Experimental Investigation on Effects of Track Configurations on Long-Term Behavior of Ballasted Track

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Abstract

The track settlement causes the deterioration of track geometry structure. Analysis of track settlement is a significant condition for determining the maintenance cycle. The long-term behavior of ballasted track may vary depending on the combination of the track configurations. In the present study, four ballasted tracks are studied through full-scale experiments to evaluate their respective performance in terms of track settlement. A cyclic load of up to 1.5 million cycles, simulated by vehicle speed of 230 km/h, is been applied to the ballasted tracks. The long-term behavior prediction equations for the ballasted tracks used in Korea are presented in this study. The size of the sleeper and the thickness of ballast are analyzed to be the most influential track configurations for the long-term behavior of ballasted track. Results of the full-scale test presented the effective area between ballast and subgrade is related to the long-term behavior of ballasted track. The track settlement decreases as the effective area between ballast and subgrade increases. Therefore, it is necessary to properly consider the effective area of sleeper and the ballast thickness to inhibit the track settlement.

Keywords: Railway ballast; track settlement; track configurations; cyclic loading; experimental study

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1. Introduction

The track settlement causes the deterioration of track geometry structure. Analysis of track settlement is a significant condition determining the maintenance cycle. The traditional ballasted tracks are still being used in high speed railways (over a vehicle speed of 200 km/h) with success, however a considerable maintenance work is needed due to the track settlements. In order to accommodate operation of high-speed trains, ballasted tracks demand high budgets to cover the maintenance costs necessary to return the track to its initial position. Therefore it is very important to predict track settlements in order to reduce track maintenance costs and enable new track structures to be designed.

A railway ballasted track typically consists of a top layer of track configurations (rails, fasteners, sleepers, etc.), a middle layer of railway ballast, and a bottom layer of sub-ballast and subgrade. For increased speed and high density train service, the rails are heavily weighted, rail fastening devices have been softened, and sleepers use pre-stressed concrete (PC) sleeper. For ballast materials, angular, crushed, uniformly graded brad stones and rocks are commonly used. As the ballast layer is placed under and around the sleepers, the sleeper movement becomes limited by resisting vertical, transverse and longitudinal forces from the trains. The layer distributes the load from the sleepers to protect the subgrade and provides necessary resilience to absorb shock from dynamic loading [1].

The track settlement occurs frequently in ballasted tracks. The track settlement is a major cause of increased track maintenance costs and an obstacle that often prevents increase of vehicle speed. It is a result of permanent deformation in the ballast and underlying soil due to the repeated traffic loading, and leads to a change in the dynamic characteristics of the vehicle.

Shenton [2] suggested that the main controlling factor of track degradation model is the settlement of the ballast. Shenton’s model does not take into consideration a number of influencing factors such as the vehicle speed and some of the track configurations conditions. Chrismer [3] studied the modelling framework for the ballast and subgrade, where deterioration of ballast and subgrade is associated with differential settlement Sato [4] suggested an equation for the tamped track settlement under repeated loading by train passage and presented a model for growth of track irregularities. Peplow [5] examined the specification of ballast materials using different methods and reviewed value for static and dynamic loading for track structure-ballast interaction. Iwnicki [6] examined the effect of different vehicles on track deterioration and consequent maintenance costs. It implies that two different tracks (one stiff and one soft) undergo the same degree of deterioration if they were subjected to the same amount of loading. Mundrey [7] presented that the main contribution to the ballasted track’s long-term behavior comes from the tonnage and the running speed. Previously developed models have some deficiencies that limit their applicability, practicability, or reliability [8]. Shaer [9] presented that the settlement was found to be a function of the acceleration of sleepers, and above all, it was observed, at a point where acceleration reaches above a critical value, the increase of settlement per cycle was very high. Sadeghi [10]
attempted a development of improved railway track degradation models through an engineering and statistical analyses of the results obtained from field investigations. The ballasted track degradation models are closely related to the track settlement, and it is necessary to study the track settlement according to the track configurations. Kennedy [11] measured the track settlement of unreinforced and polymer reinforced ballasted track under laboratory conditions. Tutumluer [12] confirmed that the track settlement was sensitive to aggregate shape, gradation and initial compaction condition (density) of the constructed ballast layer. Ishida [13] developed a track settlement progress model comprising a vehicle/track interaction model and a track settlement law. Vale [14] presented a stochastic mathematical model designed to optimize and to predict tamping operations in ballasted tracks as preventive condition-based maintenance. Navikas [15] confirmed that use of high quality aggregate mixture, proper technological parameters of laying and compacting as well as the required thickness of the mixture ensures railway sub-ballast layer properties. In Germany, the optimum ballasted track structures for each speed band is applied considering track degradation [16, 17].

