Special edition paper

Seismic Assessment of Ballasted Tracks in Large-scale Earthquakes



Takao Kumakura* Hideaki Ishii** Toshiyuki Konishi***

We have concerns that ballast of ballasted tracks will become loose in the event of a large-scale earthquake, even if no visible defects are found in on-site inspections. Inspections of CWR creeping and measurement of lateral ballast resistance force are needed, resulting in much labor and time being required before operation restart can be decided. In this research, by laying a full-size track on a shaking table tester, we observed behavior of the ballast and measured lateral ballast resistance force when shaking the track at different vibration accelerations and vibration frequencies. The purpose of such testing is quantitative seismic assessment of ballasted tracks. Test results clarified that vibration acceleration at which ballast is disturbed is around 600 gal and the vibration acceleration at which lateral ballast resistance force decreases is around 750 gal. We also found that disturbance of ballast and the decrease of lateral ballast resistance force have little dependence on frequencies in the range of 1 to 10 Hz. And we confirmed that those could be applied to operation handling rules in the event of a large-scale earthquake.

●Keywords: Large-scale earthquake, Lateral ballast resistance force, Vibration acceleration, Shaking table tester

1 Introduction

There is concern that ballast of ballasted tracks would become loose in the event of a large-scale earthquake in summer, causing track buckling in some cases. That could happen even if no visible defects are found in on-site inspections.

After occurrence of an earthquake, inspections of CWR creeping and measurement of lateral ballast resistance force are needed. Much labor and time are thus required before operation restart can be decided.

Past research covered seismic assessment on the decrease of lateral ballast resistance force by seismic movement[1) 2) 3)]. However, no verification and assessment using a full-size track had been carried out.

Upon laying a full-size track on a shaking table tester, we observed ballast shape and measured lateral ballast resistance force by shaking the track at different maximum accelerations and vibration frequencies. As a result, we have succeeded in quantification of vibration characteristics of ballasted track. In this article, we will give an overview of the shaking test of full-size ballasted track. Seismic assessment results of the track based on the test results and application to operation handling rules will be reported as well.

2 Typical Seismic Movement and Test Conditions

Table 1 shows the maximum accelerations and predominant frequencies of recent large-scale earthquakes. The maximum accelerations are around 600 to 1,500 gal and the predominant frequencies are 1 to 10 Hz. As the example records for the South Hyogo Prefecture Earthquake of 1995 and the Mid Niigata Prefecture Earthquake of 2004 shown in Fig. 1, common vibration duration of large-scale earthquakes is roughly 5 to 10 seconds.

Taking into account the aforementioned maximum acceleration, predominant frequency and vibration duration of large-scale earthquakes, we set the test conditions shown in Table 2. Specifically, the maximum acceleration is 400 to 900 gal, the vibration frequency is 1 to 10 Hz and the vibration duration including tapering time before and after the vibration is 10 seconds.

Table 1 Maximum Accelerations and Predominant Frequencies of Typical Large-Scale Earthquakes

Earthquake	Year	Record information	Maximum acceleration (gal)	Predominant frequency (Hz)
Kushiro-Oki Earthquake	1993	Record by Kushiro Marine Observatory	814.9	2.0 – 3.8
South Hyogo Prefecture Earthquake	1995	NS element record by Kobe Marine Observatory	817.8	4.8
South Hyogo Prefecture Earthquake	1995	EW element record by Kobe Marine Observatory	765.8	1.2 – 3.0
Sanriku South Earthquake	2003	At Oshika (K-net)	1103.5	3.0 – 4.2
Mid Niigata Prefecture Earthquake	2004	At Ojiya, NS element	1147.4	1.4
Mid Niigata Prefecture Earthquake	2004	At Ojiya, EW element	1307.9	1.5
Iwate Prefecture Northern Coast Earthquake	2008	At Tamayama, NS element	1019.2	4.2
Iwate Prefecture Northern Coast Earthquake	2008	At Tamayama, EW element	683.8	5.0
Iwate-Miyagi Nairiku Earthquake	2008	Ichinoseki-Nishi, NS element	1143.2	6 – 9
Iwate-Miyagi Nairiku Earthquake	2008	Ichinoseki-Nishi, EW element	1432.6	7.2 – 9.5

