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Field experiment on reinforced earth and its evaluation using FEM analysis

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ABSTRACT: In order to explain the effect of steel bars as reinforcing members in natural ground and the mechanism of stability of reinforced earth, loading tests using large-scale specimens of reinforced earth were carried out. After that, the loading tests were simulated using two-dimensional and three-dimensional FEM analysis. As a result, numerical simulations were consistent with loading tests, and it was confirmed that the two-dimensional FEM analysis which considered the discontinuity between reinforcing members and natural ground was an effective analysis method for reinforced earth.

1 INTRODUCTION

In recent years, the soil reinforcement method using steel bars has come into wide-spread use as an effective earth retaining for excavation. The soil reinforcemernt is made by steel bars put into the natural ground.

As the characteristics of the natural ground and steel bars interact effectively, steel bars improve the strength of the soil mass. This method is mainly applied to the stabilization of excavation using relatively short steel bars from 1.0 m to 5.0 m long.

The fundamental characteristics of the soil reinforcement with steel bars have been explained by model tests (Gässler et al. 1983, Tatsuoka et al. 1984) and the stability analysis method (Kitamura et al. 1987) has been established. However, the actual behavior of a reinforced slope may be remarkably different from the theoretical behavior, because of the nonuniformity of the natural ground. In this case, the design has to be modified by a change of model or soil property and an analytical method is required to simulate the behavior of a reinforced slope.

This paper describes one useful method of analysis for observations of soil reinforcement compared with the results of a large scale field loading test and a numerical simulation of the loading test. Loading tests were simulated by two-dimensional FEM analysis considering the discontinuity between the natural ground and reinforcing members, and then the results of analysis, were corrected by considering the three-dimensional stress dispersion of the loading test. In order to verify a three-dimensional stress dispersion of the loading test, a three-dimensional elastic FEM analysis was performed on a non-reinforced specimen.

2 FIELD LOADING TEST OF REINFORCED EARTH

Loading tests of reinforced earth were carried out at the Ishibe plant nursery of Japan Highway Public Corporation (Nagao et al. 1984, Nagao et al. 1985). The nature of the ground generally consists of homogeneous layers: the first sandy soil layer (ks1) and the second sandy soil layer(ks2).

The shape of the loading test specimen is 3.0 m-high, 7.0 m-wide and 3.0 m-deep as shown in Figure-1. Deformed bars (ϕ25 mm) were used as reinforcing members and were set at intervals of 1.0 m. Further, 3 in-situ strain meters, 14 deflection gauges and 3 steel bars with strain gauges were located to measure the behavior of the specimen as shown in Figure-1. The large rigid bearing plate made of concrete was set as shown in the figure.

Although seven specimens were tested with varied length, angle and interval of steel bars, the following two specimens are described in this paper.

(1) length of reinforcing bars; L = 4.0 m, position; horizontal
(2) length of reinforcing bars; L = 2.0 m, position; horizontal

The specimens were loaded, using 12 jacks, until they were yielded. As a result, the specimen with 4.0 m reinforcing bars yielded at $q = 47\ tf/m^2$, the specimen with 2.0 m reinforcing bars yielded at $q = 37\ tf/m^2$ and non-reinforced specimen yielded at $q = 29\ tf/m^2$. (See photo-1)

