Bull. Fac. Bioresources, Mie Univ.
No.30 : 13 − 33
March 15, 2003

Effect of Water Content on Pullout Strength of Reinforcement Embedded in Soil

Md. Zakaria HOSSAIN* and Sohji INOUE
Faculty of Bioresources, Mie University, 1515 Kamihama-cho, Tsu, Mie 514-8507, Japan

Abstract

It is well known that the water content of soil has a significant effect on the pullout strength of reinforcement embedded in soil, as well as on the overall performance of reinforced soil structures. Since the substantial amount of water in soil varies throughout the year, it is of prime importance to investigate the effect of water content on pullout strength of reinforcement when subjected to loading with various types of reinforcement. A series of pullout tests under variable normal stresses have been carried out in order to find out the effect of water content on soil reinforcement interactions under pullout test in reinforced soil structures. In this paper, an investigation of the pullout strength of reinforcement parameters such as cohesion and internal friction under laboratory pullout tests for woven square wire mesh with 3 mm openings and 0.8 mm wire diameter is presented. Stress-displacement relationships and volumetric changes under laboratory pullout tests are given in various charts and diagrams as a ready reference to aid in practical design and constructions. It appears from the results of the pullout tests performed that there exists a relationship between the pullout strength of reinforcement and water content of soil. It is concluded that the pullout strength of reinforcement such as frictional resistance and cohesion both are decreased with the increase in water content of the soil.

Key Words: water content, soil-reinforcement, pullout strength, wire mesh, laboratory experiment.

Introduction

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 water content of soil. Naturally, because of the substantial amount of water in soil varies throughout the year with the change of season, it is necessary to investigate the effect of water content on pullout strength of reinforcement in order to safe design of reinforced soil structures during construction and on service. Among many types of reinforcing materials, woven square wire mesh reinforcement with c/c opening 3 mm and wire diameter 0.8 mm is used in the present investigation owing to its ease of availability in the local market, cost effectiveness and their wide-spread use

Accepted: January 31, 2003

* For correspondence (e-mail: zakaria@bio. mie-u. ac. jp)

all over the world for soil reinforcement applications.

Researchers have extensively used pullout tests to evaluate interface interactions. Madhav, M. R. *et al.*, 1998[3] and Gurung, N. *et al.*, 1999[4] illustrated the general applicability of bilinear shear stress-displacement model for soil reinforcement interaction during pullout tests with extensible and inextensible geo-reinforcements. Richards and Scott, 1985[5], Lafleur, J. *et. al.*, 1987[6], Williams and Houlihan, 1987[7], Miyamori *et al.*, 1988[8], Lawers, D. C. 1991[9] and Murata, O. *et al.*, 1992[10], have studied the geotextiles/cohesionless soil interfaces and have adopted a suitable test method to simulate field conditions. A soil-geosynthetic reinforcement interface model based on rigid plastic shear stress mobilization has been reported by Sobhi and Wu, 1996[11] for extensible reinforcement (geotextiles). Mahmood, A. A. *et al.*, 2000[12] have studied geotextiles/soil interface shear behavior with two types of soils namely sandy soil and organic clay.

Currently, no method or code guideline is available on the effect of water content on pullout strength of reinforcement even though it presents considerable versatility in the development of reinforced soil structures. To the knowledge of the authors, no attempt has so far been made to study the effect of water content on pullout strength of reinforcement except for the incomplete research works that can be found by Jewell, R. A, 1996[13] on the soil strength and bearing capacity in soil-geotextile friction test. This investigation is, therefore, aimed at generating information on the overall response of water content on the pullout strength of reinforcement embedded in soil. Pullout tests are carried out using sandy soil of Mie prefecture with four stages of water content such as 11.36%, 13.4%, 16.14% and 19.19%. A series of pullout tests under variable normal stresses have been carried out in order to find out the effect of water content on pullout strength of reinforcement in reinforced soil structures. Results of these tests are depicted to understand thoroughly of the stress-displacement relationships, volumetric changes and pullout strength of reinforcement resistance of reinforced soil such as cohesion and internal friction.

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% and 26.9% respectively. The average specific gravity of the soil is calculated as 2.644. The shear behavior of the soil with optimum water content (W_{opt}) is shown in Fig. 2 and Fig. 3. The other properties of the soil used in these tests are given in Table 1.

Reinforcement properties

The physical appearance of the wire mesh obtained from commercially is shown in Fig. 4. The mesh as shown in Fig. 4 is manufactured from steel wires. This mesh is made by interweaving the wire filaments with each other. The junctions of this mesh are not directly connected nor greatly improved and the wires are not coated with protective sheathing. The strengths of the junctions are not adequate enough to transmit the

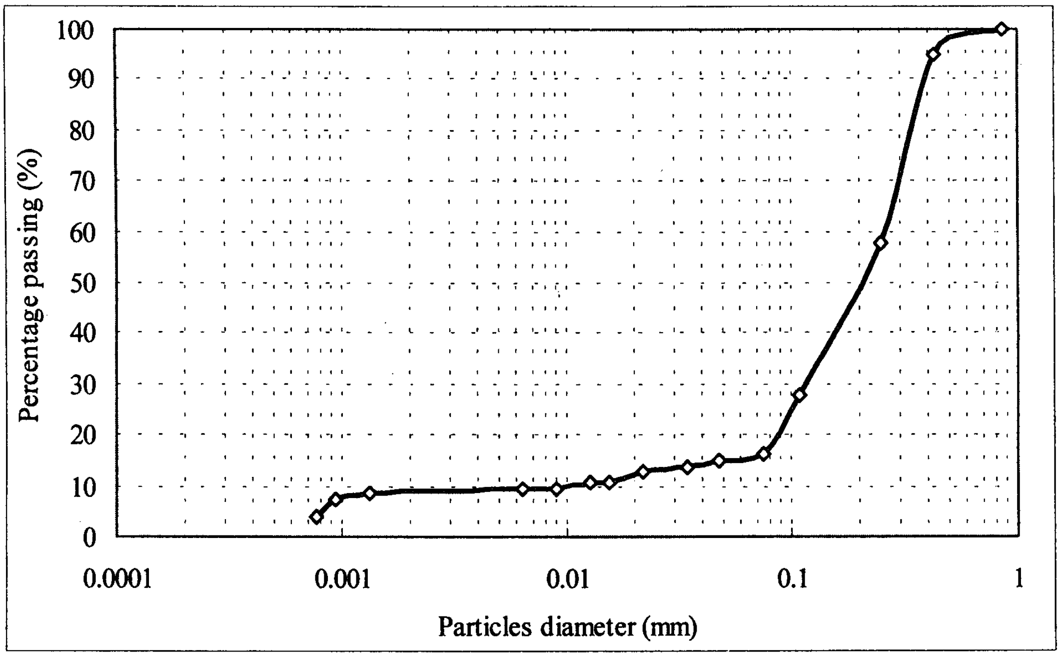

Fig. 1. Particle size distribution curve of the soil used in pullout test

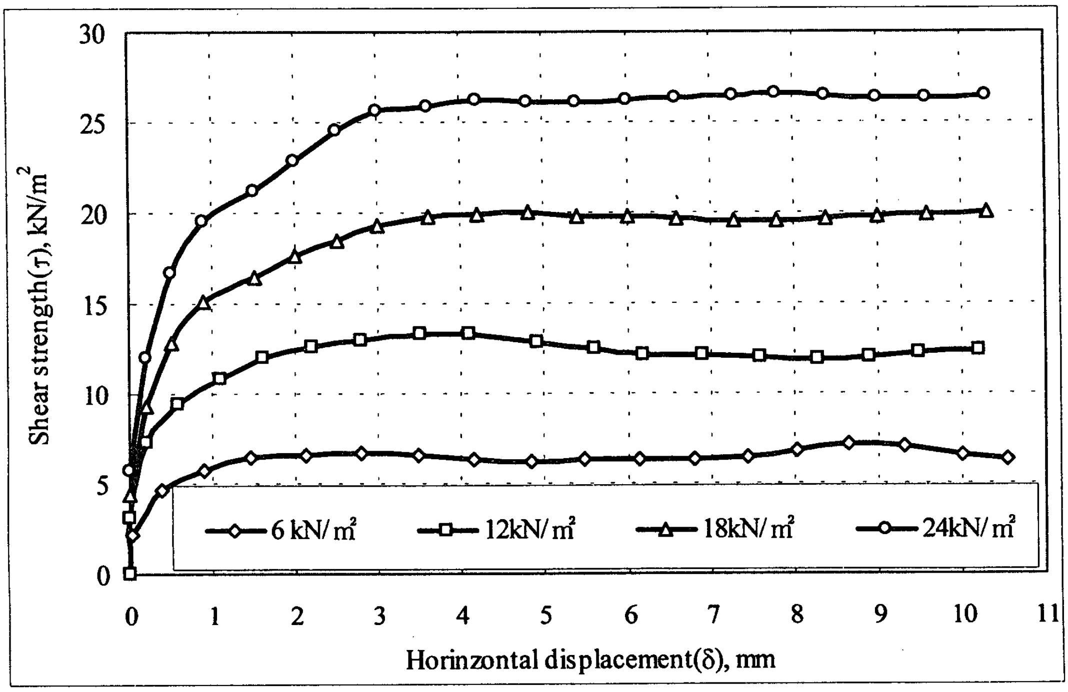

Fig. 2. Relationships of shear strength and horizontal displacement for soil

(W_{opt} = 15.3%)