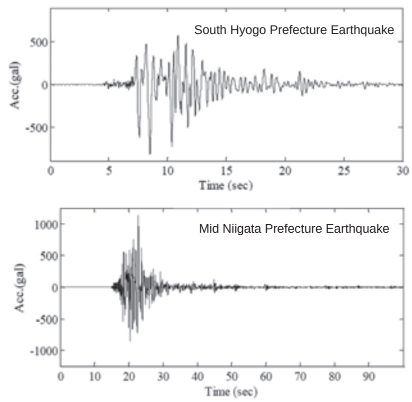


Fig. 1 Records of Large-Scale Earthquakes

Table 2 Test Conditions

Input wave	Frequency (Hz)	Set maximum acceleration (gal)	Description
Sine wave	1	400 – 900	Fixed duration time (mainly 8 sec.) (1 sec. tapering time before and after application)
Sine wave	2	400 – 900	
Sine wave	5	400 – 900	
Sine wave	10	400 – 900	
Seismic wave	—	606	At Takatori in South Hyogo Prefecture Earthquake, NS 100%
	—	1314	At Ojiya in Mid Niigata Prefecture Earthquake, EW 100%

*Technical Center, Research and Development Center of JR East Group
**Track Maintenance Section, Facilities Dept., Tokyo Branch Office (former researcher at Technical Center)
***Planning Section, Facilities Dept., Omiya Branch Office (former researcher at Technical Center)

3 Testing Equipment and Method

3.1 Testing Equipment

For the shaking device, we used a shaking table tester that can reproduce the same conditions as large-scale earthquakes (Fig. 2). The performance of the tester is ±60 mm variable displacement, 3G maximum acceleration and 50 Hz maximum vibration frequency.

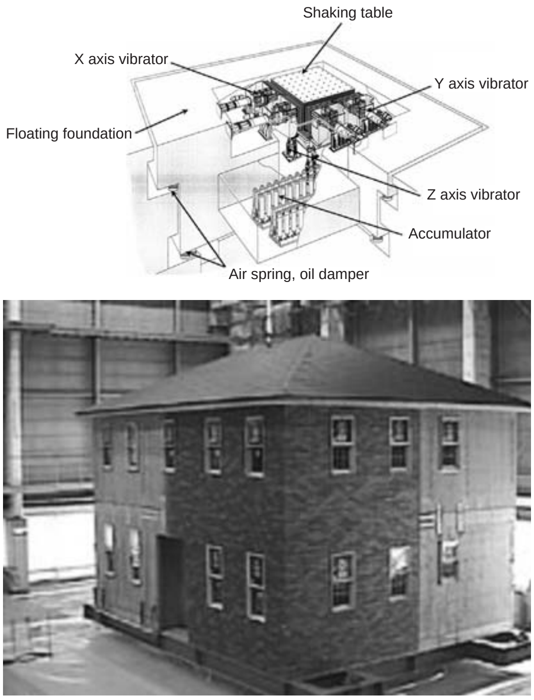


Fig. 2 Shaking Table Tester (Source: Obayashi Corporation)

The track length of the test sample is 4.5 m. We laid eight sleepers on 200 mm thick waste ballast on a road bed compacted by a roller (Table 3). No rails were laid on the test sample. Instead, weight equivalent to 50N rails was applied to each sleeper. The ballast was well compacted by a rammer and the road bed by a vibrating plate as well.

As shown in Fig. 4, we used as measuring devices four laser displacement gauges (LH, LV) for the sleepers, ballast and road bed as well as 12 contract-type displacement gauges (DH, DV), six load meters (LD), eight accelerometers (AH) and six strain gauges.

