New Horizons in Earth Reinforcement – Otani, Miyata & Mukunoki (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-45775-0

Effect of restraint deformation on stability of cut slope with soil nailing

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ABSTRACT: In this study, the reinforcement mechanism on restraint effect is firstly investigated by distinct element method, and secondly influence of the interval of reinforcements on the development of the restraint effect is examined by finite element method. It concludes that the restrain effect is capable of designing a reinforced slope with small displacement in high priority road system. If the restraint effect of deformation is satisfactorily guaranteed in the construct condition, only the analysis of external stability of reinforced zone like a overturning of retaining wall is required.

1 INTRODUCTION

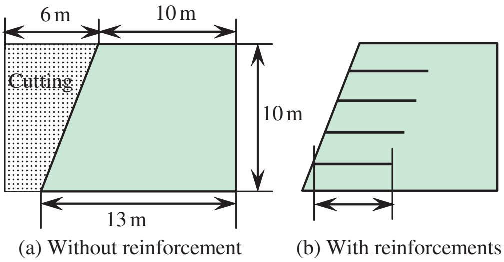
In recent years, reinforcing methods for natural slopes have been developed for a wide variety of situations. Current design methods for reinforcing natural slopes are based on the conventional limit equilibrium method and consider the effects of the components of the tensile forces oriented parallel and orthogonal to the slip surface (internal stability), however, as the tensile force developed in the reinforcing material is closely related to deformation of the slope soil, the number of reinforcement must be determined with due consideration of the allowable deformation.

There is an approach to the design of such reinforcement: external stability, which considers the entire reinforced region as a pseudo-retaining wall. Fundamentally, internal and external stability cannot coexist, since the former allows deformation and the second is based on the presumption that deformation is prevented (restrained). The design methods of external stability are becoming more important as specifications increasingly require permanent reinforced structures that minimize soil deformation. So, it is necessary to identify the mechanisms responsible for the formation of a pseudo-wall structure (restraint of soil deformation) in the reinforced region.

The present study is an investigation of the mechanisms of slope deformation is restrained by a reinforcement, based on distinct element and finite element methods and observations of the influence of the internal stresses and friction angle of the soil on the restraint of deformation. The study also involves an investigation of the number of reinforcing materials necessary to obtain restraint of deformation and observations of the relationship between the spacing of reinforcements and slope deformation.

2 DEM ANALYSIS OF REINFORCED SLOPE

Most existing methods of soil reinforcement were developed to stabilize slopes made up of sandy soils, and their effectiveness is generally attributed to the particulate nature of the soil. For this reason, we employed a DEM(PFC) as a method of observing the behavior of particulate masses and predicting the mechanisms of slope reinforcement.



(a) Without reinforcement (b) With reinforcements

Figure 1. Slope models for distinct element method.

Table 1. Physical constant for DEM analysis.

	Normal and shear stiffness (kN/m)	Friction coefficient	Bonding parameter (kN)
Soil Particles	1×10^4	0.5, 0.7	2.3
Reinforcements	1×10^{10}	0.5	–

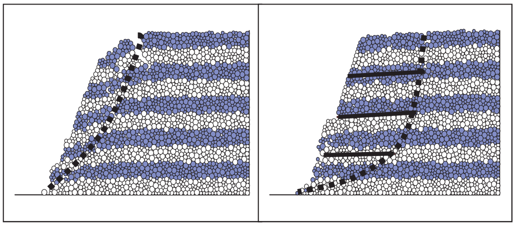

(a) Without reinforcement (b) Reinforced slope

Figure 2. Slope models for distinct element method.

