximum displacement with P_{sr} is shown in Fig. 7 from which it is clear that the rate of increase in time to reach maximum displacement increases with increasing $P_{sr.}$ This shows that smaller time is required to mobilize the pullout displacements in the linear elastic zone. As the nonlinear behaviour comes into predominance, the time required to reach maximum displacement increases considerably. This is reasonable, because, such movements will require considerable amount of readjustments and movements of soil particles, which take time. Tests performed with strain control apparatus fail to study this phenomenon fully. From above discussion it is clear that pullout resistance obtained from stress controlled apparatus is more accurate than that from strain control apparatus.

Influence of width of geotextile specimen

Test were carried out with specimen widths of 100 mm, 200 mm and 290 mm with σ_v equal to 2.774 t/m^2 and relatively density, D_r = 70 %. Three types of reinforcements were employed. Specimen RE1 was a woven geotextile and specimen RE2 and RE3 were non woven geotextiles. From Fig.8 it may observed that with increasing width of specimen, B_r, the average coefficient of pullout resistance, μ_{avs} (defined as the ratio of τ_p / σ_v), also increases nonlinearly to reach its maximum value at B_r equal to 290 mm.

Theoretical Model for stress distribution for pullout tests

At free edges of reinforcements, the tensile stress within the fabric is zero. As such, this induces no additional confining pressure on adjoining soil to increase its strength due to reinforcing action. However, with increase in distance from free edges, reinforcement gradually develops tensile stresses, which in turn induce higher confinement in adjoining soil due to reinforcing action till the maximum intensity of pullout resistance,τ_{pmax}, is mobilized at the soil-geotextile interface. It may observed from Fig.8 that τ_{pmax} has just about reached at pulling end of reinforcement. Therefore, mobilization of pullout stress, τ_p, along interface may be idealized as a smooth elliptical curve with zero intensity and a vertical tangent at the free edge to maximum intensity and a horizontal tangent at the pulling end (Fig.9).

Intensity of pullout resistance, p_r, per unit width of geotextile may also be assumed to vary elliptically along width of the fabric. Maximum value of p_r given by p_{rmax} is represented by ($L_e\ \tau_{pmax}\ \pi /4$) where the effective length of the fabric L_e is given by ($L_r - d_{pmax}$), L_r being gross length of the fabric measured in the direction of pullout force and d_{pmax} being pullout displacement. If p_{rmax} is assumed to be mobilized through out the width, B_r, of the fabric then the computed value of pullout resistance is larger than the pullout force, P_{smax}, obtained from tests. This is not admissible. At each free end of the width of the fabric the intensity of pullout resistance p_r is zero. Therefore, it is necessary to obtain an appropriate variation of p_r along B_r to obtain maximum pullout resistance p_{rmax}, equal to the maximum applied pullout force p_{smax}.

Steel grip used for gripping fabric is rigid compare to fabric. As such, applied pullout force, p_{smax}, generates a parabolic variation of pullout force, p_s, per unit width of fabric. Maximum value of p_s denoted by p_{smax} occurs at mid width of pulling end of fabric (Fig.10) and given by ($3P_{smax} / 2B_r$). Pullout resistance p_r at any point along B_r should be equal and opposite to intensity of pullout force, p_s. If $p_{rmax}>p_{smax}$, no yielding occurs at fabric-soil interface (Fig.10a). If $p_{smax}>p_{rmax}$, yielding takes place along HG where p_s

predicted by assuming parabolic curve exceeds p_{rmax} (Fig.10 b). Hence, fraction of P_{smax} represented by area OHMG gets transferred to IH and GE where fabric is subjected to $p_s<p_{rmax}$. Linear, parabolic and elliptical variations of p_r (Fig.10 c, d and e) were used. Parabolic curve with a horizontal tangent at R and F on yield width RF is more logical. Linear variation gives rise to sudden change in gradients of p_r at R and F. Yet, it