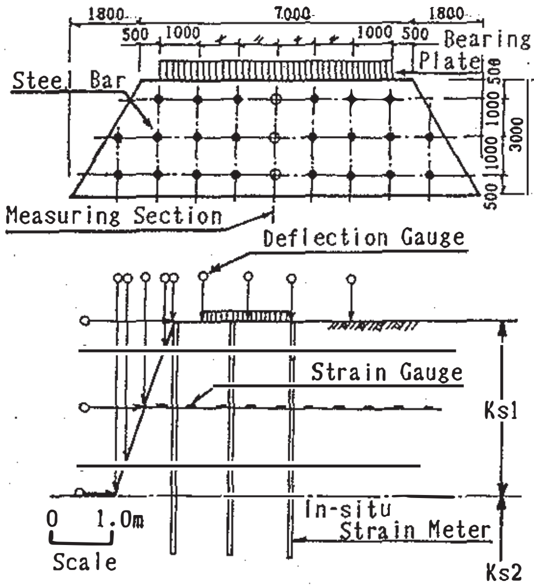

Fig.-1 Outline of Measuring Equipment

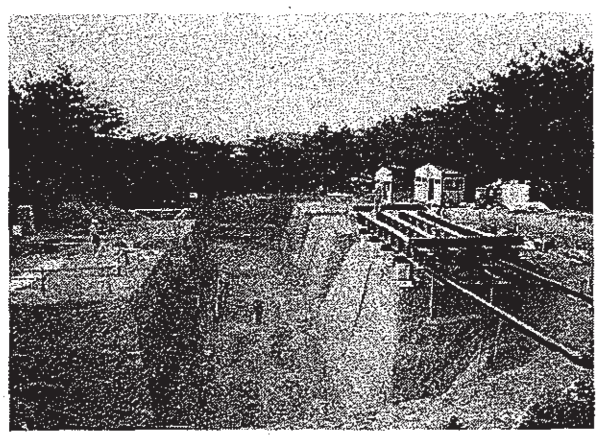

Photo-1 View of the Loading Test

3 TWO-DIMENSIONAL FEM ANALYSIS CONSIDERING DISCONTINUITY BETWEEN REINFORCING MEMBERS AND NATURAL GROUND

When the behavior of the specimen is simulated by FEM analysis, it is important to know how to evaluate the discontinuity between the reinforcing members and the natural ground.

The discontinuity is evaluated using the frictional resistance (ie. adhesion and friction force) between the reinforcing members and the natural ground (Iseda et al 1979). The discontinuous surface, as shown in Figure-2, is expressed by two different nodes which are located on the same coordinates and belong to different elements. The continuity is evaluated using the dimension comparison between the nodal force (X1) and the sliding resistance ($Y1 \cdot \tan\phi^* + C^* \cdot S$). In Figure-2, node (U1, V1) belongs to the elements of natural ground, and node (U2, V2) belongs to the reinforcing materials.

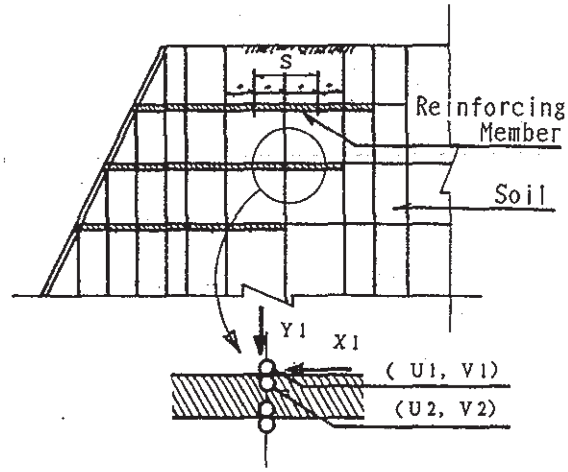

Fig.-2 Discontinuity Model between Reinforcing Member and Natural Ground

(Criterion Formula)	(Continuous Condition between Nodes)
$X1 \leq (Y1 \cdot \tan\phi^* + C^* \cdot S)$ ...	$U1=U2,\ V1=V2$ Continuous Conditions
$X1 \geq (Y1 \cdot \tan\phi^* + C^* \cdot S)$ ...	$U1 \neq U2,\ V1=V2$ Sliding Conditions

