Performance of the Reinforced Railroad Roadbed of Crushed Stones under the Simulated Cyclic Loading using Multi Purpose Loading System

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Abstract: Conventional railroad roadbeds constructed with soils in the past can easily deteriorate with time due to the increase of repeated traffic loading, increase of train speed, built-up of ground water on the roadbed and decrease of permeability in the roadbed layer, etc.

In this study, performance of reinforced railroad roadbeds with the crushed stones was investigated through the real scale roadbed tests and numerical analysis. It was found through the actual testing that for the roadbed with the same thickness, the displacement of reinforced roadbed decreases with the increase of subgrade reaction modulus. The settlement of reinforced roadbed with the same subgrade reaction modulus also decreases with the increase of thickness of the reinforced roadbed. As a conclusion, the plastic and elastic displacement of the crushed stone reinforced roadbed was found to be mainly governed by the subgrade reaction modulus.

Keywords : Reinforced Roadbed, Displacement, Subgrade Reaction Modulus

1. Introduction

The reinforced roadbed has the ability to spread out the load intensity on to the subgrade of track structure as well as to prevent the softening of subgrade by providing appropriate stiffness in the roadbed, thus fully supports the track structures. The bearing capacity and durability of roadbed are generally degraded with the duration of usage due to the train loads, freezing and thawing, rainfall and mud pumping phenomenon, etc. It is necessary to develop a reinforced roadbed design system for the Korean railroad environment as a countermeasure for the upgrading the speed of train and the safety improvement. There are several different design methods developed and used in the practice to improve the bearing capacity and to elongate the lifetime of track structures. Especially, the reinforcement method utilizing the material with high durability as a roadbed is widely used. However one should consider the functional and economical aspects as well as characteristics of site specific conditions for the construction of reinforced roadbed.

The performance of the reinforced roadbeds with the crushed stones was investigated through the real scale roadbed tests. Several real scale roadbeds were constructed in the laboratory with different subgrade conditions and tested with the estimated trainloads including the impact loading of train.

2. Assessment of Magnitude and Frequency of Loading

The magnitude of loading for real-scale railroad roadbed tests was estimated based on Eq. 1. In general, the roadbed stress should be estimated considering track structure, wheel load, train speed, etc. The tests were carried out under the assumption that continuously welded rail is installed on the straight line section, and the design speed of train is 200 km/hr and the design trainload is LS-22. Impact factor was calculated as 1.6 using Eq. 2. The magnitude of cyclic loading was estimated using Eq. 3 considering standard loading and the standard deviation of impact factor.

\[
S_p = 0.5 \times P_s \times (i - 1)
\]

\[
i = 1 + 0.3 \frac{V}{100}
\]

\[
P_w = P_o + S_p
\]

Where, \(S_p\): standard deviation, \(P_s\): static load (= 110 kN = half of LS-22 load), \(i\): impact factor (= 1.6), \(V\): train speed (= 200 km/hr in this study), and \(P_w\): wheel load (= cyclic load).
The minimum and maximum of sinusoidal cyclic loading were 10 kN and 143 kN, respectively. For the compaction and stabilization of the ballast layer, 500 cycles of cyclic loading with 0.5 Hz of loading frequency were applied on each rail sleeper before the actual cyclic loading test. The loading frequency was calculated as follows:

\[ T = \frac{d}{V} \]  

Where, \( T \): train-passing time (sec), \( d \): distance between the bogie of train, \( V \): train speed.

Since loading frequency \( f \) is equal to \( \frac{1}{T} \), it becomes \( \frac{V}{d} \).

\[ f = \frac{1}{T} = \frac{V}{d} \]  

Thus the calculated loading frequency for this study is 5 Hz.

3. Material and Experimental Procedures

3.1 Tests Materials and Loading System

A weathered granite soil (usually used in the construction practice in Korea) and the crushed stone (MS-40) were chosen as the roadbed construction materials. The particle size distribution curve and compaction curve of each material was shown in Figs. 1(a), and (b). The physical properties of test materials were summarized in Table 1.

