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Soil-Reinforcement Interactions Under Laboratory Pullout Tests Using Geosynthetics and Wire Meshes

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Abstract

It is evident that soil-reinforcement interactions have a significant effect on the overall performance of reinforced soil structures. A series of pullout tests under variable normal stresses have been carried out in order to find out the suitability and effectiveness of reinforcements in reinforced soil structures. In this paper, an investigation of soil-reinforcement interactions under laboratory pullout tests for geosynthetics (Fortrac and Nylon) and woven square wire meshes (3mm and 14mm opening) is presented. Stress-displacement relationships, volumetric changes and the soil-reinforcement interaction behavior of reinforced soil in terms of cohesion and internal friction have been given in various charts and diagrams as a ready reference to aid for practical design and constructions. It is concluded that, in general, the pullout stress of geosynthetics reinforcement is larger than that of the wire meshes and the rate of increase of the pullout stress of Fortrac reinforcement is the highest among the types of reinforcements tested in this research work. For all types of reinforcements, there is a common feature that vertical displacement takes place just after the occurrence of horizontal displacement and then some scatters in the vertical displacement are observed with the increase in horizontal displacement.

Key words: soil-reinforcement, interactions, pullout test, geosynthetics, wire meshes, laboratory experiment.

Introduction

As compared to conventional soil structures, reinforced earth is a relatively newer construction material used extensively in the civil and geotechnical engineering works. Soil reinforcement is one of the essential techniques to fortify earth structures such as slopes, embankments, dams, foundations & retaining walls[1-2]. It is well known that one of the major factors that control the performance of reinforced soil structures is the interaction between the soil and the reinforcement. Interaction mechanism has a primary importance in the use of reinforcements in view of their ease of availability and application suitability to the design of reinforced earth structures. Pullout behavior is one of the essential characteristics in soil-reinforcement interaction with geosynthetic and wire mesh reinforcements. However, the test apparatus, testing procedure, the evaluation method of the test results, reinforcement types and the interaction mechanism have not been established yet. It is desired to study of the behavior of geosynthetics and wire meshes as the

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soil reinforcement materials under pullout tests owing to their availability in the local market, cost effectiveness and their wide-spread use all over the world for soil reinforcement applications.

To date, many researchers have investigated the behavior of soil reinforcement frictional characteristics. Among them, Richards and Scott, 1985[3], Lafleur, J. et.at., 1987[4], Williams and Houlihan, 1987[5], Miyamori et al., 1988[6], Lawers, D. C. 1991[7] and Murata, O. et al., 1992[8], have studied the geotextiles/cohesionless soil interfaces and adopted a suitable test method to simulate field conditions. Some researches on geosynhetics-cohesive soil were carried out by Forie and Fabian, 1987[9], Lawers, 1991 and Mitachi, T. et al. 1992[10].

In addition to that, the shear strength of geotextile-peat interfaces was investigated by Jarret and Bathurst, 1985[11], Garbulewski and Laskowska, J. 1988[12].

There is a very few research on the use of wire meshes as earth reinforcement in the literature in spite of their great concern for reinforced earth structures. Examples of research involving deformation characteristics of hexagonal wire mesh reinforcement can be found in the works of Voottipruex, P. et al. 1998[13].

The behavior and pullout strength of geosymthetics (Fortrac, Nylon) and steel wire meshes that present considerable versatility in the development of reinforced soil structures have not received any treatment as yet, except for the incomplete research works that can be found by Burd and Brocklehurst[14], in 1990 and subsequently in 1992 on the use of finite element method for friction shear characteristics in soil-geosynthetic friction test. By drawing analogy with geosynthetics in conventional reinforced soil structures, one may argue that such reinforcements will behave in a manner similar to Fortrac, Nylon and Steel Wire Meshes. However, this needs to be substantiated by evidence requiring experimentation as well as analytical modeling, if necessary. The present research program has been taken up to fulfill these basic needs. Pullout tests are carried out using sandy soil of Mie prefecture with two types of geosynthetics (Fortrac, Nylon) and two types of woven square wire meshes (3 mm and 14 mm opening). Results of these tests are depicted to understand thoroughly of the stress-displacement relationships, volumetric changes and soil-reinforcement interaction resistance of reinforced soil such as cohesion and internal friction. Results are presented in various charts and diagrams that would help in selection of suitable material as the earth reinforcement as well as contribute to the effective design of reinforced earth structures. Design equations for ultimate pullout strength considering several types of reinforcements are also presented in this paper.

Materials and Methods

Soil properties

The particle size distribution curve given in Fig. 1 revealed that nearly 9 % of the soil is coarse clay, 7 % is fine silt, 6 % is coarse silt, 14% is fine sand, 44% is medium sand and more than 20% is coarse sand which mean that more than 90 percent of the soil being in the silt and sand fraction as can be seen from Fig. 1. Liquid limit, plastic limit and the plasticity index of the soil are 56.2%, 29.3% 26.9% respectively. The average specific gravity of the soil is calculated as 2.644. The shear behavior of the soil is shown in Fig. 2 and Fig. 3. The other properties of the soil used in these tests are given in Table 1.