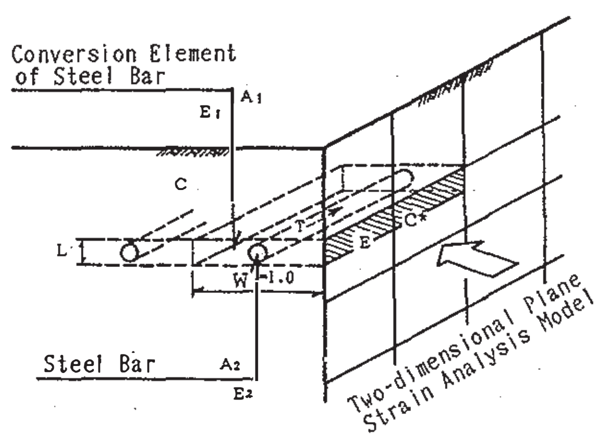

Fig.-3 Conversion Method for Two-dimensional Analysis Model of Reinforcing Member

The resistance force at the boundary surface ($Y1 \cdot \tan\phi^* + C^* \cdot S$) is expressed by the friction angle (ϕ^*) and the conversion adhesion (C^*) between the natural ground and the reinforcing members.

In order to use two-dimensional plane strain analysis, the reinforcing bars, which were originally cylindrical, were replaced with thin flat reinforcing members of uniform thickness, as shown in Figure-3. The conversion of the physical properties of the flat reinforcing members seemed to be as follows:

$$E = \frac{A1 \cdot E1 + A2 \cdot E2}{A1 + A2}$$

$$C^* = C + \frac{T}{2.0 \cdot W}$$

where, A1: sectional area of the flat reinforcing member
A2: original sectional area of the cylindrical reinforcing bar
E1: modulus of elasticity of the natural ground
E2: modulus of elasticity of the reinforcing bar
C : cohesion of the natural ground
C*: adhesion between the natural ground and the reinforcing member
T : pull-out resistance force of one reinforcing bar

However, the Poisson's ratio of flat reinforcing member was the same as the original value.

The loading tests were simulated by elastic analysis. Table-1 shows the physical properties obtained by the soil tests and used in the analysis. Figure-4 shows an example of two-dimensional FEM analysis.

Table-1 Physical Properties Used for Analysis

Description	Unit	Sand①	Sand②	Steel bar
Modulus of elasticity	tf/m^2	3700	14800	206000
Unit weight	tf/m^3	2.10	1.73	2.06
Poisson's ratio		0.35	0.25	0.3
C (soil)	tf/m^2	4.5	4.0	——
ϕ (soil)	degree	35°	34 °	——
C* & ϕ^* between soil and steel bar		C^*= 6.26 tf/m^2 ϕ^*= 35°		

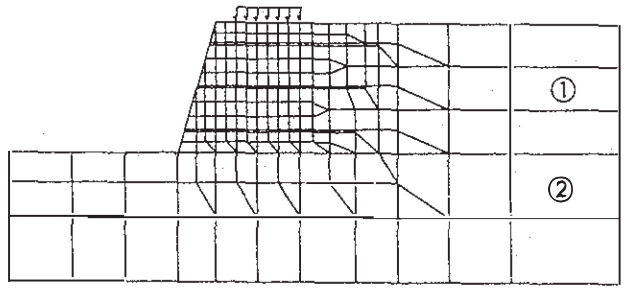

Fig.-4 Model of Two-dimensional FEM Analysis

4 THREE-DIMENSIONAL FEM ANALYSIS

The behavior of the loading test specimen was simulated by two-dimensional plane strain FEM analysis considering the discontinuity between the reinforcing members and the natural ground as described in the previous paragraph. However, it is supposed that the specimen undergoes a three-dimensional stress and strain distribution rather than a perfect two-dimensional plane strain, even in the central section of 7 m-wide specimen. Therefore, three-dimensional FEM analysis of the non-reinforced specimen was performed and compared with the results calculated by the two-dimensional plane strain FEM analysis.

Figure-5 shows a three-dimensional model. Physical properties were same as those for the two-dimensional analysis.

