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Function and evaluation of steel bars in earth reinforcement

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ABSTRACT : In order to investigate the behaviour of a reinforced cut-off slope with steel bars and the function of steel bars in earth reinforcement, two series of laboratory tests were performed. One is a series of model tests for simulating a reinforced cut-off slope with steel bars, and the other is a series of simple shear tests on reinforced sand specimens. In the model tests, to clarify the function of the reinforcement and the effects of bending stiffness of steel bars, both phosphorus bronze bars bonded to sand particles and ball chains which have no bending stiffness were used as reinforcing materials. Based on the results of these tests, a theory on the lateral resistance of foundation piles is applied to evaluate the shear resistance of reinforcing steel bars.

1 INTRODUCTION

Earth reinforcement with steel bars, which is called "soil nailing" in Europe or the United States, has been used from the 1960's in Japan under the name "nuiji (sewing earth)" or "sashikin (injecting steel bars)" for the purpose of stabilizing of the natural slopes and of the entrance of tunnels. The technique has proved to be a versatile and effective method of construction, however many consultants and contractors are still not using the technique in a routine fashion. One reason for this can be attributed to the perceived uncertainty for design caused by the many concepts and terms that have been introduced to describe the behaviour of earth reinforcement with steel bars and especially the role of the reinforcement bending stiffness.

Firstly, to investigate the effects of bending stiffness of reinforcing materials on the behaviour of earth reinforcement of a cut-off slope with steel bars in the case of a thin deposit layer as shown in Fig. 1, a series of model tests simulating a sliding force acting on the cut-off slope was performed. Both phosphorus bronze bars and ball chains were used as reinforcing materials in the model test.

Secondary, a series of simple shear tests on reinforced sand specimens with the phosphorus bronze bars has been performed. Then, a theory on the lateral resistance of foundation piles is applied to evaluate the shear resistance of reinforcing steel bars.

2 MODEL TEST OF CUT-OFF SLOPE

2.1 *Testing Apparatus and Reinforcing Materials*

A reinforced cut-off slope with steel bars for the case of a thin deposit layer is illustrated in Fig. 1. The reinforcements are placed under the conditions of nonuniform strain and are often fixed to the unmoved earth. Figure 2 shows the illustration of the model test apparatus for a reinforced cut-off slope for the case of a thin deposit layer. The side walls of the testing box consisted of 50mm-thick transparent acryl plates with steel stiffeners outside. In order to reduce the effect of side-wall friction, the inside surface of each acryl plate was lubricated by means of a thin silicone grease layer and a 0.2mm thick latex-rubber membrane.

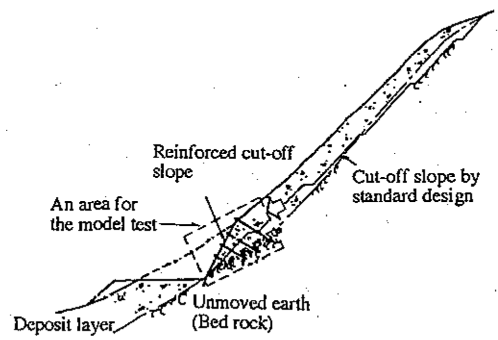


Fig. 1 Illustration of a reinforced cut-off slope with steel bars in case of thin deposit layer

In the model tests, phosphorus bronze bars of 3mm in diameter bonded to sand particles and stainless steel ball chains of 3mm in diameter were used as reinforcements. The length of these reinforcing materials and the positions of attached strain gauges are shown in Fig. 3. Twenty-eight reinforcements of 4 steps and 7 rows were connected to the bottom of the testing box with the pin hinge of

