A centrifuge model study on a slope reinforced by rock bolts with prestressed facing plate

Shion Nakamoto i), Sakae Seki ii), Naoto Iwasa iii), and Jiro Takemura iv)

i) Ph.D Student, Department of Civil Engineering, Tokyo Institute of Technology, Japan.
ii) Technician, Department of Civil Engineering, Tokyo Institute of Technology, Japan.
iii) Group Manager, Development Planning Sect, Steel & Sumikin Metal products Corp, Japan.
iv) Associate Professor, Department of Civil Engineering, Tokyo Institute of Technology, Japan.

ABSTRACT

In this study, a series of centrifuge model tests was carried out to study the mechanical behavior of the slope reinforced by a soil nailing method using rock bolts with prestressed facing plate. For that purpose, a centrifuge model test system was developed, in which the preloading process of rock bolts with facing plate in a model slope can be simulated by hoisting jacks in a centrifuge and pseudo static seismic force can be also imposed on the slope by an inclining table. The tests were performed with various preloading forces. Lateral displacements and settlements of the facing plates, lateral displacements of the slope surface and facing stresses were measured during both the preloading process and the inclining tests.

It was found that the reinforcement of slopes by the rock bolts with facing plate could effectively prevent deformation and failure. The larger the prestress was, the better the reinforcement effect. However, the effect of prestress increment on the slope stability became smaller as the prestress increased, especially after large deformations occurred. The deformation of the slope was deeper and wider for the reinforcement with smaller prestress, and shallower in limited local areas for the reinforcement with larger prestress.

Keywords: Centrifuge modeling, Slope reinforcement, Soil nailing, Prestress

1 INTRODUCTION

Rock bolt with facing plate is one of soil nailing method used on natural slopes. As other conventional soil nailing methods, it can effectively suppress slope deformation without cutting trees. Furthermore, it also can be effectively applied to a slope with weak soils, such as highly weathered rock by adding prestress to the slope through the plate. To study the reinforcement mechanisms, many researches have been done on the slope reinforced by this method using small scale 1g physical models\(^1\)\(^2\). However, it is difficult to simulate mechanical behaviour of soil caused by the self-weight, like failure of slope, in a small-scale physical model under normal Earth gravity, because stress levels in the model are much smaller than those in the prototype.

Centrifuge modelling techniques which can replicate the stress condition of large scale prototype in a reduced model have been used for the study of slope stability, including the soil reinforcement. Various loading conditions were simulated in the centrifuges to investigate the effect of soil nailing, such as excavation process by draining liquid from a rubber back\(^3\), ground water seepage\(^4\) and seismic force by a shaking table\(^5\).

From these previous studies, the reinforcing effects of soil nailing and facing plate have been confirmed for various conditions. However, because of the difficulty in controlling the preloading to the facing plate in a centrifuge, the effects of the prestress of facing plate on the stability of reinforced slope have not been well studied. In this study, a centrifuge model test system which can simulate the preloading process of the rock bolt with facing plate in a slope was developed and the static loading test were performed to the reinforced slope by an inclining table. In this paper, the model test technique and the results of preliminary tests are reported.

2 CENTRIFUGE MODEL TESTS

2.1 Loading system and test setup

In the tests, a relatively weak sand slope with 3m thickness resting on a stiff bottom slope was modeled in a rigid box with inner dimension of 450mm in length, 100mm in width and 300mm in depth.

The bottom slope is made of aluminum plate with small holes 100mm interval. Steel wires with facing plate are pulled by hoisting jacks through the hole and wheels as shown in Fig. 1. A miniature load cell was placed on the facing plate to measure the load applied to the plate from the wire (Fig. 2). The rigid box is mounted on the inclination table\(^6\)\(^7\), which can incline
the model by 20 degree. The inclination table has been used in the centrifuge model study to impose the pseudo static seismic force to the model slopes. Equivalent seismic intensity $\alpha_h$ by the inclination angle $\Delta \theta$ is given by Eq. (1).

$$\alpha_h = \tan \Delta \theta$$  \hspace{1cm} (1)

2.2 Model preparation and testing procedures

The weak sand slope was made of moist Edosaki sand with the index and mechanical properties shown in Table 1. The sand was prepared on the stiff bottom slope with 15° inclination (Fig. 1). Edosaki sand was glued on the surface of the bottom slope to create a rough surface. Before preparing the sand, the model box was placed on a 15° inclined slope base to the opposite direction to make the bottom slope surface horizontal and then the two wires were inserted into the holes with 100mm interval. The sand was statically compacted layer by layer using a rigid loading plate with holes to accommodate the wires. Having made 80mm thick sand layer, white soumen noodles with black dots are inserted in front of the slope for visual observation of ground deformation. 40mm square aluminum made model facing plates with 2mm thickness were placed on the slope surface and then the miniature load cells were fixed to the wires (Fig. 2). As the model box was placed on the 15° inclined slope base which is fixed to the inclination table as shown in Fig. 3, the initial angle of the model slope ($\theta_i$) was 30°. Lazar displacement transducers (LDTs) and potentiometers were placed on the facing plates and the slope surface as shown in Fig. 1 for the displacement measurements.