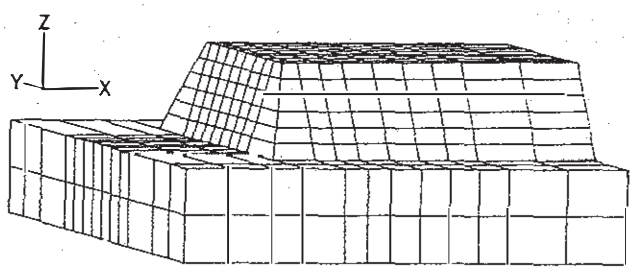

Fig.-5 Model of Three-dimensional Analysis

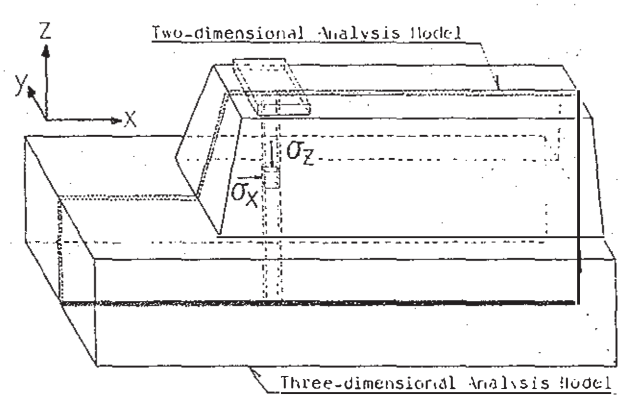

Fig.-6 Ground Stress (σx) and (σz)

Figure-7 and 8 show the stress-comparison of σx and σz at the center of the specimen and just under the bearing plate as shown in Figure-6. It was found that perfect two-dimensional plane strain condition was not indicated even in the central section of the specimen.

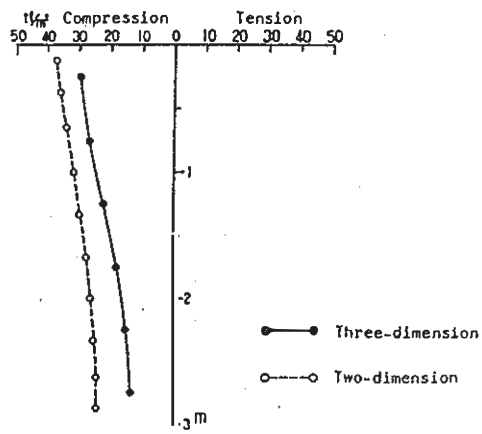

Fig.-7 Comparison of Ground Stress of Three-dimensional and Two-dimensional Analyses (σz)

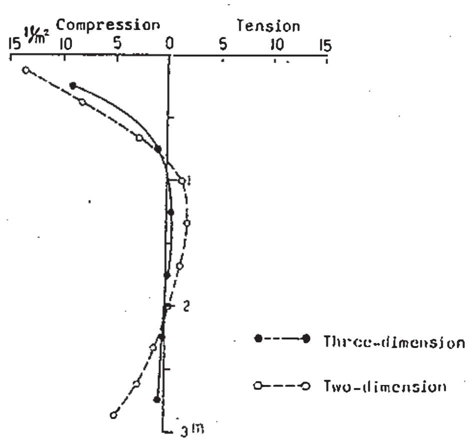

Fig.-8 Comparison of Ground Stress of Three-dimensional and Two-dimensional Analyses (σx)

The ground stress in the vertical direction σz (Figure-7) calculated by three-dimensional analysis was 0.75 ∿ 0.69 times as large as the stress calculated by two-dimensional analysis. Therefore, if the settlement of the specimen surface is simulated by two-dimensional analysis, it is necessary to be corrected by the following ratio (Nz).

$$\text{Settlement } \delta = \int_0^h \sigma z \cdot dh$$

$$Nz = \frac{\int_0^h \sigma z3 \cdot dh \text{(three-dimensional analysis)}}{\int_0^h \sigma z2 \cdot dh \text{(two-dimensional analysis)}} = 0.6$$

When the absolute value of the horizontal ground stress σx (Figure-8) is compared with the location of reinforcing bars, the result seems to be as follows.

$$Nx = \frac{|\sigma x3|}{|\sigma x2|}$$

$Nx1 = 1/2$ (upper reinforcing bar)
$Nx2 = 1/3$ (middle reinforcing bar)
$Nx3 = 1/5$ (lower reinforcing bar)

Therefore, when the axial force of reinforcing bar is simulated by two-dimensional analysis, it is necessary to be corrected by the ratio (Nx).