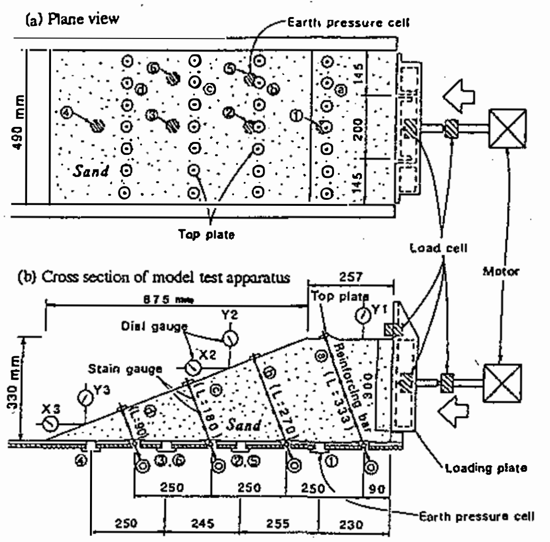


Fig. 2 Illustration of the model test for a reinforced cut-off slope in case of thin deposit layer

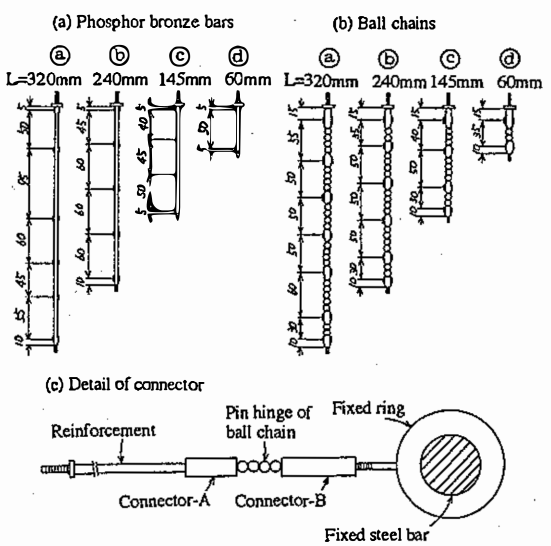


Fig. 3 Reinforcing materials for model tests and position of pasted strain gauges

a ball chain as shown in Fig. 2. Every reinforcement was equipped with a top plate of 3cm diameter made of a light metal. Toyoura sand was used for making the model slope. A densely packed slope of D_r=82% was prepared by allowing the sand in an air dry state to drop freely through a multi-layered screen from the height of approximately 94cm and at a discharge rate of approximately 6.3 kg/min. The sliding force acting on the cut-off slope was horizontally loaded by means of the loading plate in Fig. 2. The normal force and shearing force on only the central third of the loading plate were measured by means of load cell.

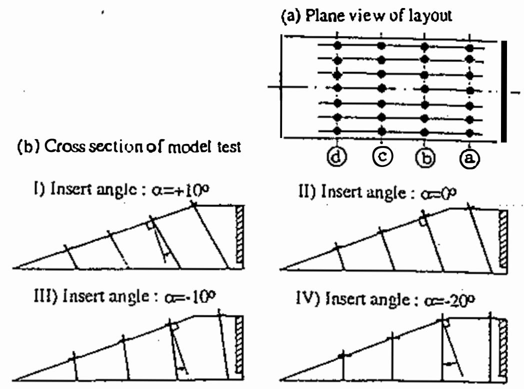


Fig. 4 Insert angle and position of reinforcing materials in the slope model tests

2.2 *Testing Cases and Results*

Figure 4 shows the insert angles and the positions of reinforcing materials in the slope model test. However, a test for the insert angle α=-20° on the ball chains wasn't performed.

