Interlocking Settlement Induced by Widening Subgrade of Railway Line

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Abstract: In areas where it is difficult to secure additional land for railways, a plan to increase rail transport capacity by widening existing embankments is required. When widening the embankment, additional stress is generated at the bottom of the existing embankment, resulting in an additional settlement (interlocking settlement) of the existing embankment. Reinforced subgrade for railways (RSR) is an efficient method for widening embankments without additional sites. In this study, an existing railway embankment in operation was widened using the RSR, with the interlocking settlement evaluated and analyzed during and after construction. Results show that a widened embankment using RSR can secure train operation stability on existing tracks, even in ground conditions including shallow soft layers. The interlocking settlement was mainly affected by the backfill load and hardly affected by the wall load of the RSR. In addition, it was confirmed that the interlocking settlement mainly occurred in the backfill construction and stabilization period of RSR construction and converged early.

Keywords: interlocking settlement; railway subgrade; field test; long-term measurement

1. Introduction

With increasingly rapid economic development in many countries, including Korea, the demand for rail transportation, such as freight and passenger railway transport, has also increased over the past decades. As the demand for additional railway transportation increases, along with the construction of new lines, it is necessary to increase its capacity by widening existing subgrades to add tracks [1]. A generally used method for adding railway tracks to existing embankment subgrades is to construct new embankments on existing subgrade slopes. When widening embankments, differential settlements and cracks between existing and new embankments may occur, due to the difference in soil properties and compressibility [2,3]. Field investigations [4], small centrifuge tests [5], and numerical analyses [6,7] have been conducted to analyze the deformation characteristics and mechanisms of widened embankments. As a result, geotextile reinforcements [8,9], geosynthetic clay liners [10], foundation columns [11], lightweight stacking materials [12,13], and combinations of these methods [14,15] have been proposed to solve problems that may occur in widened embankments.

Widened embankments not only cause additional stresses and deformations in the extension but also affect existing embankments [16]. Additional stress occurs at the bottom of the existing subgrade owing to the load of the extension. Accordingly, an additional settlement of the existing subgrade (interlocking settlement) occurs, as shown in Figure 1. Excessive interlocking settlement reduces the safety of existing tracks, causing safety problems, such as train derailment, possibly requiring excessive repair and maintenance costs. In addition, economic problems, such as the need for additional sites [17,18], civil complaints due to land occupation, and supply and demand of a large number of soil materials, may occur depending on the conditions of the construction site.
Reinforced subgrade for railways (RSR) is an efficient method to widen the embankment subgrade without additional sites. As shown in Figure 2, RSR is a construction method in which a backfill reinforced with nets of welded rebars and geogrids is pre-constructed, with the rigid facing wall post-constructed after the deformation of the backfill converges during the stabilization period. Integrating the rigid facing wall and geogrid secures the stability of the roadbed, with an excellent deformation control performance when using short geogrids with a length of 35% of the height [19–23]. In addition, it has excellent applicability in small spaces since this method uses a small foundation and short geogrids. The embankment subgrade can be widened without additional sites, significantly reducing the amount of soil material used, as shown in Figure 3 [24].
Although the RSR method has several advantages, studies on the effect on existing lines, such as interlocking settlement due to the widened subgrade, are few. In particular, it is difficult to obtain measurement data on the long-term deformation of existing operating lines considering safety, cost, and time. In this study, the embankment subgrade of an existing operating line was extended without an additional site by installing an RSR on the slope. The long-term settlements of the RSR and existing lines were evaluated by measuring the settlement during and after the construction of the RSR. The long-term settlements of the RSR and existing embankment during and after construction and the interlocking settlement occurring during the widening of the embankment were evaluated and analyzed.

2. Field Measurement When Widening the Embankment Using RSR

2.1. Description of RSR Construction

The interlocking settlement of the existing embankment by RSR construction was analyzed by constructing an RSR on the Janghang line in Korea to expand the embankment and measure the settlements. The Janghang line was opened in 1932, operating for more than 80 years before RSR construction. As shown in Figure 4, the embankment was widened using the slope of the side track of the Janghang line. The site was suitable for RSR application, as it was impossible to secure additional land for widening the embankment due to the adjacent road, as shown in Figure 5. The RSR was constructed with a height and length of 7.5 and 40 m, respectively, including the foundation. Therefore, the embankment could be widened with a width of 10 to 12 m.

Figure 3. Differences in widening embankment based on the method employed: (a) Railway embankment; (b) Widening with standard embankment; (c) Widening with RSR.
A ground survey was conducted to design and construct the RSR. The ground contained a soft layer composed of a silty sand layer with an $N$ value of 3 to 7, which was 1.8 m from the surface, and a silty clay layer with an $N$ value of 5–8, which was between 1.8 to 3.5 m in depth. Table 1 lists the ground conditions.