If a perfect two-dimensional plane strain conditions are existed, it is not necessary for the two-dimensional simulation results to be corrected.

5 COMPARISON BETWEEN THE MEASURED AND CALCULATED VALUES OF LOADING TESTS

A comparison between the measured and calculated values of the specimen with 4.0 m reinforcing bars is shown in Figure-9 ∿ 12, and a comparison of the specimen with 2.0 m reinforcing bars is shown in Figure-13 ∿ 16. These figures show the settlement of ground surface, the deflection of slope surface and axial force of the reinforcing bars. According to these figures, each calculated value is similar to the measured value.

The original axial force distributions calculated by the two-dimensional plane strain analysis are shown in Figure-12 and 15. It is recognized that the non-corrected value is not similar to the measured value.

Safety factor distributions calculated by two-dimensional FEM analysis are shown in Figure-17. Although unstable elements are widespread in the non-reinforced specimen, many elements of the reinforced specimens maintain stability and unstable elements are distributed only near the slope surface. Further, the unstable elements of reinforced specimens are divided into thin layers by reinforcing bars and a failure zone caused by compression occurs near the slope surface of each layer. Consequently, this means that the slope can be protected by simple slope protection work, and the slope protection work for such a slope is very effective. The specimens were failed, except for the lower reinforcing bars, and the failure range calculated by two-dimensional FEM analysis corresponds closely with the test results. The specimens reinforced by 4.0 m steel bars and 2.0 m steel bars show the same tendency.

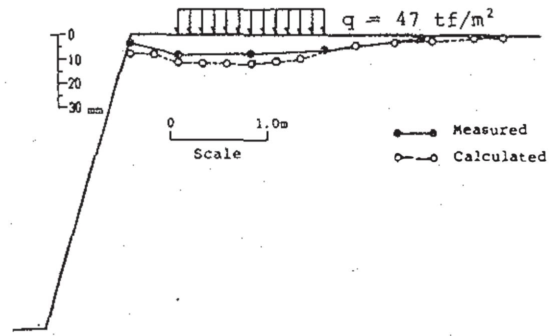

Fig.-9 Settlement of Ground Surface
(reinforcing members L = 4.0 m)

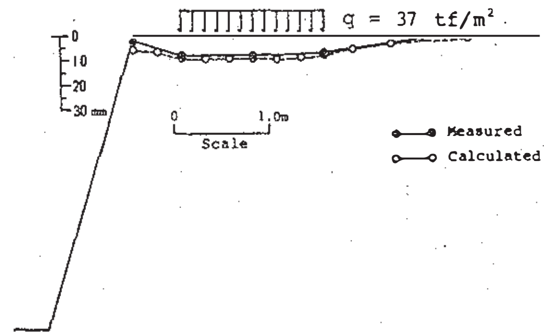

Fig.-13 Settlement of Ground Surface
(reinforcing members L = 2.0 m)

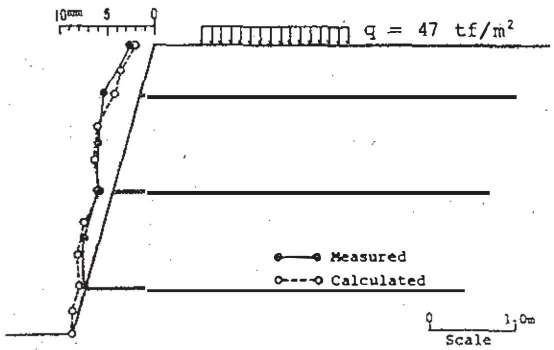

Fig.-10 Deflection of Slope Surface
(reinforcing members L = 4.0 m)

