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Reaction of reinforcing force and restrainment effect on soil nailing

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At present, the main method of design in soil nailing depends on calculation of the tensile force in reinforcement material. On the other hand, it has been considered that the reinforcing materials restrains the deformation of the soil, and leads to massing of the reinforced area. So, model tests using iron ore for backfill material was conducted to clarify the reinforcing mechanism, and interaction of the effect from reinforcing force and restrainment was investigated in detail.

1. INTRODUCSION

The soil nailing method is a type of earth reinforcement applicable to both natural and cut slopes. Basically, it is considered to increase slope stability through the tensile force, shear and bending resistance generated in the reinforcing materials which are called reinforcing force in this paper. At present, the main purpose of most commonly used design depends on calculation and assessment of the tensile force in reinforcement material. So, many researches in this field were intended to investigate the interaction between the generating process of such forces and their effect on the reinforcement. However, these forces develop as rather passively generated by possible ground deformation. Therefore, reinforcement effect must essentially be shown as a function of deformation.

Meanwhile, it has been assumed that the reinforcing materials effectively restrains the deformation of the soil around the reinforcing materials, and leads to restrainment of the reinforced area. However few quantitative studies have been done in this field. The restrainment effect is generally regarded as a factor of stabilization by restraining deformation which might locally take place within the reinforced area. If excessive deformation must be avoided in the soil reinforcement method as permanent structure, the effect of soil restrainment should be considered as the primary one. With the restrainment effect as the main effect to be achieved the main purpose of design should be confined to examine of external stability for the entire reinforced area.

In view of the above, this study was undertaken using model test aligned with reinforcing steel bars for the purpose of quantitatively clarifying the restrainment phenomenon over the reinforced area. And possible effect by the rigid facing was also studied from the same point.

2. EXPERIMENTAL TEST METHODS

2.1 Test apparatus and materials

The experimental test model of a reinforced slope was formed of 150cm in height and width inside a steel box of 150cm height, 200cm width and 30cm

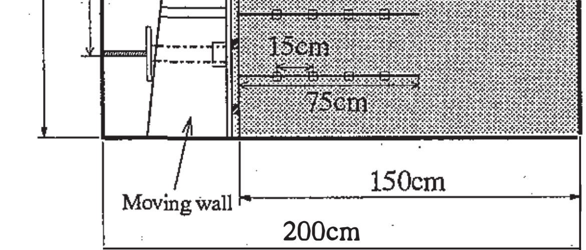


Fig.1 Test model

Table 1 Properties of iron ore

Composition	(%)	T-Fe : 67.5
		SiO_2 : 0.6
		Al_2O_3 : 0.8
Natural moisture	(%)	7.3
Density	(g/cm^3)	4.50
Unit weight	(gf/cm^3)	2.95
Water absorption	(%)	2.1
Mean particle size	(mm)	0.55
Uniformity coefficient		84.0
Coefficient of curvature		1.36

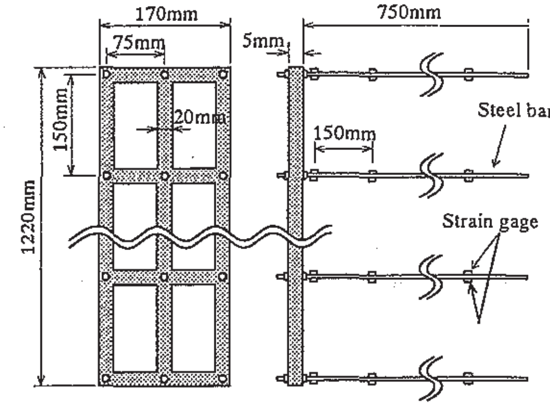


Fig.2 Facing model

as shown in Fig.1. The test apparatus was designed to cause active failure of the slope model by moving backward the wall setting in front of the reinforced slope. Since this study was intended to observe the reinforcing effect from the earth pressure and strain on the reinforcing bars these physical quantities need to be measured as precisely as possible. To satisfy this requirement, high dense iron ore was used for slope soil, and the properties are shown in Table 1. From the result of direct shear test on iron ore, cohesion of c_d=0.048kgf/cm^2, and friction angle of ϕ_d=42.8° were obtained. From these results, it is clear that the physical properties of iron ore used for tests do not make any remarkable difference, except in term of density, when compared with those of commonly used sandy soil.

