Finite Element Analysis of the Pull-out Test

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요 지

인발시험은 보강토 구조물의 설계에 있어 보강재와 흙사이의 강도 정수를 결정하는데 사용된다.

그러나 이 시험의 해석시 보강재를 따라 발생하는 전단강도가 일정한 것으로 가정하는데 이는 인발시험중 흙과 보강재 사이의 점진성 전단으로 인해 흙과 보강재의 전단－변위 관계 계산시 오류가 발생하게 된다.

흙과 보강재 사이의 shear stiffness계산시 점진성전단의 영향을 평가하기 위하여 유한요소법으로 인발시험을 해석하였다. 흙과 보강재는 선형과 비선형거동으로 해석하였고 shear stiffnss는 일반적인 방법으로 계산하였는데 수정된 shear stiffness와는 많은 차이가 있었으며 그 차이로 인해 유한요소해석의 결과가 달라지게 된다. 본 논문에서는 유한요소해석결과와 시험치를 비교 분석하였으며 개선된 인발시험 해석방법에 대하여 논하였다.

Abstract

The pull-out test is a common test for detemining the strength and deformation parameters between reinforcement and soil in the design of reinforced earth structures. It is often assumed in the interpretation of the results from the test that the mobilization of shear strength along the reinforcement is uniform. The progressive shearing at the soil-reinforcement interface during the pull-out test often leads to incorrect calculation of the shear-displacement response between the reinforcement and the soil.

To investigate the effect of progressive shearing during the calculation of the shear stiffness of the soil-reinforcement interface, the finite element method is used to simulate the pull-out test. The reinforcement, soil, and interface behaviors are modeled by using linear and non-linear constitutive models. Shear stiffnesses are calculated by using conventional methods. It is found that there are considerable discrepancies between the calculated shear stiffnesses and the correct stiffnesses which are used in the finite element analysis. The amount of error depends on the relative stiffness between reinforcement and soil and the size of the specimen being analyzed. The finite element results are also compared with the observed response from laboratory experiments. A revised interpretation of the pull-out test results is discussed.

Keywords : Pull-out Test, Finite Element Analysis, Progressive Shearing, Shear Stiffness

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1. Introduction

Design of reinforced soil using geosynthetics currently adopts a limit equilibrium approach. In this approach the stability of the structure is evaluated at a limiting state of incipient failure satisfying force equilibrium but not strain compatibility. A satisfactory design emerges from the analysis by ensuring an adequate factor of safety for the structure. Although this current procedure is a logical extension of the well established method of designing and analyzing unreinforced soil, there is one basic difference between the reinforced and unreinforced structures ; namely, the unreinforced structure usually consists of one material while the reinforced structure has at least two materials. The calculation of one factor of safety for the reinforced soil assumes the same degree of mobilization of shearing resistance for the soil and the reinforcement, which is not true for most serviceability conditions except at the state of incipient failure. The use of partial factors of safety is an attempt to account for such discrepancies in mobilized resistance. Thus, reinforced soil structures from a composite material and the deformation in the backfill soil and the reinforcement must satisfy compatibility. However, it is recognized that the calculation of mobilized resistance should account for strain compatibility. The importance of strain compatibility in a reinforced soil analysis has been discussed by Beech(1987). Procedures have been proposed to incorporate strain compatibility in conventional methods of design(Rowe and Mylleville, 1989). Proper account of strain compatibility can only be made by using a deformation analysis. The finite element method is well suited for this purpose.

Numerous studies have been carried out to use the finite element method in analyzing reinforced soils(Schaefer and Duncan, 1988). In most of the finite element analyses, the soil is modeled by using conventional solid elements. The reinforcement is generally modeled by using flexible beam elements incapable of providing bending or compressive resistance. The connection of the reinforcement and the soil can be modeled in two ways. The first approach assumes that the reinforcement is firmly bonded to the soil, allowing no slip until the shear stress between the two materials reaches a critical value. This critical value is often determined using the Mohr-Coulomb failure criterion modified to account for the reduced resistance at the interface. Once slip occurs at the interface, a limiting shear stress is applied on the reinforcement and the soil. This approach requires no special treatment at the interface between the soil and reinforcement.