As centrifugal acceleration of 37g was applied to the model in this study, the prototype scales of sand slope thickness ($t$), facing plate size ($B$) and reinforcement interval ($S$) were 3m, 1.48m and 3.7m respectively. Preloads were applied to the facing plate by pulling the wires in 37g. After applying the preload, the model slope was inclined up to $\theta_i$=50° from $\theta_i$=30°. In this study a relatively low compaction degree of the sand, $D_c$=70%, was adopted in order to create reasonable amount of deformation in the slope by this range of inclination. Lateral displacements ($\delta_{P,1}$, $\delta_{P,2}$) and settlements ($S_{P,1}$, $S_{P,2}$) of the facing plates, lateral displacements of the slope surface ($\delta_{S,1}$, $\delta_{S,2}$) and tensile forces applied to the wires ($T_{P,1}$, $T_{P,2}$) were measured. Deformation of the slope was also monitored by a video camera during the inclining test.

Table 2 shows the conditions for the five tests presented in this paper. The prestress applied from the facing plate to the slope ($\sigma_{P}$) is the main parameter focused in this study. The average prestress of the two facing plate varied from 54 kPa to 136kPa, which was about 30% to 80% of the ultimate load intensity of the plate obtained from the pull-in loading test (Fig. 4). $R_D$ showed in Table 2 is the ratio of prestress to overburden pressure at the bottom of the sand slope ($t\gamma_b$).

![Fig. 1. Front and top views of model slope.](image1)
![Fig. 2. Miniature load cell placed on the facing plate.](image2)
![Fig. 3. Inclination table.](image3)

**Table 1. Properties of compacted Edosaki-sand used in the tests.**

| Property                      | Value     |
|-------------------------------|-----------|
| Specific gravity: $G_s$        | 2.72      |
| Mean grain diameter: $D_{50}$  | 0.29 mm   |
| Uniformity coefficient: $U_c$ | 26.4      |
| Maximum dry density: $\rho_{max}$ | 1.78 g/cm³ |
| Optimum water content $\omega_{opt}$ | 15 % |
| Bulk density of compacted sand: $\rho_b$ | 1.45 g/cm³ |
| Water content of compacted sand: $w$ | 15 % |
| Degree of compaction: $D_c$   | 70 %      |
| Friction angle*: $\phi'$ (degree) | 29.4 |
| Cohesion*: $c'$ (kPa)         | 2.7       |

*: strength parameters obtained from direct shear test under the vertical stresses from 9 to 41 kPa.

**Table 2. Conditions of test cases and tests results.**

| Test case | B/S | Prestress: $\sigma_P$ | $R_D$ | $\Delta \theta_i$ | $\Delta \theta_f$ |
|-----------|-----|-----------------------|-------|-------------------|-------------------|
| Case NR   | —   | —                     |       | —                 | —                 |
| Case1     | 0.4 (B=40mm) | 54kPa                | 1.3   | 10°               | 15°               |
| Case2     | 0.4 (B=40mm) | 89kPa                | 2.1   | 12°               | 16°               |
| Case3     | 0.4 (B=40mm) | 112kPa               | 2.7   | —                 | —                 |
| Case4     | 0.4 (B=40mm) | 136kPa               | 3.2   | 14°               | 20°               |
3 TEST RESULTS AND DISCUSSIONS

3.1 Preloading process

Fig. 4 shows relationships between the contact pressure and settlement of the facing plate observed in the preloading process. The relationships obtained in the pull-in loading tests are also shown in the figure. There were some scattering in the relation. This could be partly attributed to heterogeneity of the slope and rotation of the facing plate. Due to the space limitation, the settlement and lateral displacement were measured by one potentiometer and one LDT respectively, which could not detect the rotation. None the less the preloading could be applied by the system developed. In all cases, the pressures decreased to some extent after the loading process and became constant. These constant values are considered as the pre-stress in this study and shown in Table 2.

3.2 Ground deformation

Relationships between the slope inclination angle (θ) and the measured displacements (δ) in the inclining tests are shown in Fig. 5. From this figure, it can be confirmed that the displacement can be greatly reduced by the reinforcement. In the cases with smaller prestress, the displacements at different locations were not so much different as compared to those in the cases with larger prestress. In the former cases, large displacement were measured at all points; while in the latter cases, the movements of the upper part of the slope were tend to be larger than that of the lower part.

Slope deformations observed in no-reinforcement case (CaseNR), the smallest prestress case (Case1) and the largest prestress case (Case4) are shown in Fig. 6. Broken lines in the figures show potential slip lines observed in the slope. Deep deformation with a clear slip line was observed in CaseNR. In Case4, only shallow and local deformation occurred. While the cases with the smallest prestress (Case1) showed deep and large deformation, but no clear slip surface. Fig. 7 shows the displacement of markers along the noodles placed between the two facing plates for the three cases shown in Fig.6. In CaseNR, a large displacement occurred near the observed slip line (Fig. 6) after Δθ=5°. In the reinforcement cases, simple shear type deformations were observed and the displacements gradually increase with increasing inclination without showing abrupt increase of the displacement.