As an example of the results of model test, the relationships between the normal stress and displacement of the loading plate are shown in Fig. 5. Figure 5.(a) shows the result of tests which used the phosphorus bronze bars as reinforcements and (b) shows the result on the ball chains. In the case of reinforced slope by phosphorus bronze bars, which has not only frictional resistance of reinforcement surface but also bending stiffness in spite of the insert angle, the normal stress - displacement curves of the loading plate are close to each other until a displacement of approximately 10mm. The stress ratio R expressing the effects of reinforcement, which is defined by a following formula, ranges between 3.6 to 3.9.

$$R=\frac{\tau_{Reinf.}\ \text{(Normal stress on reinforced slope test)}}{\tau_{Nonrein.}\ \text{(Normal stress on nonreinforced slope test)}}$$

During displacements between 10mm to 20mm, influence of the insert angle appears on the normal stress and in the case of the insert angle α=-10° and -20°, the reinforcement ratio decreases to 2.6 and 3.2. After a displacement of approximately 20mm, the reinforcement ratio of all cases again increases gradually as the displacement increases.

In the case of reinforced slope by ball chains, which has only tensile resistance, the effects of reinforcement R ranges between 3.4 to 3.5 at a displacement of approximately 10mm except in the case of α=-10° in which compressive stress in the reinforcement is observed at the initial displacement.

The difference of behaviour and reinforcing effects on these model tests depends upon the difference of reinforcing materials. Especially, it's very important that the high reinforcing effect in the initial displacement is obtained by using the reinforcing materials having bending stiffness in spite of the insert angle.