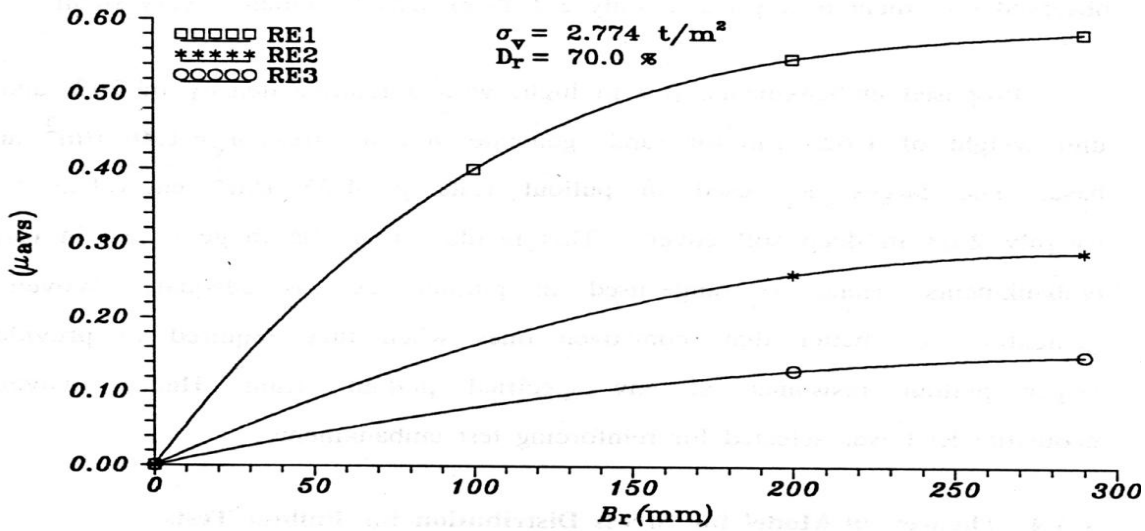


Fig. 8 Variation of average coefficient of pullout resistance, μ_{avs}, with width of reinforcement, B_r

has been used for simplicity. Resistance p_{rmax} has developed along the yield width, B_{ry}, represented by RF. Dimensionless yield width, B_{rd}, may defined as (B_{ry} / B_r). In the field, B_r is large and ($B_r - B_{ry}$) is quite small. From lab tests, B_{ry} may be assessed. Reduction on pullout resistance due to ($B_r - B_{ry}$) may be accounted for by computing effective coefficient of pullout resistance $\mu_{avsfield}$ obtained as (μ_{avs} C_μ) where C_μ is [($B_r - B_{ry}$)/2B_r]. This relationship is useful in estimation of field value of pullout resistance based on lab tests. This leads to an important conclusion that use of many reinforcements of small widths at horizontal intervals is less efficient compared to use of reinforcements of large and continuous widths.

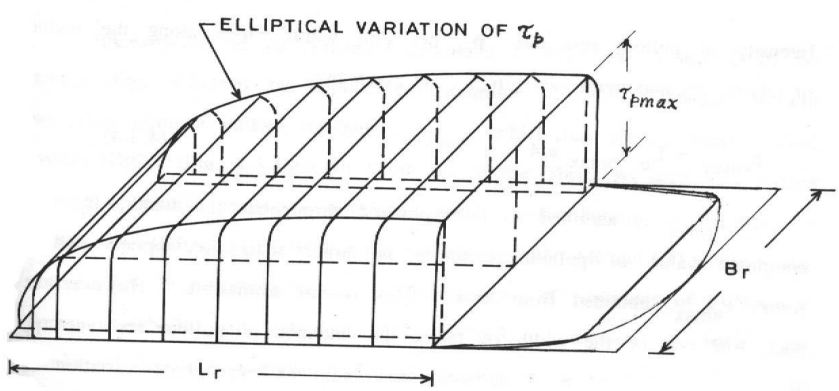


Fig. 9 Idealization of pullout resistance and applied pullout force

Arching action in the test setup

When fabric is pulled out, it creates a void in the soil which causes arching action behind the rear end of the fabric. This has been eliminated by providing extra length of 100 mm or more of the geotextile specimen. As a result void created by pullout displacement of fabric is replaced by the extra length of the

fabric entering in to the soil. The clear gap between the upper and lower halves of the test box is slightly larger than the thickness of the fabric. As a result small grains of sand get pulled out along with the fabric at the pulling end, which also creates voids in the soil near the pulling end. This also gives rise to some arching action, which may be reduced by reducing the difference between the clear gap and the thickness of the fabric. Sprinkling same sand on the textile projecting out behind the test box will result into entry of soil