![Figure 1. Particle Size Distribution Curves(a) and Compaction Curves(b) for Roadbed Materials](image)

<table>
<thead>
<tr>
<th>Test Items</th>
<th>Weathered Granite Soil</th>
<th>Crushed Stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D_{10}(mm) )</td>
<td>0.16</td>
<td>0.8</td>
</tr>
<tr>
<td>( C_u )</td>
<td>11.87</td>
<td>13.5</td>
</tr>
<tr>
<td>( C_g )</td>
<td>0.96</td>
<td>2.35</td>
</tr>
<tr>
<td>% Passing #200 Sieve</td>
<td>12</td>
<td>24.1</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>( G_s )</td>
<td></td>
</tr>
<tr>
<td>( \gamma_{\text{max}} ) (kN/m(^2))</td>
<td>17.1</td>
<td>24.02</td>
</tr>
<tr>
<td>( w_{\text{opt}}(%) )</td>
<td>11.3</td>
<td>7.65</td>
</tr>
<tr>
<td>Compaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \phi(\circ) )</td>
<td>24.7</td>
<td>-</td>
</tr>
<tr>
<td>Triaxial Compression</td>
<td>( \phi(\circ) )</td>
<td>32.9</td>
</tr>
<tr>
<td>Uniaxial Compression</td>
<td>( q_u(MN/m^2) )</td>
<td>-</td>
</tr>
<tr>
<td>Abrasion Ratio</td>
<td>( R(%) )</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Physical Properties of Test Materials
The special pit (W x D x L: 5m x 3m x 22m) for real scale railway roadbed model were constructed in order to build several models with different conditions. The loading system is mainly consisted of a mobile loading frame, two loading actuators and control and measurement system. The loading system can duplicate a wheel load of 250 kN which covers most of wheel loads of trains in service in Korea.

3.2 Test Conditions and Construction of Model Tracks
A total of 5 sections were constructed with different conditions as shown in Table 2. In order to monitor the behavior of rail, ballast layer, roadbed and subgrade, several sensors, such as, 8 displacement sensors with settlement plates, 4 particle velocity sensors (geophone) and 4 earth pressure cells were installed at each model section. Prior to dynamic loading test, a sequence of static loading up to maximum of 140kN with a 20kN increment were applied to each section and the same unloading sequence was performed. One million cycles of sinusoidal dynamic loading with the magnitude of 140kN (minimum loading of 10kN was maintained to prevent the unnecessary impact loading to the track) was followed the static loading.

Table 2. Test Condition of Real Scale Roadbeds

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Coeff. of Subgrade Reaction Modulus (MN/m³)</th>
<th>Thickness of Roadbed (cm)</th>
<th>Roadbed Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>K7d80</td>
<td>68.6</td>
<td>80</td>
<td>crushed stone</td>
</tr>
<tr>
<td>K11d80</td>
<td>107.8</td>
<td>80</td>
<td>crushed stone</td>
</tr>
<tr>
<td>K11d50</td>
<td>107.8</td>
<td>50</td>
<td>crushed stone</td>
</tr>
<tr>
<td>K11d30</td>
<td>107.8</td>
<td>30</td>
<td>crushed stone</td>
</tr>
<tr>
<td>Soil</td>
<td>107.8</td>
<td>30</td>
<td>weathered granite soil</td>
</tr>
</tbody>
</table>

A clean sand layer of 20 cm was placed at the bottom of the pit for drainage purpose. Weathered granite soil layer of 30 cm thick was placed on the top of the sand layer and compacted with a vibrating roller compactor to obtain the required condition of roadbed and this process was continued until whole subgrade layer is completed. The plate bearing test was performed to check the bearing capacity of subgrade and the desired subgrade condition of Kₚₐ = 68.6MN/m³, 107.8MN/m³ were achieved.

