Proposal of Constructional Countermeasures for the Widening of Embankments with a Focus on Their High Stability

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The improvement rate of countermeasures adopted in constructing a second track on an embankment on soft ground is determined empirically due to unknown factors such as the deformation properties of soft ground. In this study, centrifuge model tests were performed to grasp the deformation properties of soft ground for such construction cases. Based on the test result, a new countermeasure was proposed, which has high horizontal support performance and combines deep mixing wall-type ground improvements and cement-mixed gravel. The proposed method having the same improvement rate as deep mixing was confirmed as being able to reduce the deformation of the embankment and the surrounding ground.

Keywords: soft ground, widening of embankment, wall type ground improvement, cement-treated gravelly soil slab, centrifuge model tests

1. Introduction

In the railways, embankment widening is often used for converting a single track that has been used for many years to a double track. However, widening an embankment on soft ground can create a wide range of problems such as reduced stability of the entire embankment, deformation of the original embankment due to consolidation, settlement or shear deformation of the soft ground and upheaval of the ground adjacent to the widened portion of the embankment. In addition, boundaries between the widened and original portions of the embankment can easily become bleeding channels or other weak points, inviting damage in earthquakes.

To minimize the problems associated with soft ground, countermeasures such as ground improvement must be taken. It is difficult, however, to introduce countermeasures to soft ground beneath an original embankment while it is in use for train services, making the ground directly beneath the widened portion of the embankment the only area to which countermeasures can be applied.

Traditionally, the area of the ground adjacent to the toe of the original embankment has often been improved by installing piles with a diameter of about 1.0 m in a staggered pattern (Fig. 1) [1]. In this case, the piles are subject not just to vertical loads but also horizontal loads from the widened part of the embankment, making the piles prone to a combination of problems such as sliding displacement, shear failure, bending failure and overturning. On the other hand, these behaviors and the effect of the piles are still not yet fully understood. Due to this limited knowledge, it is not possible in practical design processes to quantitatively determine the rate of improvement expected to be achieved by the ground improving piles.

With the above background in mind, this study considered soft ground that would require a deep mixing method of soil stabilization and, through model tests, evaluated the behaviors of a widened embankment and the soft ground beneath it and also examined the effects of two of the existing countermeasures. In addition, based on the results of

Fig. 1 Example of the ground reinforcement piles for widening of an embankment to convert a single track to double track
the model experiments, a best countermeasure was proposed, designing procedures were established and a trial design was applied.

2. Impact of embankment widening on soft ground and effects of existing countermeasures

When conducting model experiments to evaluate the deformation of an embankment and that of the soft ground beneath it and to examine the effect of countermeasures, it is necessary to adopt a consolidation settlement process of the soft ground that best reflects the actual phenomena. While the actual consolidation settlement of soft ground takes place in the time period of several to several dozen years, this study simulated the consolidation of the soft ground and the construction process of widening an embankment by applying centrifugal acceleration to a model ground. In addition, considering that widened embankments built on soft ground often get damaged during earthquakes, shaking table tests using Level 1 earthquake input motion were conducted. This report will discuss the embankment widening simulation in detail. For details about the shaking table tests, please refer to the previous study [2].

2.1 Simulation conditions

2.1.1 Outlines of the models used

Figure 2 shows the outlines of the models used in the simulation. As centrifugal experiments on models are conducted with a maximum force of 50 G, these models were made to a scale of 1/50. It is important to note that the values shown in the following text and some of the values shown in the following figs. are actual dimensions converted from those measured on the models.

To simulate soft ground, a layer of kaolin clay was laid upon a drainage layer. The original embankment measured about 6.0 m in height, which is the standard dimension for railway embankments. Considering that the material used for the widened portion of an embankment is often better in quality and heavier per unit volume than the original embankment, a material heavier in dry density than the original embankment was used for the widened portion of the embankment.

The effects of two existing countermeasures, such as piles and a combination of piles and earth reinforcements, were evaluated. The piles, each measuring 1.0 m in diameter, were arranged vertically in two rows 1.5 m apart, in the direction of the tracks at intervals of 1.7 m, within 3.0 m from the toe of the original embankment to achieve an improvement rate of 30 %. The earth reinforcements, each measuring 250 mm in diameter and equipped with a continuous thread, were arranged in upper and lower layers of the original embankment, 2.0 m apart in each array. The reinforcements in the upper layer were 5.0 m long and those in the lower layer 7.5 m long.