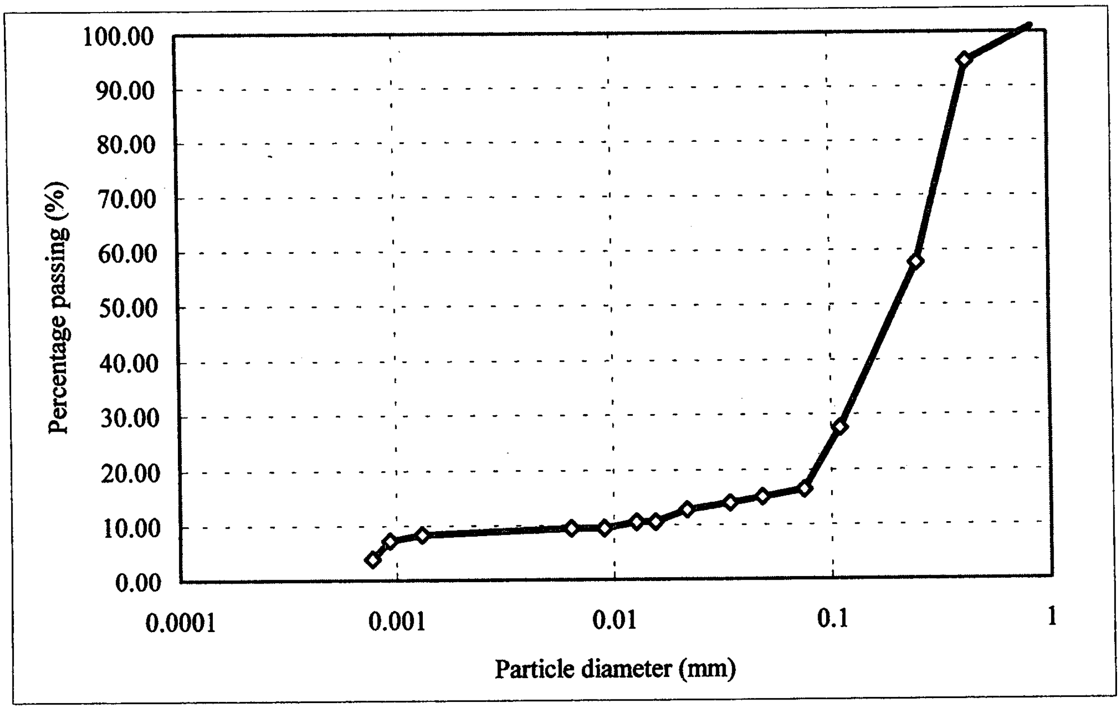

Fig. 1 Particle size distribution curve of the soil used in pullout test

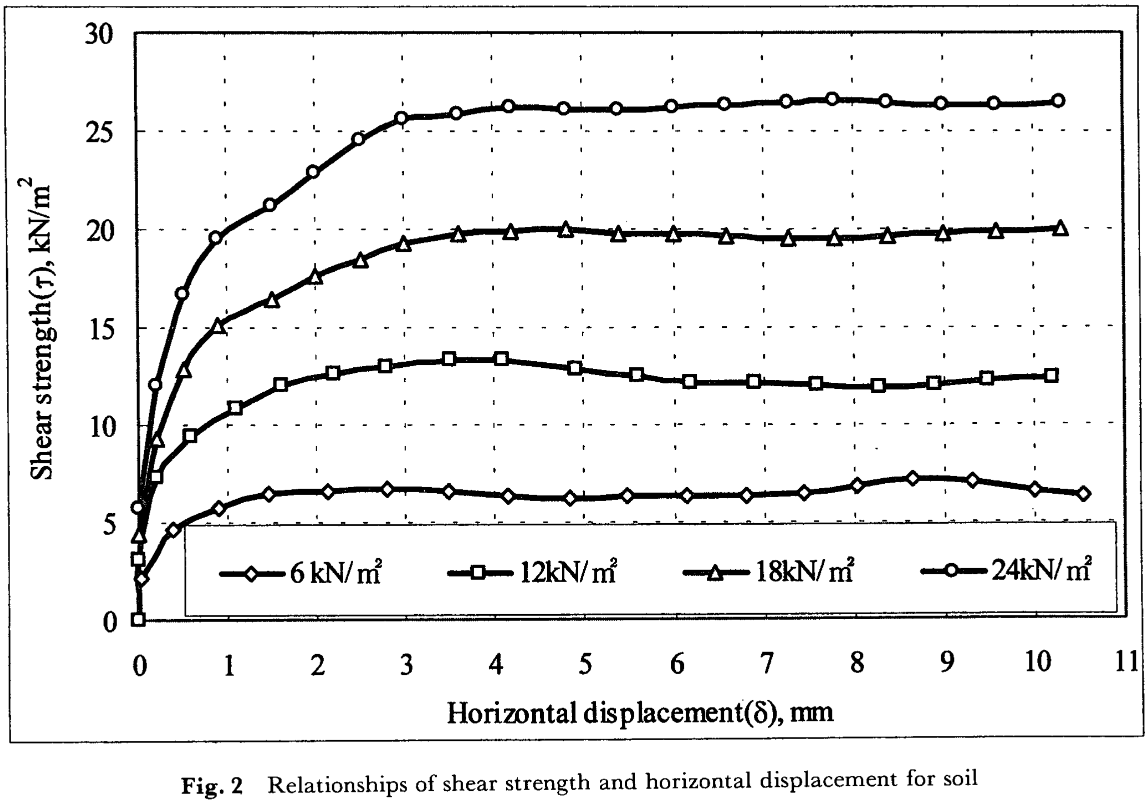

Fig. 2 Relationships of shear strength and horizontal displacement for soil

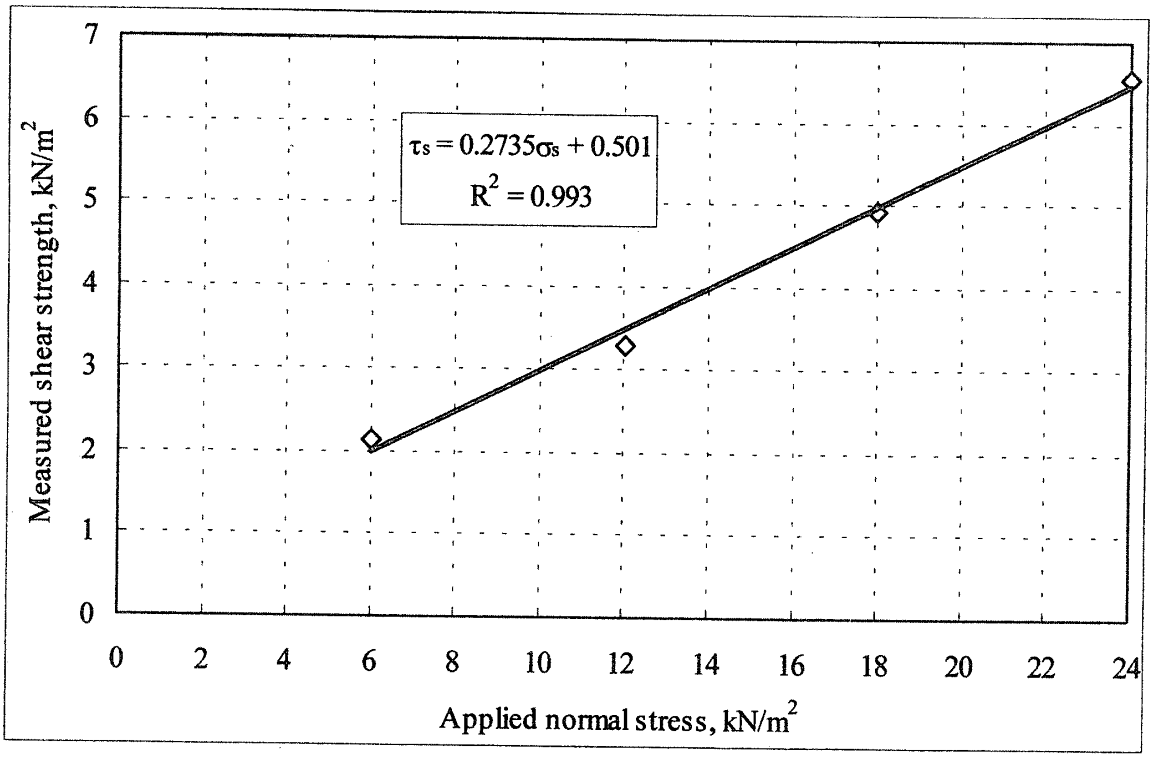

Fig. 3 Relationship of measured shear strength and applied normal stress for soil

Table 1 Soil properties

Unit weight of the soil (γ_d), t/m^3	1.83
Optimum water content (OWC), (%)	15.3
Specific gravity of the soil (ρ_s)	2.64
Cohesion (C), kN/m^2	5.01
Angle of internal friction (ϕ), (°)	32.19
Aggregates content	
Sand, >75 μm (%)	78
Silt, 5-75 μm (%)	13
Clay, <5 μm (%)	9

Reinforcement properties

The physical appearance of the geosynthetics and wire meshes obtained from commercially is shown in Fig. 4. The Fortrac mesh as shown in Fig. 4a is manufactured from polyester yarns. The junctions of this mesh are directly connected and greatly improved by interweaving the yarns and then it is coated with protective sheathing. The strength of the junctions is adequate to transmit the envisaged loadings. The cross -section of geogrid strands is 2mm × 6mm in longitudinal direction and filament diameter of 1.0mm in transverse direction with center to center openings of 24mm in longitudinal direction and 20mm in transverse direction. The Nylon mesh is given in Fig. 4b. The filament of this mesh is circular in cross section. This mesh is made by weaving the filament with each other and the junctions are not sheathed nor connected. The diameter of the filament is 0.5mm and the center to center opening is 2mm in both directions. The small grid wire mesh and the large grid steel wire mesh are depicted in Fig. 4c and Fig. 4d,

Table 2 Detailed description of the reinforcing materials.

Reinforcements name and identification			C/C opening (mm) Longitudinal direction	C/C opening (mm) Transverse direction	Grid cross-section/Wire dia. (mm)
Geosynthetics	Fortrac geogrid	Type I	24	20	Lomgitudinal-2mm×6mm Transverse-dia.1.0
	Nylon mesh	Type II	2	2	0.5
Wire mesh	Woven square mesh (Smaller size)	Type III	3	3	0.8
	Woven square mesh (larger size)	Type IV	14	14	1.2

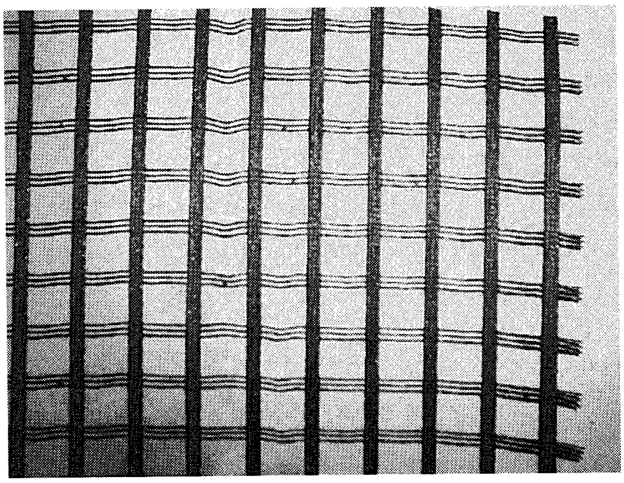

Fig. 4a Fortrac mesh (Type I)

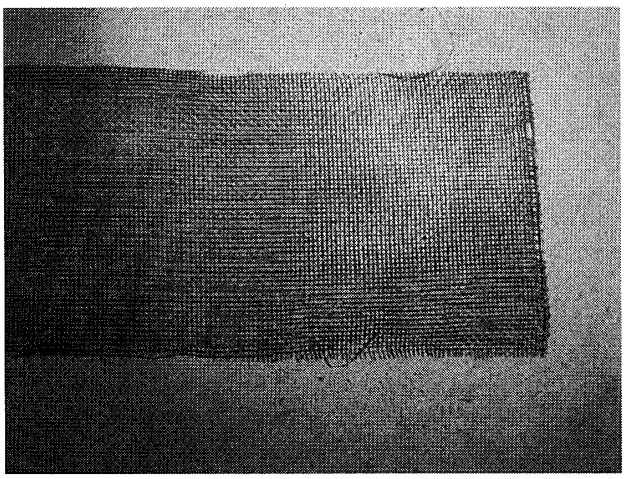

Fig. 4b Nylon mesh (Type II)

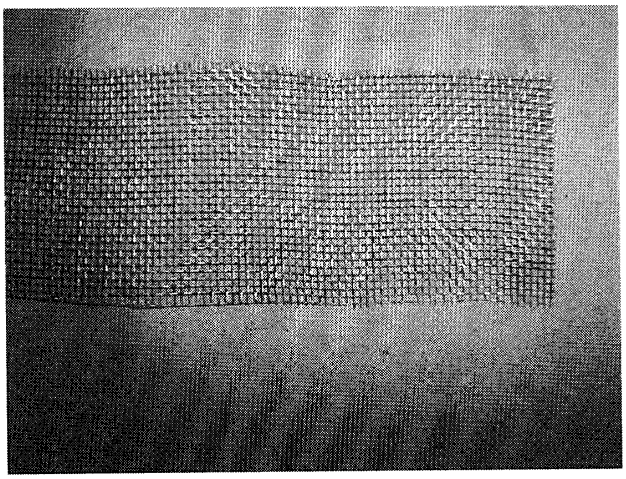

Fig. 4c Small grid steel wire mesh (Type III)

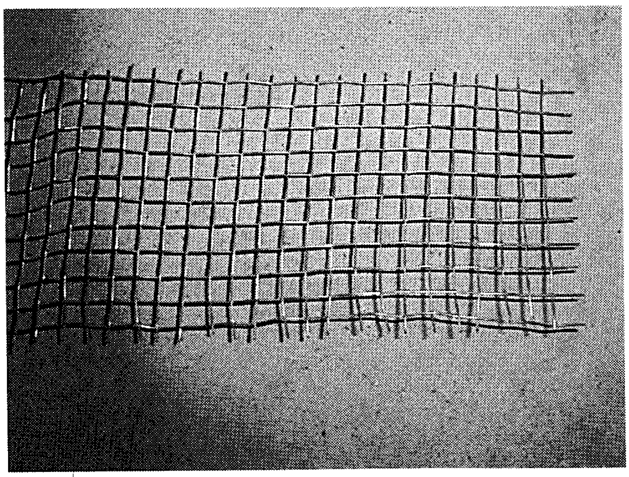

Fig. 4d Large grid steel wire mesh (Type IV)

Fig. 4 Physical appearance of geosynthetics and woven square wire meshes respectively. Alike to the Nylon mesh, the wire strands are weaved each other to form both types of mesh and they are not welded at the junctions. Therefore, the junctions are not adequate enough to bear the stresses. The wires of both the steel meshes are circular in cross section having diameter 0.8mm and 1.2mm for small and large grid meshes, respectively. Other properties and specifications of the meshes are shown in Table 2.

Reinforcement identification code

In view of convenience, the reinforcements described above are identified in the following way as given in Table 2. For example, the geosymthetics such as Fortrac and Nylon meshes are assigned as Type I and Type II, respectively and woven square steel wire meshes such as smaller grid and larger grid meshes are encoded as Type III and Type IV, respectively.

Test apparatus

The apparatus used in this study is shown in Fig. 5 which is capable of performing both pullout and direct shear tests. For convenience of the readers, the important components of the testing equipment are numbered numerically starting from top-left to right-down in the increasing way such as, the number from [1] to [10] where the number [1] is the pullout stress monitoring display, [2] is the supporting plate of reaction of the applied normal stress, [3] is the horizontal displacement measuring dial gauge, [4] is the pullout stress measuring device, [5] is the reinforcement clamping jack, [6] is the upper part of the pullout box, [7] is the electrically operated pullout jack, [8] is the lower part of the pullout box, [9] is the vertical displacement measuring dial gauge and [10] is the applied normal stress measuring dial gauge.