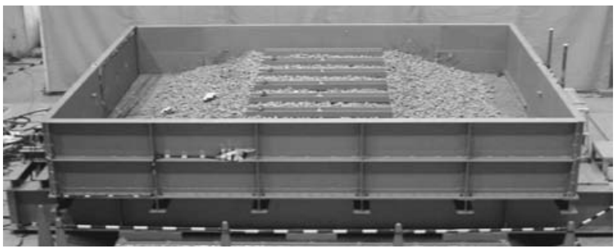


Fig. 3 Shaking Table Tester and Test Sample

Table 3 Components and Dimensions of Test Sample

Component	Item	Description
Road bed	Grain diameter	Crushed stone No. 5 (grain diameter 13 - 20 mm)
	Density	1.656 t/m³
Ballast	Grain diameter	Waste ballast (grain diameter 20 - 60 mm)
	Density	1.668 t/m³
Sleeper	Type	PC No. 3
	Number of sleepers	8
Rail	Type	Not used (weight equivalent to 50N rails applied to rails)

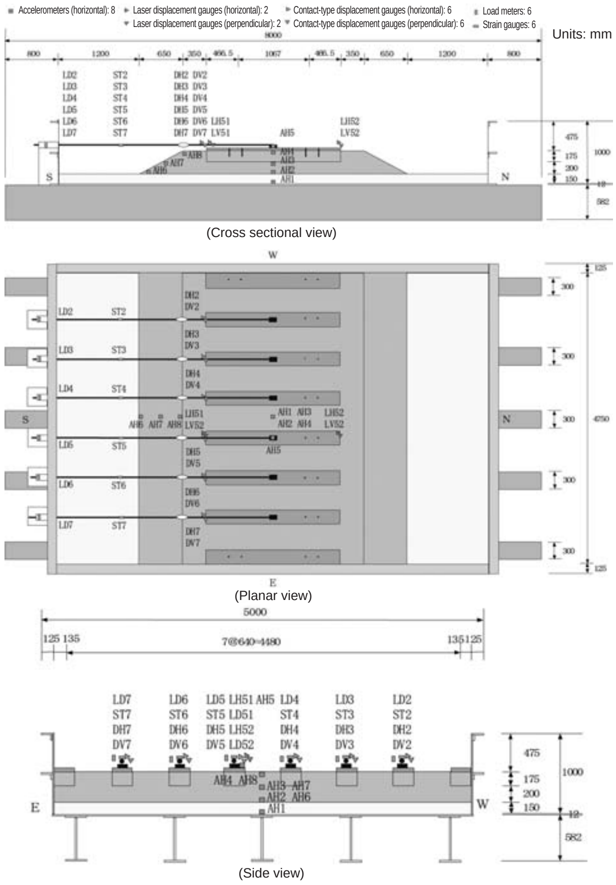


Fig. 4 Test Sample and Measuring Devices

3.2 Testing Method

We applied for a fixed time of 10 seconds a sine wave combined with the maximum acceleration and frequency set in the test conditions. At that time, response acceleration and displacement of sleepers and ballast were measured, and ballast shape was observed.

Before and after the vibration, we chose three sleepers that were not adjacent to each other. We measured lateral displacement by applying a horizontal load to each of those sleepers in a direction lateral to the track. The minimum applied load at which lateral displacement reached 2 mm was considered the lateral ballast resistance force.

4 Test Results

4.1 Acceleration at Slope of Ballast and Observation Results of Ballast Shape

Fig. 5 and 6 show the response accelerations to 500 gal and 600 gal maximum accelerations at the ballast slope at frequencies of 1 Hz and 10 Hz respectively. The wave shape of the response acceleration was similar to that of input acceleration at up to 500 gal maximum acceleration. However, the wave shape for input acceleration differed from that of response acceleration at the ballast slope in maximum acceleration of more than 600 gal. The results were similar with 2 Hz and 5 Hz frequencies.