Although many studies for predicting the ballasted track settlement have been previously reported, they have largely relied on the use of either the field investigations or the reduced scale experiments. These approaches tend to have limited results depending on the track maintenance methods and are not sufficient to clearly determine the effect of ballasted track configurations on the track settlement. In this study, the available literatures related to the track settlement models were reviewed and a method for analyzing the track settlement models was selected. Four types of ballasted tracks were constructed and dynamic excitation tests were performed to analyze the effects of the long-term behavior on various combinations of ballasted track configurations. In addition, the main factors influencing the long-term behavior of the ballasted track under the same loading conditions were analyzed.

2. Materials and Methods

2.1 Track settlement models

Several attempts [1-2, 4, 6, 10, 18-24] had been made to develop a predictive settlement model for the ballasted track (see Figure 1 (a)).
Hettler [24] suggested a logarithmic form of the following function for ballasted track settlement.

\[ u_N = u_1[1 + c \ln(N)] \]  

(1)

where \( u_N \) is the track settlement, \( u_1 \) is the initial settlement after the first loading cycle, \( N \) is the loading cycles and \( c \) is a constant between 0.25 and 0.55 (Hettler obtained \( c=0.43 \) as mean value). This function may be considered reasonable for testing parameters of over a short period of time, but the results of such testing regime might significantly underestimate the settlement in the case of large numbers of loading cycles [1].

Sato [4] suggested that the track settlement \( y \) under repeated loading \( x \) can be expressed in the form

\[ y = \gamma(1 - e^{-\alpha x}) + \beta x \]  

(2)

where \( \alpha, \beta \) and \( \gamma \) represent coefficients (see Figure 1 (b)). The coefficients \( \alpha, \beta \) and \( \gamma \) in equation (2) are parameters describing the short-term and long-term settlement behavior. The first part of equation (2), i.e. \( \gamma(1 - e^{-\alpha x}) \), describes the short-term settlement of the track immediately after a tamping; the factor \( \gamma \) gives the severity (size) of the settlement and the factor \( \alpha \) indicates how quickly the initial part of the settlement attenuates. The long-term behavior of the track settlement is described by the second term in equation (2), i.e. the term \( \beta x \). It can be seen that the track is then modelled to settle proportionally to the loading \( x \); the severity of the settlement is given by the parameter \( \beta \) [1].

Hecke [19] suggested a model to estimate track settlement. This is expressed as
where $e_0$ is track settlement directly after tamping, $h$ is a constant, $T$ is the traffic volume, $Q$ is the dynamic wheel load, $v$ is the vehicle speed, and the parameters $\alpha$, $\beta$ and $\gamma$ have to be evaluated from experimental data.

Many researchers [1, 2, 4, 19, 21] suggested that the track settlement is characterized by two phases. The first phase is the initial consolidation phase where rapid settlement occurs. During this phase the ballast is compressed to higher density to reduce the volume of voids between ballast particles are diminished. In the second phase, the long-term settlement is slower and there is a more or less linear relationship between the settlement and the load. Therefore, in this study, the long-term behavior of ballasted track settlement according to track configurations was analyzed by applying equation (2) to the test results.

2.2 Experimental design

Four types of ballasted tracks were constructed to analyze the effect of track settlement on various combinations of track configurations (see Table 1 and Figure 2).