The second approach is to model the soil and reinforcement interface by using an interface element such as that proposed by Goodman et al.(1968) or Carol and Alonso(1988). Movement, or partial slip, is allowed between the soil and the reinforcement. This relative movement is controlled by a shear stiffness, ks, until the shear stress is sufficiently high to cause slippage. To assess the soil-reinforcement interface characteristics such as interface friction angle and the shear stiffness, pull-out tests and/or shear box tests are commonly employed. Although the choice of test to obtain the relevant characteristics is a matter of debate, pull-out tests have been generally acknowledged to provide a better simulation of the behavior of reinforcements in reinforced soil structures(Garbulewski, 1990 : Venkatappa and Kate, 1990).

The numerical modeling and the mechanism of the pull-out test are described in this paper. Numerical modeling of the pull-out test was carried out by applying a corrected shear stiffness which considers the progressive development of stress and strain in the reinforcement. The implication of assuming uniform shear stress in calculating the shear stiffness from the results of the pull-out test was examined in detail. Results were compared to examine the effect of progressive deformation on the pull-out test and to understand the pull-out resistance mobilization process.

2. Pull-out Test Mechanism

The mobilization of a pull-out resistance is a complicated process. The pull-out resistance of the geogrid reinforcement is basically mobilized by three interaction mechanisms : soil friction on the longitudinal member of the reinforcement, soil passive resistance on the transverse elements, and particle interlocking in the apertures in the reinforcement as shown in Fig.1. The mechanisms by which the reinforcement develops depend on the size of the apertures, stiffness, geometry, roughness of the surface of the reinforcement, and the grain size of the soil. For a small soil-reinforcement displacement there is initially a mobilization of the friction along the longitudinal element of the reinforcement. The soil passive resistance on the transverse element is mobilized under a larger displacement which is influenced by the stiffness, structure, and geometry of the reinforcement(Schlosser and Delage, 1987). However, friction and passive soil resistance are not necessarily additive and some relative reinforcement and soil displacement occur for either friction or passive soil resistance to mobilization. Irsyam and Hryciw(1991) showed experimentally that shear surfaces develop around the ribs of the reinforcement during the shearing process. The particle interlocking resistance is often neglected because the particles of the soil are significantly smaller than the fiber or grid spacing and the grains cannot effectively interlock within the geosynthetics apertures(Sarsby, 1985). The soil passive resistance on the transverse elements plays an important role on the total pull-out resistance. It is a function of soil cohesion, friction angle, and the bearing capacity factor(N_q) in the Terzaghi bearing capacity equation. The expression for N_q depends on the assumed failure mechanisms such as the general shear failure mode and the punching failure mode, which provide apparent upper and lower bounds of actual pull-out test results(Jewell et al., 1984).

When a load is applied to the front end of the reinforcement, shear stresses at the soil-reinforcement interface are developed as the reinforcement is strained. Load is then transferred progressively along the entire length of the reinforcement. In extensible grid reinforcement under the influence of pull-out force, considerable elongation of grid longitudinal members will occur. The magnitude of the mobilized resistance of each bearing member varies along the pull-out direction. The maximum resistance occurs at the front bearing member. In addition, under an applied pull-out force and a confining pressure, only a certain portion of the grid reinforcement has a relative displacement with the backfill soil. Therefore, the mobilized shear stress along the reinforcement during the pull-out test may have a highly non-uniform distribution. It is possible that the shearing process might not occur at the rear part of the reinforcement. However, for inextensible reinforcement the pull-out resistance may mobilize the entire length of the reinforcement under a small relative displacement, and a uniform shear stress distribution along the entire length of the reinforcement.

When the load at the pull-out slot is applied and the mobilized frictional resistance is greater than the rupture strength of the reinforcement, the reinforcement ruptures. On the other hand, if a shorter length of reinforcement is used, the frictional resistance along the reinforcement is lower, thus allowing displacement to occur over the entire length of the reinforcement. If the load generated is higher than the frictional resistance developed along the entire length of the reinforcement, slippage of the reinforcement will occur. Frictional resistance can be assessed based on the normal stress on the reinforcement and the friction angle, which depends on the soil and properties of the reinforcement. To prevent the slippage failure of the reinforcement in reinforced soil structures the use of a higher confining stress or granular materials are needed as backfill materials. Understanding the pull-out resistance mobilization process is important because the reinforced soil structure does not always work at a limit equilibrium condition. Thus, the designed pull-out resistance should be compatible with the deformation condition of the structure, i. e., the deformation in the backfill soil and in the reinforcement must be compatible.