2.1.2 Application of centrifugal force

Centrifuge tests were conducted using the Mark II geotechnical centrifuge [3] of the Port and Airport Research Institute. Centrifugal loading was performed in two stages with centrifugal force accelerated in steps up to 50 G. In the first centrifugal loading, consolidation settlement of the soft ground was facilitated with the weight of the original embankment. Following the first loading, the test environment was returned to 1 G. In the second centrifugal loading, embankment widening simulation was conducted. In the evaluation of the existing countermeasures, shown in Fig. 2 (b) and (c), these measures were arranged into the models after the first centrifugal loading.

The measurement items taken include: pore water
pressure and the deformation of the soft ground induced by the construction of the widened embankment and the following consolidation process; the displacement of the original embankment and that of the ground; and earth pressure. In addition, two-dimensional displacement of the targets arranged in the models were measured by image analysis. For details of the simulation models and conditions, please refer to the previous study [2], [4] and [5].

2.2 Test results and discussion

2.2.1 Behaviors of the embankment and soft ground associated with embankment widening

Figure 3 shows the deformation of the model associated with embankment widening. Table 1 shows the displacements of key targets in the soft ground that were obtained by image analysis. Figure 3 shows the following: that the soft ground beneath the entire embankment settled in the arched form; displacement was most significant near the toe of the original embankment (Point A in Fig. 3), the area subjected to extreme vertical loading; and that an upheaval of about 135 mm was observed on the surface of the soft ground adjacent to the toe of the widened portion of the embankment (Point B in Fig. 3).

Figure 3 and Table 1 (a) show that the soft ground underneath the widened portion of the embankment (Target 62 in Fig. 3) settled by as much as 230 mm vertically and was displaced by about 238.5 mm horizontally outward in immediate deformation associated with the embankment widening. In all, after subsequent displacement during consolidation settlement process was added, that area of the soft ground settled about 420.0 mm vertically and was displaced about 279.0 mm horizontally outward. This indicates that, when carrying out embankment widening on soft ground, it is essential to take measures to minimize both vertical and horizontal displacement of the soft ground beneath the widened portion of the embankment.

Horizontal displacement similar to that at Target 62 (Table 1 (a)), mentioned above, was confirmed in the area of the soft ground near the toe of the widened portion of the embankment (Target 22 in Fig. 3). Also in that area, an upheaval of about 71.5 mm was observed in immediate deformation. The total vertical displacement, after subsequent consolidation settlement was factored in, reached about 45.5 mm, which was much smaller than the total vertical displacement at Target 62 beneath the widened portion of the embankment. Accordingly, vertical displacement of soft ground can be minimized more effectively by installing countermeasures as near as possible to the toe of the original embankment.

In addition, the top surface of the original embankment settled about 50.0 mm, and settled further about 65.0 mm in subsequent consolidation settlement, indicating that embankment widening can cause the original embankment to settle.

2.2.2 Effects of the existing countermeasures

Figure 4 shows the deformation of the model after the completion of consolidation settlement following embankment widening, for which a combination of piles and earth reinforcements was used.

Compared with the model with no countermeasures, a combination of piles and earth reinforcements slightly, but not significantly, mitigated the deformation of the original embankment. Figure 5 shows the model with piles and earth reinforcements after centrifugal loading (this picture was taken during the process of removing the model from

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Table 1 Displacements of key targets in the soft ground

| (a) Deformation of soft ground below the widened embankment | (Target 62) (unit:mm) |
|----------------------------------------------------------|-----------------------|
| Horizontal displacement | Immediate deformation | Consolidation settlement | Total |
| 238.5 | -40.5 | -279.0 |
| 190.0 | -71.0 | 117.0 |
| 45.5 |

| (b) Deformation of surface of soft ground adjacent to toe of widened portion of the embankment (Target 22) (unit:mm) |
|----------------------------------------------------------|
| Horizontal displacement | Immediate deformation | Consolidation settlement | Total |
| -277.5 | -42.0 | -319.5 |
| 117.0 | -71.5 | 45.5 |
The piles were clearly shown tilted, indicating limited effect of piles (discretely distributed) in preventing horizontal displacement of the soft ground under load from a widened embankment.