**Table 1. Ballasted tracks for full-scale test**

<table>
<thead>
<tr>
<th>Case</th>
<th>Rail type</th>
<th>Fastening system*</th>
<th>Sleeper type</th>
<th>Ballast thickness</th>
<th>Ballast type</th>
<th>Specimen size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60kg K (KR code)</td>
<td>e-clip, TPU 5 mm ($\approx$400 kN/mm)</td>
<td>PC sleeper (L=2,400 mm)</td>
<td>300 mm</td>
<td>Angular crushed rock</td>
<td>L: 4,500 mm W: 4,900 mm</td>
</tr>
<tr>
<td>2</td>
<td>UIC60</td>
<td>e-clip, Rubber 10 mm (80~120 kN/mm)</td>
<td>PC sleeper (L=2,620 mm)</td>
<td>300 mm</td>
<td>Angular crushed rock</td>
<td>L: 4,500 mm W: 5,460 mm</td>
</tr>
<tr>
<td>3</td>
<td>UIC60</td>
<td>e-clip, Rubber 10 mm (80~120 kN/mm)</td>
<td>PC sleeper (L=2,620 mm)</td>
<td>350 mm</td>
<td>Angular crushed rock</td>
<td>L: 4,500 mm W: 5,800 mm</td>
</tr>
<tr>
<td>4</td>
<td>60kg K (KR code)</td>
<td>W14K Rubber 12 mm (80 kN/mm)</td>
<td>PC sleeper (L=2,400 mm)</td>
<td>300 mm</td>
<td>Angular crushed rock</td>
<td>L: 4,500 mm W: 4,900 mm</td>
</tr>
</tbody>
</table>

* Static stiffness test load: 20~95 kN
Case 1 is that of a ballasted track used in conventional railway lines (vehicle speeds between 120 and 200 km/h) [26], case 2 shows a ballasted track applied to the Korea high-speed railway, and case 3 is based on the case where the ballast thickness is increased in the ballasted track of case 2. Case 4 is a case in which the high-resilient rail pads are applied as compared with case 1.

The ballasted tracks were constructed on the reinforced concrete floor designed to support the weights of the ballasted tracks (see Figs 3 (a) and (b)). A total of 7 sleepers (sleepers spacing 625 mm) were placed in the transverse direction of the concrete floor, and the loading platen was located on both rails above the fourth sleeper in the middle of the ballasted track (see Figure 3 (a)). The load was applied to
the top of the two rails and two hydraulic actuators connected to the loading frame were applied to one loading platen at a time. As shown in Figure 3 (b), the four ballasted tracks were arranged side-by-side, ensuring that sufficient space was not adversely affected by the lateral movement of the ballast. In this full-scale test, the lateral direction of the ballasted track was not constrained.
The ballast was filled with graded 70mm maximum sized crushed rock. The ballast material had gradations that comply with the Korean railway standards requirements (see Figure 4). A 300 to 350 mm thick layer was placed on the concrete floor of all ballasted tracks. Before the installation of sleepers, the ballast layer was compacted by electrical vibro-tamper applying vibration through a plate to the ballast surface. After installing the rail and sleeper, additional ballast was placed on either side of the sleepers and the ballast surface was compacted for more than ten seconds at each location with electrical vibro-tamper. The ballast shoulder on the side of sleeper was compacted with hand tamper.

**Figure 4.** Gradations of ballast materials studied
2.3 Experiment metrology

In the full-scale test, the rail and the sleeper displacements were measured to analyze the long-term behavior of the ballasted track by cyclic loading using linear variable differential transformers (LVDTs), installed on a separate steel frame from the ballasted tracks as shown in Figure 3 (c). This arrangement allowed compensation for the inevitable uneven settlement caused by the random packing of the ballast particles. The loading platen was installed on the two rails on the fourth sleeper, the center of the ballasted track. The rail and sleeper deformation data were recorded with a data logger. A standard test duration of 1.5 million cycles was applied. This was sufficient to determine the long-term behavior of ballasted track.

2.4 Applied force: cyclic load

Hung [27] investigated the impact of load patterns generated by high-speed trains on the track settlement accumulation. They concluded that high-speed train could potentially cause higher ballast settlement rate. This study investigates the long-term behavior of ballasted track when the maximum speed of 200 km/h is increased to 230 km/h in the Korean conventional railway.