3. Shear Stiffness

The interaction between the grid reinforcement and the soil has two components : the passive soil resistance and the frictional resistance. The contribution of the soil passive resistance to the interaction between the reinforcement and the soil is considered to be substantial. The passive soil resistance is usually expressed as effective bearing resistance which can be developed on the transverse members, and is a function of the vertical effective stress. A definition of shear stiffness used to simulate the interface behavior between the soil and the reinforcement is

$$k_s = \frac{\Delta\tau}{\Delta\delta} \tag{1}$$

where $\Delta\tau$ is the change in shear stress and $\Delta\delta$ is the corresponding change in relative displacement between the soil and reinforcement.

The shear stiffness expressed in Equation (1) depends on the soil and type of reinforcement and it is often determined experimentally for use in a finite element analysis. The direct shear and the pull-out tests are commonly used to determine the interaction properties between the soil and the reinforcement. In particular, the pull-out test simulates the anchorage condition of the reinforcement and provides an estimation of the pull-out resistance for design. It is also used to provide an estimate of the shear deformation between the reinforcement and soil (Katagiri et al., 1990). In calculating the shear stiffness by using Equation (1), it is necessary to calculate the shear stress acting on the reinforcing material. In calculating the shear stress it is assumed that the mobilization of shear stress is uniform along the reinforcement and the change in shear stress is given by

$$\Delta\tau = \frac{\Delta P}{2A} \tag{2}$$

where ΔP is the measured change in axial force and A is the one-sided surface area of the reinforcement. Therefore, Equation (1) becomes

$$k_s = \frac{\Delta P}{2A\ \Delta\delta} \tag{3}$$

The change in displacement in Equation (3) is often taken as the displacement measured on the reinforcement at the pull-out slot. However, the shear stiffness value is clearly a function of the specimen size.

Shear stiffness is also expressed as a non-linear form, stress-dependent and inelastic which represented by a hyperbolic model similar to that for soil. The shear stiffness, k_s is expected to decrease with increasing shear stress and displacement, as the applied shear stress approaches the shear strength of the interface. In other words, there could be nonlinear variation of shear stiffness with respect to shear stress levels. If the interface element is in tension or has a shear stress above the failure level, then the shear stifffness is reduced to a very small value.

It is recognized that the mobilization of shear stress is non-uniform along the extensible reinforcement. At failure, that is, at the fully slipping condition, the mobilization of shear strength is approximately uniform if the interface does not possess a strain weakening characteristic. Most granular material used in reinforced soil structures does not exhibit strain weakening behavior. For clayey soil, the strain weakening behavior results in non-uniform mobilization of shear strength.

It is possible to account for the non-linear characteristic of k_s with respect to the displacement as well as the normal stress(Katagiri et al., 1990). However, the assumption of

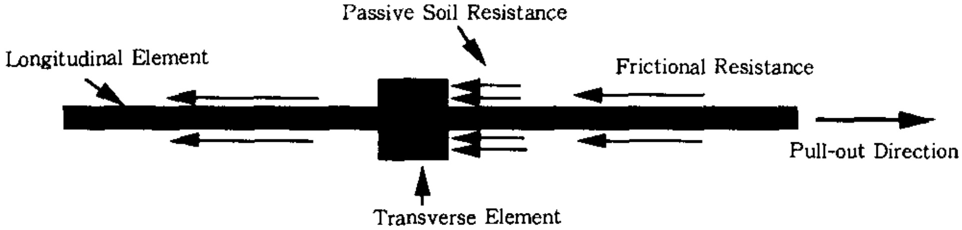

Fig. 1 Load Transfer Mechanism of Grid Reinforcement

uniform shear stress can produce serious error in obtaining k_s. The mobilized shear stress is highly non-uniform along the reinforcement during the loading process. Although the shear stress can be estimated by using the load transfer approach proposed by Coule and Reese(1966) the corresponding relative displacement cannot be determined easily.

4. Finite Element Modeling of the Pull-out Test

The pull-out test is simulated by using the finite element method. An interface element is used, which is capable of sustaining tensile stress but not the bending or compressive stress. A description of the formulation of the joint element can be found in Chalaturnyk (1988).

A two dimensional plane strain idealization of the pull-out specimen is shown in Fig.2. A total of 170 elements, including 17 reinforcing and 34 interface elements, with 636 nodes is used in the simulation. The reinforcing elements are a three node element capable of sustaining only tensile stress. The interface is modeled by a 6 node element. An eight node isoparametric element is used to simulate the soil.