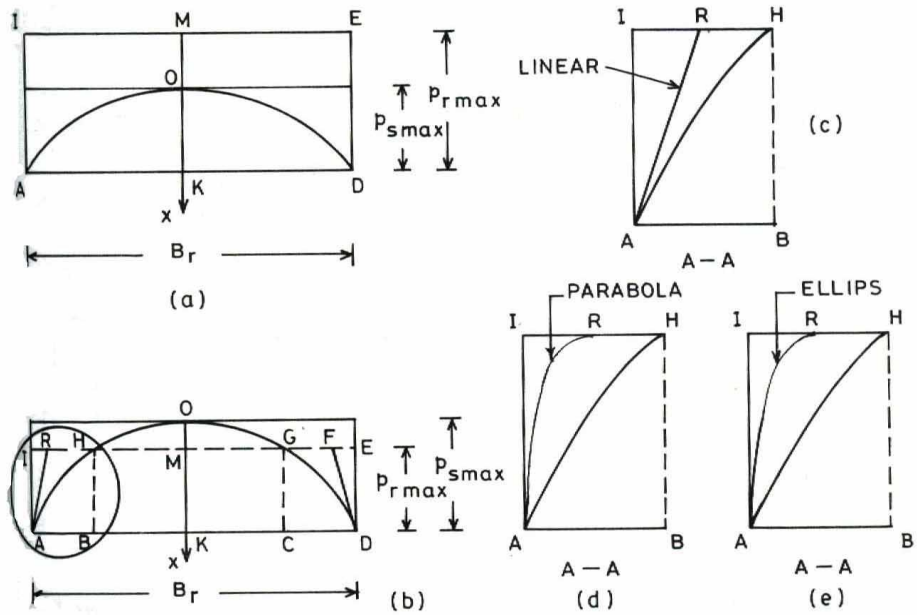


Fig 10 Different idealized variations of pullout resistance after redistribution along width of reinforcement.

into the test box, which may partly compensate the loss of soil due to pulling out of geotextile at the pulling end of box. The effect of the arching action may be further reduced by using a box of longer length or by providing a spout projecting inside the box near the pulling end. Arching action may also depend on the depth of soil above and below the geotextile. This important phenomenon needs to be carefully studied. However, this has not been attempted in development of this setup. A full fledged analytical investigation accounting for arching action has not been carried out in this investigation.

PRESENTATION OF RESULTS FROM DYNAMIC TESTS

Acceleration-time and displacement-time plots obtained from tests have not been presented due to space restriction and also because no significant conclusions are based on these figures in this study. Dynamic pullout tests were carried out with vertical stress, σ_v, of 32.962 kN/m^2 at various frequencies with sustained pullout stress, τ_s, values of 5.333 kN/m^2, 5.897 kN/m2 and 6.461 kN/m^2. Results obtained are shown in **Fig.11**. Total pullout displacement, d_{tpd}, is defined as the sum of static pullout displacement, d_{sp}, and dynamic pullout displacement, d_{dpd}. Due to limitation of the speed control unit discussed earlier, tests could not be conducted precisely at predetermined frequencies even though actual frequencies during tests could be measured accurately. It may be noted that for each τ_s there is a particular pullout displacement, d_{sp}, at zero frequency which is the same as the pullout displacement under static stress equal to τ_s. It may be also observed from this figure that for a given τ_s, d_{tpd} increases with increasing frequency and the rate of increase increases with increasing frequency, f. For a given frequency, the d_{tpd} increases with increasing τ_s. Up to frequency of 5 Hz, the curves are almost linear and relatively flat with relatively small d_{tpd}

comparable to d_{sp}. This indicates that low frequencies are not very effective in causing large dynamic pullout displacements. This is in agreement with observations of Mehdi (1998), i.e., dynamic pullout resistance obtained by back analysis of experimentally obtained results for a reinforced earth test embankment is substantially smaller than the ultimate static pullout resistance provided resonance is avoided.