Kim [28] and Korea Rail Network Authority [29] presented a maximum dynamic wheel load prediction equation for speed between 150 and 230 km/h through the speed-up tests of a Korea Train Express (KTX) vehicle (see Figure 5).

![Figure 5](image)

**Figure 5.** Field test results of dynamic wheel load and regression analysis result [28-29]
A maximum dynamic wheel load prediction equation for the KTX is as follows.

\[ y = 0.304x + 52.08 \]  

(4)

where \( y \) is a maximum dynamic wheel load and \( x \) is the speed of the KTX.

Equation (4) was derived from the results of the field test for a straight track on the conventional railway lines in Korea. Here, the rail is a continuously welded 60kg K rail. PC sleeper type is selected, the sleeper spacing is set to 625 mm, the ballast thickness is set to 300 mm, and e-clip type rail fastener is used.

In this study, the maximum load value of the full-scale test is calculated by multiplying equation (4) by a factor 1.2 [30] taking account of the increase in wheel load in curve because of the cant deficiency or excess. The maximum load value of the full-scale test thus calculated is 150 kN. The excitation frequency is modeled as 3.4 Hz, corresponding to a speed of 230 km/h for the KTX with a center-to-center distance of 18.7 m. Therefore, the sinusoidal cyclic loading has a maximum magnitude of 150 kN and a minimum magnitude of 10 kN with a frequency of 3.4 Hz. The cyclic loading condition is shown in Figure 6. The sinusoidal cyclic loading is performed up to 1.5 million cycles.

![Figure 6. Dynamic cyclic loading pattern applied to full-scale test](image)

3. Results

Figure 7 shows the displacement results measured on the rail and sleeper, Figure 8 shows the displacement results measured on the rail for up to 80000 cycles.
Figure 7. Monitored displacement in rail and sleeper at loading point: (a) case 1, (b) case 2, (c) case 3 and (d) case 4
Figure 7 also presents that displacement results of the rail and sleeper are different depending on the ballasted track configurations. In case 1, which the hardest rail pad is applied, the sleeper displacement is the largest, and the displacement difference between the rail and the sleeper due to cyclic loading is large (see Figure 7 (a)). Case 3, which sleeper size and ballast thickness increased, resulted in the smallest rail and sleeper displacement (see Figure 7 (c)). In case 4, which the soft rail pad is applied, the rail displacement is larger than the sleeper displacement (see Figure 7 (d)).

As shown in Figure 8, there is a sharp increase in the rail displacement at approximately 20000 cycles, followed by a more gradual increasing pattern. It is noted that case 1 shows the largest track settlement and displacement amplitude (see Figure 8 (a)). Case 3, which uses the soft rail pad and increased ballast thickness and sleeper size, shows the smallest track settlement and displacement amplitude (see Figure 8 (c)).

The ballasted track changes dramatically due to ballast conditions (ballast particle size, voids between ballast particles, number of compactions, etc.), making it is very difficult to consider the stiffness at the
design phase. In Korea and Japan, ballast stiffness of 200 kN/mm is adopted for the ballasted track design regardless of the ballast thickness [31]. Applying the ballast stiffness of 200 kN/mm, the track support stiffness for each track is 93.4 kN/mm for case 1, 77.2 kN/mm for case 2, 82.9 kN/mm for case 3, and 74.4 kN/mm for case 4. The results of full-scale test are different from the tendency of rail deflection due to the calculated track support stiffness. This result indicates that the initial track settlement is more affected by the ballast conditions and track configurations than the track support stiffness calculated when designing the ballasted track structure. In particular, the displacement amplitude due to the dynamic cyclic load changes depending on the ballast conditions and track configurations and affects the track settlement.