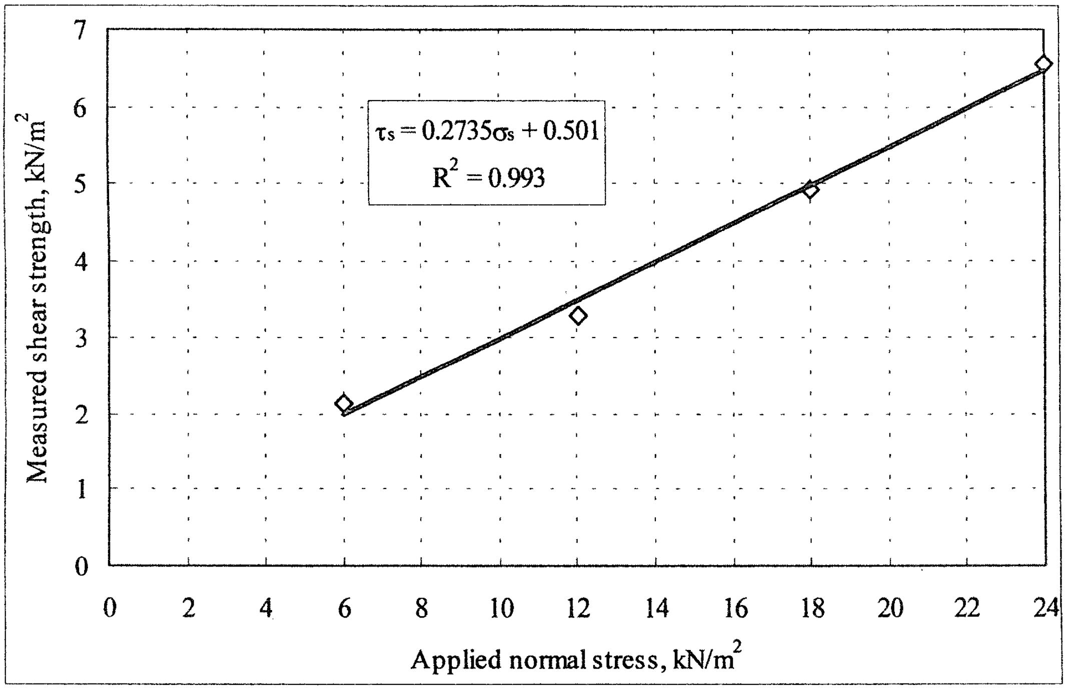

Fig. 3. Relationship of measured shear strength and applied normal stress for soil (W_{opt} = 15.3%)

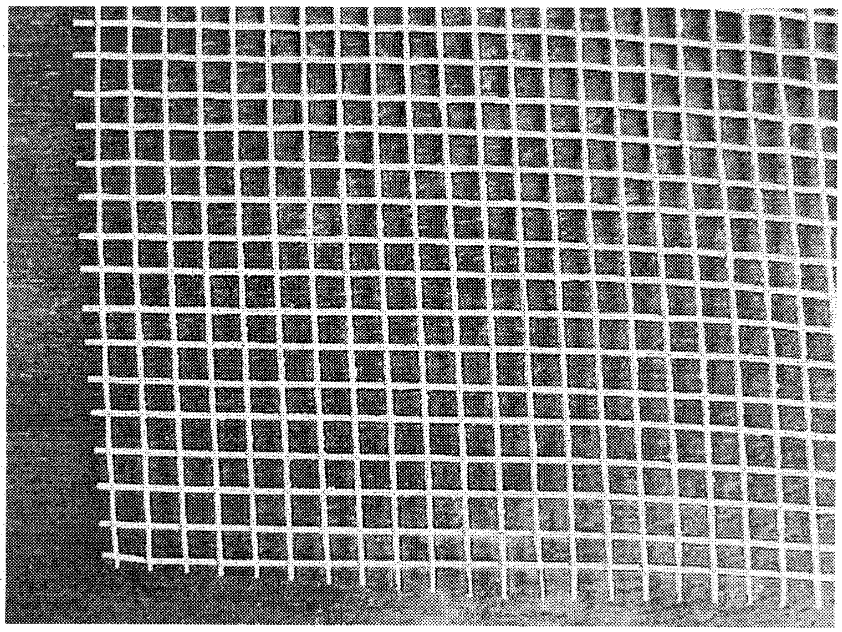

Fig. 4. Physical appearance of woven square wire mesh, c/c wire opening 3mm, ϕ = 0.8 mm.

Table 1. Soil properties

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

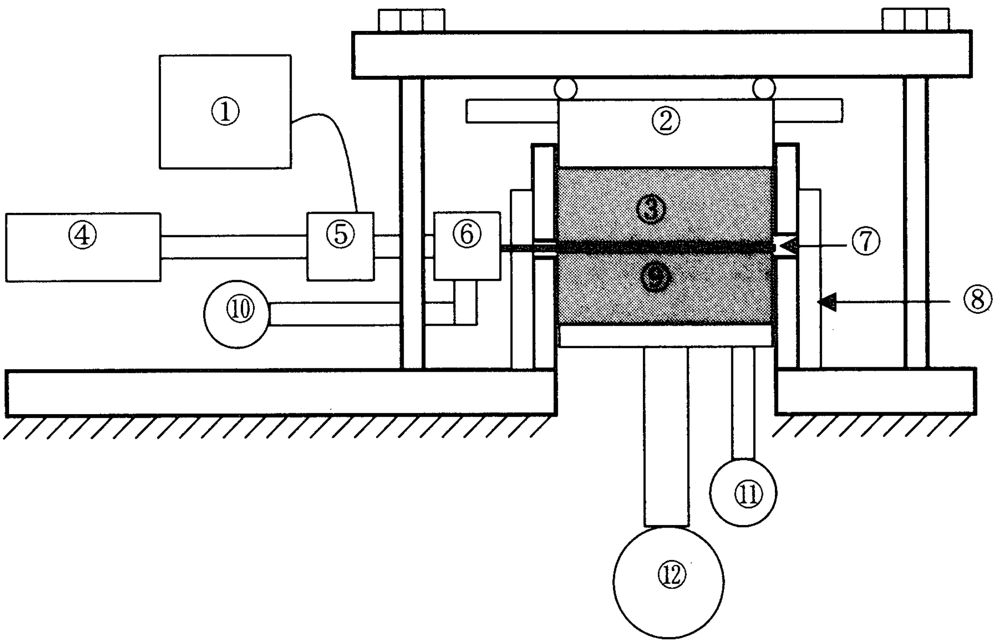

Fig. 5. Schematic diagram of pullout testing machine

envisaged loadings. The wire filament of this mesh is circular in cross section with 0.8 mm diameter in both transverse and longitudinal directions and c/c mesh opening is 3 mm in both the directions.

Components of pullout machine

The schematic diagram of the pullout machine 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 [12], 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 upper part of the pullout box, [4] is the electrically operated pullout jack, [5] is the pullout stress measuring device, [6] is the reinforcement clamping jack, [7] is the test reinforcement, [8] is the clearance adjusting screw and fixing system of the upper box, [9] is the lower part of the pullout box, [10] is the horizontal displacement measuring dial gauge, [11] is the vertical displacement measuring dial gauge and [12] is the applied normal stress measuring dial gauge.