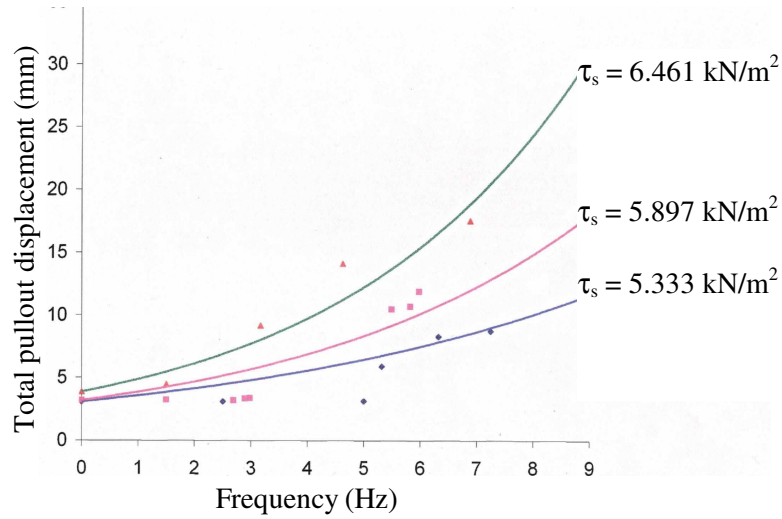


Fig. 11 Variation of total pullout displacement with frequency for σ_v = 32.962 kN/m^2

Frequencies larger than 5 Hz during tests are more severe for given single amplitude of displacement, d_{tb}, of test box. This is reasonable, because, d_{tb} of 3.73 mm remains the same for all tests. As a result higher frequencies generates higher accelerations, higher inertia forces (constituting larger dynamic pullout force) and hence, larger total pullout displacements, d_{tpd}.

For sustained pullout stress of 5.897 kN/m^2, results for σ_v of 27.987 kN/m^2, 32.962 kN/m^2 and 37.936 kN/m^2 shown in **Fig.12** indicate that as σ_v increases total pullout displacements, d_{tpd}, decreases at any frequency and rate of increase in d_{tpd} increases with increasing frequency, which is expected as acceleration and hence dynamic pullout stress increases in proportion to square of frequency. For low σ_v and for a given sustained pullout force, pullout displacement is larger in view of the associated low mobilization of reinforcing action. Hence, reinforced earth is not very advantageous at shallow depth below top end of earth-fill where σ_v is low. If its use is a must at allow depths, it is better to provide a continuous geotextile connecting facing elements on both faces of embankment or connect geotextile to a suitable anchor behind the sloping surface. Disturbing earth forces and moments will be resisted by tension in reinforcements to help stability of embankment. Observations cited earlier for effect of frequencies larger than 5 Hz based on Fig. 11 may be made from Fig. 12 also. Earlier observations dealing with influence of frequencies less than 5 Hz resulting into lower reinforcing action based on Fig. 11 may also be made from Fig. 12.

Fig. 11 may be discussed using displacement dependent pullout resistance useful in earthquake engineering. For failure defined at 5 mm pullout displacement for σ_v of 32.962 kN/m^2, displacement amplitude of box of 3.73 mm and for sustained pullout stress of 6. 461 kN/m^2 allowable frequency is 1Hz only. Such data from Fig.11, is shown in Fig.13 in which total pullout displacement vs. sustained pullout stress are given at various frequencies. It is clear from the figure that higher frequencies lead to larger pullout displacement.