An actual experimental set-up with 1050×200×760mm pull-out box carried out at the University of Alberta is used for modeling(Costalonga, 1988). The reinforcement is extended from one side of the box to the other side. The advantage of this arrangement is that the area of contact between the reinforcement and soil remained constant throughout the experiment. Also the displacement of the reinforcement at the opposite end of the

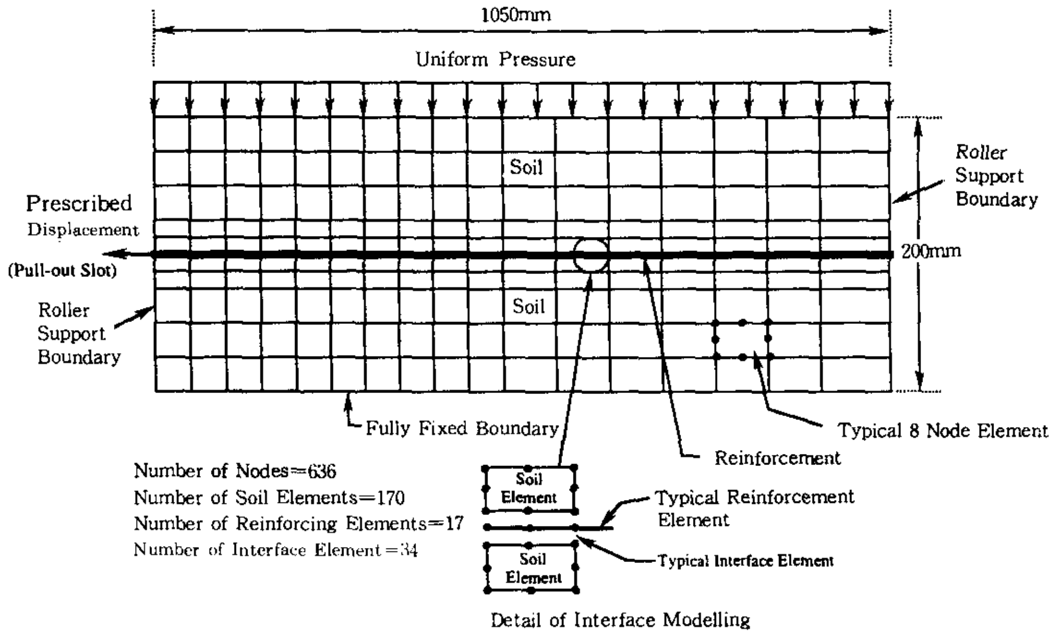

Fig. 2 **Finite Element Idealization of Soil and Reinforcement for Pull-out Test**

pull-out slot can be monitored to determine the load at which movement occurs. A pyramidal steel bar is used to apply the uniform vertical load. Piano wires are attached to the reinforcement and connected to LVDTs(Linear Variable Differential Transformer) to measure the displacement of the reinforcement during the test.

The reinforcement is modeled by using a non-linear force-strain relationship. The tensile force in the reinforcement can be expressed as

$$F = D_i\left(\varepsilon_a - \frac{\varepsilon_a^2}{2\varepsilon_f}\right) \tag{4}$$

where D_i is the initial load modulus and ε_f is the axial failure strain in the reinforcement.

Equation (4) is based on a parabolic relationship between stress and strain developed in the reinforcement. This is found to be a good approximation for polymeric geogrid within the range of strains of interest in this study.(Chalaturnyk, 1988). The reinforcement which is studied is Tensar SR-2 geogrid. The force vs. strain relationship used in the present modeling is shown in Fig.3. The force-strain relationship is considered not to be time-dependent.