4. Discussion

4.1 Long-term behavior analysis of ballasted tracks

The long-term behavior of ballasted track against the number of cycles is presented in Figure 9. Track settlement is calculated by averaging the readings of the two rail LVDTs located on both sides of the loading platen. The experimental results are regressed in the form of equation (3) (see Figure 9 and Table 2). The total number of data collected through the full-scale tests is 1479 for case 1, 1173 for case 2, 1460 for case 3, and 1486 for case 4. Here, data corresponding to the initial 100,000 tons (about 7,000 cycles) are excluded in the regression analysis. This is due to the tonnage through which the dynamic track stabilizer works and the test vehicles pass in order to stabilize the ballasted track prior to normal operation. In other words, since the ballasted track has stabilized, only the long-term behavior of ballasted track due to vehicle operation is analyzed.
As shown in Figure 9, track settlement is relatively fast and gradually slows down. The initial stage of track settlement is due to the reduction in the voids between the ballast particles and the deceleration of the track settlement is due to a more or less linear relationship between settlement and number of loading cycles. When the bottom area of the sleeper increases, it is more advantageous to increase the length than the width in order to prevent track settlement [32].

The largest track settlement occurred in case 1, which is a standard ballasted track using in the Korea conventional railway. In comparison, with case 4 where soft rail pads were used on the same track structure as case 1, a relatively small track settlement improvement was achieved. Case 2, which increased the size of sleeper and used soft rail pads, presented the second lowest track settlement. Case

**Figure 9.** Long-term behavior of ballasted track in each case: regression analysis results for offset displacement data

**Table 2.** Prediction equations of ballasted track settlement by full-scale test

<table>
<thead>
<tr>
<th>Case</th>
<th>Regression equation</th>
<th>Adj. R-Square</th>
<th>Number of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>( y = 2.12(1 - e^{-1.10 \times 10^{-5}x}) - (9.73 \times 10^{-7})x )</td>
<td>0.968</td>
<td>1,472</td>
</tr>
<tr>
<td>Case 2</td>
<td>( y = 1.77(1 - e^{-2.78 \times 10^{-6}x}) - (2.03 \times 10^{-7})x )</td>
<td>0.802</td>
<td>1,166</td>
</tr>
<tr>
<td>Case 3</td>
<td>( y = 0.77(1 - e^{-5.42 \times 10^{-6}x}) - (3.96 \times 10^{-7})x )</td>
<td>0.919</td>
<td>1,453</td>
</tr>
<tr>
<td>Case 4</td>
<td>( y = 1.81(1 - e^{-6.22 \times 10^{-6}x}) - (1.10 \times 10^{-6})x )</td>
<td>0.986</td>
<td>1,479</td>
</tr>
</tbody>
</table>
3, which used soft rail pads and increased the sleeper size and the ballast thickness, presented the least track settlement among the ballasted tracks. Comparing the results of case 1 and case 4, the effect of reducing the track settlement by using soft rail pads in the ballasted track is not significant. In particular, the sleeper size and the ballast thickness were found to have a significant effect in reducing track settlement.

The regression equations shown in Figure 9 (b) and Table 2 have high reliability with a determination coefficient of 0.8 or higher. Therefore, in this study, the influencing factors affecting track settlement were analyzed by using the regression equations in Table 2 at a fixed loading cycle of one million cycles.

4.2 Parametric studies

A. Effects of the track configurations

The track settlement and variation rate for the ballasted tracks at one million cycles are presented in Figure 10. The rail profile has no effect on track settlement. Case 2, which increased the sleeper size and used the soft rail pad, was 42.7% less than case 1. Case 3, which used the soft rail pad and increased the sleeper size and the ballast thickness, was 61.7% less than case 1. In comparison case 4, using the soft rail pad on the same track structure as case 1, the track settlement decreased by 3.1%. In particular, in case 2 and case 3, the variation rate of track settlement decreased by 33.2% when the ballast thickness of 50mm was increased. A comparison of case 2 and case 4 presents that the sleeper size has a significant effect on inhibiting the track settlement. Therefore, the main track configurations that affect the track settlement are the sleeper size and the ballast thickness.
Figure 10. Effects of track configurations on long-term behavior of ballasted track

B. Effect analysis of the effective area of track configurations

The purpose of ballasted track is to transfer train loads to the subgrade. A rail accommodates the wheel loads and distributes these loads over the sleepers. A sleeper sustains the rail and transfers them as uniformly as possible to the ballast. The effective area of track configurations due to train loads is shown in Figure 11. The effective rail support area of the rail support is calculated as the area of the baseplate of the rail fastening device. The contact area between sleeper and ballast for half sleeper is 1 in 2 of the total sleeper area. The effective area between ballast and subgrade for half sleeper can be calculated from equation (5) [33].