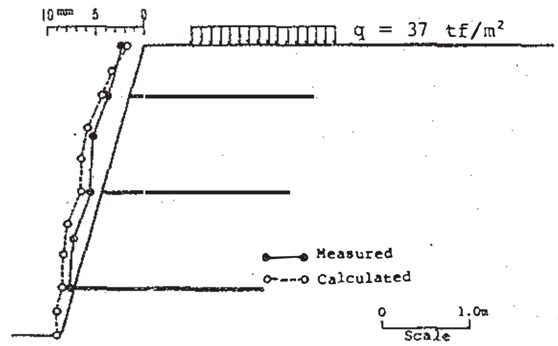

Fig.-14 Deflection of Slope Surface
(reinforcing members L = 2.0 m)

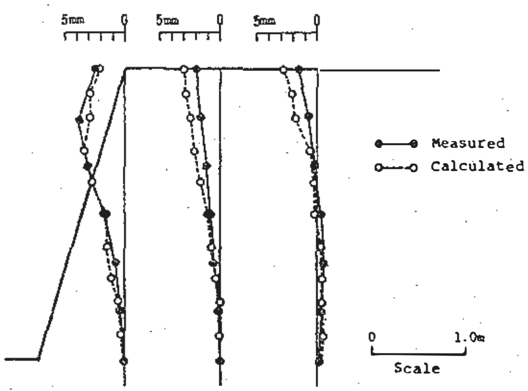

Fig.-11 Horizontal Deflection
(reinforcing members L = 4.0 m)

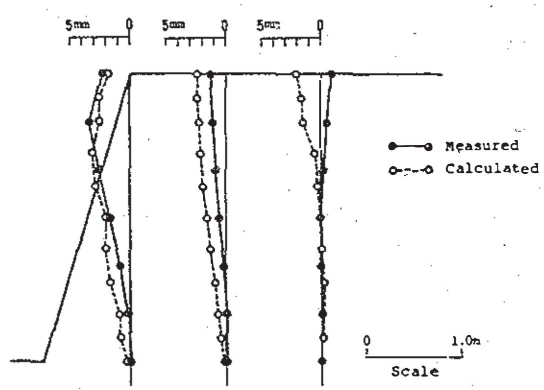

Fig.-15 Horizontal Deflection
(reinforcing members L = 2.0 m)

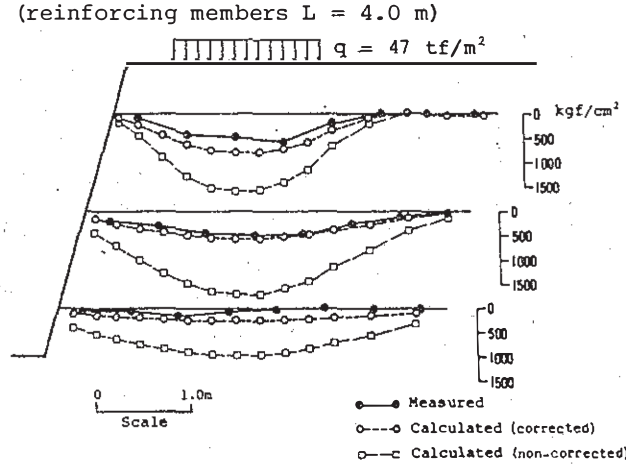

Fig.-12 Axial Force of Reinforcing Member
(reinforcing members L = 4.0 m)