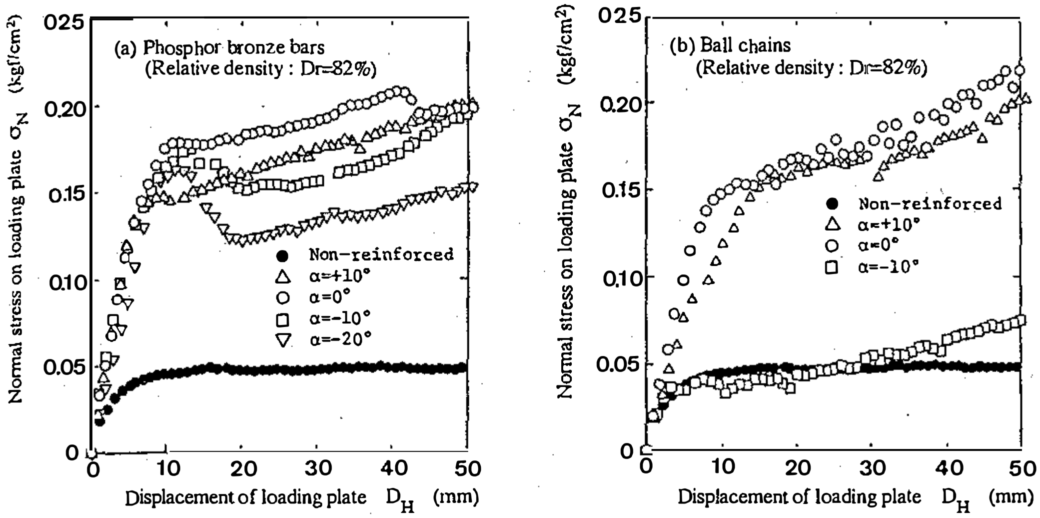


Fig. 5 Relationship between normal stress and displacement of loading plate

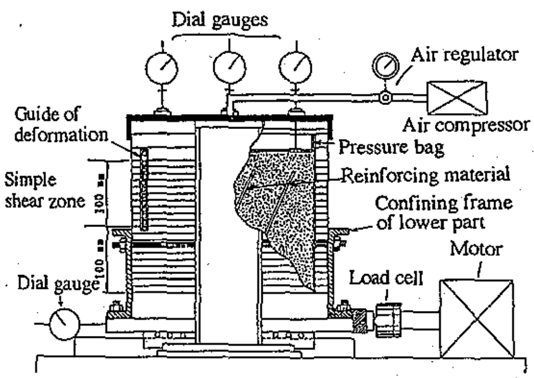


Fig. 6 Illustration of a simple shear apparatus

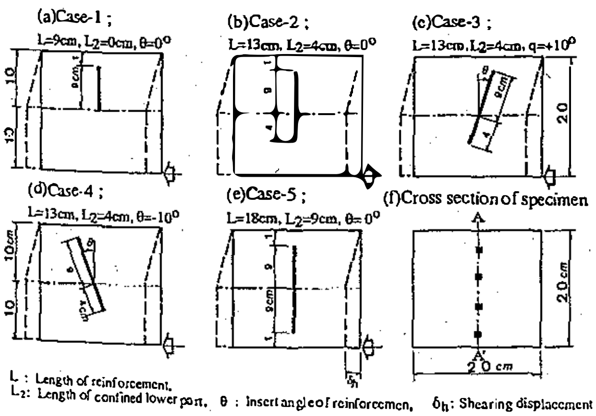


Fig. 7 Test case and layout of reinforcement

3. SIMPLE SHEAR TEST

3.1 *Apparatus and Testing Cases*

Figure 6 shows an illustration of the simple shear test apparatus. The cubical shear box of 200 x 200 x 200mm consists of twenty elements made of aluminum plate. The friction between elements is reduced by using flat bearings. Due to conducting a simple shear test of reinforced specimen with steel bars under the nonuniform and discontinuous strain condition as described above, the ten elements of the lower part were fixed by steel frames and the ten elements of the upper part are restrained by four guided pins and rods to make the shear deformation uniform. As the specimen is cubical and is covered with a latex rubber membrane of 0.3mm in thickness, the test can be conducted in a plane strain condition. In this test, for the purpose of strictly measuring the bending and the axial strain of reinforcements by means of strain gauges, phosphorus bronze square bars of 4mm x 4mm were used. The reinforced specimen by means of using Toyoura sand was prepared by the same method as mentioned above in the model test to keep the relative density of 82% constant.

The test were conducted by changing the length of reinforcing materials from 9cm to 18cm and the direction angle θ of reinforcement from -10° to +10°. The test case and layout of reinforcements in the specimen are illustrated in Fig. 7.

3.2 *Test Results and Discussions*

The simple shear tests were performed under a normal stress loading of σ_n=0.75 kgf/cm^2 and under a controlled shear displacement velocity of 1 mm/min. Figure 8 shows the relationships between shearing stress and displacement obtained from the simple shear test.

The stress-displacement curve of the Case 1, of which the reinforcements are 9cm in length and are situated in uniform strain area, is close to the curve of the nonreinforced specimen. The observed tensile stress of the reinforcement increases as shear displacement increases, however, as only one row of four reinforcing bars was installed in specimen and