The crushed stone and weathered granite soil were used as the reinforced roadbed materials and the thickness of both reinforced roadbeds was 30 cm, 50 cm and 80 cm. The ballast layer of 30 cm was then placed on top of the roadbed. The track was 5 m(W) x 3 m(L) in size and is consisted of 5 sleepers and 2 rails. The plane and sectional view of real scale model was shown in Fig. 2.

4. Test Results and Analysis

4.1 Plate Bearing Test
Plate bearing test was carried out on top of the subgrade for each section of model track to confirm if the desired
condition was achieved. The reaction modulus of subgrade was obtained either load-settlement or log(load)-settlement relationship as shown in Fig. 3. The resulting subgrade reaction modulus of all sections were satisfactorily well within the desired condition.

![Diagram](a) 68.6MN/m³ < k₃₀ < 107.8 MN/m³  
(b) k₃₀ > 107.8 MN/m³

Figure 3. Typical Result of Plate bearing Test on the Subgrade

4.2 Load and Displacement Distribution

Track was consisted of 5 sleepers which is different with field condition as shown in Fig. 4(b). Comparison between the track used for this study with actual field track was performed with the help of FEM analysis. Stress distribution and displacement upon cyclic loading were shown in Fig. 4(a), 4(b) and 4(c). As it can be seen in Fig. 4(c), there was almost no difference in stress distribution under the sleepers except for the third sleeper from the center sleeper, whereas, the displacement at the outer end of track shows difference in its magnitude due to discrepancy in their end conditions. The actual differences in magnitude was however very small and the effect on the test result was considered to be negligible.

![Diagram](a) Original Track (b) Real Scale Model (c) Stress Distribution

Figure 4. Displacement and Stress Distribution under the Sleeper for 2 Different Track Conditions:
(a) Original Track (b) Real Scale Model (c) Stress Distribution

The displacement distribution under the concentrated cyclic loading was investigated to confirm the widely used practice, i.e., 40% at the sleeper of concentrated loading, 20% at the sleepers next to the center sleeper and 10% at the sleepers second from the center sleeper. The actual measured displacement distribution shown in Figs. 5 and 6 reveals that greater displacements occurred at the sleeper #2,3 and 4, whilst less displacement occurred at the sleeper # 1 and 5. This result was not much different with the widely used distribution ratio and the differences were mainly due to the usage of 5 sleeper for testing. Therefore it is recommended to use at least 7 sleepers to reasonably simulate the actual track condition.
4.3 Elastic and Plastic Displacement

The measurement was periodically performed during the cyclic loading such that each continuous measurement contains at least 25 cycles of loading period. The peak to peak displacement under the cyclic loading was considered as the elastic displacement, whereas the absolute mean value of cyclic displacement from the datum at the beginning of the test was considered as the cumulative plastic displacement.

The crushed stone roadbed and weathered granite soil roadbed with the same condition (i.e., thickness: 30cm, subgrade reaction modulus: 107.8MN/m$^3$) was statically tested, and the maximum static displacements at each surfaces were compared in Fig. 7. The displacements at the rail and roadbed surface of crushed stone roadbed were smaller than that of soil roadbed as expected. The magnitude of difference in displacement was greater at the surface of the rail since it is a cumulative displacement of whole section. It is also interesting to see in Fig. 8 that the percentage of displacement at the roadbed and subgrade surface of both roadbeds sections relative to that of rail surface are almost identical to each other.

The plastic displacements of both roadbed sections after the one million cycles of loading were compared in Fig. 9. It can be seen that the absolute displacement at the rail surface of both roadbeds section were greater than that of static test result shown in Fig. 7. It is obvious that the main reason is the number of loading cycles. The fact that displacements at the surface of roadbeds however has no difference with that of Fig. 7 could be explained by the stress concentration at the upper layer.
Roadbed Thickness : 30cm
Subgrade Stiffness : 107.8MN/m

Figure 7. Comparison of Displacement at each Surface of Crushed Stone and Soil Roadbed Section