From the above, it is clear that, to reduce the deformation of soft ground around a widened embankment, it is necessary to install measures highly effective in preventing the horizontal displacement of the ground.

3. Evaluation of the effect of our proposed countermeasure consisting of a wall of piles and a cement-treated gravelly soil slab

3.1 Outline of the proposed countermeasure and experiment conditions

The simulation of the existing countermeasures revealed that deformation of the ground associated with embankment widening occurs predominantly in horizontal directions and that piles discretely distributed have limited effect in preventing horizontal displacement of the ground. This suggests that, in order for any countermeasure to offer both an improvement rate equivalent to that of piles and the capability to better prevent the ground’s horizontal displacement, it should be taken in such a manner as to make embankments have high bending resistivity. It is difficult to achieve such resistivity by discretely arranging piles.

One possible countermeasure that is highly effective in preventing horizontal displacement of the ground is “block type improvement”, consisting of piles arranged in an overlapping or joined pattern and covering the entire area that needs correction. However, implementing such measures along the tracks is often too costly to be practical. Given these thoughts, our study adopted “Wall type improvement” in which piles are joined to each other to form a wall, as shown in Fig. 6.

For walls to achieve the same improvement rate as piles, they need to be installed at intervals greater than the existing countermeasure in which the piles are arranged discretely. Otherwise this can cause uneven settlement of the widened portion of the embankment along the tracks. To minimize such uneven settlement, a cement-treated gravelly soil slab consisting of cement-stabilized crushed stones for mechanical stabilization and sheet reinforcement (geotextile) was placed above each wall. Cement-treated gravelly soil slabs have been used for embankment construction on soft ground or liquefiable ground during earthquakes. For details, please refer to the previous study [6].

In the experiment, the same specifications including the materials and the conditions that were used in the
previous experiments were used for the soft ground and the original and expanded portions of the embankment. Each wall type improvement shaped in a rectangular parallelepiped measured 0.85 m in width and 3.3 m in depth, and was installed in such a way as to achieve the general improvement rate of not more than 30% which is the average rate for the existing pile improvement across the entire range (5.0 m) of the widened portion of the embankment. A cement-treated gravelly soil slab was made of gravel obtained by removing particles larger than 10 mm from the well-graded gravel (M-40). Little amount of cement was added (cement/gravel ratio in weight equal to 2.5 %) and two polyester reinforcements (geogrid model) were arranged horizontally inside the slab.

3.2 Evaluation of the effect of the proposed countermeasure

Figure 7 shows deformation of the model caused by the construction of a widened embankment. Figure 8 shows, two-dimensional displacements of the targets (targets 22 and 62 in Fig. 7) which was obtained by image processing, the settlement of the top surface of the original embankment and upheaval of the ground adjacent to the toe of the widened portion of the embankment each of which was measured by a displacement transducer. All of these were induced by the construction of the widened embankment.

On Target 62 beneath the widened portion of the embankment, the proposed countermeasure, in comparison with no countermeasures, enabled the horizontal displacement of the ground to reduce by around half while there was no significant improvement in vertical displacement. Similarly, on Target 22 adjacent to the toe of the widened portion of the embankment, the proposed countermeasure reduced horizontal displacement by around three quarters and vertical displacement by around half. These indicate that the proposed countermeasure is effective in preventing horizontal displacement.

In addition, in comparison with no countermeasures, the proposed reduced the settlement of the top surface of the original embankment by around half and the upheaval of the ground adjacent to the toe of the widened portion of

**Fig. 7** Deformation of model caused by widening of the embankment (proposed countermeasure)

![Fig. 7](image_url)

**Fig. 8** Deformation of models following embankment widening (top: obtained by image processing bottom: measured by displacement transducer)

the embankment by around three quarters, indicating that the proposal is effective in mitigating the deformation of the original embankment. Based on precise observations after the test (during the process of removing the model), the wall type improvement units were not seen tilting nor had the soft ground between the units separated or slipped through the units.