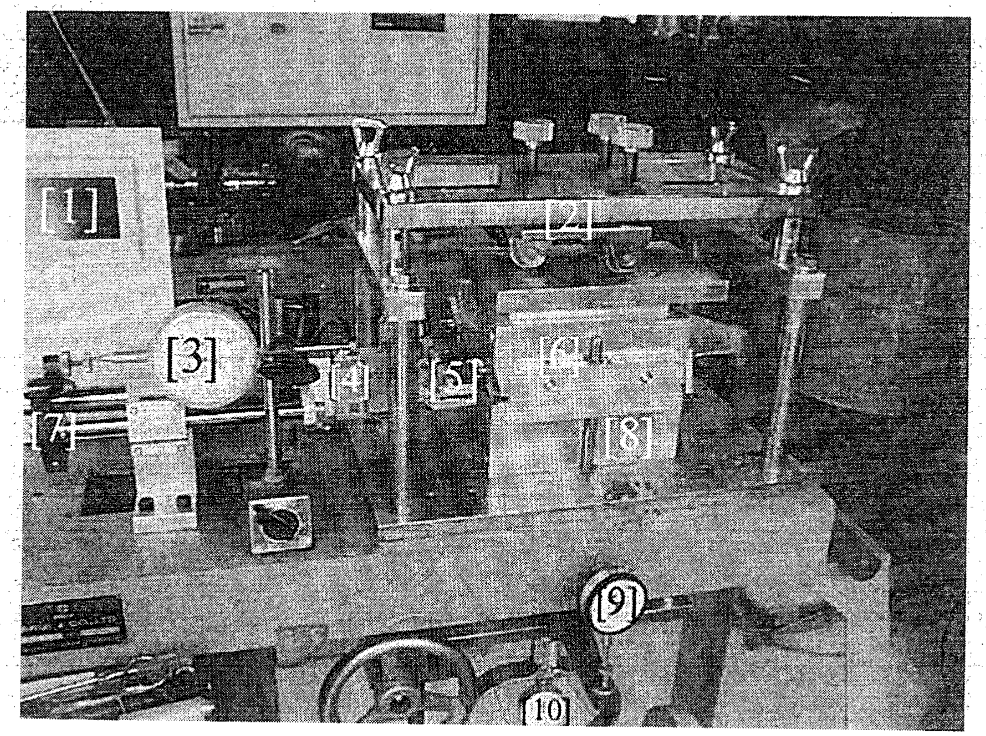

Fig. 5 Pullout and shear test apparatus of Soil-geosynthetics interaction

Some important features incorporated in the testing equipment are the monitoring of soil dilatancy and the testing arrangement wherein the clamping system for pullout test is located outside the compacted soil to ease of clamping the reinforcement. The pullout box is a rectangular shape of size 150mm in length, 100mm in width and 100mm in height. The box is divided into two parts namely lower box (50mm in depth) and upper box (50mm in depth). The apparatus is designed in such a way that the upper box can be separated from the lower box to ease in pouring the soil into the lower box as well as mesh setting and clamping. The lower half box is fixed while the upper half box can be moved relative to the lower box during shear testing. The friction between the upper box and the reinforcements is eliminated with the help of the vertical screw has been set at both sides of the upper part. The vertical pressure in the lower half box applied through the lower jack is balanced by the opposite stresses of the upper box. The stresses into the soil are uniformly distributed by adjusting the screw of the top box. The bottom and top boxes are set in such a way that there is no friction between the box wall and the reinforcements. For the pullout test, the upper part is set to the lower parts with clamping screw. It can be freed while running the direct shear test. The upper box can then be pushed relative to the lower box. As for the instrumentations, the pullout/direct shear force can be measured by means of an electrical loading cell. Front displacements, vertical displacements, and the displacements along the reinforcement (for pullout test only) can be monitored using dial gages.

The width of the reinforcements was the same as that of the pullout box (inner sides). Pullout tests of several kinds of reinforcements are performed. Among these only four types of mesh those are usually used, low priced and easily available in the local market are presented herein. Two of these are grouped under geosynthetics and the remaining two are woven square steel wire meshes. The detailed specifications of these reinforcements are given in Table 2. The physical appearances of geosynthetics and woven square steel wire meshes are shown in Fig. 4.

Testing procedure

The geosynthetics and wire meshes were cut to obtain rectangular pieces of 200mm by 100mm in size. The specified length of the pieces was selected in order to facilitate clamping with the pullout apparatus. The meshes were clamped in the box in such a way that the embedded length of the mesh is 150mm in the loading direction and 100mm in the transverse direction. Water was added gradually to the soil and mixed up to obtain desired water content uniformly throughout the soil and then it was poured into the bottom box. After embedding the reinforcements (geosynthetics/mesh) on the soil poured in the lower part of the box, the upper part was fastened to the lower part and then additional soil was filled in the top box. The tests were carried out in the way of pulling out the mesh from the soil with constant speed of 1mm/min by means of screw jack under electrically operated constant pressure. The pullout force was measured using a tension load cell with least count of 5N. The load cell was set between the mesh and jack to facilitate direct load measurement on the cell avoiding any frictional discrepancy on the machine components. The displacements were measured at the front of the mesh by means of a dial gage with least count of 0.001mm. All the tests were carried out under normal stresses of five stages from 6 kN/m^2 to 36 kN/m^2 such as 6 kN/m^2, 12 kN/m^2, 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2. After each test, the reinforcement piece was removed and replaced with another one to account for the damages in the reinforcement's texture that might have occurred as a result of previous test. The dilatancies were measured at the lower side of vertical load jack by means of a dial gage with least count of 0.001mm.

The soil was compacted in three layers for all the tests and thus obtained the same density of the soil for all soil-reinforcement interaction. For all tests, the water content of the soils were 14.63%, 14.29%, 14.36% and 14.56% for reinforcements Type I, II, III and IV, respectively where the optimum water content of the soil was measured as 15.3%. This was being done in order to carry out experiment in the dry side of optimum and closer to the optimum water content because of the ease of handling the material as well obtaining maximum compaction of the soil which may be expected during field construction works.

Results and discussion

Pullout stress-displacement relationships

The relationships between the pulling stress and the displacement of geosynthetic (Fortrac, Type I) under normal stress of 6 kN/m^2, 12 kN/m^2, 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2 for sandy soil with water content of 14.63% are given in Fig. 6. It can be seen from this figure that the pullout stress is increasing linearly with the increase in displacement in the amount of about 12mm. After that the pullout stress increases nonlinearly with the increase in displacement of about 16mm. The pullout stress fluctuates with displacements exceeding 16mm and continued in the same fashion of up to 50mm. This may be due to the variation of stress distribution along the reinforcement in the loading direction. Because of the rectangular cross section of the Fortrac reinforcement, there might be accumulation of some soil in the front side of the filament section which gives an increase in the soil pressure and after accumulation of certain amount of soil i.e. while the accumulation exceeds the limit to cause failure, the pullout stress becomes decrease by slippage of the soil particles. As expected, for all the test results, the pullout resistance is more for higher normal stress. It is noted here that almost all the stress-displacement curves became horizontal or changed their upward trends to downward directions at pullout displacement of 15mm i.e. at 10% strain for most of the cases indicating the ultimate pullout strengths of the stress-displacement curves. Therefore, the pullout displacement in the amount of 15mm is considered as the key distance of calculating the ultimate pullout strengths by taking account of the maximum cases reported in this paper. The ultimate pullout strengths for Fortrac reinforcements were calculated as 14.4 kN/m^2, 12.4 kN/m^2, 26.6 kN/m^2, 30.8 kN/m^2, 36.6 kN/m^2 and 58.4 kN/m^2 for normal stress 6 kN/m^2, 12 kN/m^2, 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2, respectively.

Fig. 7 indicates a typical stress-displacement relationship for geosynthetics (Nylon, Type II) reinforcement having center to center opening 2mm and wire diameter 0.5mm under pullout tests. The water content of the test soil was 14.29%. All the six graphs belong to the same characteristic curves like to flat parabolic shape and can be taken in a group with the linear portion restricted to the displacement of about 2mm. After that all the curves becomes non-linear. The non-linear range at the lower limit starts with displacement of nearly 2mm and then continues downswing until the displacement of 5mm. Unlike the curves of Fortrac (Type I) of Fig. 6, all the graphs of Nylon (Type II) reinforcements are almost smooth shape owing to the effect of small grid of the mesh as well as the effect of small diameter of strands. Also, there might be some effects of the circular cross-section of the filaments. Smaller grids of mesh, circular cross-section and smaller diameter of strands allowed it to pullout out smoothly without accumulation of soil in it. The ultimate pullout strengths for Nylon reinforcement are recorded as 17.6 kN/m^2, 28.4 kN/m^2, 27.7 kN/m^2, 36.2 kN/m^2, 44.4 kN/m^2 and 41.1 kN/m^2 corresponding to normal stress of 6 kN/m^2, 12 kN/m^2, 18

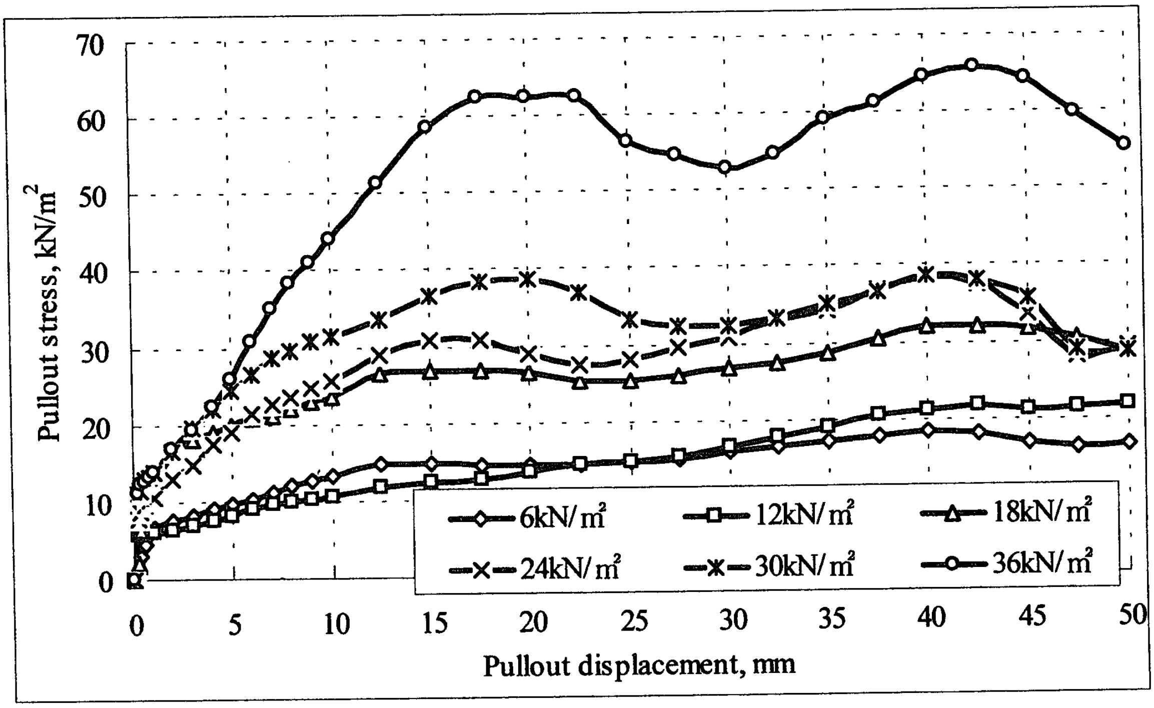

Fig 6 Pullout stress-displacement curve, Type I (Fortrac) reinforcement, Sandy soil with 14.63% water content.