Table 1. Ground conditions.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Thickness (m)</th>
<th>Layer Description</th>
<th>$N$ Values $^1$ (Numbers/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00–1.80</td>
<td>1.8</td>
<td>Land fill layer</td>
<td>3/30–7/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soft to very soft</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silty sand</td>
<td></td>
</tr>
<tr>
<td>1.80–3.50</td>
<td>1.7</td>
<td>Sedimentary layer</td>
<td>5/30–8/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soft to medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silty clay</td>
<td></td>
</tr>
<tr>
<td>3.50–5.70</td>
<td>2.2</td>
<td>Sedimentary layer</td>
<td>21/30–31/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium to stiff</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandy gravel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weathered soil layer</td>
<td></td>
</tr>
<tr>
<td>5.70–23.50</td>
<td>17.8</td>
<td>Soft to Very stiff</td>
<td>14/30–50/30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fully weathered</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silty sand</td>
<td></td>
</tr>
</tbody>
</table>

$^1 N$ value: The number of hammer blows required to penetrate the sampler by 0.3 m in the standard penetration test.

Figure 6 shows the detailed cross-sectional view of the RSR installed on the embankment slope and the locations of the settlement measurements. The geogrid layout was determined through a stability analysis of the RSR. The vertical spacing of the short rein-
forcemoment was 0.4 m, and the length was 2.8 m, which is 40% of the height. Long reinforcing materials were placed on every 4th layer from the top to prevent overturning.

**Figure 6.** Section view of the RSR and measurement point.

Figure 7 shows the construction procedure for the RSR. Considering the soft layer, the ground was replaced with cement-mixed gravel with a width of 1.8 m and a depth of 1.1 m from the bottom of the foundation to prevent residual settlement after wall construction. After replacing the ground, a foundation was installed, and the upper and lower subgrades were constructed after a curing period. The backfill materials were compacted and reinforced with nets of welded rebars and geogrids. The backfill was constructed by stacking up 17 floors repeatedly. According to the unified classification method, SM and SP-SM were used for the lower and upper subgrade soils, respectively. Compaction quality control was conducted following the Korea Railroad Design Standards [25]. The compaction criteria for the lower subgrade (\(E_v^2 > 60\) MPa and \(E_v^2/E_v^1 < 2.7\)) and the upper subgrade (\(E_v^2 > 80\) MPa and \(E_v^2/E_v^1 < 2.3\)) were satisfied. A rigid facing wall was constructed after the settlement of the backfill, and the ground sufficiently converged during a stabilization period of approximately six months. To satisfy the design flexural strength, 16 mm diameter main rebars were placed with double reinforcement at a spacing of 250 mm, and the wall section was constructed with a top thickness of 300 mm and a front slope of 1:0.025.

**Figure 7.** Cont.
Figure 7. Construction of RSR: (a) Excavation and ground replacement; (b) Installing the foundation; (c) Installing net of welded re-bars and geogrids; (d) Placement of the backfill material; (e) Compaction; (f) Repetition of steps (c–e); (g) Installing the rigid facing wall; and (h) Completion.

2.2. Description of Measurement

Settlement measurements were conducted for 983 days, starting from the completion of the backfill to 765 days after the completion of the rigid-facing wall construction. As shown in Figure 8, the measurements were performed on the ground and surface in the RSR and at 10 points on the outer and inner rail at spaces of 10 m in the existing track. Based on the results of the settlement measurement, the settlement of the ground and the interlocking settlement in the existing operating line due to the construction of the RSR were analyzed. Settlement rods were installed, as shown in Figure 9, to measure the settlement of the ground and surface. The ground settlement rod was installed at the bottom of the backfill (the first stage of the reinforcement), 2.5 m away from the wall. It was made by connecting a 15 mm diameter steel bar to a 1 × 1 m plate and extending it as the height of the backfill increased. It was protected with 0.2 m diameter pipes and separated from the backfill soil. The surface settlement rod was installed 2.0 m away from the wall of the RSR surface. It was made by connecting a 0.4 m long steel bar to a 0.3 m diameter plate. After the backfill construction was completed, it was installed 0.1 m below the surface and covered with soil to be fixed. Settlement measurements were conducted using an electronic
leveling device capable of measuring up to $10^{-5}$ m to ensure the accuracy of the settlement calculation, as shown in Figure 10.

Figure 8. Plan view of the measurement point.

Figure 9. Settlement measuring device: (a) Ground settlement rod; (b) Surface settlement rod.

Figure 10. Field measurement of the settlement.
3. Analysis of Results

Figures 11 and 12 show the results of long-term settlement measurements over time during and after RSR construction on the ground, surface, and rail. The maximum settlements at the ground and surface, which are the positions directly loading the RSR’s weight, were 32.50 and 58.50 mm, respectively. The maximum interlocking settlements measured on the outer and inner rails of the existing track were 9.50 and 6.89 mm, respectively, which were relatively larger in the outer rail close to the center of gravity of the RSR. The interlocking settlements tended to appear larger towards the center (at 20 m), which was heavily affected by the RSR loads. Interlocking settlements occurred at 15–28% and 9–16% compared to the ground and surface, respectively. The interlocking settlements occurred within the range of 10 mm, which is the Korean track maintenance standard. Therefore, a widened embankment using RSR can secure the stability of the existing track, even in ground conditions including a shallow soft layer. Regarding the overall tendency of settlements, the closer to the center of gravity of the RSR, the greater the settlement, which is similar to the traditional widening of embankments in previous studies [26,27]. The large difference in the interlocking settlement with the ground or surface is due to the difference in the distance from the center of gravity of the RSR and the difference in the stiffness of the ground. Because the bottom ground near the embankment toe is less loaded than at the lower part of the existing embankment, where the self-weight of the embankment and the train operation load continued, the difference in stiffness of the bottom ground due to the compression difference [28] may have affected the settlement.