Figure 1 shows the shape of the slope used for analysis. The distinct element method was performed as follows. We generated circular discrete elements with 10–30 mm in diameter and a density of 2.6 g/cm^3 in the rectangular region of 16 × 10 m. A initial stress condition accounting for the weight of the discrete elements was established, and the cutting portion at the front, as shown in Fig. 1, was removed to perform the analysis of the resulting deformation after the stress release. The reinforcements were handled in this analysis as rigid bodies and constructed of rigid elements of 10 cm in diameter and 5 m in length. Next, reinforcing was installed to the model in horizontal positions in an evenly spaced configuration. Table 1 shows the physical properties employed in the analysis. To study the influence of the internal friction angle ϕ of the slope soil on the reinforcing effect, the soil particles were given the two friction coefficient values shown in Table 1.

Figure 2 shows how the deformation occurred after the cutting as due to stress release. When there was no reinforcing (Fig. 2a), a slip surface developed at a shallow location in the slope. With three nails inserted (Fig. 2b), a little bulging is observed at the toe of the slope, but overall the slip surface has moved behind the reinforcing: the reinforcing has restrained deformation of reinforced region.

Figures 3 and 4 show the distribution of horizontal displacement along a vertical plane in the reinforced region with varying frictional coefficients (0.5 and 0.7). The arrows in the figures show the locations of the reinforcements. If we assume that the coefficient of friction of the discrete elements has the same physical quantity as ϕ in ordinary soil, the two figures clearly indicate that the greater ϕ gives the lower the magnitude of deformation. In addition, both cases show that for the case of small numbers of reinforcements the local horizontal deformations are large in the spaces between the bars. Thus, the distribution of deformation has a wavy shape. For the case of greater numbers of bars, the restraint zones near the reinforcements begin to interact, broadening the extent of restraint to the entire slope, and the wavy profile disappears. This phenomenon corresponds to the complete restraint of the reinforced region by the reinforcements. Figure 5 shows a conceptual picture of progressing of restraining effect throughout the reinforced region. It has been said that reinforcement had a extent to restrain a soil particle around it and when these extents contact each other, the reinforcement effect comes up to maximum. The analytical results of Figs. 3 and 4 indicate the progress of the restrain effect shown in Fig. 5.

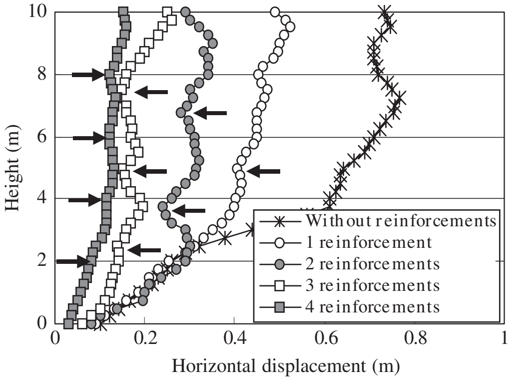


Figure 3. Horizontal displacement in reinforced area for the case of friction coefficient = 0.5.

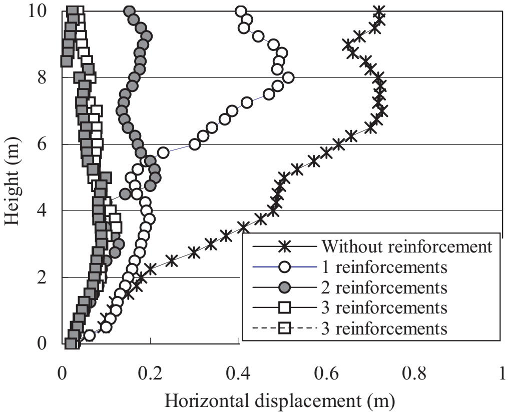


Figure 4. Horizontal displacement in reinforced area for the case of friction coefficient = 0.7.

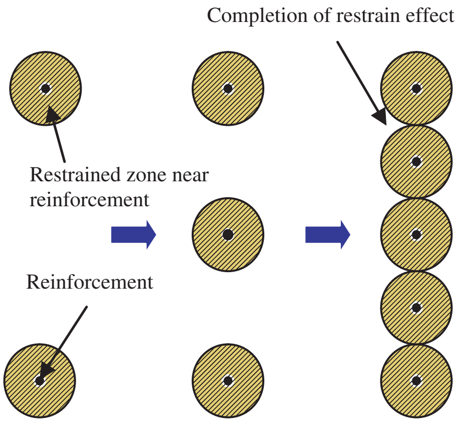


Figure 5. Progress and completion of restrain effect.