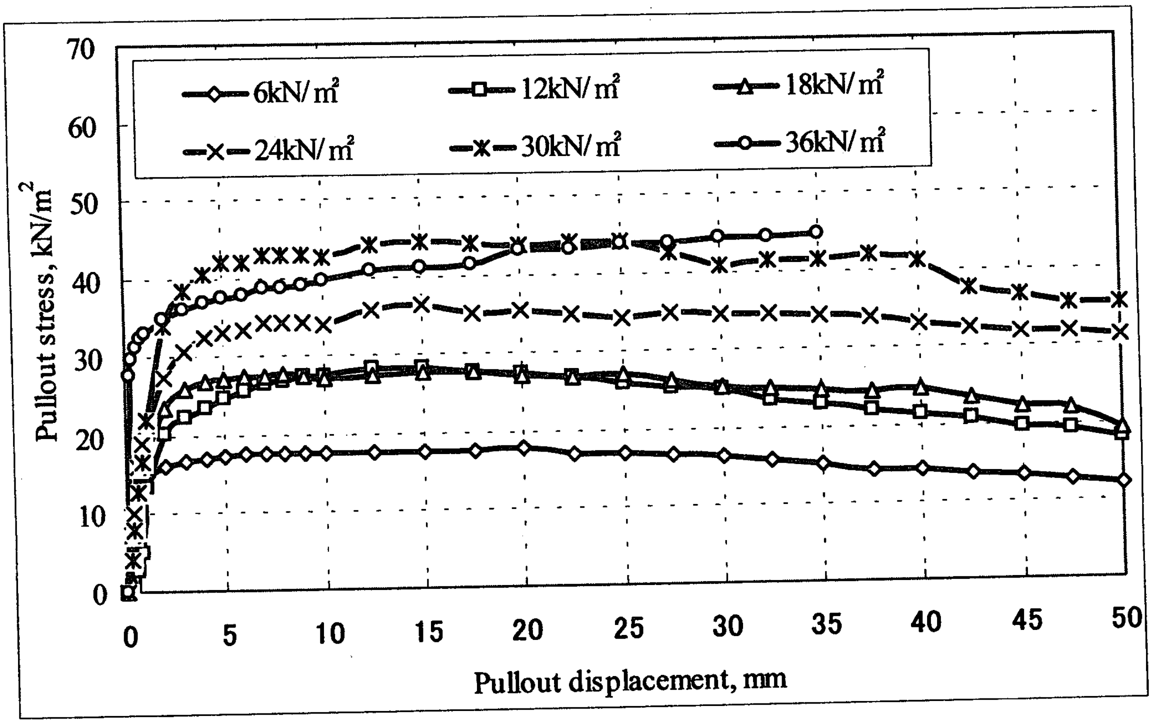

Fig. 7 Pullout stress-displacement curve, Type II (Nylon) reinforcement, Sandy soil with 14.29% water content.

kN/m², 24 kN/m², 30 kN/m² and 36 kN/m², respectively.

The stress-displacement relationships of woven square steel mesh of 3mm opening and 0.8mm diameter under pullout stress with six normal loading conditions for sandy soil with water content of 14.36% are depicted in Fig. 8. An inspection of the plotted results of the stress-displacement relationships indicates that they are, in general, apparently bi-linear characteristics. However, a resemblance of linearity is seen for smaller part of the relationships between 0.0mm to 1.5mm displacement. A greater part of linearity can be taken from 5mm to 50mm displacement. It is also found from this figure that there is a slight upswing of the pullout stress with the increase in displacement. This phenomenon mainly depends on the mesh shape, grid size and wire diameter. Alike to the Nylon mesh, wire of the Type Ⅲ mesh is circular in cross section but slightly larger in diameter and grid size which allows a little more accumulation of soil with the increase in displacement and thus gives slightly upward trends of the stress-displacement curves as compared to Type Ⅱ mesh. As in the previous cases, the ultimate strength varies apparently; it has values of 17.5 kN/m², 23.8 kN/m², 22.5 kN/m² , 27.3 kN/m², 31.1 kN/m² and 37 kN/m² for the six normal applied stresses.

Fig. 9 depicts the stress-displacement relationships of pullout tests for woven square steel mesh reinforcement of 14mm opening and wire diameter 1.2mm with sandy soil with 14.56% water content. It can be observed from this figure that the applied pullout stress increases proportionately with the increase in displacement of about 3mm. It is clearly evident from this figure that the pullout stresses are getting downswing or become horizontal depending of the normal stress condition. With the lower overburden pressure such as 6 kN/m² and 12 kN/m², the pullout stress-displacement curves showed its horizontal trends whereas it is downswing gradually with the increase in displacement for higher overburden pressure such as for 18 kN/m², 24 kN/m², 30 kN/m² and 36 kN/m². Obviously, this discrepancy depends on the larger grid

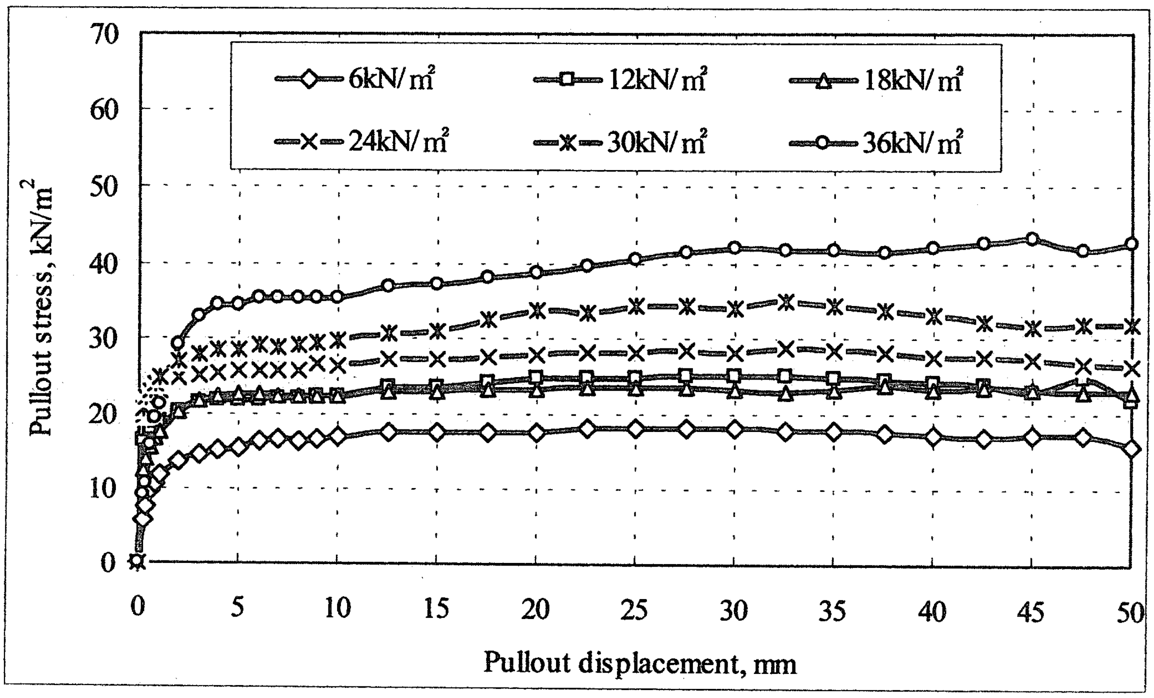

Fig. 8 Pullout stress-displacement curve, Type Ⅲ (Woven square mesh, 3mm) reinforcement, Sandy soil with 14.36% water content.

size of mesh as well as mesh texture and wire diameter. Unlike to Type Ⅱ and Type Ⅲ mesh, larger grid and larger wire diameter for Type Ⅳ mesh allows more soil particles in front of the wires which create more resistance under higher overburden pressure during pulling out of the mesh. Owing to the woven nature of the mesh, the transverse wires of the mesh are getting to slip after a certain amount of pressure on it causing the decreasing trends of the stress-displacement curves at higher normal stress. On the other hand, for the lower normal stress, there is not enough pressure to cause the slippage of the transverse wire strands. As in the previous cases, the ultimate pullout stresses were found as 9 kN/m^2, 19.8 kN/m^2, 31.6 kN/m^2, 29.6 kN/m^2, 34.9 kN/m^2 and 34.3 kN/m^2 corresponding to the normal stresses of 6 kN/m^2, 12 kN/m^2, 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2, respectively.

It could be found that the pullout stress with Type Ⅰ reinforcement fluctuates (upswing and downswing) until the end of the horizontal displacement whereas it is almost smooth for the other cases. For the cases of Type Ⅱ and Type Ⅳ, the pullout stress decreases gradually after its peak value until the end of horizontal displacement while all the curves become almost parallel to the x-axis for the case of Type Ⅲ. These features may be due to the combined effect of the reinforcement texture and the reinforcement stiffness. The parallel lines for Type Ⅲ mesh indicates no slippage of soil particles and transverse wires, and no enlargement of the mesh filament even at the higher displacement stage whereas the downswing of the Type Ⅱ and Type Ⅲ meshes indicates the extension and slippage of the mesh filaments, respectively.