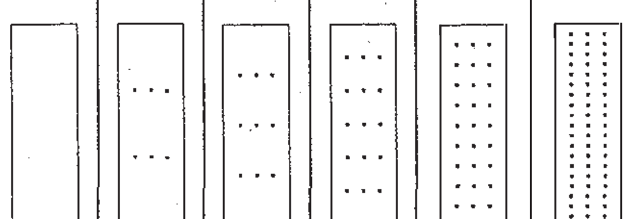
The reinforced slope model was designed to obtain the unit weight 2.95tf/cm^3 that the iron ore in dry condition dropped in air from 150cm height.

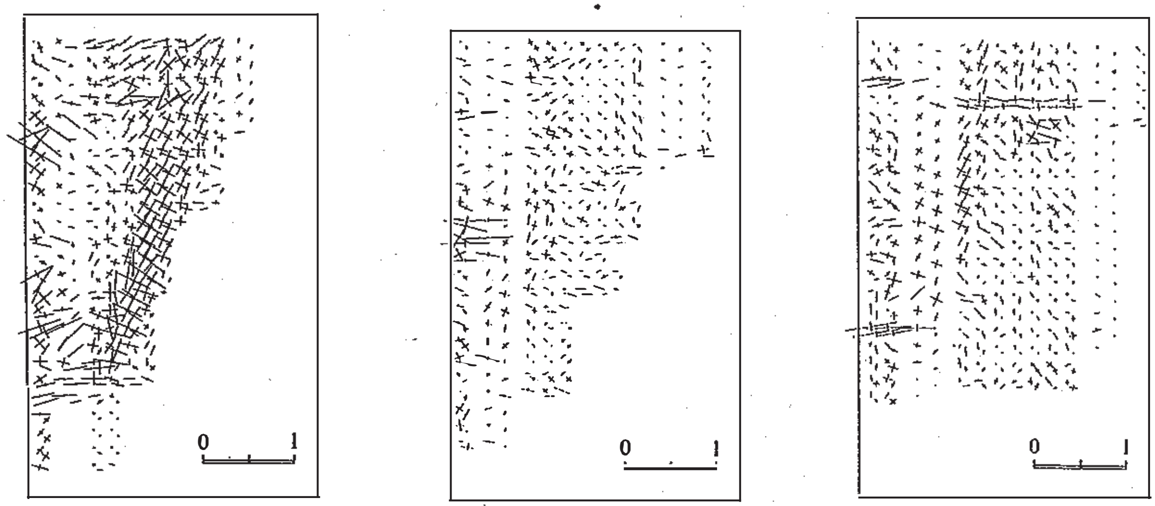
The reinforcement material in the test model was phosphate-bronze round rod of 0.5cm in diameter and 75cm in length (E=1.1 × 10^6 kgf/cm^2). The surface of the rod was coated with sand to ensure friction with the peripheral iron ore. Strain gage were mounted on the upper and lower side of rod to measure the bending strain on the rod.

2.2 Test procedure

The test was conducted by moving the wall, as shown in Fig.1, slightly backward 1mm a stage using a rear side jack, and allowing the model slope at each stage to stabilize before moving the wall again. In this way, the wall was moved back a maximum 50mm, causing active failure due to the weight of the slope. To reduce friction on the steel box face, the boundary face between the inside faces of the box and the backfill material consisted of three layers of Teflon sheet, grease and silicone rubber membrane.

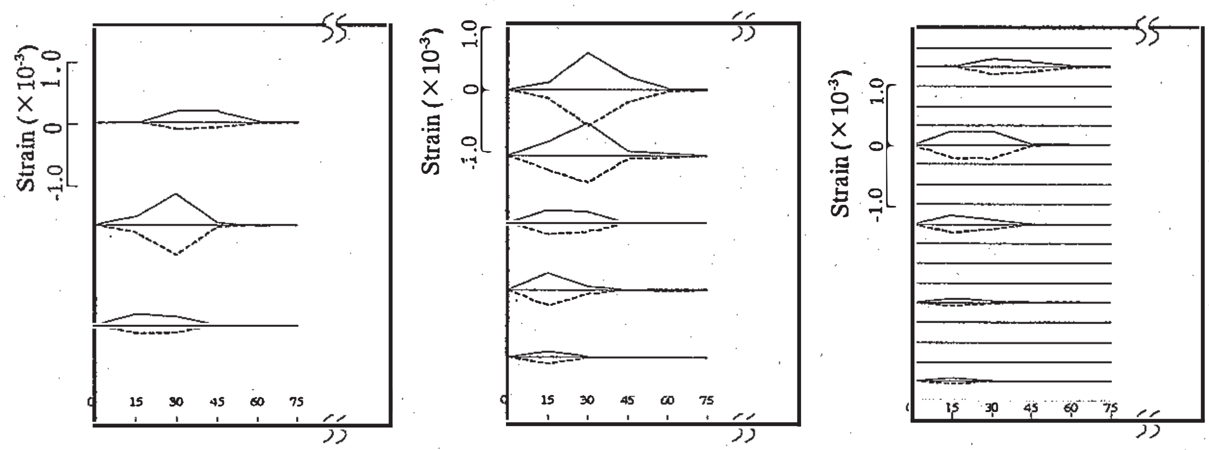
Table 2 Arrangements of reinforcing bars in model tests

umber of reinforcement	0	6	9	15	27	57
Space	—	50.0cm	37.5cm	25.0cm	15.0cm	7.5cm
Arrange						