3 INFLUENCE OF SOIL PROPERTIES ON RESTRAINT EFFECT

It is necessary to quantitatively identify the size of the restrained zone influenced by a single reinforcement in order to find the optimal spacing of the bar. This restrained zone is also affected by the internal friction angle ϕ of the slope soil and its stress condition (overburden pressure). The authors continued this investigation using FEM.

Figure 6 shows the model of the slope used in the FEM(PLAXIS); it had the same dimensions as the model used in the DEM, being 10 m high, with an 80° slope and 5 m reinforcements. The bars were installed horizontally in evenly spaced positions, adjusted to the number of bars in each case. The initial stress condition due to the weight of the soil was applied throughout the analytical region, then cuts were taken and reinforcements were installed. The soil was treated as an elasto-plastic material and the reinforcing material was treated as elastic. Joint elements were inserted between the soil and the reinforcements, and the friction angle in the joint elements was set at two-thirds the value of ϕ of the soil. Table 2 shows the other physical characteristics employed in this analysis. Fore values were used for the internal friction value of the soil in order to observe its influence.

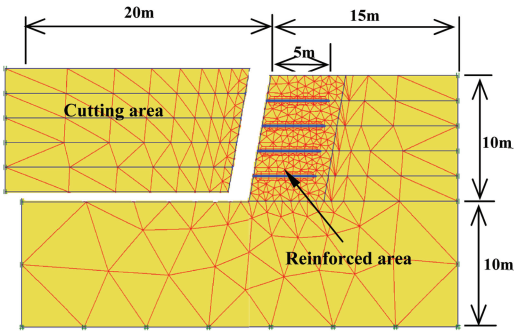


Figure 6. Reinforced slope model for FEM Analysis.

Table 2. Physical constants for FEM analysis.

	Slope soil	Reinforcement
Unit weight (kN/m^3)	18	–
Elastic modulus (kN/m^2)	33000	1.6×10^5
Poisson's ratio	0.35	0.3
Internal friction angle (°)	25, 30, 35, 40	–
Cohesion (kN/m^2)	10	–
Bending stiffness (kN · m^2)	–	40

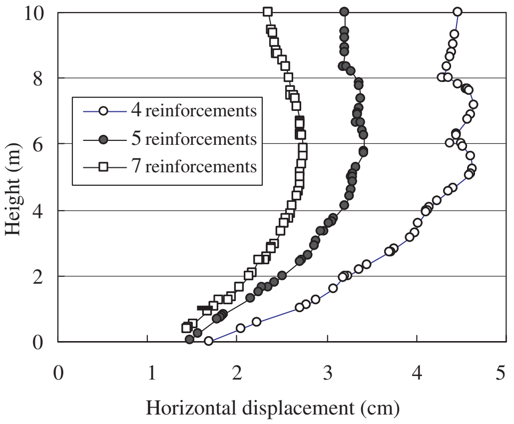


Figure 7. Horizontal displacement in reinforced area by FEM analysis for internal friction $\phi = 30°$.