Outlines of the pullout machine

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 150 mm in length, 100 mm in width and 100 mm in height. The box is divided into two parts namely lower box and upper box both are 50 mm 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 box is fixed while the upper 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 those have been set at both sides of the upper part. The normal stress at the bottom surface of the lower box applied through the lower jack in the upward direction is balanced by the opposite stresses of the upper box. The stresses into the soil are uniformly distributed by adjusting the screw at the top surface of the upper box. The lower and upper 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 part with clamping screw. It can be freed while running the direct shear test. The upper box can then be pushed forward 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 width of the pullout box (inner sides). Pullout tests with four stages of water content are performed where each stage has six normal stress conditions.

Preparation of test specimen

At first, the required amount of soil with desired water content were poured into the lower part of the pullout box and compacted uniformly by means of a compactor made of same width as of the pullout box. The lower box was filled completely and the surface of the soil was leveled precisely. Then the wire mesh of same width was laid on the soil of lower box and fastened with clamping jack as shown in Fig.5. The upper part of the pullout box was ten placed on the wire mesh and required clearance between the wire mesh and upper box was set by means of adjusting screw. In the second stage, the soil was gradually spread over the mesh inside the upper box and compacted uniformly to be able to get the soil into the grids of mesh. The distribution and insertion of soil into the mesh grids as well as compaction were carried out with visible observation by nacked eyes in such a way so that the soil particles were tightly and firmly entered into the mesh and thereby, it provided a complete shear and frictional resistance between the mesh and the soil.

Methodology

The wire mesh was cut to obtain rectangular pieces of 200 mm by 100 mm in size. The specified lengths of the pieces were selected in order to facilitate clamping with the pullout apparatus. The mesh was clamped into the box in such a way that the embedded length of the mesh is 150 mm in the loading direction and 100 mm 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 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 upper box. The tests were carried out in the way of pulling out the mesh from the soil with constant speed of 1 mm/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 5 N. The load cell was set between the mesh and the 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 0.001 mm. All the tests were carried out under normal stresses of six 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 0.001 mm.

The soil was compacted in three layers for all the tests and thus obtained the same density of the soil for all the pullout tests. The optimum water content of the soil was measured as 15.3% and the tests were carried out with the water content of the soil of 11.36%, 13.4%, 16.14% and 19.19%. This was being done in order to perform the experiment in the dry side and wet side of optimum water content (W_{opt}) as well as to understand the effect of the water content at the both sides of optimum water content.

Results and discussion

Pullout stress-displacement relationships

The relationships between the pulling stress and the displacement of wire mesh 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 11.36% 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 2 mm. After that the pullout stress increases nonlinearly with the increase in displacement of about 5 mm. The pullout stresses are almost horizontal with displacements exceeding 5 mm and continued in the same fashion of up to 50 mm. At the higher normal stresses such as 30 kN/m^2 and 36 kN/m^2, the pullout stresses are upswing with the increase in pullout displacement. This may be due to the variation of stress distribution along the reinforcement in the loading direction. Because of the lower water content of the soil which is far from the W_{opt}, there might be uneven distribution of reinforcement's stresses at the higher normal stresses. 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 15 mm 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 15 mm 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 water content of soil were calculated as 17.5 kN/m^2, 23.86

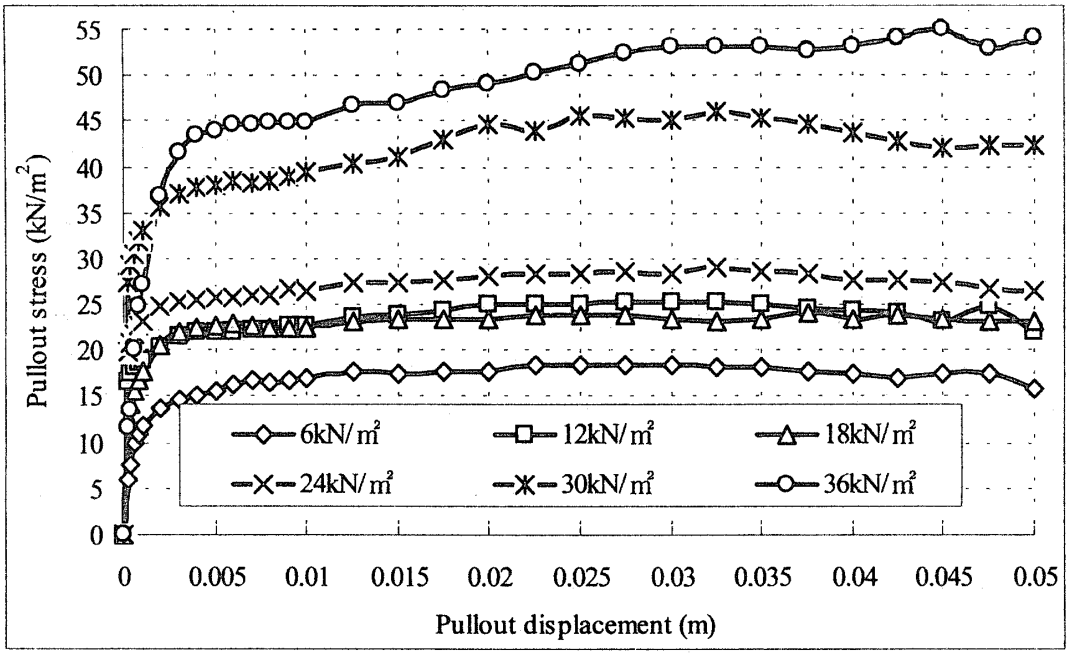

Fig. 6. Pullout stress-displacement curve, woven square mesh (3 mm) reinforcement, sandy soil with 11.36% water content.

kN/m², 23.26 kN/m², 27.3 kN/m², 41.13 kN/m² and 47.01 kN/m² for normal stress 6 kN/m², 12 kN/m², 18 kN/m², 24 kN/m², 30 kN/m² and 36 kN/m², respectively.

Fig. 7 indicates a typical stress-displacement relationship of the pullout tests for 13.4% water content of the test soil. 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 0.0 mm to 2 mm displacement. A greater part of linearity can be taken from 5 mm to 35 mm displacement. The non-linear range at the lower limit starts with displacement of nearly 2 mm, continues parallel to the x-axis of upto 35 mm and then downswing until the displacement of 50 mm except the normal stress of 12 kN/m² which is gradually upward till the end of the test. Unlike the curves of 11.36% water content of Fig. 6, all the graphs of 13.4% water content are almost same trend owing to the effect of even distribution of stress on the mesh. The water content closer to the W_{opt} allows the soil particles to undergo deformation easily and thereby facilitates uniform compression. Similar to the previous case, ultimate pullout strengths for 13.4% water content are recorded as 17.8 kN/m², 18.4 kN/m², 26.8 kN/m², 27.2 kN/m², 37.1 kN/m² and 45.2 kN/m² corresponding to normal stresses 6 kN/m², 12 kN/m², 18 kN/m², 24 kN/m², 30 kN/m² and 36 kN/m², respectively.

The pullout test results show that the pullout stresses are changing almost smoothly with the change of pullout displacement up to the end of the test and there is no sudden drop of stresses even after the occurrence of pullout displacement as well as shear failure. It is expedient to point out here that a gradual increase of shear resistance takes place while a shear force applied on a solid body and just after the applied