(a) Without reinforcing (b) 6 reinforcing bars (c)15 reinforcing bars

Fig.3 Distribution of principal strain in reinforced area



(a) 6 reinforcing bars (b) 15 reinforcing bars (c) 57 reinforcing bars

Fig.4 Distribution of strain in reinforcing bars

The rubber membrane surface was marked with 5cm square mesh to measure the displacement within the model slope. The quantities of reinforcing bars and their arrangement for experimental tests are indicated in Table 2.

Further, to examine the effect of the facing, aluminum bars, each 20mm wide and 5mm thick were latticed to form the facing as shown in Fig.2, and the head of the reinforcing bars were bolted tight.

Measurements as a described above were done for the total horizontal earth pressure acting on the movable wall, the bending strains on reinforcing bars, and the deformation of the reinforced area.

3. EFFECT OF SPACING OF REINFORCING BARS

3.1 Slope deformation and strain on the reinforcing bars

Fig.3 shows the distribution of principal strain at a 30mm movement of the moving wall, as obtained from deformation of the silicone rubber membrane In the absence of the reinforcing bars referred to as (a), a area of large principal strain can be apparently observed along the active shear zone. In using 6 reinforcing bars (b), the principal strains tend to be largely disappeared. Where the reinforcing bars are installed in wide space, it appears that the deformation can take place locally between the bars and still remains unrestrained. In using an additional number of reinforcing bars (c), the strains tend to dissipate and local deformations between the reinforcing bars are reduced. These results show that reinforcing bars in the slope help to greatly restrain the potential of the deformation in the reinforced area.

Figure 4 shows the distribution of strain on the reinforcing bars at a movement of 30mm backward of the wall. In all figures, it is observed that large strain occurs at the crossing point with the active shear zone. Since the typical pattern of the distribution is almost symmetrical, the reinforcing bars are in a state of pure bending. Therefore, it considered that the bending resistance of reinforcing bars should not be neglected in a design of the soil nailing method. Moreover, the strains are not so large when 9 bars are used, and tend to increase with increments of bars up to 15. At further increase in the number of reinforcing bars, however, the strains begin to decrease gradually. This reveals that there exists an optimum installing ratio of the reinforcing bars that is obtained from ratio of total section area of reinforcing bars to area of reinforced slope surface. In the optimum installing ratio condition, strain on the bars takes the maximum and the reinforcement members work most effectively.

Figure 5 illustrates the relationship between the mean value of maximum strain on the each bar and its installing ratio. It means that if the mean value of the maximum strain is larger, the effect of the bending or tensional resistance of each bar is also large accordingly.

From the figure, it is inferable that when a small number of reinforcing bars are used, the strain on the bars is small. The reason of this fact is as follows ; if the bars are spaced widely each other, each of the bars fail to restrain its peripheral soil, and the soil might pass through them subsequently. Another finding is that with up to 15 bars, the mean value of maximum strain on the bars tends to increase with increments in the number of the bars. In this range, the reinforcing bars begin to work gradually.

Secondly, it is seen that in excess of 15 bars, the strain shows a decreasing tendency. This range corresponds to progressive stage to soil restrainment, and the effect of reinforcing force begins to decrease as deformation in the reinforced area is restrained.

In past studies (Toriihara,1988, Soto,1990), it is stated that there is an upper limit in the reinforcement effect even increasing in number of reinforcing bars. It is considered that such upper limit is dependent on a decrease of reinforcing force in each bar. Therefore, in term of the effect of reinforcing force, the result of the experimental test show that the optimum number of bars is 15, corresponding to installing ratio equal to 0.065%.