Figure 7 shows the distribution of horizontal displacement along the vertical plane in the reinforced area under the condition of $\phi = 30°$. This FEM result shows the wavy distribution of deformation as can be seen in the DEM results. The locations of the local small deformation correspond to the locations of the bars. In other words, the horizontal displacement of the soil on the slope was locally restrained in the vicinity of the reinforcements, while in the spaces between the bars, the displacement was large because it was unrestrained. In the case of seven reinforcements, the wavy shape of the displacement curve almost disappears. This indicates that the soil displacement was restrained between the bars. These results quantitatively agree with those found in the DEM. Figures 8 and 9 similarly show the results for $\phi = 35°$ and 40°, respectively. These figures indicate that the zone of influence of the bars is a function of the angle of internal friction. From Figs. 7, 8 and 9, the number of reinforcement which

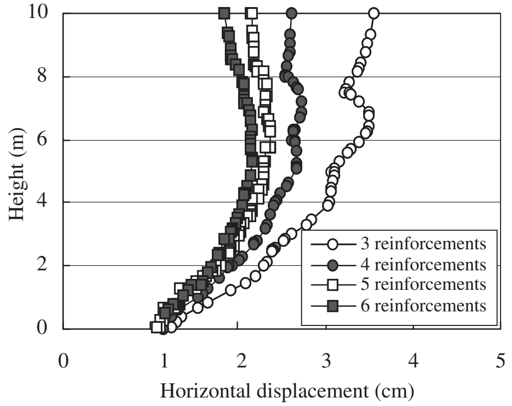


Figure 8. Horizontal displacement in reinforced area by FEM analysis for internal friction $\phi = 35°$.

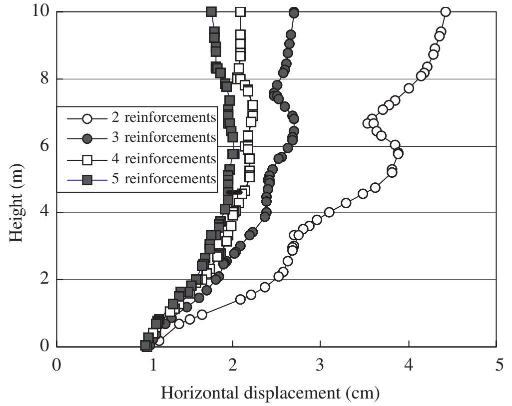


Figure 9. Horizontal displacement in reinforced area by FEM analysis for internal friction $\phi = 40°$.

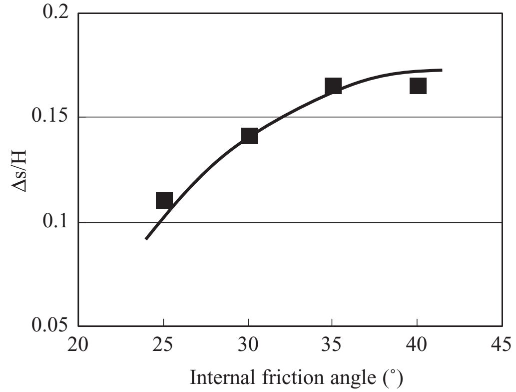


Figure 10. Relationship between friction angle and space of reinforcement on condition that the restraint effect becomes effective.

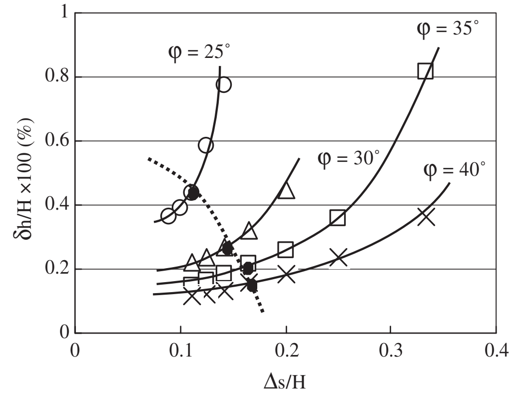


Figure 11. Relationship between deformation at top of slope and space of reinforcement.

the wavy shape of the displacement curve disappears is decreasing with increasing the internal friction ϕ.