Dilatancy behavior

The relationships between the horizontal displacement and vertical displacement of pullout test containing geosynthetic (Fortrac, Type Ⅰ) reinforcements under normal stresses of 6 kN/m^2, 12 kN/m^2, 18

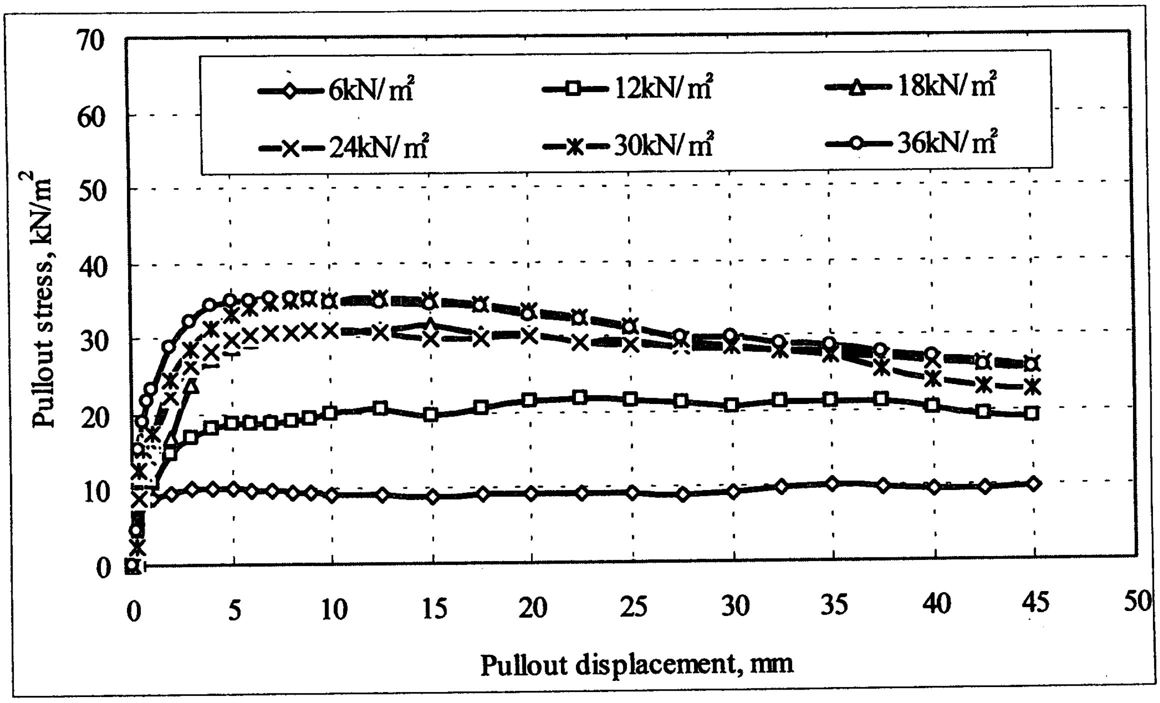

Fig. 9 Pullout stress-displacement curve, Type Ⅳ (Woven square mesh, 14mm) reinforcement, Sandy soil with 14.56% water content.

kN/m², 24 kN/m², 30 kN/m² and 36 kN/m² for sandy soil with water content of 14.63% are given in Fig. 10. The vertical displacement increases nonlinearly with the increase in horizontal displacement of about 5mm under higher overburden pressure. With lower overburden pressure such as 6 kN/m² and 12 kN/m², there is no vertical displacement till end of the whole horizontal displacement. Vertical displacement gets maximum value with the horizontal displacement of amount 7-10mm and vertical displacement becomes parallel to the x-axis when the horizontal displacement beyond 10mm. As expected, the vertical displacement is more for higher normal stresses. In relation with the same factor as of the stress-displacement relationships and in compatibility with it, the maximum vertical displacements were taken at the horizontal displacement of 15mm similar to that of the stress-displacement condition. The maximum vertical displacement are recorded as 0.12mm, 0.10mm, 0.21mm and 0.635mm corresponding to the normal stresses 18 kN/m², 24 kN/m², 30 kN/m² and 36 kN/m², respectively.

Fig. 11 indicates vertical displacement versus horizontal displacement relationships for geosynthetics (Nylon, Type II) reinforcement with center to center opening 2mm and wire diameter 0.5mm under pullout stresses. The water content of the test soil was 14.29%. It is evident from this figure that vertical displacement is almost zero for normal stress of 6 kN/m² whereas negative values are found for normal stress of 12 kN/m². The vertical displacement increases nonlinearly for normal stresses of 18 kN/m² − 36 kN/m² with the increase in horizontal displacement and this increment continued until the horizontal displacement of about 22mm. The rate of increase of the vertical displacement is more at the higher horizontal displacement. Unlike to Fortrac reinforcement, vertical displacement for Nylon reinforcement gets maximum value at the end of the horizontal displacement. As expected, the vertical displacement is more for higher normal stresses. The maximum vertical displacement are found to be 0.11mm, 0.20mm, 0.135mm

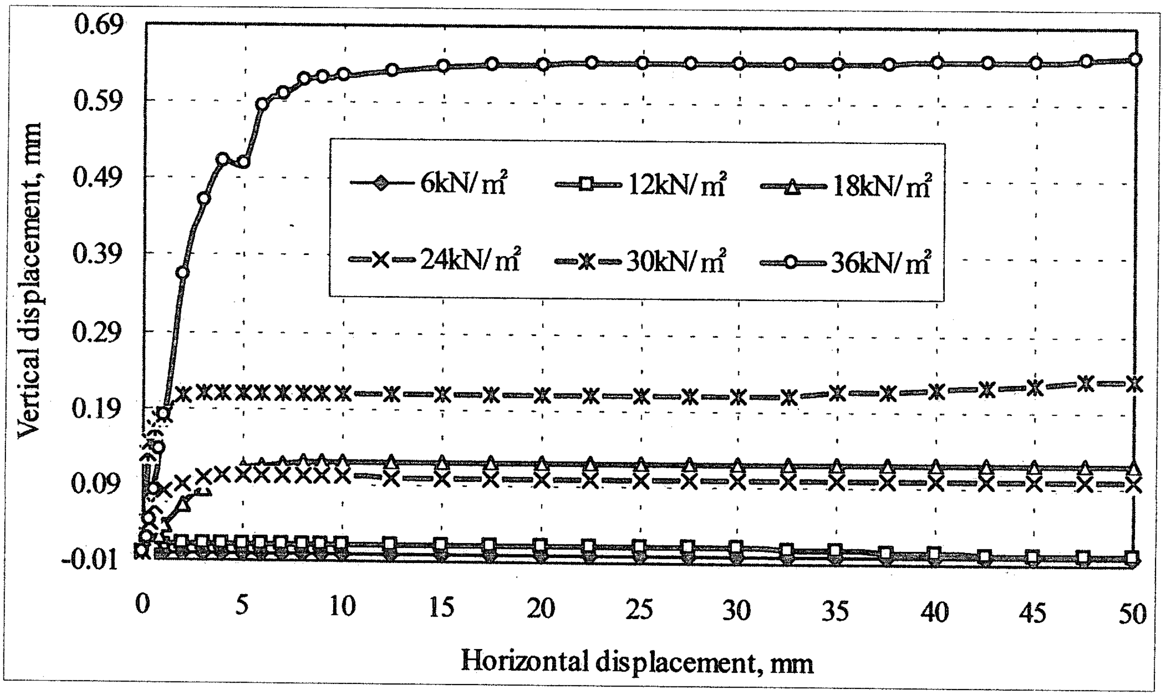

Fig. 10 Dilatancy behavior of pullout test, Type I (Fortrac) reinforcement, Sandy soil with 14.63% water content.

and 0.24 mm corresponding to the normal stresses 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2, respectively.

The dilatancy behavior in the form of vertical displacement and horizontal displacement of pullout test with Type III (Woven square mesh, 3mm) reinforcement in sandy soil of water content 14.36% is plotted in Fig. 12. Alike the dilatancy behavior of geosynthetics given in the previous figures (Fig. 10 and Fig. 11), the change of the vertical displacement for 3mm square mesh started at the beginning of the horizontal displacement. Negative vertical displacement can be seen for normal stress of 6 kN/m^2 and the decreasing trend continues gradually till the horizontal displacement of nearly 23mm and then becomes parallel to the x-axis. No dilatancy was found for 12 kN/m^2 normal stress. In case of 18 kN/m^2, 24 kN/m^2 and 30 kN/m^2 normal stress, a sudden increase of vertical displacement was observed within 2 mm of horizontal displacement. The rate of increase of the vertical displacement for 36 kN/m^2 normal stress is smaller than that of the middle ranges normal stresses (18 kN/m^2, 24 kN/m^2 and 30 kN/m^2). These characteristics are in variant in the case of geosynthetic reinforcement. However, a similarity among the geosynthetic and wire mesh reinforcement can be seen that the higher vertical displacements are attained at the higher horizontal displacement. The maximum vertical displacements are found as 0.212mm, 0.31mm, 0.30mm, and 0.39 mm respectively for normal loading condition of 18-36 kN/m^2.

Fig. 13 depicts the relationships between vertical displacements and horizontal displacements of the pullout tests for woven square mesh reinforcement of 14mm opening and wire diameter 1.2mm with sandy soil of 14.56% water content. Slightly negative vertical displacement can be observed for the case of 6 kN/m^2 normal stress only in Type IV reinforcement. There is very small amount of vertical displacement for normal stress of 12 kN/m^2, 18 kN/m^2 and 24 kN/m^2. The vertical displacement for normal stress of 30 kN/