Another interpretation of above data is in terms of mobilized angle, $\phi_{mp,}$, of pullout resistance for a given total pullout displacement. In each loading cycle, dynamic pullout force gets added or subtracted to the sustained pullout force. Hence, $\phi_{mp,}$ fluctuates in each cycle. As such, it is prudent to consider mean force,

i.e., sustained pullout force for this purpose. Figure 14 is prepared using this information for a total pullout displacement of 5 mm and σ_v of 32.962 kN/m^2. It is clear from this figure that ϕ_{mp} ranges from 7.25^0 to10.5^0 which is very low compared to angle of shearing resistance, ϕ_s, of 42^0 for soil from direct shear stress. Similar plots may be developed for different values of failure pullout displacements. Obviously, if

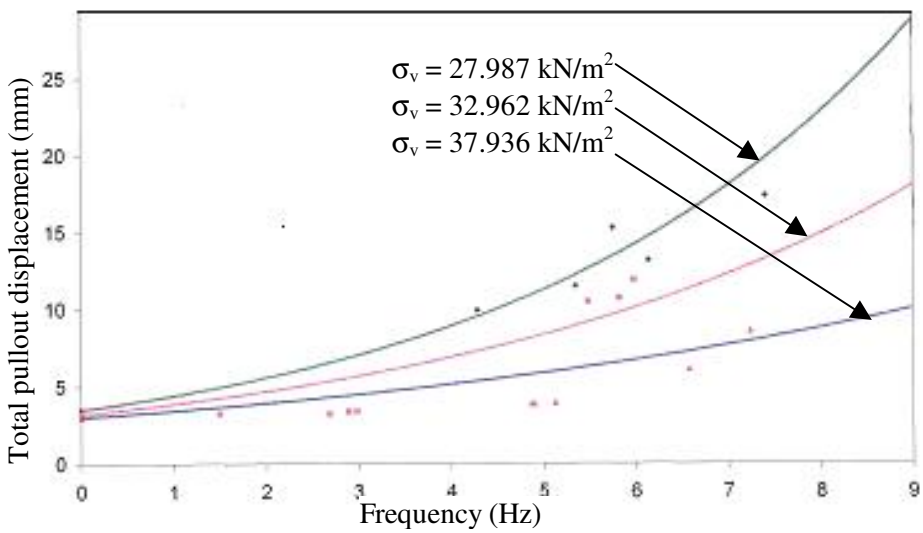


Fig. 12 Variation of total pullout displacement with frequency for τ_s = 5.897 kN/m^2