Figure 10 shows relationship between the number of reinforcement which the wavy shape of the displacement curve disappears and ϕ. The vertical axis of the figure represents the spacing between reinforcements (Δs) divided by the height of the slope (H = 10 m).This figure can be considered to show the relation between the maximum spacing that the restraint effect works and the angle of internal friction of the slope. Since the object of study in this research was 10-m slopes, Figure 11 is applicable to reinforced cut slopes of approximately 10 m in height. This figure also clearly indicates that the spacing of reinforcements in ordinary slopes of sandy soil (with $\phi = 30–40°$) is about $\Delta s/H = 0.15–0.17$ (actual spacing of $\Delta s = 1.5–1.7$ m). As most actual worksites use spacings of 1–2 m between reinforcements, the above results imply that the restraint effect works sufficiently under the actual design.

4 DEFORMATION OF REINFORCED SLOPE AND RESTRAINT EFFECT

Usually, execution management in a reinforcement works is carried out while observing the extent of displacement that occurs during the project. Fig. 11 shows the results obtained from the FEM analysis for predicting the relationship between the spacing of reinforcements (Δs/H) and the horizontal displacement ($\delta h/H \times 100\%$) of the top of the slope. The spacing of reinforcements shown in Fig. 10 that a complete restraint effect of deformation works are plotted using solid circles on the lines of constant ϕ, and a dashed line connects the each solid circles. This Figure indicates that the restrain effect works sufficiently, if the

Table 3. Provided horizontal deformation for management of safety by Japan Highway Public Corporation.

	Safety level (%)	Caution level (%)	Unsafe level (%)
Soil	$\delta h/H \leqq 0.20$	$0.20 \leqq \delta h/H \leqq 0.40$	$0.40 < \delta h/H$
Soft rock	$\delta h/H \leqq 0.15$	$0.15 \leqq \delta h/H \leqq 0.30$	$0.30 < \delta h/H$
Hard rock	$\delta h/H \leqq 0.10$	$0.10 \leqq \delta h/H \leqq 0.20$	$0.20 < \delta h/H$

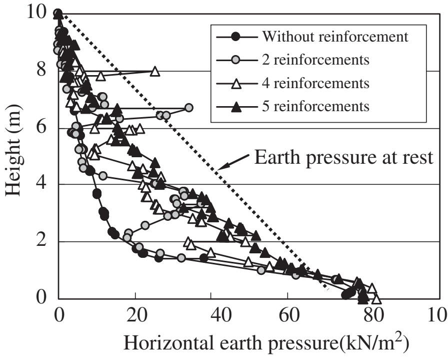


Figure 12. Distribution of horizontal earth pressure in reinforced area.

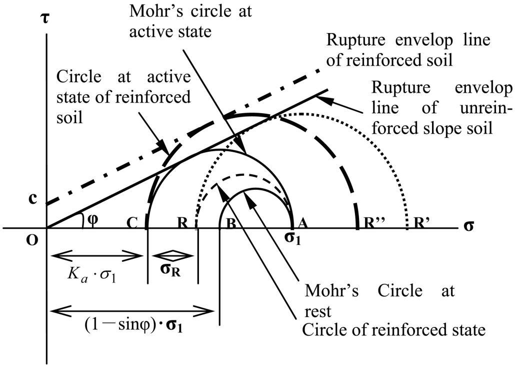


Figure 13. Expression of Mohr's stress circles for reinforced slope.

spacing between reinforcements that is used at the appropriate value of soil ϕ (Fig. 11) is less than the values indicated by the dashed line in the figure.

Table 3 shows the levels of deformation provided in the stability management of cutting procedures mandated by Japan Highway Public Corporation for work on slopes. Comparing the values shown in the table for soil with the present results shown in Fig. 11, Fig. 11 shows that at a low internal friction angle of 25° the reinforcement restrains deformation; however, the predicted deformation ($\delta h/H$) exceeds 0.4%, an unsafe level according to the regulations. In contrast, to meet the safe level of ($\delta h/H$) $\leq 0.2\%$ for soils with $\phi = 30°$, the normalized spacing of reinforcements ($\Delta s/H$) must be less than 0.1; in soils with $\phi = 35°$, $\Delta s/H \leq 0.17$ is acceptable. In other words, for soils with internal friction angles in the range of 30–40°, the values given in Fig. 11 will satisfy the required safety levels given in Table.