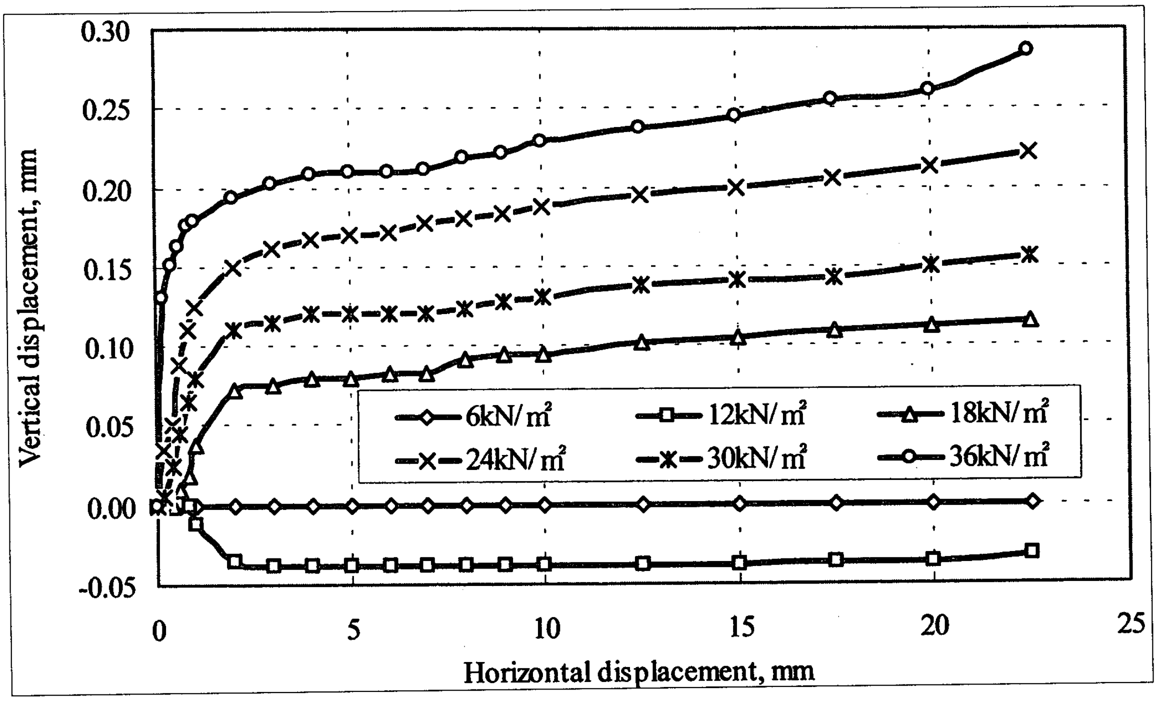

Fig. 11 Dilatancy behavior of pullout test, Type II (Nylon, 2mm) reinforcement, Sandy soil with 14.29% water content.

m² and 36 kN/m² increases stiffly with the increase in horizontal displacement ranging from 4mm to 10mm and resumes its upswing trend until the horizontal displacement of amount nearly 45mm. Both the curves assume the same pattern and these characteristics can be attributable in the previous two cases (Type II and

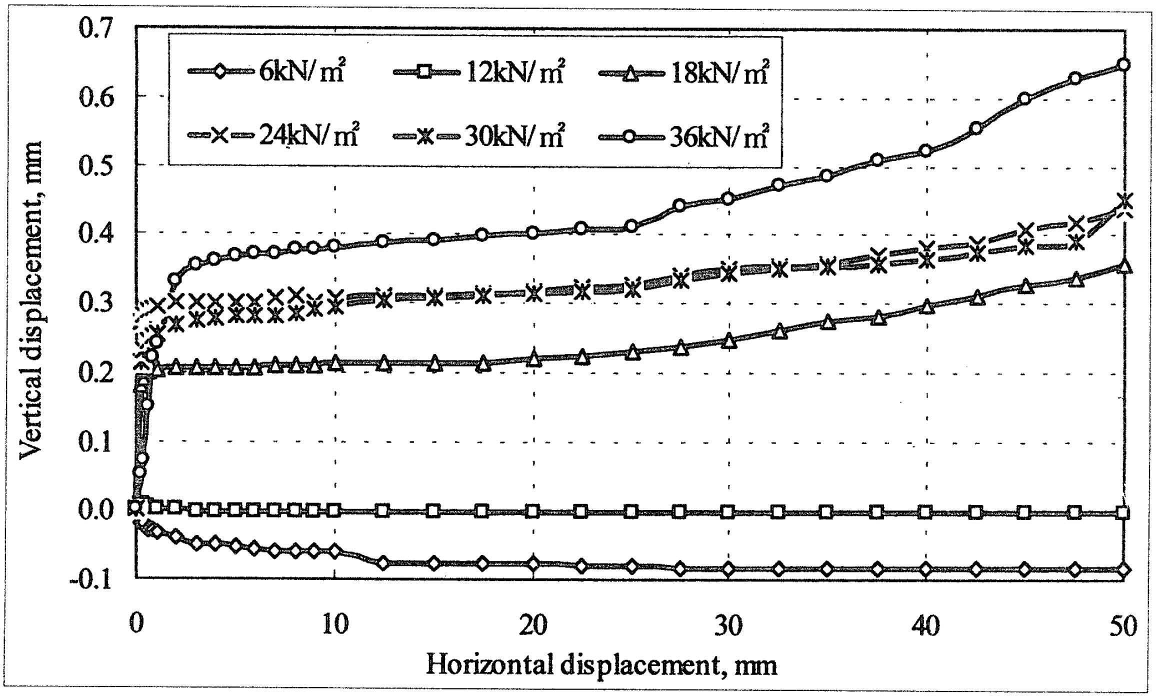

Fig. 12 Dilatancy behavior of pullout test, Type III (Woven square mesh, 3mm) reinforcement, Sandy soil with 14.36% water content.

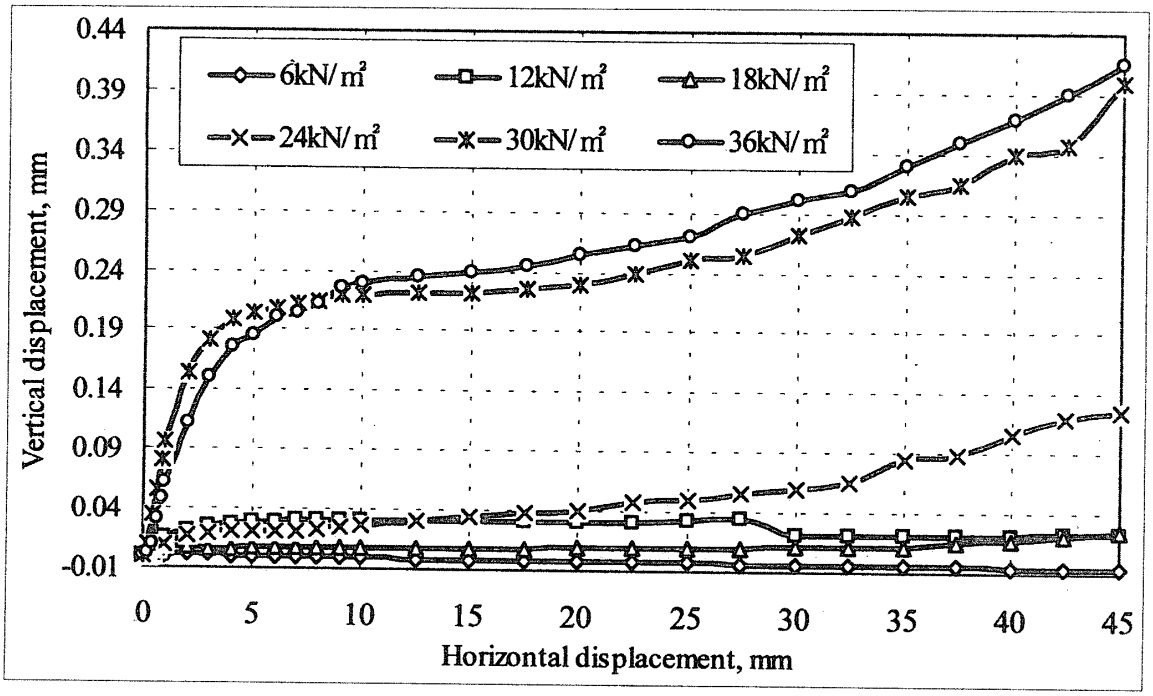

Fig. 13 Dilatancy behavior of pullout test, Type IV (Woven square mesh, 14mm) reinforcement, Sandy soil with 14.56% water content.

III) except Type I. The maximum vertical displacements were calculated as 0.034mm, 0.008mm, 0.031mm, 0.22mm and 0.24mm for the normal stresses of 12 kN/m^2, 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2, respectively.

In order to obtain a clear comparison among the volumetric changes under pullout tests, maximum vertical displacements corresponding to normal stresses of different types of reinforcements are given in Fig. 14. In general, there are some scatters of the volumetric changes under pullout test with various types of reinforcements. The negative value indicates the increase in volume whereas the positive values are for decrease in volume. Very few cases have negative vertical displacements means that increase in volume occurred for few cases especially in the lower normal stresses such as 6 kN/m^2 and 12 kN/m^2 containing Type II and Type III reinforcement. The decrease in volume under lower normal stress with smaller grid reinforcements mainly depends on the disturbance of soil layers at the interfaces of reinforcement. Because of the smaller grid of reinforcement, the soil particles became more precisely intermixed with the reinforcement resulted comparatively more disturbances of the soil layer during pullout tests under lower normal stresses. On the other hand, most of the test results have positive vertical displacement as well as decrease in volume of soil of the pullout test under higher normal stresses with any type of reinforcement. This is thought to be due to the fact that as the normal stress increase, the additional pressure is applied to the soil-reinforcement interface and thereby, the soil particles re-intermixed with the surface particles of the fabric. Also, there are some effects of compression of the soil itself by draining out the water and air as well as by rearrangement of the soil particles with higher normal loads.

Ultimate pullout strength

For the sake of clear perception of the bearing capacity of reinforced soil under pullout test, the ultimate

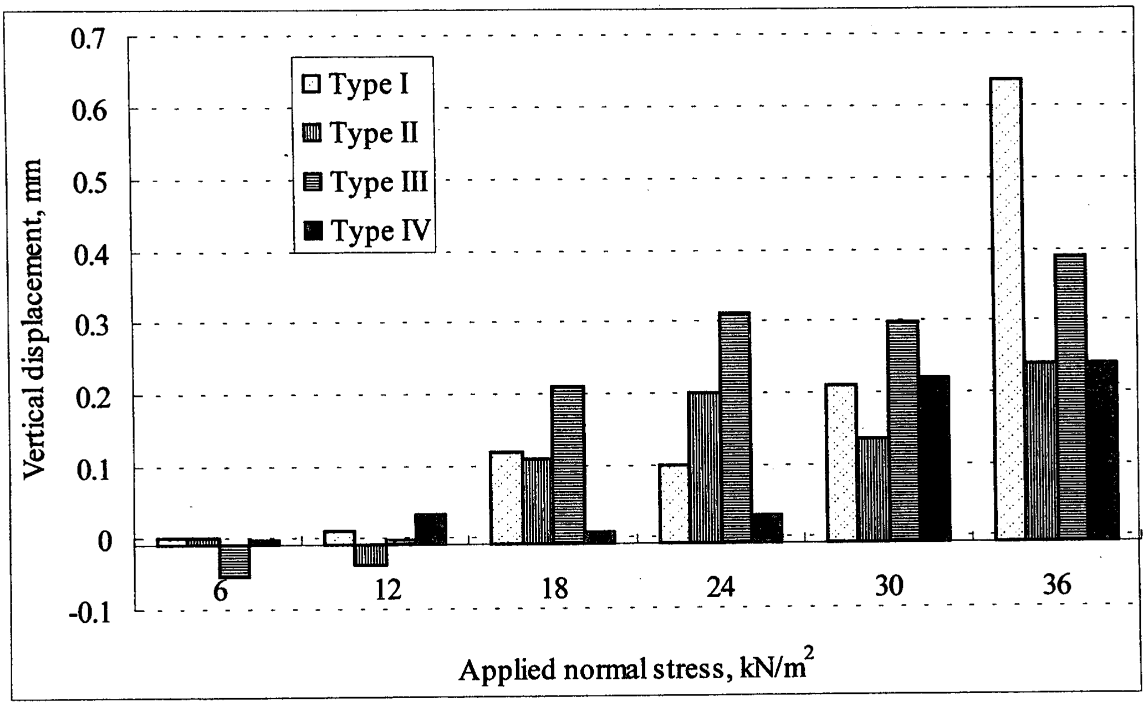

Fig. 14 Comparison of volumetric changes of pullout tests with four types of reinforcements