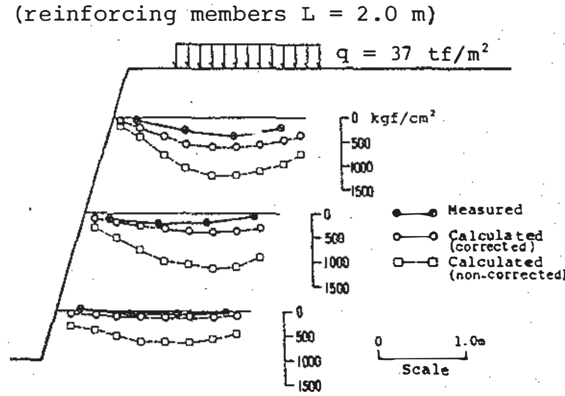

Fig.-16 Axial Force of Reinforcing Member
(reinforcing members L = 2.0 m)

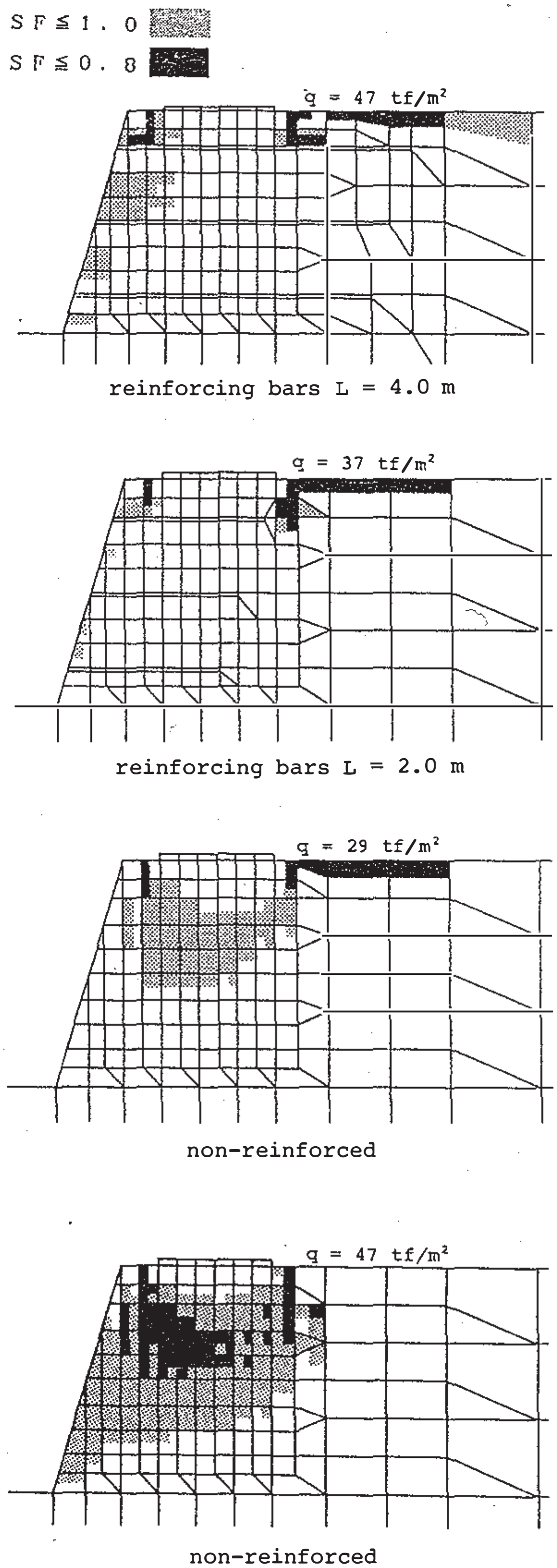

Fig.-17 Safety Factor Distribution of Specimen Simulated by Two-dimensional FEM Analysis

6 CONCLUSION

It was proven on the basis of the results that the behavior of an actual reinforced slope and the axial force of reinforcing bars can be estimated by two-dimensional plane strain FEM analysis considering the discontinuity between the reinforcing members and the natural ground. Consequently, it was confirmed that the two-dimensional FEM analysis which considers the discontinuity between natural ground and reinforcing members is an effective analysis method for the observational procedure of reinforced earth.

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