5 STRESS CONDITIONS IN THE REINFORCED AREA

Next, we observe the restraint effect of deformation from the viewpoint of the stress condition within the reinforced slope. Figure 12 shows the horizontal stress distribution on a plane that passes through the top of the reinforced slope with internal friction $\phi = 40°$. As seen in the cases with 2 or 4 reinforcements, high magnitudes of horizontal soil stress occur locally in the vicinity of the bars, whereas no such high stresses are present in the spaces between members. These local minima in the horizontal stress are of exactly the same significance as the minima seen in the results in Figs. 7–9. For large numbers of reinforcements (5), no local high earth pressure points were observed and the pressure was uniformly high. The figure simultaneously shows the distribution of earth pressure at rest (coefficient of static earth pressure, $K_0 = 1 - \sin\phi$). The stress condition of the slope without the reinforcement reaches to the active state, and the stress conditions with reinforcement remain the intermediate position between that in the active and rest conditions. Since deformation is more highly restrained with increasing numbers of reinforcements, the reinforcements are clearly holding high soil pressures. Thus, when soil deformation is restrained by reinforcing material, the soil zones become interlocked, and it considers that variations in the stress condition depend on the characteristic of dilatancy of slope soil.

Mohr diagrams were constructed to describe the stress conditions and the mechanics of the deformation restrained effect in the reinforced area (Fig. 13). The cohesion of the slope soil was neglected for simplicity. Since the stress condition must be constant in the static condition regardless of whether reinforcing is present, it is represented by a circle whose diameter is AB (point A at x = maximum principal stress = vertical stress σ_1'; point B at x = minimum principal stress = $(1 - \sin\phi) \cdot \sigma_1$). When the slope is deformed by making a cutting, the horizontal soil pressure is reduced and deformation occurs. The horizontal soil pressure in the case of without reinforcement drops during deformation, and the stress condition is represented by a circle whose diameter is AC that the soil is in the active state. When a reinforcement is installed, the stress condition can be represented by a circle whose diameter is AR, where R is a point on the x-axis somewhere between B and C. Thus, the horizontal stress condition is held at a higher level than the active pressure by the amount σ_R (see Fig. 13). From the viewpoint of soil strength, this σ_R plays a role that is equivalent to suction in unsaturated soil. When the minimum principal stress is at point R, the Mohr circle for the soil elements at rupture has a diameter RR′. As with the suction effect, CR″ becomes the circle that represents the apparent strength, and this becomes the Mohr stress circle for the reinforced soil. This means that the increase in strength in the reinforced soil can be estimated as the increase in *c* in the slope soil.

6 SUMMARY

This study presented investigations of the mechanisms of restraint effect of deformation in soil slopes with the use of reinforcements. The following results were obtained.

(1) A distinct element method was carried out to examine the restrained zone of soil that is influenced by the reinforcements. When the reinforcements have sufficiently closely spaced, their effects are mutually additive, the restrained effect of the soil over a wider volume.

(2) Use of the finite element method also revealed the restrained zone of influence of the reinforcements. The relationship between internal friction angle and the spacing of the reinforcement was stated quantitatively.

(3) The spacing of the reinforcement which slopes first began to affect the restraint effect was investigated. In soils with internal friction angles of 30–40°, restraint of deformation was observed at spacings of $\Delta s/H = 0.15$–0.17 (spacings of 1.5–1.7 m for a slope of height $H = 10$ m).

(4) Slope deformations maintain the stable levels that are designated by Japan Highway Public Corporation when the reinforcements are installed at the spacing found to provide restraint effect of deformation in the present research.

(5) Observations of the stress condition in the reinforced area of the slopes revealed uniformly high horizontal soil stresses when deformation was restrained.

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