![Figure 11. Ground and surface settlements.](image1)

![Figure 12. Cont.](image2)
The period of increasing settlement can be divided into three parts: backfill stabilization, wall construction, and after wall construction. Figure 13 shows the settlement that occurred according to the measurement period at each measurement point as a percentage of the total settlement. The settlement during the backfill stabilization period compared to the total occurred at 62% and 44% of the ground and surface, respectively, and from 69% to 100% of the interlocking settlement. During the backfill stabilization period, the time-dependent settlement was induced in the soft layer of the bottom ground, owing to the soil weight, and the overall settlement increased with time but showed a tendency to converge at a certain level. The greater the distance from the measurement position to the RSR center of gravity, the greater the rate of settlement during the stabilization period. This can be attributed to the wall load being smaller than the backfill and the wall being installed close to the center of gravity of the RSR.

The interlocking settlement during the wall construction period compared to the total occurred at 0–29%. The interlocking settlement due to the wall load was larger in the central part, which was significantly affected by the RSR load, as shown in Figures 12 and 13. However, considering that the interlocking settlement decreased after wall construction at several measurement points and the interlocking settlement only slightly increased (up to 2.02 mm), external factors, such as climate, precipitation, and measurement error, may have affected the results. It can be observed that the effect of the wall load on the interlocking settlement was insignificant.

Similarly, in the long-term measurement after RSR wall construction, the closer the wall load applied, the larger the settlement measured. However, the settlement rate was
extremely small (up to 4%), or additional settlement did not occur at several measurement points after wall construction. The interlocking settlements increased for a certain period and then decreased, contrary to those on the ground and the surface. This may be caused by external factors, such as temperature and measurement error. No significant change was confirmed in the interlocking settlement during the after-wall construction period based on the last measurement date. After RSR wall construction, additional settlements of 5.50 and 17.89 mm occurred on the ground and surface, respectively, and time-dependent settlements hardly occurred in the existing track. This is due to the difference in the degree of consolidation of the bottom ground owing to the long-term embankment load and train operating load.

When the rail embankment was widened using the RSR, the interlocking settlement of the existing embankment occurred mainly during the backfill construction and stabilization period. The settlement converged earlier than the ground and surface of the RSR. Therefore, it is important to manage the interlocking settlement of the existing embankments at the initial stage of construction.

With the increasing demand for railway transportation capacity, the demand for widening embankments with RSR is also expected to increase in areas where it is difficult to secure additional sites. Under favorable ground conditions, RSR can be used to widen embankments without additional land and interfering with the train operations of an existing railway. Interlocking settlements in existing embankments mostly occur when constructing the backfill and during stabilization; thus, management during the early stages of construction is crucial. Interlocking settlements from additional wall loads are extremely small, but caution is required because there is a possibility of excessive settlements in soft ground conditions. The degree of consolidation of the ground below the existing subgrade affects the interlocking settlement in soft ground conditions. Therefore, factors related to consolidation, such as the operation period of the existing line, must be investigated. If an interlocking settlement is excessive in design, the generally used ground reinforcement method can be considered.

4. Conclusions

In this study, the long-term settlement behavior for a widened embankment using RSR was analyzed, and its performance was evaluated through test construction and field measurements. The conclusions of this study are as follows:

(1) When widening an embankment using RSR, interlocking settlement occurs within a range of 10 mm, which is the Korean track maintenance standard. Therefore, a widened embankment using RSR can secure train operation stability on existing tracks, even in ground conditions including shallow soft layers.

(2) The interlocking settlement is hardly affected by the wall load compared with the ground and surface of the RSR. Owing to the wall installation location and structural characteristics of the RSR, in which the backfill shares the wall load, the farther from the center of gravity of the RSR, the less the influence of the wall load.

(3) After wall construction, time-dependent settlement increased in the original ground and surface settlement, but there was little change in the interlocking settlement owing to the difference in the degree of consolidation in the lower bottom ground. Interlocking settlement mainly occurred in the early stage of the widening of the embankment (backfill construction and stabilization) and converged early. Therefore, interlocking settlements require intensive management during the early stages of construction.

The operational stability of existing tracks and the importance of the early management of interlocking settlements during the widening of an embankment using RSR were confirmed in this study. However, this study is limited since it is a field study of a single case. The applicability of this study can be expanded in subsequent studies (e.g., conducting numerical analyses and field tests in other conditions).
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