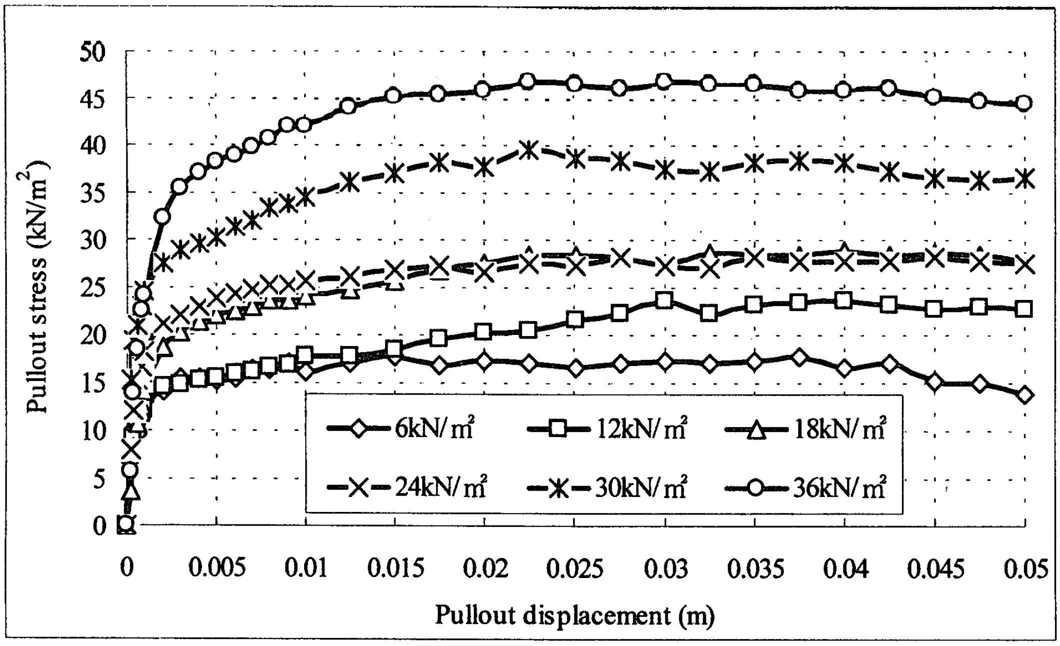

Fig. 7. Pullout stress-displacement curve, woven square mesh (3 mm) reinforcement, sandy soil with 13.4% water content.

force exceeds the pick shear resistance, a sudden drop of shear resistance may occur in the case of two solid bodies without any restraint acting perpendicularly to the shear surface. This phenomenon is in variant in the case of pullout test of reinforcement embedded in soil where the soil particles are firmly entrained and greatly interlocked into the grids of reinforcement. Moreover, there is a continuous application of normal load in the direction perpendicular to the shear surface prohibiting the sudden drop of pullout stresses just after the verge of shear failure.

The stress-displacement relationships under pullout tests with woven square steel mesh of 3 mm opening and 0.8 mm diameter with six normal loading conditions for sandy soil with water content of 16.14% are depicted in Fig. 8. All the six graphs belong to the same characteristic curves like as flat parabolic shape and can be taken in a group with the linear portion restricted to the displacement of about 1.5 mm. After that, all the curves become non-linear with the pullout displacement of 1.5 mm to 10 mm. A greater part of linearity can be taken from 10 mm to 50 mm displacement in the downward direction except 6 kN/m^2 normal stress. The downswing trend of the pullout stress with the increase in pullout displacement is clearly evident from this figure. This phenomenon mainly depends on the higher water content beyond the W_{opt} limit. Unlike to the previous two cases, pullout stresses reach its ultimate values with the pullout displacement of 5 mm to 15 mm at the water content of wet side of W_{opt} and closer to W_{opt}. Owing to the water content closer to W_{opt} and wet side of W_{opt}, the soil gets quick compression as well as gives more normal stresses on the mesh. These extra normal stresses are released gradually with the increase in pullout displacement and thereby allowing a downward trend of the pullout stresses. Similar to the previous two cases, the ultimate strengths vary apparently; they have values of 12 kN/m^2, 20.2 kN/m^2, 28.13 kN/m^2, 31.86

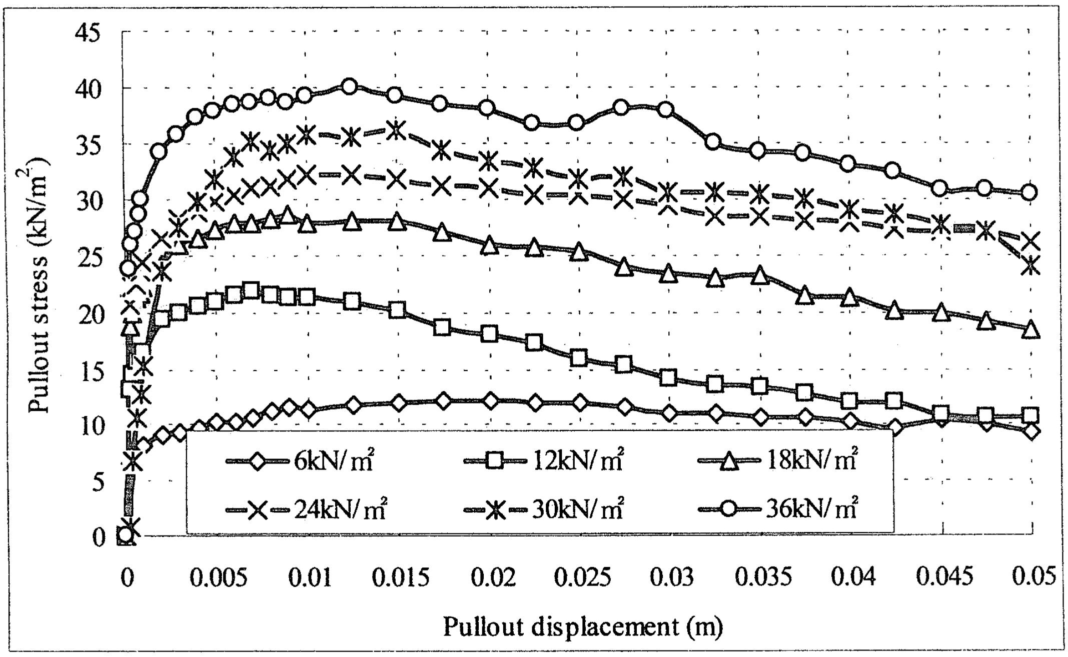

Fig. 8. Pullout stress-displacement curve, woven square mesh (3 mm) reinforcement, sandy soil with 16.14% water content.

kN/m², 36.06 kN/m² and 39.26 kN/m² for the six applied normal stresses.

Fig. 9 depicts the stress-displacement relationships of pullout tests for the same woven square steel mesh as discussed above with sandy soil having 19.19% water content. It can be observed from this figure that the applied pullout stress increases proportionately with the increase in displacement of about 4 mm. 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, pullout stress-displacement curves showed its downward trends whereas it is horizontal 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 higher water content of soil on the wet side of W_{opt} and far beyond the W_{opt}. Unlike to all the previous cases, the water content of the soil is much higher and therefore, it takes time to release from the soil which allows gradual increase of pullout stresses with the increase in pullout displacement. Higher water content inhibits compression of the soil particles with the application of normal stress and also the soil particles may get slippage with the increase in pullout displacement. The ultimate pullout stresses were found as 10.2 kN/m², 17.26 kN/m², 21.2 kN/m², 26.46 kN/m², 27.66 kN/m² and 29.73 kN/m² corresponding to the normal stresses 6 kN/m², 12 kN/m², 18 kN/m², 24 kN/m², 30 kN/m² and 36 kN/m², respectively.

Dilatancy behavior

The relationships between the horizontal displacement and vertical displacement of pullout test with 11.36% water content under normal stresses 6 kN/m², 12 kN/m², 18 kN/m², 24 kN/m², 30 kN/m² and 36 kN

/m² for sandy soil are given in Fig. 10. The vertical displacement increases nonlinearly with the increase in horizontal displacement of about 3 mm under higher overburden pressure. With lower overburden pressure

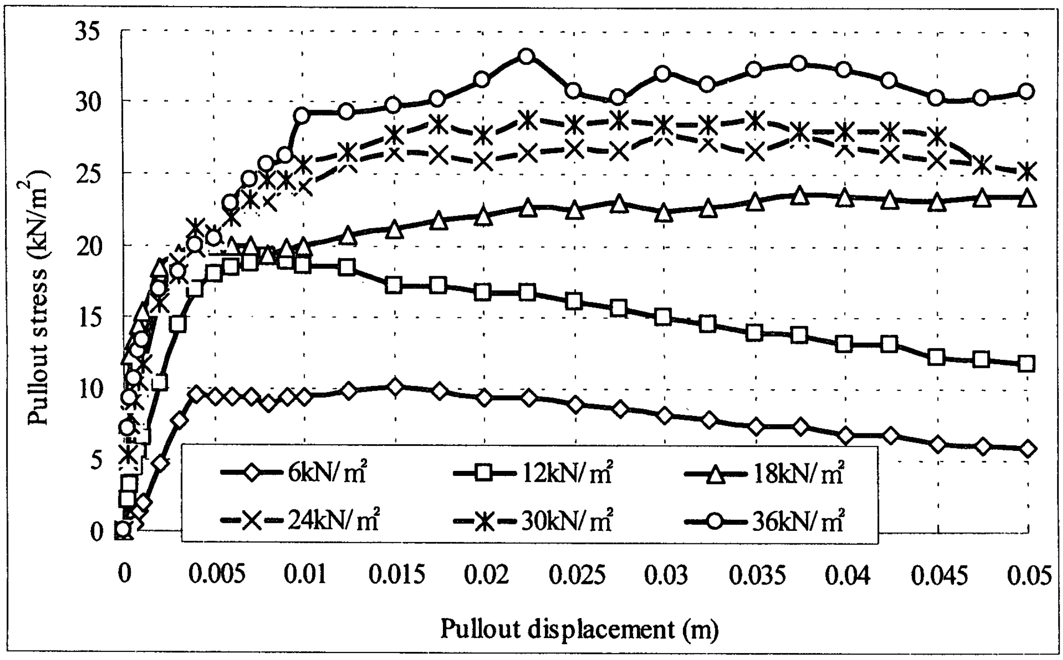

Fig. 9. Pullout stress-displacement curve, woven square mesh (3 mm) reinforcement, sandy soil with 19.19% water content.