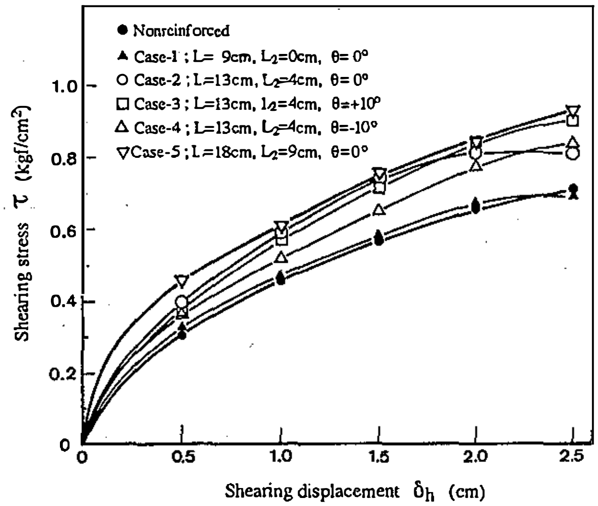


Fig. 8 Relationship between shearing stress and shearing displacement

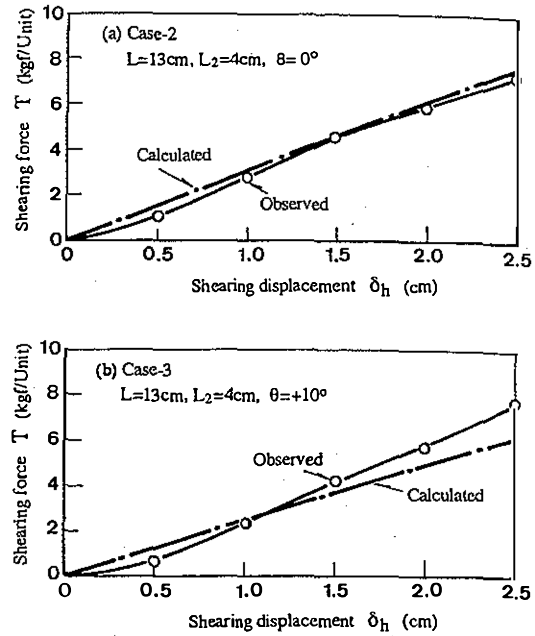


Fig. 9 (1) Relationships between shearing force and shearing displacement

the bending moment of the reinforcement did not occur, the effect of reinforcement is very small.

On the other hand, in Cases 2 to 5, of which the reinforcements are 13cm or 18cm in length and are spanned over uniform strain zone and confined area of lower part of specimen, not only the axial stress of reinforcement but also the bending moment of reinforcement increase as shearing displacement increases, so the marvelous effects of reinforcements are recognized as shown in Fig.8.

Here, in further detail, the magnitude of axial stress occurring in the reinforcement is affected by the direction angle θ of reinforcement and the shearing displacement. In Cases 2, 3 and 5 with θ =0° or +10°, tensile stress in the reinforcement occurs from the initial stage of shearing displacement and increases as shearing displacement increases. While in Case 4 with θ =-10°, in the initial stage of shearing displacement, compression stress occurs as axial stress in the reinforcement. Then, after the shearing displacement becomes approximately 1cm, the axial stress changes to a tensile stress.

On the other hand, in every case except the Case 1, the bending moment of reinforcement is mobilized from the initial shearing displacement. In the cases of the same length of reinforcement, the distribution shape of observed bending moment is similar to each other, however the magnitude of bending moment is the largest in Case 4 with θ=-10° and decreases in order for θ =0° and +10°. Comparing between Case 2 of 13cm length and Case 5 of 18cm length, with the same insert angle, the longer the length of reinforcement was, the larger the magnitude of bending moment observed and, resultantly, the higher the effect of reinforcement was recognized.

3.3 *Role and Evaluation of Reinforcements*
(1) Evaluation of shearing force

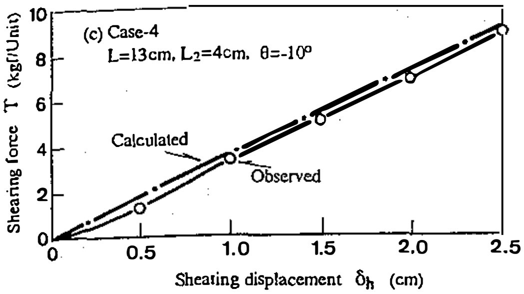
A mobilizing mechanism of shear resistance on the reinforcing steel bars which is installed across a sliding surface or a nonuniform strain zone must be similar to the development mechanism of lateral resistance on a foundation pile loaded by a horizontal force. Therefore, by means of invoking a evaluation formula for the lateral resistance of a foundation pile, the following equation is proposed for the evaluation of the shearing force of a reinforcement:

$$T = C\,(1-\sin\theta)\,EI\,\xi^3\,\delta_h \quad \cdots\cdots\cdots\cdots \quad (1)$$

Where,

- T : Shear force in a steel bar occurring at the intersection with the sliding surface (kgf/unit)
- C : Coefficient related to the reinforcement and soil, $C=f\,(L_1, L_2, \xi)$
- L_1, L_2: Length of reinforcement in sliding mass and unmoved ground, respectively (cm)
- ξ : Coefficient of the stiffness of reinforcement and soil, $\xi = (k_h\,D/4EI)^{1/4}$ (kgf·cm^{-1})
- k_h : Coefficient of subgrade reaction (kgf·cm^3)
- EI : Bending stiffness of reinforcing material (kgf·cm^2)
- D : Diameter of reinforcement (cm)
- δ_h : Shearing displacement (cm)