The shear behavior of the interface between the soil and the reinforcement is modeled using an elastic-plastic model. The shear modulus remained constant until a failure condition is reached along the interface. The failure condition is defined by the Mohr-Coulomb relationship :

$$\tau_f = c + \sigma_n \tan\delta \tag{5}$$

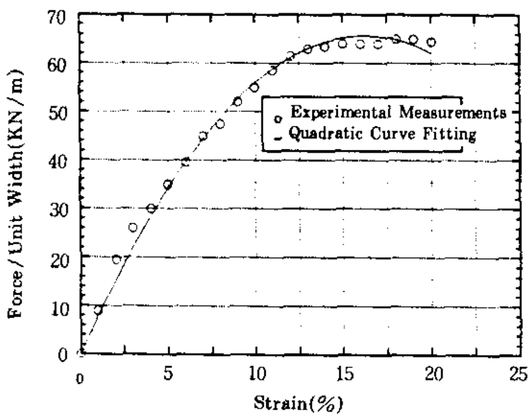

Fig. 3 Load-strain Response of Tensar SR-2 Used in the Simulation(strain rate : 2%/min.)

where c and δ are the cohesion and frictional resistance between the soil and the reinforcement and σ_n and τ_f are the normal and shear stress on the reinforcement respectively.

In the finite element analysis the shear stress at each integration point is checked with the failure criterion. If failure is reached, a constant shear stress is applied and maintained at the integration point throughout the remainder of the analysis.

A linear elastic model is used to model the behavior of the soil. Since it is expected that the amount of straining in the soil will be smaller than the strain in the interface and reinforcement, the initial tangent modulus, based on triaxial testing of the soil, is used to calculated the elastic parameters for the model. A summary of the material parameters used in the analysis is given in Table 1. The shear stiffness for the interface is calculated on the basis of the pull-out test conducted by Costalonga(1988). The normal stiffness, k_n, is assigned a very high value to prevent incompatibility in the normal direction.

In simulating the pull-out experiment, a vertical uniform pressure of 51 kPa and the weight of the soil are applied prior to imposing force on the reinforcement located at the

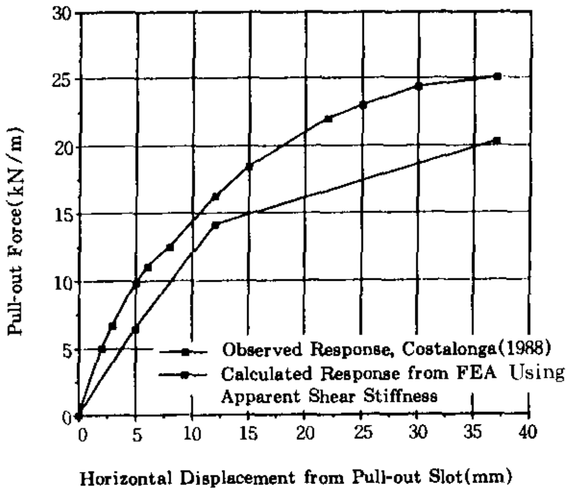

Fig. 4 Calculated and Observed Force-Displacement Response of Reinforcement

Table 1. Summary of Material Properties Used in the Finite Element Analysis

Silty Clay	Unit Weight(kN/m^3)	18.86
	Initial Elastic Modulus(kPa)	3600
	Poisson's Ratio	0.36
	Cohesion(kPa)	29
	Internal Friction Angle(°)	20
Geogrid	Tensile Strength(kN/m)	78.8
	Initial Load Modulus(kN/m)	800
	Failure Strain(%) ε_f	16.4
Interface	Normal Stiffness(kN/m^3), Kn	1.0×10^{17}
	Shear Stiffness(kN/m^3), Ks	1240
	Cohesion(kPa), C	2
	Friction(°)	14

mid-height of the apparatus. The pull-out forces acting on the reinforcement during the test are calculated from prescribed displacements specified on the reinforcement at the pull-out slot. The reinforcement is extended to the back of the apparatus which gives a constantly embedded length during the entire shearing process.

5. Results of Finite Element Analysis

The forces-displacement response calculated from the finite element analysis is shown in Fig.4. It is seen that the finite element model underestimated the force required for certain displacements. For the analysis shear stiffness is calculated on the basis of the observed load-displacement response from the pull-out test. It is clear that the assumption of uniform mobilized shear stress along the reinforcement used in calculating the shear stiffness underestimated the actual shear stiffness. Katagiri et al.(1990) also simulated the pull-out test and the calculated response was lower than the experimental observations.

The mobilized shear stress along the reinforcement is shown in Fig.5. As a result of the progressive shearing along the interface between the soil and reinforcement, the mobilized shear stress is highly non-uniform. The calculated shear stress decreases along the reinforcement. The mobilized shear stress remains relatively constant over the porton of the reinforcement where slip has occurred.