3.2 Horizontal earth pressure and restrainment phenomenon

As already mentioned, it can be said that the effect of restrainment in reinforced slope means the effect of massing of the reinforced area. In other words, it

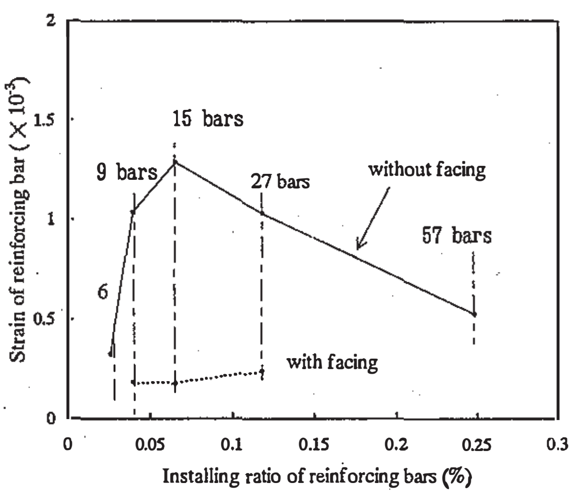


Fig.5 Strain versus Installing ratio of reinforcing bar

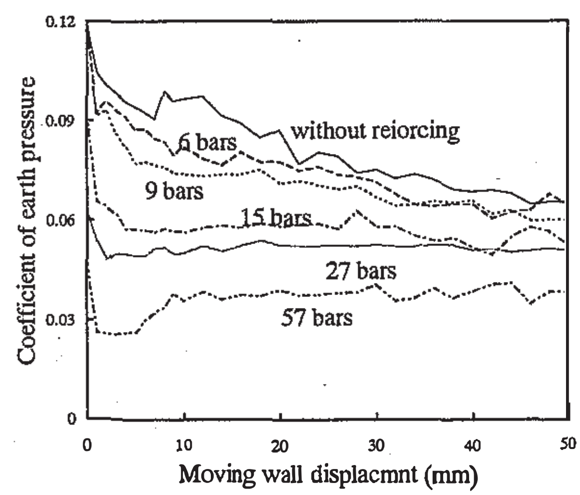


Fig. 6 Variation of earth pressure with moving wall displacement

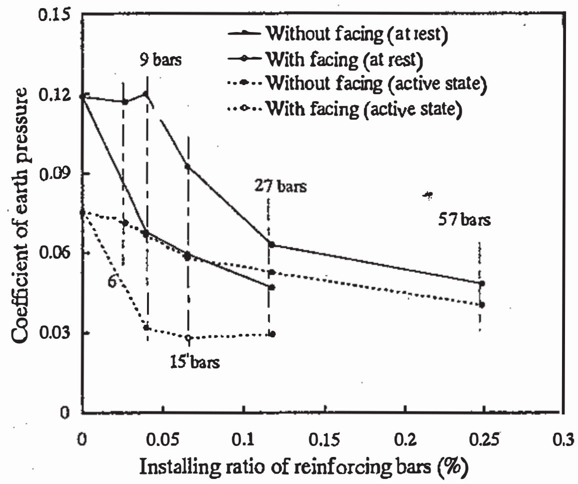


Fig.7 Variation of earth pressure with installing ratio of reinforcing bars

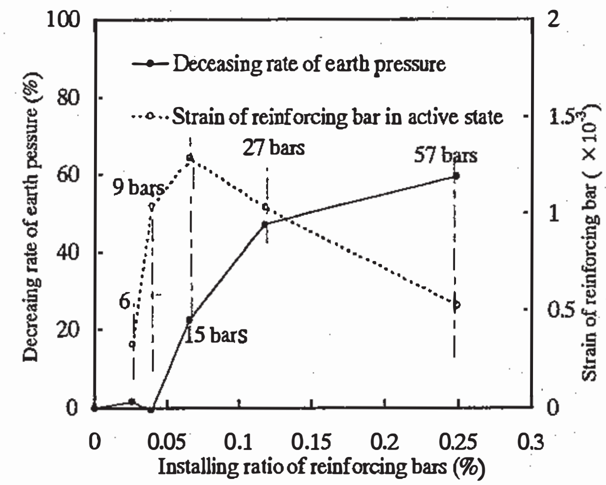


Fig.8 Interaction between earth pressure and strain of reinforcing bar

can be regarded that the effect is developed in a slope without deformation. Therefore, restrainment has a relation with earth pressure at rest.

Figure 6 shows the relationship of the coefficient of earth pressure versus the wall movement which is measured by load cells fixed to the moving wall surface. It can be found from the figure that as the number of reinforcing bars increase, horizontal earth pressure tends to decrease. The differences between horizontal earth pressure with a number of reinforcing bars and that without them are remarkable at small movement of moving wall and tends to decrease during the transit to active state.

Figure 7 shows the relationship between the coefficient of earth pressure and installing ratio of reinforcing bar at 0mm (at rest state) and 30mm (at active state) of the wall. The variation in the coefficient of earth pressure at rest tends to decrease as the number of reinforcing bars increase. This variation indicates the growing of stability of the reinforced slope. It is also seen that the coefficient of earth pressure at rest falls nearly to the minimum at about 27 bars, and even if increased beyond this number, does not ensure any further effect in decreasing earth pressure.