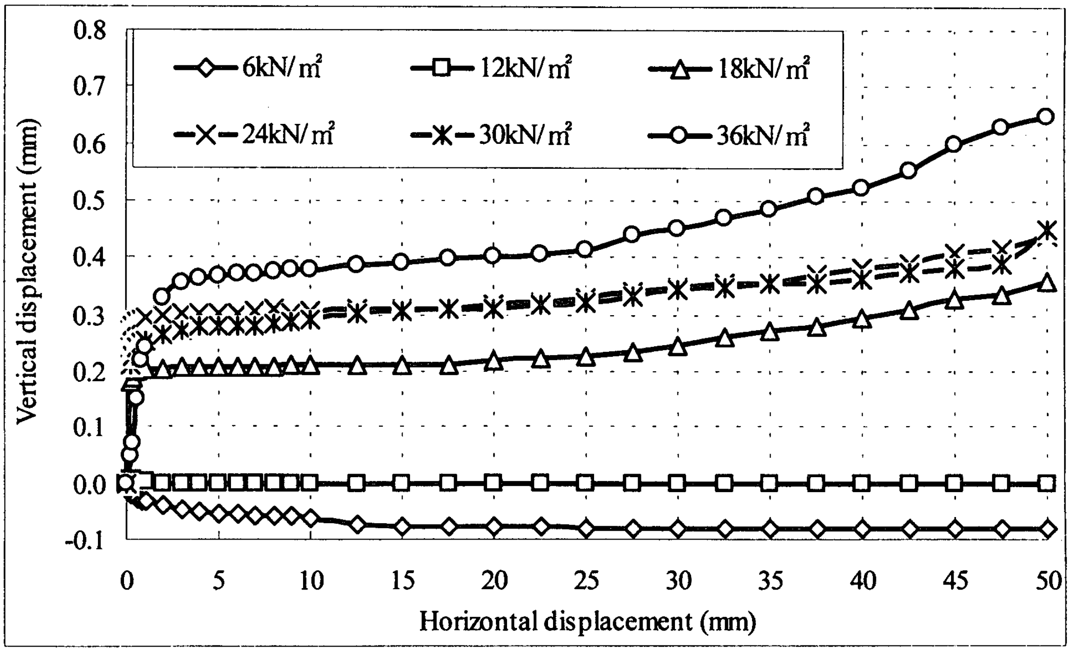

Fig. 10. Volumetric changes under pullout test, woven square mesh (3 mm) reinforcement, sandy soil with 11.36% water content.

such as 6 kN/m^2 and 12 kN/m^2, there are negative and no vertical displacements till the end of horizontal displacement. Vertical displacement gets maximum value with the horizontal displacement of amount 7-10 mm. It is evident from this figure that vertical displacement increases nonlinearly for normal stresses of 18 kN/m^2 – 36 kN/m^2 with the increase in horizontal displacement and this increment continued until the horizontal displacement of about 50 mm. The rate of increase of the vertical displacement is more at the higher horizontal displacement. As expected, the vertical displacement is more for higher normal stresses. According to the same consideration like as the stress-displacement relationships and in compatibility with it, the maximum vertical displacements are taken at 15 mm horizontal displacement which is similar to that of the stress-displacement condition. The maximum vertical displacement are recorded as 0.21 mm, 0.31 mm, 0.32 mm and 0.40 mm corresponding to the normal stresses 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2, respectively.

Fig. 11 indicates vertical displacement versus horizontal displacement relationships for soil with 13.4% water content under pullout stresses. Alike to soil of 11.36% water content, vertical displacements for soil of 13.4% water content gets maximum value at the end of horizontal displacement. As expected, the vertical displacement is more for higher normal stresses. The maximum vertical displacement are found to be 0.19 mm, 0.29 mm, 0.30 mm and 0.35 mm and 0.38 mm corresponding to the normal stresses 12 kN/m^2, 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 water content 16.14% is plotted in Fig.12. Alike to the dilatancy behavior of soil with lower water

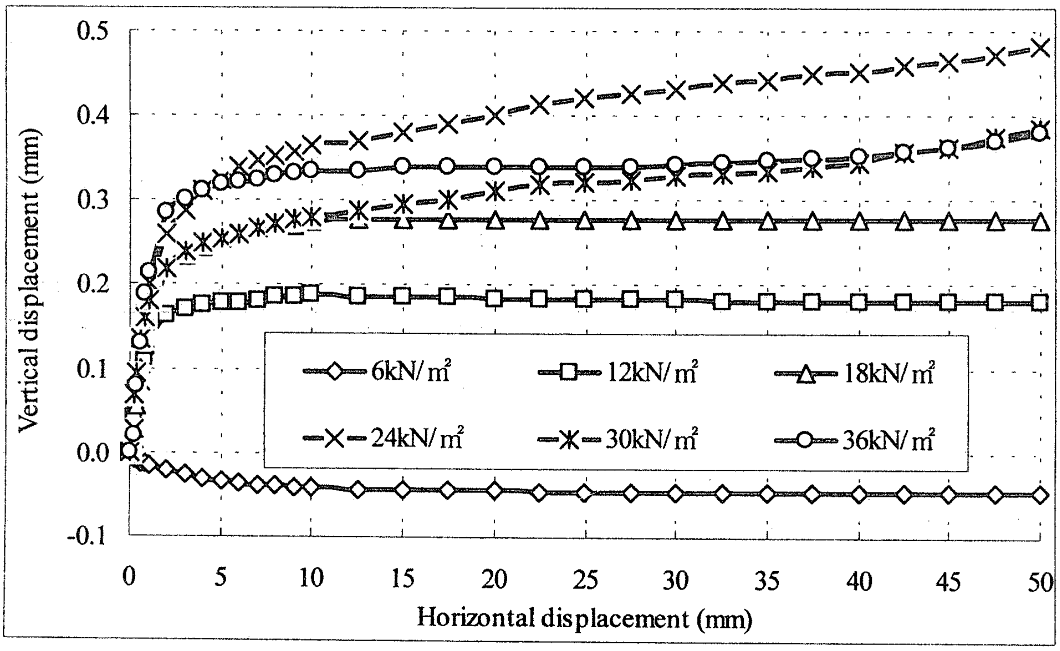

Fig. 11. Volumetric changes under pullout test, woven square mesh (3 mm) reinforcement, sandy soil with 13.4% water content.