Figure 9 shows the comparisons between the calculated shearing force by Equation (1) and the obtained shearing force by using the observed bending moment of reinforcement at the intersection with the discontinuous strain surface. As shown in Fig.9, in spite of the insert angle and the length of reinforcement, in every case the calculated shearing force agrees well with the observed one in all stages of displacement. It's therefore recognized that the



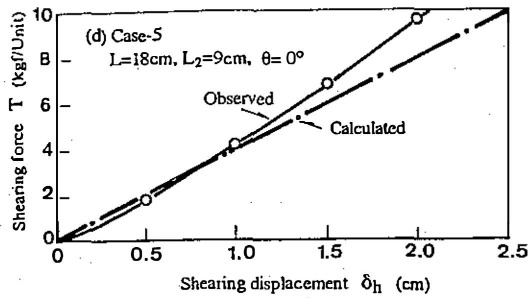


Fig. 9 (2) Relationships between shearing force and shearing displacement

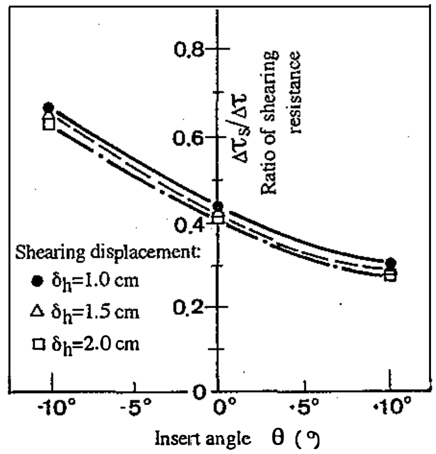


Fig. 10 Effects of bending stiffness and insert angle of reinforcement on shearing resistance

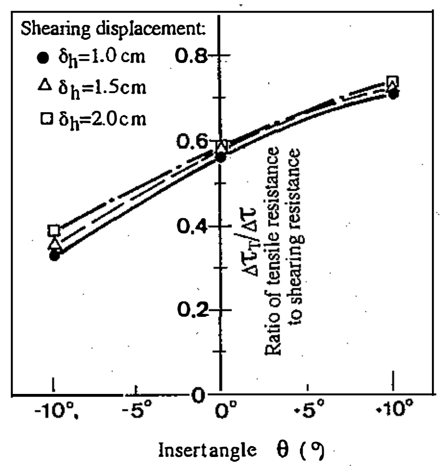


Fig. 11 Effects of tensile resistance and insert angle of reinforcement onshearing resistance

shearing force of a reinforcement which is situated in a nonuniform strain condition can be evaluated by the proposed equation (1).

(2) Role of shearing force in reinforcement effects

The additional component of the shearing strength of a reinforced specimen by the shearing force occurring at the discontinuous strain surface can be calculated by the following equation.

$$\Delta\tau_S = nT/A \quad \cdots\cdots (2)$$

Where,
- T : Shearing force calculated by Eq. (1) (kgf/unit)
- n : Number of reinforcements
- A : Cross section area of specimen (cm^2)

Figure 10 shows the relationships between the ratio of increment of shearing resistance $\Delta\tau_S/\Delta\tau$ and the insert angle as a parameter of displacement. Here, $\Delta\tau_S$ is obtained by the equation (2) and $\Delta\tau$ is the total increment of shearing resistance of specimen added by reinforcements. From figure 10, the role of shearing force of the reinforcing materials in reinforcement effects is very important and is influenced by the insert angle of reinforcement, as it is approximately 30% in the case of an insert angle of +10° and it becomes 60% in the case of -10°.