\[ A_{sg} = \frac{[B + D] \times (L + D)}{2} \]  

where \( A_{sg} \) is the effective area between ballast and subgrade for half sleeper, \( B \) is the width of sleeper, \( L \) is the length of sleeper, and \( D \) is the ballast thickness. Table 3 shows the comparison between the effective area of the track configurations and the track settlement.
Table 3. Comparison between the effective area of track configurations and the track settlement

<table>
<thead>
<tr>
<th>Track settlement*</th>
<th>Total track support stiffness (included rail)</th>
<th>Effective rail support area of rail support</th>
<th>Effective area between sleeper and ballast for half sleeper</th>
<th>Effective area between ballast and subgrade for half sleeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm Difference %</td>
<td>kN/mm Difference %</td>
<td>mm² Difference %</td>
<td>cm² Difference %</td>
<td>cm² Difference %</td>
</tr>
<tr>
<td>Case 1</td>
<td>3.58 -</td>
<td>93.4 -</td>
<td>29340 -</td>
<td>3021 -</td>
</tr>
<tr>
<td>Case 2</td>
<td>2.05 ↓</td>
<td>77.2 17.3 ↓</td>
<td>33500 14.2 ↑</td>
<td>3440 13.9 ↑</td>
</tr>
<tr>
<td>Case 3</td>
<td>1.37 ↓</td>
<td>82.9 11.2 ↓</td>
<td>33500 14.2 ↑</td>
<td>3440 13.9 ↑</td>
</tr>
<tr>
<td>Case 4</td>
<td>3.47 ↓</td>
<td>74.4 20.3 ↓</td>
<td>23200 20.9 ↓</td>
<td>3044 0.8 ↑</td>
</tr>
</tbody>
</table>

* at 1 million cycles

In Table 3, there is no clear correlation between track support stiffness and track settlement, but the track settlement decreases as the track support stiffness decreases. Increasing the effective area of the track configurations decreases the track settlement. In particular, when the effective load supporting area of the subgrade increases as the ballast thickness increases, the track settlement decreases by reducing the pressure distribution of ballast. In other words, the sleeper size and the ballast thickness, which are factors of the effective area acting on the subgrade, are the main influential factors in the track settlement. Here, the sleeper size refers to the effective area where the wheel load is applied, and corresponds to the case where the gradations of the ballast materials and the degree of ballast compaction are the same.

5. Conclusions

Ballasted tracks comprised of rails, rail fasteners, sleepers, and ballast is subject to long-term track settlement due to repeated train loads. The track settlement causes the deterioration of track geometry. The analysis of the track settlement is very important in determining the maintenance cycle.

In order to evaluate the effect of track configurations on the long-term behavior of ballasted track, four full-scale ballasted tracks were constructed and cyclic loading test was conducted at a vehicle speed of 230 km/h. The experiment was able to being about the following conclusions:

1. The track settlement prediction equations for the ballasted tracks which are used in Korea are presented in this study. In order to determine the maintenance cycle of the ballasted tracks, the proposed functions should be adequately considered.

2. The long-term behavior of ballasted track may vary depending on the combination of the track configurations. The size of the sleeper and the thickness of ballast are analyzed as the most influential...
track configurations for the track settlement. The long-term behavior of ballasted track decreases by approximately 30% when the ballast thickness is increased by 50 mm. However, this is applicable when the degree of ballast compaction and the gradations of ballast materials are the same.

(3) The effective area between ballast and subgrade for half sleeper to be calculated in the ballasted track design is related to the long-term behavior of ballasted track. The track settlement decreases as the effective area between ballast and subgrade for half sleeper increases. This is due to the load-balancing effect. Therefore, it is necessary to properly consider the effective area of sleeper to be transferred to the ballast and the thickness of ballast to inhibit the track settlement.

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Conflicts of interest

The authors declare no conflict of interest.

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