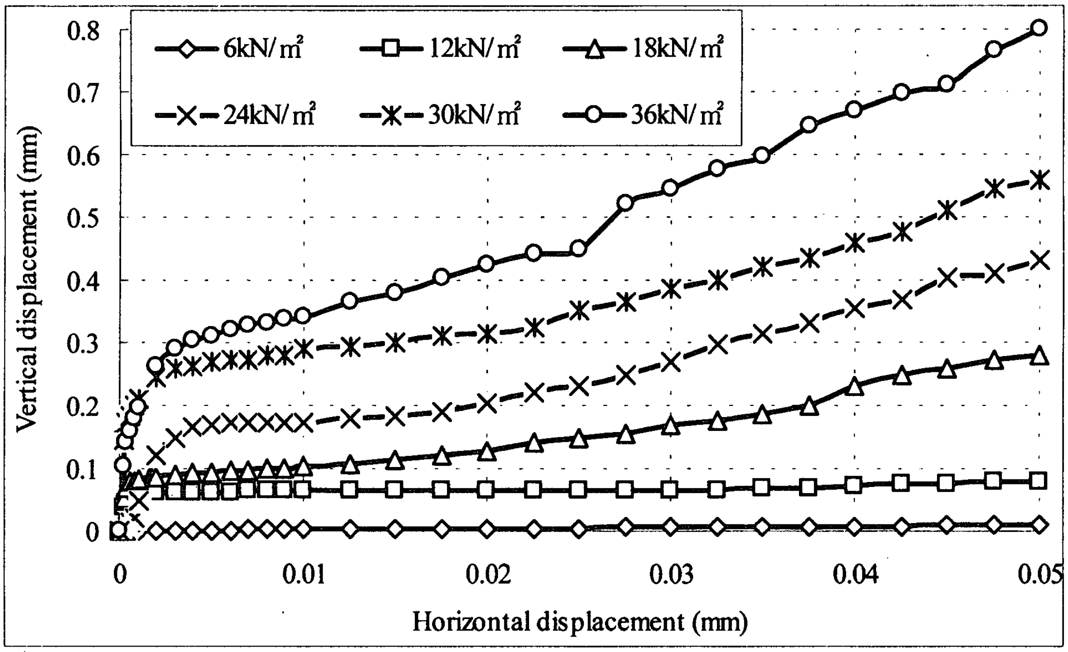

Fig. 12. Volumetric changes under pullout test, woven square mesh (3 mm) reinforcement, sandy soil with 16.14% water content.

content at the dry side of W_{opt} given in the previous figures (Fig. 10 and Fig. 11), the change of the vertical displacement for soil of 16.14% water content started at the beginning of the horizontal displacement. Negative vertical displacements that were observed in the previous two cases of soil with water content at the dry side of optimum are conspicuously absent. No dilatancy is found for 6 kN/m^2 normal stress and the curve of 12 kN/m^2 normal stress is almost parallel to the x-axis even to the end of the pullout displacement. In cases of 18 kN/m^2, 24 kN/m^2, 30 kN/m^2 and 36 kN/m^2 normal stresses, gradual increase of vertical displacements are observed up to 50 mm of horizontal displacement. The rate of increase of the vertical displacement for 36 kN/m^2 normal stress is more 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 cases of lower water content. However, a similarity among the lower and higher water content can be seen that the higher vertical displacements are attained at the higher horizontal displacement. The maximum vertical displacements are found as 0.06 mm, 0.12 mm, 0.18 mm, 0.3 mm and 0.38 mm respectively for normal loading condition of 12-36 kN/m^2.

Fig. 13 depicts the relationships between vertical displacements and horizontal displacements of the pullout tests for woven square mesh reinforcement of 3 mm opening and wire diameter 0.8 mm with sandy soil having 19.19% water content. Alike to the case of 16.14% water content, there is no negative vertical displacement that was observed for the cases of 11.36% and 13.4% water content. There are very small amount of vertical displacements for normal stresses of 6 kN/m^2 and 12 kN/m^2. The vertical displacement for normal stress of 18 kN/m^2 increases rapidly with the increase in horizontal displacement ranging from 15 mm to 50 mm whereas it is decreases for 30 kN/m^2 normal stress. All the curves assume different pattern and these characteristics did not attributable in the previous cases of 11.36%, 13.4% and 16.15% water

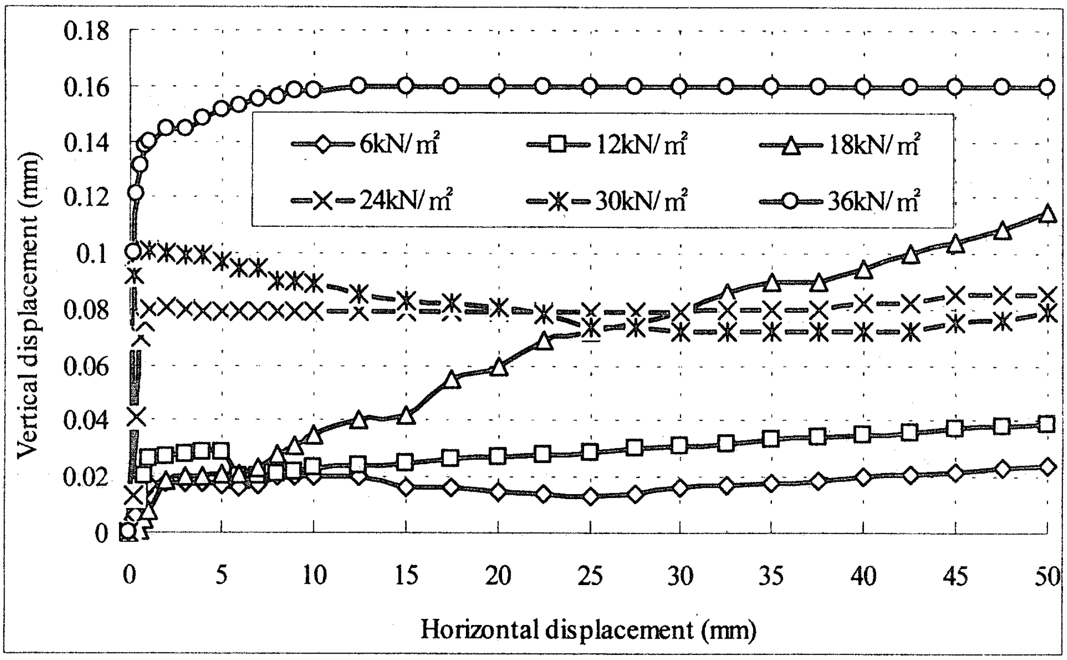

Fig.13. Volumetric changes under pullout test, woven square mesh (3 mm) reinforcement, sandy soil with 19.19% water content.

content. The maximum vertical displacements are calculated as 0.016 mm, 0.025 mm, 0.042 mm, 0.079 mm, 0.083 mm and 0.16 mm for 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.

Comparison of dilatancy behavior

In order to obtain a clear comparison among the volumetric changes under pullout tests, maximum vertical displacements corresponding to normal stresses with different water content are given in Fig. 14. In general, there are some scatters of the volumetric changes under pullout test with different water content of the soil. 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 stress such as 6kN/m^2 only with the dry side of optimum. The increase in volume under lower normal stress with lower water content mainly depends on the disturbance of soil layers at the interfaces of reinforcement. Because of the lower water content, the soil particles became stiffer 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 W_{opt} limit. 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 wire mesh. Also, there are some effects of compression of the soil itself by draining out the water as well as by rearrangement of the soil particles with higher normal loads.