3.3 Effects of reinforcement on the slope stability

In Fig. 8, tanΔθ-δ relationships measured at the mid part of facing plate are shown in a log-log graph. tanΔθ is equivalent to the horizontal seismic intensity to the slope with the initial inclination (θi). From the figure a rapid increase of the displacement in the relationship can be obtained at a very small δ, which is defined as onset of the deformation and the increment of inclination at this point is denoted by Δθi. As discussed before, no abrupt increase of displacement was observed, 4mm displacement of slope measured between the two plates (δSi) is defined as a failure point, and the inclination increment at this point (Δθi) is employed as an index of the stability of the slope. 4mm displacement at the surface corresponds to shear strain of 5% of the slope. Both of Δθi and Δθi are also shown.
in Table 2. The $\tan\Delta\theta_f$ and the $\tan\Delta\theta_y$ are also plotted to $R_p$ in Fig. 9. Some data points are missing because of the fault of measurements. The larger the $R_p$, that is, the larger the prestress, the larger the effects of reinforcement could be obtained. However, the increment of $\tan\Delta\theta_y$ becomes smaller as $R_p$ increases. It is also noted that the onsets of displacement are almost the same between the slope and the facing plate.

Fig. 10 shows the variation of face contact pressure $\sigma_p$ measured at both the upper and lower facing plates during the inclination test. In the figure, the points of the onset of displacement ($\Delta\theta_f$) and $\Delta\theta_y$ are also indicated. In the cases with $R_p$ greater than 2.1, the contact pressure showed decreasing at some $\Delta\theta$ slightly larger than $\Delta\theta_f$ and then turned to increase as $\Delta\theta$ increased. In the case of $R_p=1.3$ (Case1), the upper facing plate contact pressure did not decrease but increased from the beginning. $\Delta\theta$ values of the onsets of the increment of the contact pressure and the decrement of contact pressure were larger as $R_p$ increased. This variation of facing plate contact pressure could be a reason why the increase of $\tan\Delta\theta_f$ becomes smaller as the prestress of the facing plate increases.

The variation of the upper plate settlement ($S$) and lateral displacement ($\delta$) with $\Delta\theta$ are shown in Figs. 11 and 12 respectively. The cases with the smaller prestresses (Cases1&2) shows relatively small settlement increment in the beginning of the inclination as compared to the cases with the larger prestresses (Cases3&4). While Cases1 and 2, especially Case1, the lateral displacement started the increase before the clear settlement occurred. Furthermore in Cases3 and 4 the clear settlements were observed before the clear displacement took place. These differences in tendency of the facing plate settlement and lateral displacement can be considered as a cause of the facing plate contact pressure variation as shown above.

Because only 2 rock bolts used in this study, the reinforced area is defined within 50mm [1.85m] from rock bolt (which is the same-distance between rock bolt and container wall with smooth surface). As shown in Fig. 13, the sliding force and sliding resistance due to the self-weight of the reinforced block are $W\sin\theta$ and $W\cos\theta\tan\psi+Ac$, which are not balanced. The difference of the two forces is considered as the net sliding resistance $N_f$ of the slope (Eq. (2)):

$$N_f = W\sin(\Delta\theta_f + 30^\circ) - W\cos(\Delta\theta_f + 30^\circ)\tan\psi - Ac \quad (2)$$

Therefore the difference between $N_f$ calculated in reinforced cases and no-reinforcement case ($N_{f\text{NR}}$) can be considered as resistance force due to facing plates. The $N_f$ value are plotted to $R_p$ in Fig. 14. In the figure, the contributions of the facing plate contact pressure on the additional mobilization of shear resistance on the bottom of the slope ($T_{tan}\theta$) are also shown plotted. Total force acting on the base ($T$) was
calculated by elastic theory using the contact stress of the assumption, that is infinite slope and test condition. $N_{FR}-N_{INR}$ is slightly larger than $T\tan\phi$, however the trends of the effects of $R_p$ on the resistance mobilization agree well between the two calculations. This implies the effect on the contact pressure as the main factor for the conditions in the tests, which are flexible wire inserted in the sliding slope made of the relatively soft soil.

4 CONCLUSIONS

In this study, centrifuge model tests were carried out to investigate the effects of pre-stress of rock bolt with facing plate in a slope with weak soils. Following conclusions are derived.

1). Reinforcement of slope by rock bolts with facing plate can effectively prevent the deformation and failure of the slope.

2). By increasing the prestress, the better reinforcement effect can be obtained. However the effect of the prestress increment on the stability becomes smaller as the prestress increases especially after large deformation occur. This can be attributed to the variation of face plate contact pressure as the deformation of slope progresses.

3). Deformation pattern of the slope also depends on the prestress, deeper and wider for the reinforcement with smaller prestress and shallower in limited local areas for larger prestress.

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