(3) Role of tensile force in reinforcement effects

On the other hand, for the role and the evaluation of tensile resistance of reinforcing materials, various methods have been already proposed. One of these is the following equation proposed by Jones (1984);

$$\Delta\tau_T = \Sigma(P_R/A_S)\cdot(\cos\theta \tan\phi + \sin\theta) \quad \cdots\cdots (3)$$

Where,
- P_R : Tensile force in reinforcement occurring at an intersection with shearing surface (kgf)
- A_S : Reinforcing area shared by one reinforcement (cm^2)
- θ : Inclination angle of reinforcement with sliding surface (°)
- ϕ : Internal friction angle of soil (°)

Figure 11 shows the relationships between the ratio of increment of tensile resistance to shearing resistance $\Delta\tau_T/\Delta\tau$ and the insert angle θ as a parameter of displacement δ_h. The increment $\Delta\tau_T$ is calculated by Equation (3) using the observed tensile force in the reinforcement and $\Delta\tau$ is the total increment of shearing resistance of the specimen added by the reinforcement. As shown in Fig.11, the role of tensile force in the reinforcing materials in proving shearing resistance is approximately 70% in the case of an insert angle of +10° and it becomes 40% in the case of -10°.

(4) Comparison of Reinforcing Effects

The comparisons between the calculated increment of shearing resistance by means of using Equations (2) and (3) and the observed increment of shearing stress of specimen added by reinforcement are shown in Fig. 12. The calculation curves agree well with the observed curve until a shearing displacement of approximately 2mm.

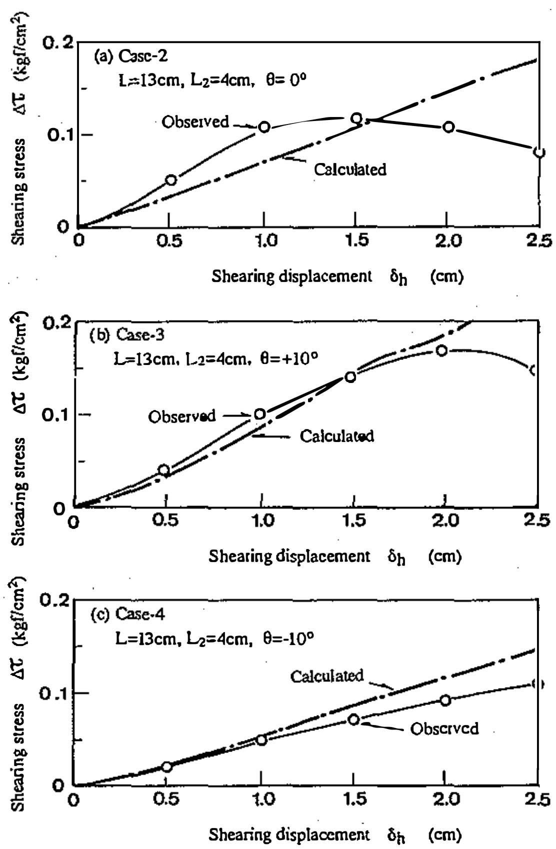


Fig. 12 Comparison of the observed shear stress with the calculated shear stress

4 CONCLUSIONS

From a series of laboratory tests and discussions on the function and evaluation of steel bars in earth reinforcement, the following can be concluded.

(1) The behaviour of reinforced model slopes is effected by the bending stiffness of reinforcing materials.

(2) By means of using reinforcing materials having bending stiffness, the reinforcement is highly effective during the initial displacements in spite of the insert angle of reinforcing materials.

(3) By means of invoking a theory on the lateral resistance of foundation piles, an equation is proposed for the evaluation of shearing resistance of reinforcing steel bars.

(4) The role of shearing force of reinforcing materials in reinforcement effects is very important and is influenced by the insert angle of reinforcements.

(5) Tensile force in the reinforcing materials plays a major role with respect to providing shear resistance. The effects range from 40% to 70% depending on the insert angle.

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