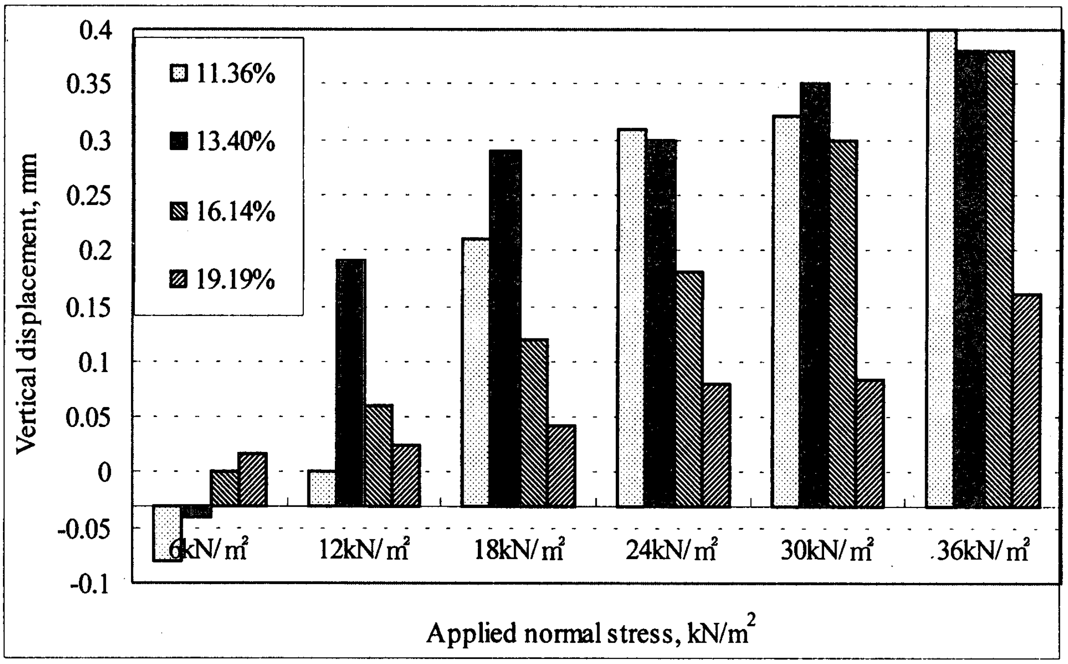

Fig. 14. Comparison of volumetric changes of pullout tests

Ultimate pullout strength

For the sake of clear perception of the bearing capacity of reinforced soil under pullout test, the ultimate pullout strengths corresponding to the different overburden pressures (normal stresses) of the reinforced soil with different water content are plotted as 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 amount of water content such as 11.36%, 13.4%, 16.14% and 19.19%. Both the soil with water content at dry side of W_{opt} showed more stress bearing capacity under pullout test than that of the soil of water content at wet side of W_{opt}. This may be the effect of surface resistance as well as cohesion of the soil and the reinforcement. The surfaces resistance and cohesion are comparatively more for soil of lower water content than that of the soil of higher water content. A slight scatter is observed in the test results that the ultimate pullout strengths of soil having 13.4% water content with normal stress 6 kN/m^2, 18 kN/m^2 are more than that of the soil having 11.36% water content. In the similar way, the ultimate pullout strengths of soil having 16.14% water content with normal stress 12 kN/m^2, 18 kN/m^2 and 24 kN/m^2 are more than that of the soil having 13.4% water content. The others are followed the usual trends of the ultimate pullout strengths.

Regression analysis

For more clarification of ultimate strengths among the four types of water contents 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 ultimate pullout 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 11.36% water content is more than that of the other cases with the increase in overburden pressure i. e. applied normal stress. This

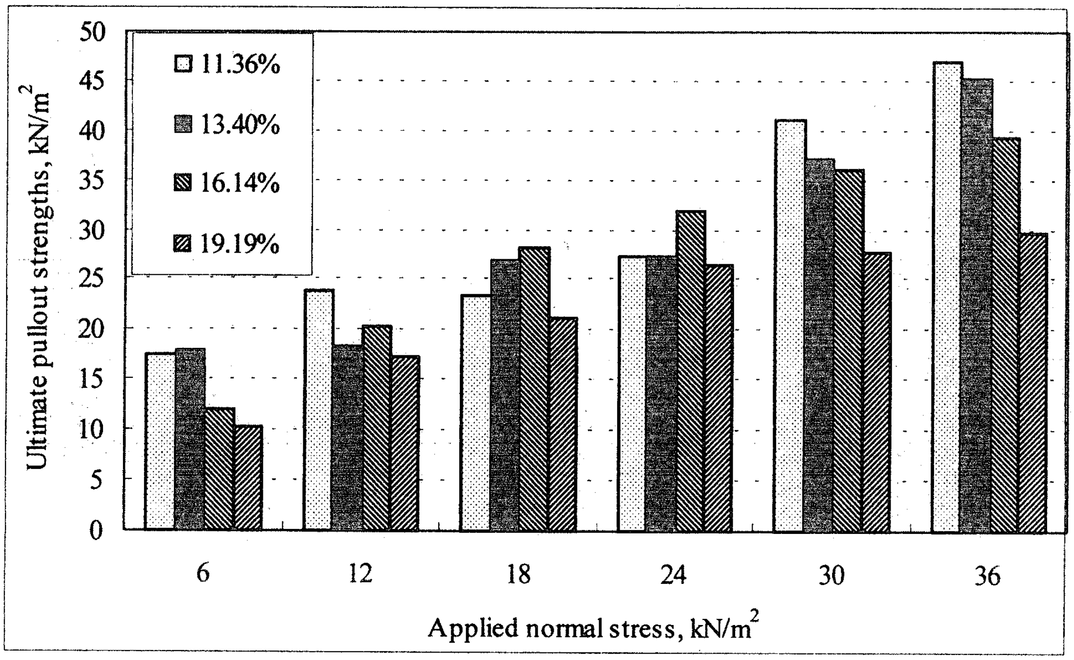

Fig. 15. Comparison of ultimate pullout strengths

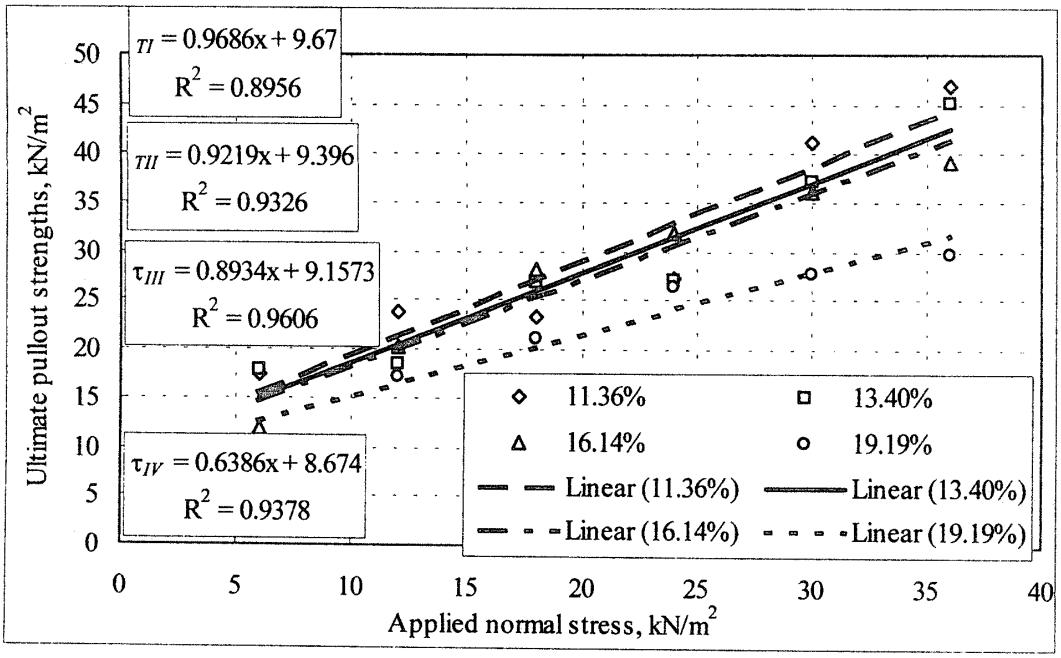

Fig. 16. Applied normal stresses versus ultimate pullout strengths.

feature is mainly attributed owing to the more frictional resistance of the soil with lower water content than that of the other cases. Because of the lower water content, the soil particles possess higher surface traction and thus, it gives more frictional resistances as compared to others. Even though the ultimate pullout strength of soil with 13.4% water content is more than that of the soil with 16.14% water content, the rate of increase of the ultimate pullout strength of 13.4% water content is not significantly varied as compared to 16.14% water content with the increase in applied stresses. This is thought to be due to the compression phenomena of the soil particles. The water content of the soil closer to W_{opt} provides better compression effect as compared to other cases. It is also observed that the rate of increase of the ultimate strengths of the soil having 19.19% water content is slightly smaller than that of the other cases. This may partially depends on the liquidation of the soil. For this case, the 19.19% water content is too high beyond the limit of W_{opt} which gives more liquidation between the soil particles as well as more slippage of the reinforcement. It is noted here that the R-square or the coefficient of determination of the regression analysis has the values of 0.8956, 0.9326, 0.9606 and 0.9378 for the soil of 11.36%, 13.4% 16.14% and 19.19% water content, 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. 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 stages of water content 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 of reinforcement. 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 the soil of 11.36%, 13.4% 16.14% and 19.19% water content, respectively, from the straight lines as plotted in Fig.16.

$$\tau_{I}=0.9686\sigma_{I}+9.67 \quad ---- \quad (1)$$
$$\tau_{II}=0.9219\sigma_{II}+9.39 \quad ---- \quad (2)$$
$$\tau_{III}=0.8934\sigma_{III}+9.15 \quad ---- \quad (3)$$
$$\tau_{IV}=0.6386\sigma_{IV}+8.67 \quad ---- \quad (4)$$

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 applied normal stress (overburden pressure) on reinforcement in kN/m^2. The subscripts I, II, III and IV in the above equations indicate 11.36%, 13.4% 16.14% and 19.19% water content of the soil, respectively. Therefore, the angles of internal friction are obtained as 44.08, 42.67, 41.77 and 32.56 degrees. The values of cohesion as given in the above equations are calculated as 9.67 kN/m^2, 9.39 kN/m^2, 9.15 kN/m^2, 8.67 kN/m^2. For the sake of clarity, relationships of the interaction resistances and cohesion with the variation of water content of soil are plotted in Fig. 17 and Fig. 18, respectively. As it is evident from these figures, in general, it can be said that the angle of shear resistance and cohesion of soil-reinforcement interaction under pullout tests decrease with the increase in water content of the soil.