4. Designing procedure and trial calculations of the proposed method

4.1 Designing procedure

The simulation by means of a geotechnical centrifuge revealed that the proposed cement-treated gravelly soil slabs countermeasure efficiently transferred the weight of the widened portion of an embankment onto the wall type improvement units placed under each of the slabs, integrating wall type improvement units and the soft ground between the units into one body to prevent shear failure from vertical and horizontal loads as well as rotational slips.

Figure 9 shows the flow of the proposed measure designing techniques. Based on the failure prevention mechanism described above, the flow was designed to ensure that cement-treated gravelly soil slabs would not fail under the weight of the widened portion of an embankment and that an integrated body of wall type improvement units and the ground between the units would meet requirements for the stability (bearing capacity, sliding and overturning) of the integrated body as well as for the anti-rotational slip resistance of the body. In addition, an integrated body of wall type improvement units and the ground between them was examined in order to confirm that the integrated body, not allowing the soft ground to be separated from the units, hold together.

Furthermore, the results of centrifuge model tests
revealed that the weight of the widened portion of an embankment subjected the bottom faces of the wall type improvement to substantial subgrade reaction (hereafter “bottom pressure”), the flow was designed to consider bottom pressure as long as the subsoil below the improvement would not be damaged.

Figure 10 shows the distribution of earth pressure on the proposed integrated body of wall type improvement units and the ground between them. This is based on the weight of the widened portion of an embankment being the only load in the following environment: the soft ground has been consolidated sufficiently under the weight of the original embankment even before it is widened; and the proposed countermeasure installed near the toe of the original embankment has reduced the effect of weight of the original embankment onto the integrated body of wall type improvement units. For details of the designing techniques for the proposed measure, please refer to the previous study [7].

### 4.2 Trial calculations of the proposed method

Trial calculation was conducted on both the embankment and that with a reinforced-soil retaining wall. For this, the height of the embankment was set to 6.0 m and soft ground of about $N = 2$ (SPT value) with a layer depth of 10.0 m was used to build the embankment on. Figure 11 shows the models used for the calculations. The calculations revealed that the required performance with regards to stability, rotational slip were satisfied with improvement rates almost equal to those for the existing countermeasures; an improvement rate of 30.0 % is necessary in case of an embankment (Fig. 11a) and 32.7 % in case of a reinforced-soil retaining wall. For both methods, the improvement rate was determined based on cement-treated gravelly soil slabs failure (excluding from earthquakes) and improved strength based on bottom pressure (during Level 1 earthquakes).

All this indicates that using the proposed countermeasure, it is now possible to improve the ground specifically for supporting a widened embankment and to calculate improvement rates based on relevant requirements and ground conditions which thus far has not been possible.

### 5. Conclusion

In an attempt to propose a method for sufficiently supporting a widened embankment built on soft ground, centrifugal experiments were conducted and, based on the results of the experiments, a method with high horizontal support performance was developed. In addition, based on the results of the experiments, design procedures were discussed and related calculations of improvement rates were performed.

The following are key findings from this study.

(1) Centrifugal experiments on a pile-type countermeasure revealed that piles installed in soft ground and under the weight of a widened embankment can tilt due to horizontal loading that they receive. Therefore, any countermeasure for a widened embankment on soft ground must have high horizontal support performance.

(2) A combination of a wall of piles (wall type improvement) and a cement-treated gravelly soil slab was proposed as a ground improvement measure with high horizontal support performance. Experiments revealed that the proposed measure reduced horizontal displacement of the ground by around three quarters and settlement of the embankment by around half and that the slabs helped prevent uneven settlement of the embankment between the slab-wall units.

(3) Techniques for designing the proposed measure were proposed and trial calculations were conducted to determine the improvement rates. The exercise established a quantitative calculation procedure to measure...
improvement rates.

Based on the above, the proposed measure can be an effective tool in overcoming the problems discussed in this paper that are associated with embankment widening on soft ground.

![Diagram](image)

**Fig. 10** The distribution of earth pressure on the proposed counter measure’s integrated body of wall type improvement units and the ground between them

![Diagram](image)

**Fig. 11** The model used for the calculation
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