Displacement Ratio = \frac{\text{Disp. at each surface}}{\text{D.P at Rail}}

Figure 8. Distribution of Displacement at the Roadbed and Subgrade Surface of both Roadbed Sections

Loading Magnitude
Min. ~ Max. : 10~140kN
Loading Frequency : 5Hz

Figure 9. Comparison of Plastic Displacements of both Roadbed Sections after Cyclic Loading
The relationship between the plastic, elastic displacement and number of loading cycles for both roadbed sections was shown in Figs. 10(a) and 10(b). It is clearly shown in Figs. 10(a) and 10(b) that the plastic and elastic displacements of crushed stone roadbed section were always less than that of weathered granite soil roadbed section. It is also interesting to see the plastic displacement at the roadbed surface of both roadbed sections occurs rapidly at initial loading stage and converges to certain values after approximately 200 thousands loading cycles. The trend of plastic displacement at the rail surface of both roadbed sections is very similar throughout the entire loading cycles. The same explanation of trend as mentioned above can be used to the elastic displacement of both roadbed sections as shown in Fig. 10(b).

Figure 10. Relationship between the Plastic (a), Elastic (b) Displacement and Number of Loading Cycles for both Roadbed Sections

4.4 Effect of Roadbed Thickness on Displacement

The effect of roadbed thickness on the static displacement of each layer is shown in Fig. 11(a) and (b). The static displacement at each layer decreases with the increase of roadbed thickness. The magnitude of displacement in the ballast layer is largest occurred in the ballast layer and smallest in the roadbed layer. The percentages of displacement in the roadbed and subgrade section relative to the total displacement were 33% ~ 37% and 22%~26%, respectively. The plastic and elastic displacement after one million cycles of loading was shown in Fig.12. The effect of roadbed thickness on the plastic and elastic displacement indicates that the magnitude of displacement in the roadbed layer tends to decrease with the increase of the thickness of roadbed. In case of the test section with 80cm thick roadbed, however, the ballast layer was so poorly prepared that the measured displacements turn out to be unreasonably greater than expected. The magnitude of plastic and elastic displacements of the subgrade layer was so small (i.e., less than 1mm in all cases) that it is very difficult to confirm any general trend.
In order to check the difference in the displacement of roadbed with different stiffness, cumulative plastic and elastic displacement of two crushed stone roadbeds (K_{30} = 68.6 and 107.8MN/m\(^3\) with 80cm thick layer) was compared in Fig. 13. The displacement occurred up to 10 thousands cycles of loading could be considered as the displacement in the ballast layer. The displacement after 10 thousands cycles of loading could be considered as the displacement occurred in the roadbed and subgrade layers. The final elastic and plastic displacement was 3.0mm and 4.9mm for the subgrade reaction modulus with K_{30}=68.6MN/m\(^3\) and 2.3mm and 4.0mm for the subgrade reaction modulus with K_{30}=107.8MN/m\(^3\). Therefore with the result of measurement data analysis, the subgrade reaction modulus has more influence on whole displacement than the thickness of roadbed.
5. Conclusions

In this study, characteristics of crushed stone reinforced roadbeds were investigated through the real scale model test with the estimated actual train loads including impact load which is dependent on the train speed. The final conclusions are as follows:

1. The load distribution in the test model with 5 sleepers was similar to the actual track condition, and the effect on the test result is necessary to be studied in detail. The displacement distribution was also similar to the actual track condition however it is recommended to use at least 7 sleepers to reasonably simulate the actual track condition.

2. The plastic and elastic displacements of crushed stone roadbed section were always less than that of weathered granite soil roadbed section. The plastic displacement at the roadbed surface of both roadbed sections occurs rapidly at initial loading stage and converges to certain values after approximately 200 thousands loading cycles.

3. The subgrade reaction modulus is a more important factor to the total plastic displacement of the track than the thickness of the crushed stone roadbed.

4. The effect of roadbed thickness on the plastic and elastic displacement indicates that the magnitude of displacement in the roadbed layer tends to decrease with the increase of the thickness of roadbed.

References