It is noted here that the present research is focused mainly on the pullout test with wire mesh reinforcement of 3 mm grid size only and a vast researches are necessary for effective use of different size of reinforcement with variable water contents of soil and is expected to continue this work in the future.

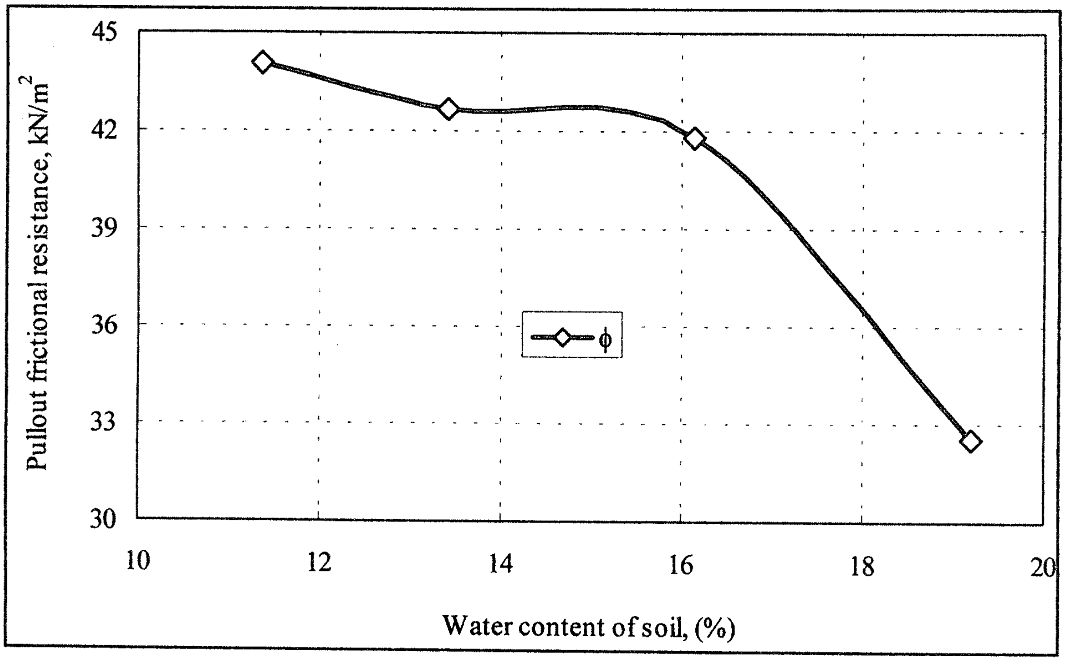

Fig. 17. Pullout frictional resistance versus water content of soil.

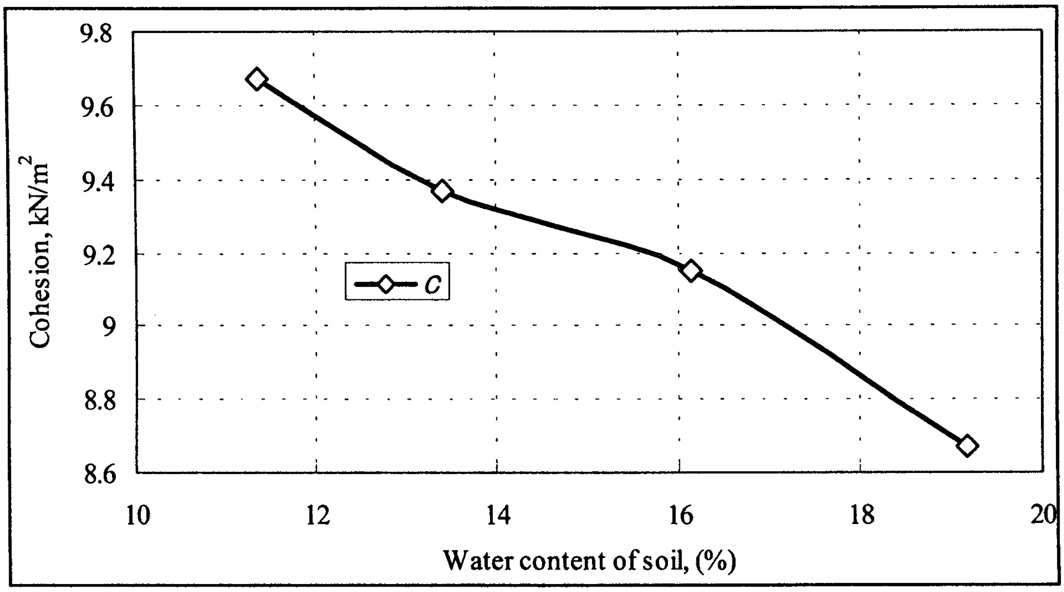

Fig. 18. Cohesion versus water content of soil under pullout test.

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 any water content of soil under pullout test in this study, the usual characteristic is that there is an increase in pullout stress with the increase in displacement as well as with the increase in normal stress.
3. Variation in the pullout test results regarding the vertical displacement as well as volumetric changes is a common feature for any amount of water content under different normal stresses.
4. For all the water contents of soil tested in this investigation, it is generally found that the vertical displacement occurred at the start of the horizontal displacement. After that the vertical displacement is increased with the increase in horizontal displacement especially under higher normal stresses for any water content.
5. Equations for strength parameters of reinforced soil such as cohesion and internal friction of the individual water content given in this paper will be useful in the design of reinforced soil structures.
6. In designing reinforced soil structures, the water content far beyond the W_{opt} limit should be taken into careful consideration in view of safety and stability of the reinforced soil structures during on service.
7. The design cohesion values may be taken as the halves of the pullout cohesion values where the soil structures tends to slip over the reinforcement like as a direct shear failure on one surface of the reinforcement.

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) MADHAB, M. R. et al. A theoretical model for the pullout response of geosynthetic reinforcement, *Geosynthetic International*, **5** (4): 399-424 (1998).

4) GURUNG, N and IWAO, Y. Pullout test analysis for georeinforcement, *Geotextiles and Geomembranes*, **17**: 157-170 (1999).

5) 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).

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

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

8) 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).

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

10) 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).

11) SOBHI, S. and WU, J. T. H. An interface pullout formula for extensible sheet reinforcement, *Geosynthetic International*, **3** (5): 565-582 (1996).

12) MAHMOOD, A. A. et al. Studies on geotextiles/soil interface shear behavior, *Electronic Journal of Geotechnical Engineering*, **13**: 1-14 (2002).

13) JEWELL, R. A. Soil strength and bearing capacity, *Soil reinforcement with geotextiles, CIRIA, Thomas Telford*, 55-83 (1996).

補強材の引き抜き強度に対する土含水比の影響について

Md. Zakaria HOSSAIN・井上　宗治

三重大学生物資源学部

補強土構造の全体的な性状は言うに及ばず土中に埋め込んだ補強材の引き強度に対して土の含水比が重要な影響を与えることはよく知られている。その点で載荷状態にある種々のタイプの補強材の引き抜き強度について含水比の変化による効果を定量的に把握しておく必要がある。土〜補強材間の相互作用と含水比との関係を知るために，垂直応力を変化させた一連の引き抜き実験を行った。補強材として3mm間隔で径0.8mmの正方形ワイヤーメッシュを用い，引き抜き強度に関するパラメータとして土の粘着力とせん断抵抗角を測定した。また，これから得られる応力〜ひずみ関係及び体積変化特性を実際の設計，施工に利用できるように種々のチャートと図に表した。結論として，補強材の引き抜き強度と土の含水比との間に強い相関性が見られ，含水比の増加とともに粘着力，せん断抵抗角成分が減少していく傾向が明らかとなった。