pullout strength corresponding to the different overburden pressures (normal stresses) of the reinforced soil with geosynthetics (Type I and Type II) and woven square wire meshes (Type III and Type IV) are plotted as the bar diagram in Fig. 15. It is evident that the ultimate pullout strengths are increasing with the increase in overburden pressure on soil containing any type of reinforcements such as Fortrac, Nylon, small and large sized wire meshes. Both the geosynthetics (Fortrac and Nylon) showed more stress bearing capacity under pullout test than that of the wire meshes of any type. This may be the effect of surface roughness of the geosynthetics strands as well as surface smoothness of the steel wires. The surfaces of steel wires are comparatively smoother than that of the geosynthetics which facilitate relatively lower resistance at the soil-reinforcement interfaces. The ultimate pullout strengths of Type II reinforcement with normal stress 6 kN/m^2, 12 kN/m^2, 18 kN/m^2, 24 kN/m^2 and 30 kN/m^2 are more than that of the Type I reinforcement where as it is less with normal stress of 36 kN/m^2. In the same way, the ultimate pullout strengths of Type III reinforcement with normal stress 18 kN/m^2, 24 kN/m^2 and 30 kN/m^2 are more than that of the Type IV reinforcement where as it is less with normal stress of 6 kN/m^2, 12 kN/m^2 and 36 kN/m^2.

Regression analysis

For more clarification of ultimate strengths among the four types of meshes reported in this paper, least square linear regression lines of the ultimate pullout strengths corresponding to applied normal stress are depicted in Fig. 16. This figure indicates the applied normal stress as the controlled variable as given in abscissa and pullout ultimate strengths as the random variable as given in the ordinate. As it can be observed from this figure that the rate of increase of the ultimate pullout strength for Type I reinforcement is more than that of the other types (Type II, III and IV) with the increase in overburden pressure i.e.

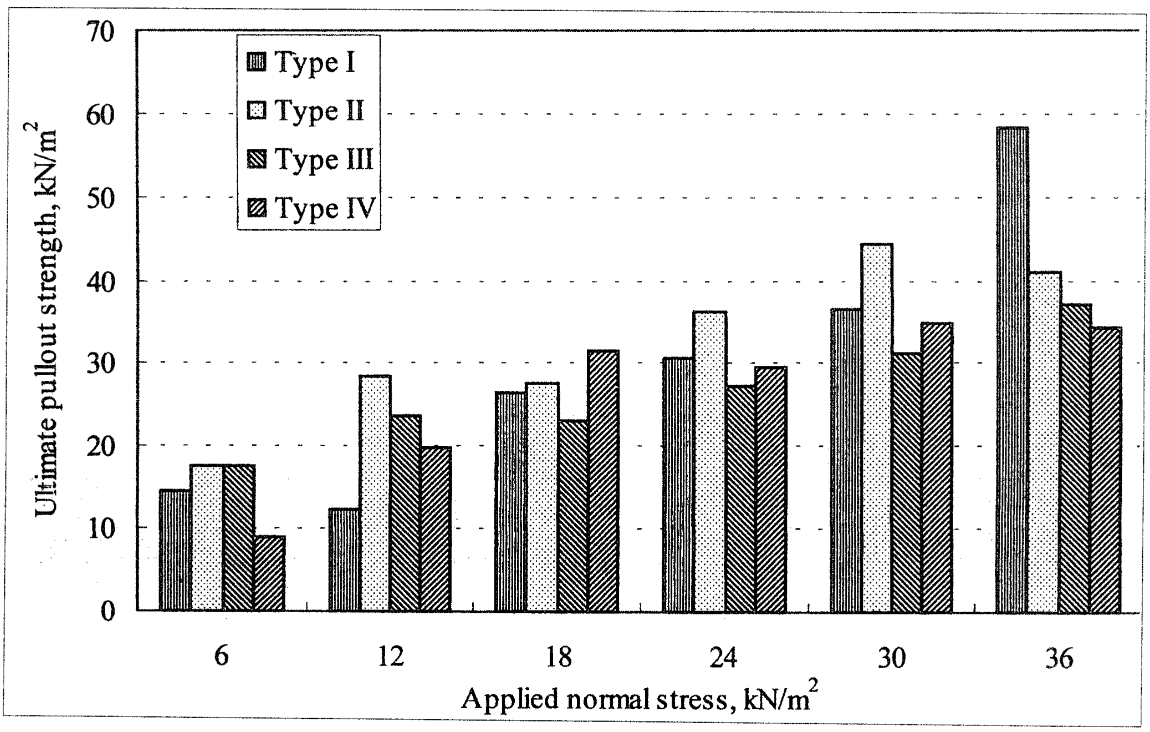

Fig. 15 Comparison of ultimate pullout stresses for geosynthetic and wire mesh under various applied normal stress conditions.

applied normal stress. This feature is mainly attributed owing to the more frictional resistance of the Type I reinforcement than that of the other Types. Because of the rectangular cross section and rough surface of the mesh filaments of Type I, it gives more frictional resistances as compared to others. Even though the ultimate pullout strength of Type II reinforcement is more than Type III and IV, the rate of increase of the ultimate pullout strength of Type II is not significantly varied as compared to other types with the increase in applied stresses. This is though to be due to the bonding phenomena between the soil and the reinforcements. Very fine mesh strands and smallest grids of Type II mesh provide larger bonding effect as compared to other Types of meshes. It is also observed that the rate of increase of the ultimate strengths of the Type III reinforcement is slightly more than that of the Type IV reinforcement. This may be partially depends on the water content of the soil. For Type IV mesh, the water content of the soil is 0.2% higher than the Type III mesh and therefore, it gives more bonding properties between the soil and the reinforcement. It is noted here that the R-square or the coefficient of determination of the regression analysis has the values of 0.89, 0.88, 0.94 and 0.79 for the reinforcements of Type I, Type II, Type III and Type IV, respectively, i.e. the R-square value for all the cases close to 1.0 indicates that the tests data are fitted well and we have accounted for almost all of the variability with the variables specified in this paper.

Interaction resistances (cohesion and internal friction)

In calculating the interaction resistances such as cohesion and internal friction under pullout test, it is necessary to clarify the common method of finding out these important parameters. In general, the methods of Failure Envelope and Mohr-Circle are well known in determination of cohesion and internal frictional resistances. In the first method, for obtaining a failure envelope, a number of identical specimens are tested under different normal stress. The shear stress required to cause failure is determined for each normal stress.

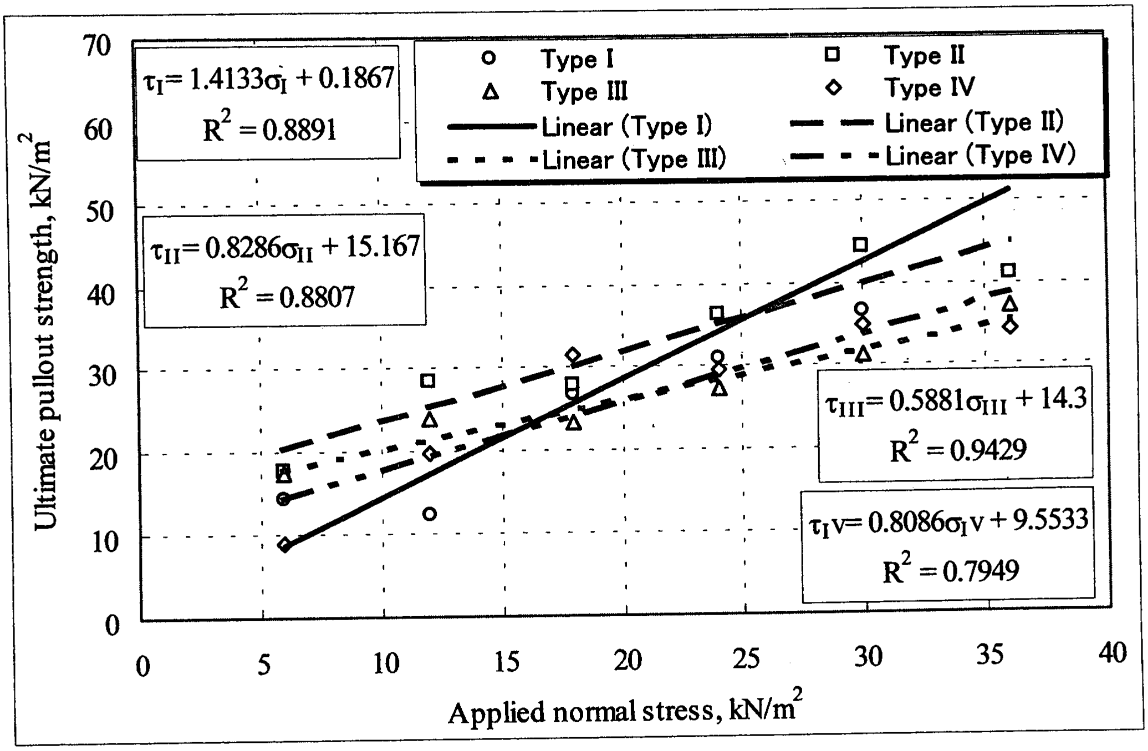

Fig. 16 Relationships between ultimate pullout strength and applied normal stress.