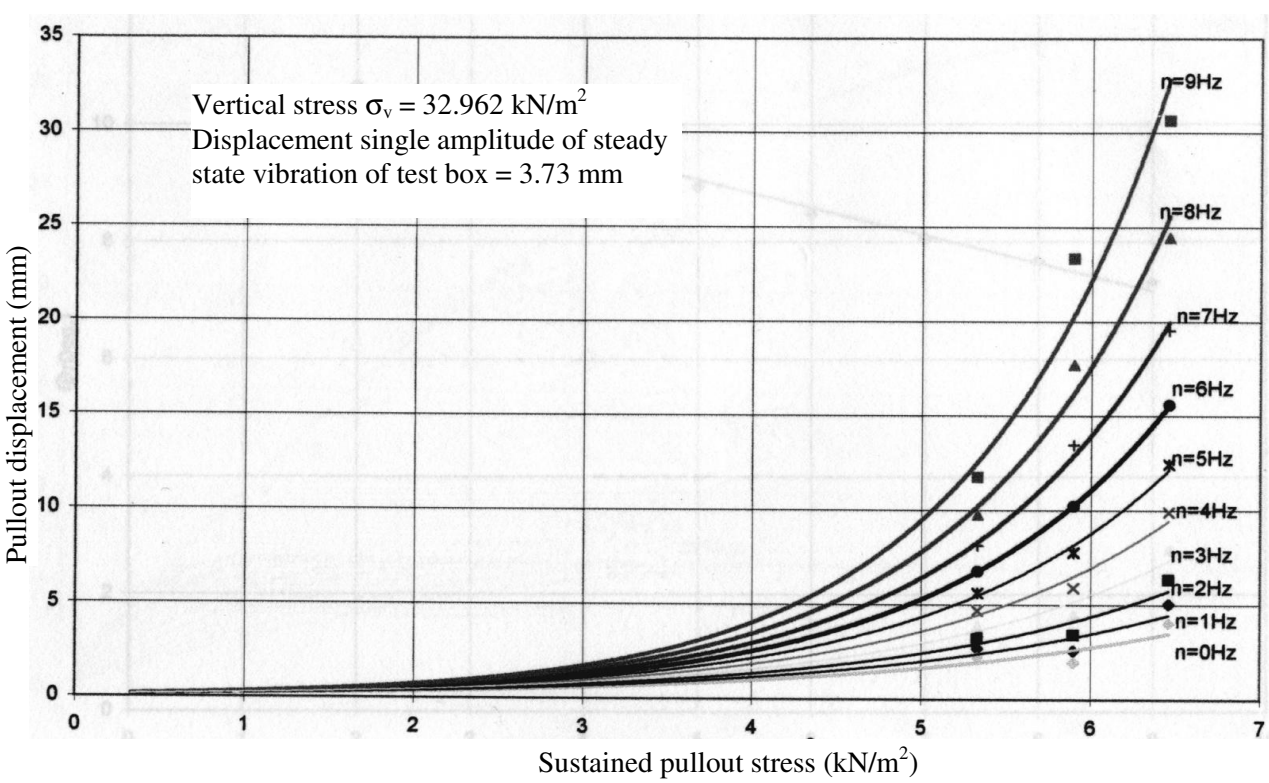


Fig. 13 Relationship between pullout displacement and sustained pullout stress for different frequencies.

failure pullout displacements of the order of 15mm to 20mm are specified, corresponding angles of ϕ_{mp} will be larger than those cited in Fig.14. Nevertheless, it is worth noting that the angles of mobilized pullout forces are expected to be much smaller compared to the angle of shearing resistance of the soil obtained from static shear tests. As such, reinforced earth is more advantageous when large pullout displacements are allowable. Concept of displacement dependent static and dynamic pullout resistance is important in design of reinforced earth structures, particularly under earthquake loading conditions.

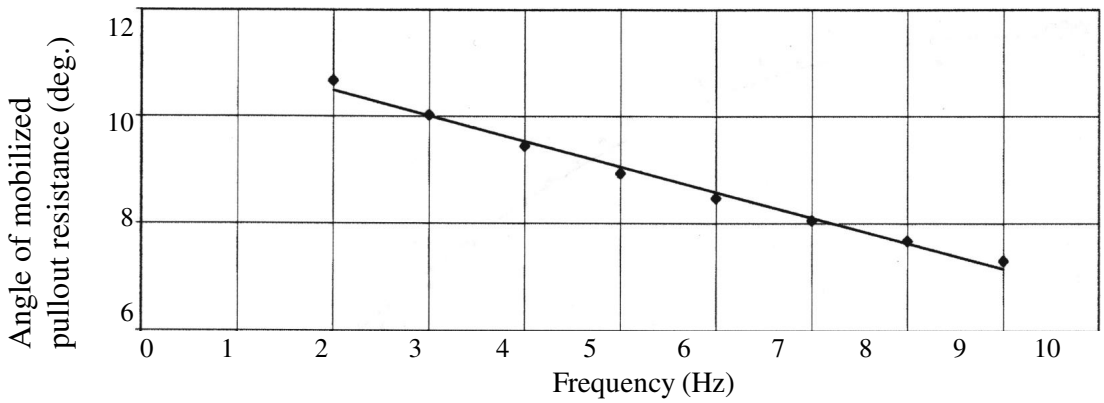


Fig. 14 Variation of angle of mobilized pullout resistance with frequency for 5 mm pullout displacement