In order to calculate the "true" stiffness for use in a finite element analysis, it is required to perform a series of simulations of the pull-out test and determine the apparent stiffness, using Equation (3) from the finite element results. A relationship between the apparent stiffness and the true stiffness can be determined.

It is observed that the stiffness of the reinforcement influences the load transfer mechanism. The degree of progressive deformation will depend on the relative stiffness between

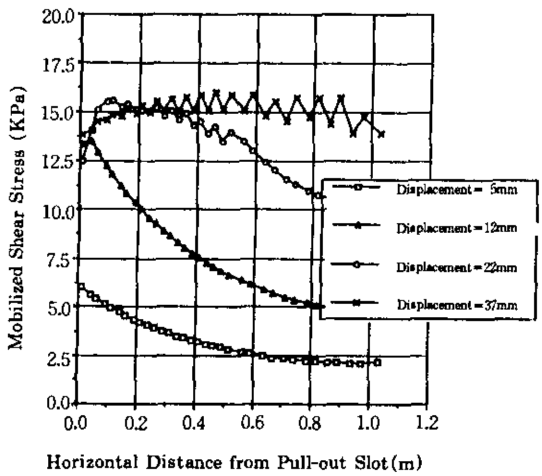

Fig. 5 Mobilized Shear Stress along the Reinforcement

the reinforcement and the interface. It is therefore appropriate to introduce a quantity called the true stiffness ratio, r. The true stiffness ratio is defined as the ratio of the true stiffness of the interface, k_{st}, to the initial stiffness of the reinforcement, k_{ri},

$$r = \frac{k_{st}}{k_{ri}} \tag{6}$$

For very stiff reinforcements such as metalic strips, the value of r is relatively small and the mobilized shear stress and displacements along the reinforcement are uniform. Very soft reinforcement, such as nonwoven geotextile, develops non-uniform shear stress and displacements along the reinforcement. The value of r will be relatively high for this material. It is expected that a higher value of r will result in a larger error when calculating the shear stiffness from the pull-out test results. A series of numerical simulations of the pull-out test was carried out for different values of the stiffness ratio. In each analysis, a shear stiffness, K_{st}, was specified for the interface between the soild and reinforcement. The apparent stiffness K_{sa}, was calculated from the load-displacement response. The result of the analysis is shown in Fig.6. As r increases, i. e., the stiffness of the reinforcement decreases, progressive shearing becomes more significant and the discrepancy between the apparent shear stiffness and true shear stiffness increases.

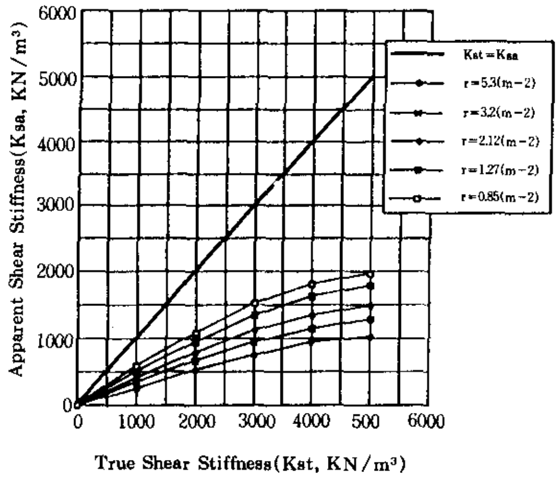

Fig. 6 Relationship between the Apparent and True Shear Stiffnesses

Based on an apparent shear stiffness of 1.24x $10^3 \times kN/m^3$, a true shear stiffness value for use in the finite element analysis was found to be 2.0×10^4 kN/m^3. Fig.7 shows the observed and calcuated load-displacement response by using both the apparent and true stiffnesses. It is seen that the corrected stiffness provides better agreement between calculated and observed values. The mobilized shear stress along the reinforcement at different stages of the test is shown in Fig.8. Since the true stiffness is higher than the apparent stiffness, the mobilized shear stress using the true stiffness is higher than that calculated by using the apparent stiffness for a given displacement of the reinforcement. The mobilized shear stress is the same for both cases when slipping occurs.

The calculated displacement along the reinforcement is also compared with the experimental results at a displacement of 37mm. The results shown in Fig.9 indicate that the finite element solution slightly overestimated the displacement along the reinforcement. It is interesting to note that the difference between the calculated and the observed displacements remains relatively constant along the entire length of the reinforcement.