The failure envelope is obtained by plotting the points corresponding to the shear strength at different normal stresses and joining them by a straight line. The inclination of the failure envelope to the horizontal gives the angle of the shearing resistances and its intercept on the vertical axis is equal to the cohesion intercept. The Mohr-Circle method is needed when the stress on failure planes are not directly known. In the present research, the pullout test is carried out by pulling out the reinforcement from the soil under different normal stresses. The pullout stresses acted on both sides of reinforcement are measured directly and plotted in Fig. 16 with the applied normal stresses as abscissa and pullout out stresses as ordinate. The least square linear lines obtained by the regression analysis for the four types of meshes are similar to that of the method of failure envelope for direct shear test but having the resistance at two surfaces of the reinforcements. Two surfaces of reinforcement means two times of pullout stresses as compared to direct shear test which gives double intercept at Y axis but there is no effect on the angle of the linear lines because all the normal stresses will increase in the same fashion when the resistance acted on two surfaces. These points should be taken into account in calculating the cohesion and internal frictional resistances under pullout test.

The following equations are obtained as a result of pullout tests for reinforcements of Type I, II, III and IV respectively from the straight lines as plotted in Fig. 16.

$$\tau_{I}=1.4133\,\sigma_{I}+0.1867 \quad \cdots \quad (1)$$
$$\tau_{II}=0.8286\,\sigma_{II}+15.17 \quad \cdots \quad (2)$$
$$\tau_{III}=0.5881\,\sigma_{III}+14.3 \quad \cdots \quad (3)$$
$$\tau_{IV}=0.8086\,\sigma_{IV}+9.55 \quad \cdots \quad (4)$$

Where, τ is the shear resistance of reinforced soil on both surface of reinforcement under pullout test in kN/m^2 and σ is the normal stress (overburden pressure) on reinforcement in kN/m^2. The subscripts I, II, III and IV in the above equations indicate the mesh Type I, Type II, Type III and Type IV, respectively. Therefore, the angles of internal friction are obtained as 54.72, 39.64, 30.46 and 38.96 degrees. In order to make a similar condition to direct shear test and considering the friction on one side of the reinforcements as explained above, the values of cohesion should be the halves of the values as given in the above equations and are calculated as $0.09\ kN/m^2$, $7.59 kN/m^2$, $7.15\ kN/m^2$, $4.78\ kN/m^2$. For the sake of clarity, a relationship between the interaction resistances and the Types of reinforcement is plotted in Fig. 17 as the bar diagram. As it is evident from this figure, in general, it can be said that the angle of shear resistances of soil-reinforcement interaction decrease and the cohesions of the soil-reinforcement interaction increase if the reinforcement texture changes from coarse mesh to fine mesh under pullout tests.

Conclusions

From the above compilation of the test results, we can arrive at the following conclusions:

1. The results of the pullout test given in various charts and diagrams in terms of stress-displacement and volumetric changes may be helpful to aid in practical design of reinforced soil structures.
2. For all types of reinforcements under pullout test in this study, the common feature is that there is an increase in pullout stress with the increase in displacement as well as with the increase in normal stress.

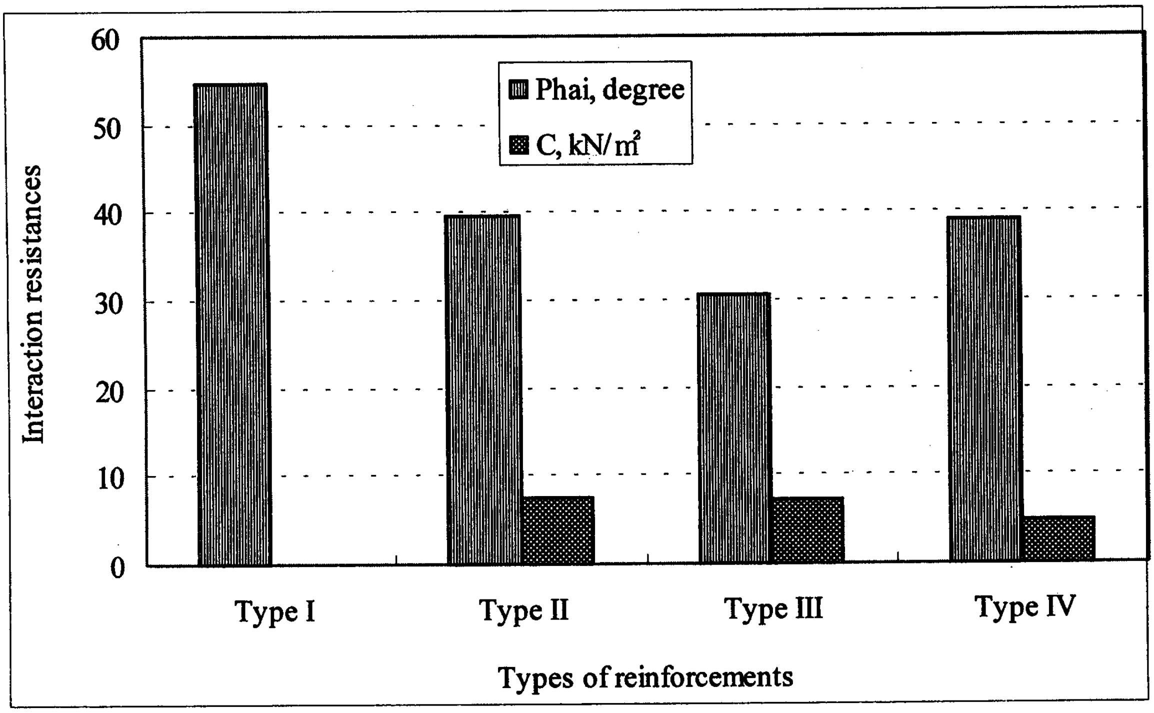

Fig. 17 Relationships between interaction resistances and reinforcement types.

3. Variation in the pullout test results regarding the vertical displacement as well as volumetric changes is a common feature for the individual type of reinforcement under different normal stresses.
4. There is also another common feature for all types of reinforcements tested that the vertical displacement occurred at the start of the horizontal displacement. The vertical displacement is increased with the increase in horizontal displacement especially under higher normal stresses for all types of reinforcements.
5. Equations for strength parameters of reinforced soil such as cohesion and internal friction of the individual reinforcement given in this paper will be useful in the design of reinforced soil structures.
6. In designing reinforced soil structures with coarse sand or gravel where cohesion needs to be improved, the use of smaller grid mesh may be recommended.
7. Designing soil structures with clay, the utilization of large grid mesh such as geosynthetics may be more suitable.
8. In designing large soil structures where higher strength is a major factor, the utilization of geogrid mesh that is greatly connected at the junctions may be recommended.

References

1) SCHLOSSER, F. and LONG N.T. Recent results in French Research on Reinforced Soil, *J. of Construction Engineering, ASCE*, **100** (3) : 223-237 (1973).
2) LECHCHINSKY, D. Keynote Lecture. Issues in geosynthetic reinforced soil, *Proc. Int. Sym. On Earth Reinforcement Practice*, **2**: 871-897 (1992).
3) RICHARDS, E.A. and SCOTT, J.D. Soil geotextile frictional properties, *Proc. 2nd. Canadian Sym. On Geotextile and*

Geomembrane. Canadian Geotechnical Society, Edmonton. Alberta, 13-24 (1985).

4) LAFLEUR, J., SALL, M.S. and DUCHARME, A. Frictional characteristics of geotextiles with compacted lateritic gravels and clays, *Geosynthetics, New Orleans*, 205-215 (1987).

5) WILLIAMS, N.D. and HOULIHAN, M.R. Evaluation of interface friction properties between geosynthetics and soils, *Geosynthetics, New Orleans*, 616-627 (1987).

6) MIYAMORI, T., IWAI, S. and MAKIUCHI, J.K. Frictional characteristics of non-woven fabrics, *Proc. 3rd. Int. Conf. on Geotextiles, Osterreichischer Ingenieur-und Architekten, Vienna*, 701-705 (1988).

7) LAUWERS, D.C. *PVC* geocomposite for improved friction and performance properties, *Geosynthetics, IFAI, Atlanta, GA*, 101-112 (1991).

8) MURATA, O. et al. Loading test of geosynthetic-reinforced soil retaining walls and their stability analysis. *Proceedings of the International Symposium on Earth Reinforcement Practice*, **1**: 373-378 (1992).

9) FOURIE, A.B. and FABIAN, K.J. Laboratory determination of clay-geotextile interaction, *Geotextiles and Geomembranes*, **6** (4) : 275-294 (1987).

10) MITACHI, T. et al. Estimation of in-soil deformation behavior of geogrid under pull-out loading, *Proceedings of the International Symposium on Earth Reinforcement Practice*, **1**: 121-126 (1992).

11) JARRET, P.M. and BATHURST, R.J. Frictional development at a gravel-geosynthetic-peat interface, *Proc. 2nd. Canadian Symp. Geotextiles and Geomembranes, Edmonton*, 1-6 (1985).

12) GARBULEWSKI, K and LASKOWSKA, J. Stress-strain characteristics of geotextile reinforced peat, *Proc. 2nd. Baltic Conf. Soil Mechanics and Foundation Engineering*, **1**: 90-96. (1988).

13) VOOTTIPRUEX, P. et al. Deformation characteristics of hexagonal wire mesh reinforcement, *Proceedings of the International Symposium on Lowland Technology, Saga, Japan*, 259-266 (1998).

14) BURD, H.J. and BROCKLEHURST, C.J. Finite Element studies of the mechanics of reinforced unpaved roads, *Proc. 4th. Int. Conf. on Geotextiles, Geomembranes and Related Products, A.A. Balkema, Rotterdam, The Netherlands*, 217-221 (1990).

15) BURD, H.J. and BROCKLEHURST, C.J. Parametric studies of a soil reinforcement problem using finite element analysis, *Proc. 7th. Int. Conf. on Computer Methods and Advances in Geomechanics, Cairns, Australia*, **3**: 1783-1788 (1992).

ジオシンセティクスとワイヤーメッシュの引き抜き試験における土－補強材間の相互作用

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土－補強材間の相互作用が補強土構造物の全体的な性能に重要な影響を与えることを考慮して，垂直応力を変化させた一連の引き抜き実験を行い，本論文では補強材の適合性と有効性を調べた。補強材として，ジオシンセティクスはフォートラックとナイロンメッシュから成り，正方形ワイヤーメッシュはその間隔が 3mm と 14mm のものを用いた。補強土の体積変化性状，応力-ひずみ関係や土－補強材の相互作用に直接関連する粘着力とせん断抵抗角を実際の設計，施工に供用できるように種々のチャートと図に表わした。結論的にはジオシンセティクス補強材の引き抜き応力はワイヤメッシュのそれより大きいことが明となった。すべての補強材に対して水平変位が生ずる直後に鉛直変位は現れ，そののち若干ばらつきながら増加していくという特徴的な傾向が得られた。