If the mitigating effect of such horizontal earth pressure can be regarded as an effect of restrainment over the reinforced area, it can be concluded that the optimum number of bars is about 27 (installing ratio = 0.12%). The value differs slightly from the optimum number as obtained from the effect of reinforcing force. This result suggests that these two effects have different reinforcing mechanisms from each other.

4. EFFECT OF RIGID FACING

Some past experiences have demonstrated that slope stability can be enhanced through facing construction[7]. Figure 5 also illustrates the possible influence of the facing on the strain of the reinforcing bar. It can be observed that strain on the reinforcing bar is reduced largely by setting up the facing. Within a range of 9 to 27 bars, there is no remarkable decrease in the strain. From these facts it is considered that the restrainment effect with rigid facing is nearly completed when 9 reinforcing bars have been arranged. Moreover, the degree of strain with 9 bars is almost the same as that of when 57 bars are installed without the facing.

Figure 7 also shows the relationship between the coefficient of earth pressure and installing ratio of reinforcing bar with the facing. In both rest and active state, even a small number of reinforcing bars can reduce horizontal earth pressure significantly with the facing. Thus, the effect of reinforcing force with facing may be considered as a secondary function, and effect of restrainment should be regarded as a primary one.

5. INTERACTION BETWEEN EFFECT OF REINFORCING FORCE AND RESTRAINMENT

Figure 8 shows both the strain of reinforcing bar in active state and the relationship between reduction rate of the earth pressure at rest and installing ratio of reinforcing bars. From the figure, the reinforcing

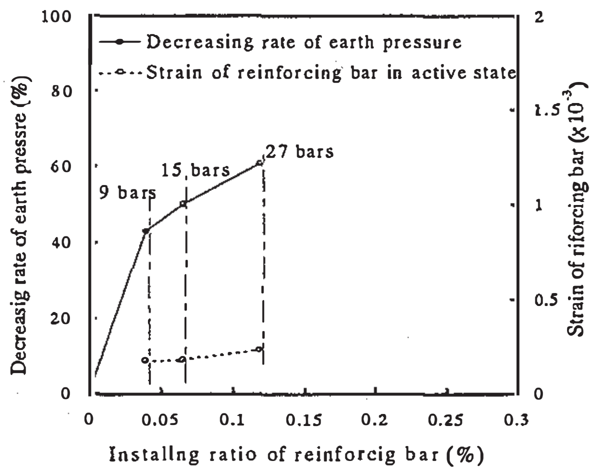


Fig.9 Interaction between earth pressure and strain of reinforcing bar with facing

conditions may be classified as follows:

(1) Stage where reinforcing materials is hardly effective (less than 6 bars).
(2) Stage where only the reinforcing force is functional (6 to 9 bars).
(3) Stage where restrainment effect begins to appear with increasing of reinforcing force effect (9 to 15 bars).
(4) Stage where reinforcing force effect begins to decrease gradually with increasing effect from restrainment (15 to 27 bars).
(5) Condition at which reinforcing force is no longer effective and restrainment effect leaches to upper limit (more than 27 bars).
It can thus be determined that the optimum number of reinforcing bars for well-balanced effect should be in the range of 15 to 27. This range may be equivalent to 0.06% to 0.12% in term of installing ratio of reinforcing bar. In field practice, commonly used installing ratio of reinforcing bar is 0.02% to 0.05%. Therefore, it is considered that the effect of restrainment can be achieved with slight increment of reinforcing bar.

Figure 9 shows the earth pressure reduction rate and the relationship between the strain and installing ratio of reinforcing bar with the facing. The earth pressure almost stops to decrease at about 9 bars, and providing a maximum value. As described before, the effect of reinforcing force is reduced to very low level. Therefore, external stability of overall reinforced area is important factor on the design concept using rigid facing rather than internal stability.

6. CONCLUSION

(1) When reinforcing bars are arranged in a slope beyond their specific number, the effects become obvious not only due to the reinforcing force ,but also due to restrainment of the reinforced area.
(2) Reinforcement mechanism from increased number of bars may be classified by considering the interaction between the effect of reinforcing force and restrainment.
(3) If the effect from restrainment is taken into account, the design should be based on the installing ratio of reinforcing bars at which bar strain begins to decrease.
(4) With rigid facing, restrainment effect can be accelerated with fewer reinforcing bars. In this case, the restrainment effect is so distinguished that it must be incorporated as a primary effect in design method.

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