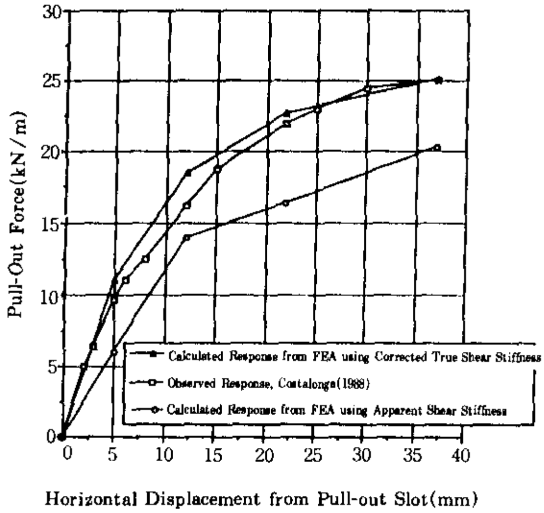

Fig. 7 Calculated and Observed Force-Displacement Response of the Reinforcement in the Pull-out Test

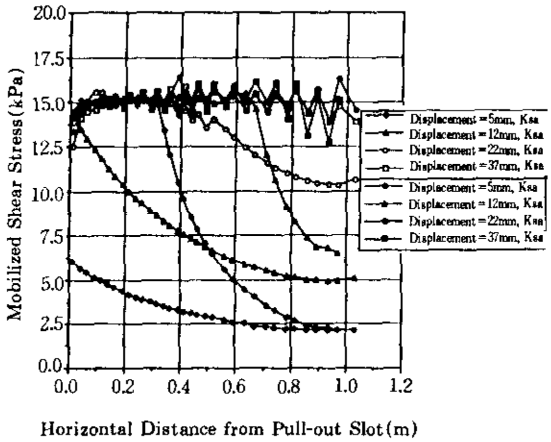

Fig. 8 Mobilized Shear Stresses along the Reinforcement

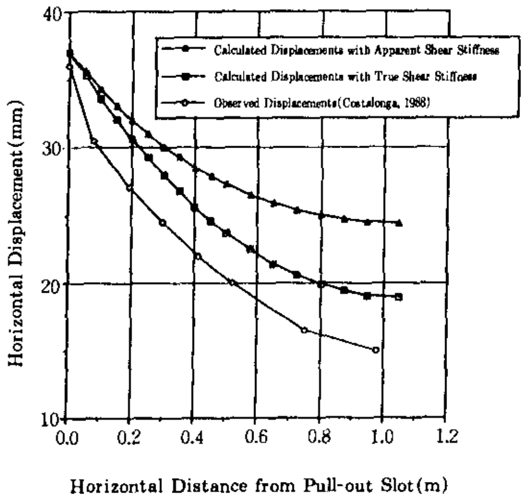

Fig. 9 Comparison of Horizontal Displacement along Reinforcement

6. Conclusion

The pull-out test was simulated numerically by using the finite element method. It was found that the mobilization of shear stress along reinforcement is highly non-uniform during the initial stage of the test. If the force-displacement response of the pull-out test was used to obtain a shear stiffness for modeling the interface between the soil and the reinforcement, the assumption of uniform stress distribution can result in considerable error between the apparent shear stiffness and the true shear stiffness values. This discrepancy depends on the relative stiffness between the interface and the reinforcement. It was illustrated that stiffer reinforcement results in less degree of progressive shearing and, therefore, results in less discrepancy between the true and apparent stiffness values. The true stiffness can be estimated from the results of the pull-out test by using an appropriate stiffness correction. The calculated force-displacement response using true stiffness value gives better agreement with the experimental observations.

Notations

A	One side surface area of reinforcement
δ	Change in relative displacement between soil and reinforcement
D_i	Initial load modulus
$\Delta\delta$	Change in axial force along reinforcement
$\Delta\tau$	Change in shear stress
ε_a	Axial strain in reinforcement
ε_f	Axial strain at failure of reinforcement
F	Tensile force of reinforcement
kri	Intial stiffness of reinforcement
K_s	Shear stiffness of interface
k_{sa}	Apparent stiffness of interface
k_{st}	True stiffness of interface
N_q	Bearing capacity factor
r	True stiffness ratio
σ_n	Normal stress on reinforcement
τ_f	Shear stress on reinforcement

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