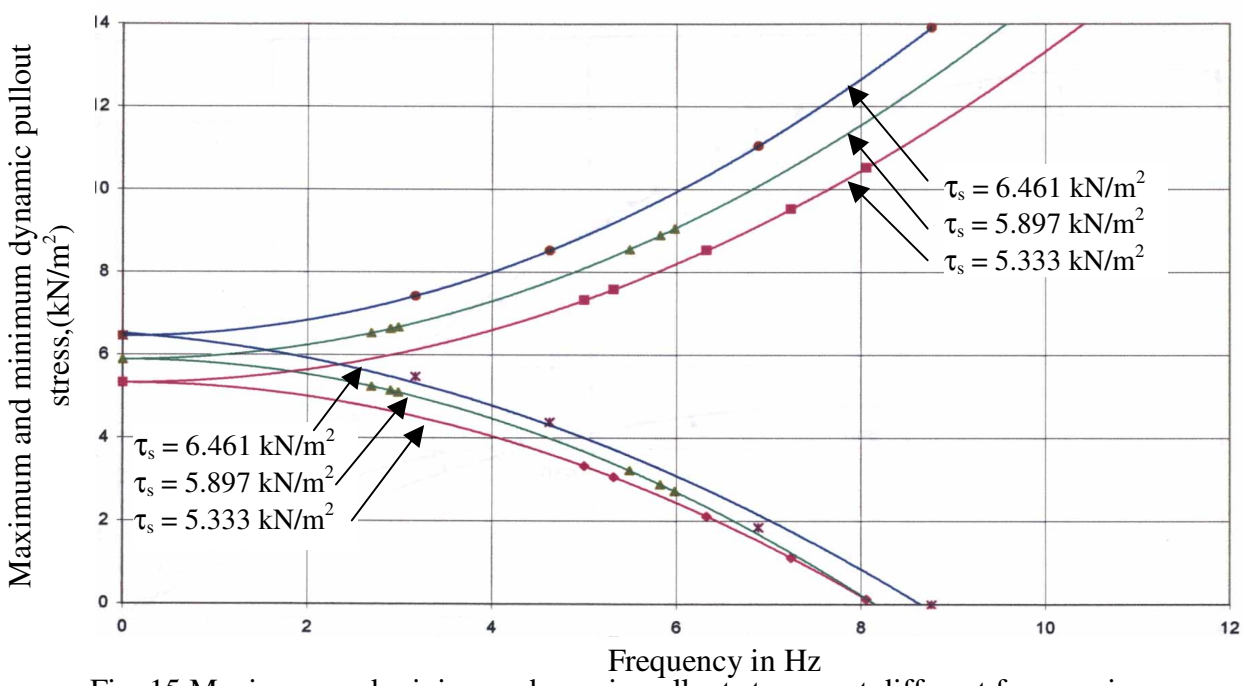


Fig. 15 Maximum and minimum dynamic pullout stresses at different frequencies.

Limiting values of dynamic pullout forces relative to the sustained pullout forces

In tests to obtain dynamic pullout force, sum of sustained and dynamic pullout forces are transferred to geotextile as tension in flexible wire. However, wire can only take tension and not compressive forces.

When dynamic pullout force is larger than sustained pullout force, compressive push-in forces are required to be transferred to geotextile, which is impossible. In fact, some minimum tension will have to be maintained for successful testing. As such, dynamic pullout force should not exceed sustained pullout force. In Fig.15, the maximum and minimum dynamic pullout forces generated for the testing conditions specified for the results cited in Fig.11 are shown. The lowest values of minimum pullout stress are cited as zero though there is no upper bound limit for the maximum pullout stress. The maximum value will be limited by the tensile strength of the string used in the set up.

CLOSURE

Pullout resistance of geotextiles is an important design parameter if tensile failures of geotextiles are to be avoided in design of reinforced earth structures. Results obtained from strain control apparatus for determination of pullout resistance of geotextiles tend to over-estimate it, which is unsafe and should be avoided. Stress control apparatus is superior in this regard. In this presentation, a stress control apparatus developed in the Department of Earthquake Engineering, Indian Institute of Technology, Roorkee India for determination of static and dynamic pullout resistance has been described. Results of parametric experimental studies have also been discussed. The ability of this equipment to give displacement dependent static and dynamic pullout resistance is a great advantage in geotechnical earthquake engineering.

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ABSTRACT

Since tensile failures of geotextiles cause catastrophic failures, they should be designed fail under pullout stress. Static and dynamic pullout resistances are important design parameters and overestimated by strain control apparatus available in the stste of the art. This is unsafe. A stress control apparatus developed in I.I.T., Roorkee India to obtain the parameters and results of experimental studies have been presented. The apparatus works satisfactorily. Reinforced earth is advantageous when pullout strains are large. Dynamic pullout resistance is smaller than static pullout resistance. Such evaluation of displacement dependent static and dynamic pullout resistance is useful in earthquake resistant design of reinforced earth structures.