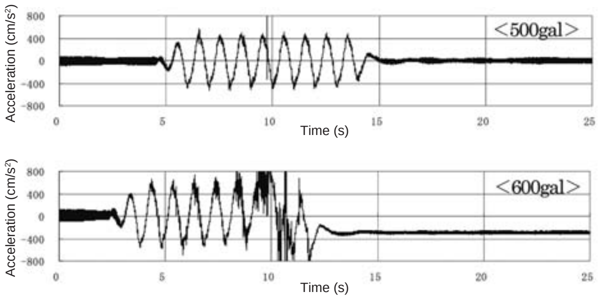


Fig. 5 Acceleration at Ballast Slope (1 Hz, 500 gal & 600 gal)

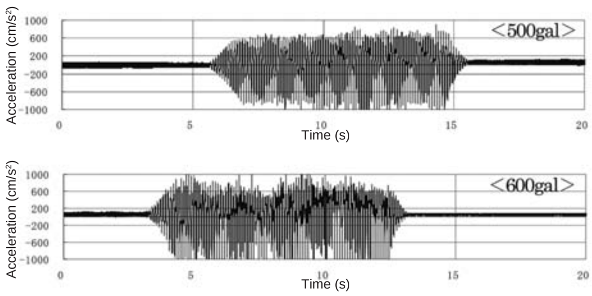
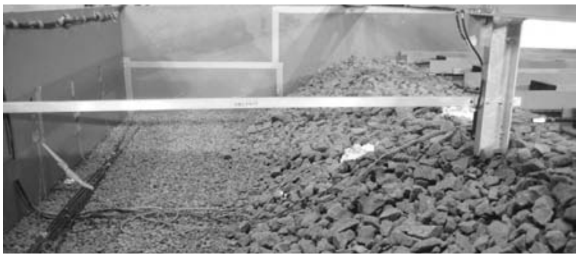


Fig. 6 Acceleration at Ballast Slope (10 Hz, 500 gal & 600 gal)

Fig. 7 shows the ballast shape after being shaken at the maximum acceleration from 500 to 800 gal with 1 Hz frequency. At 500 gal, the shaking table, sleepers and ballast vibrated together and the ballast was not disturbed. At 600 gal, some disturbance was found on the surface of the shoulder and slope of the ballast. At 700 gal and 800 gal, remarkable phase difference between the vibration of the sleepers and the ballast occurred and the ballast was significantly disturbed on the shoulder and slope. This event occurred with other frequencies too.

4.2 Results of Lateral Ballast Resistance Force Measurement

Fig. 8 shows the measurement results of horizontal load in relation to horizontal displacement of sleepers at 1 Hz frequency. Larger decrease of lateral ballast resistance force was found as the maximum acceleration increased. That force was reduced by around 15% at 800 gal, while no remarkable decrease was observed up to 700 gal.



(1 Hz frequency, 500 gal maximum acceleration)

(1 Hz frequency, 600 gal maximum acceleration)

(1 Hz frequency, 700 gal maximum acceleration)

(1 Hz frequency, 800 gal maximum acceleration)

Fig. 7 Ballast Shape after Shaking (1 Hz, 500 - 800 gal)

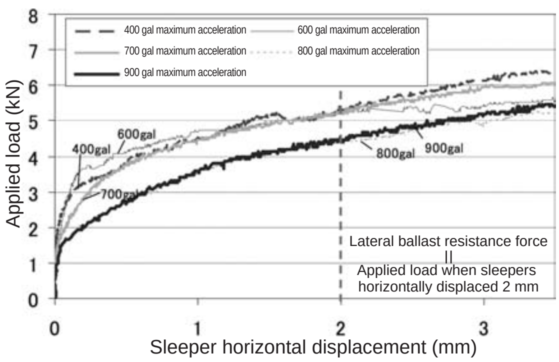


Fig. 8 Results of Lateral Ballast Resistance Force Measurement (Example at 1 Hz Frequency)

Fig. 9 shows the measurement results of lateral ballast resistance force per frequency. No remarkable difference was found in the decrease tendency of lateral ballast resistance force due to difference in frequency. The force sharply decreased starting at around 750 gal.

The results by seismic movement of the South Hyogo Prefecture Earthquake in 1995 and the Mid Niigata Prefecture Earthquake in 2004 showed no difference from the results by sine wave.

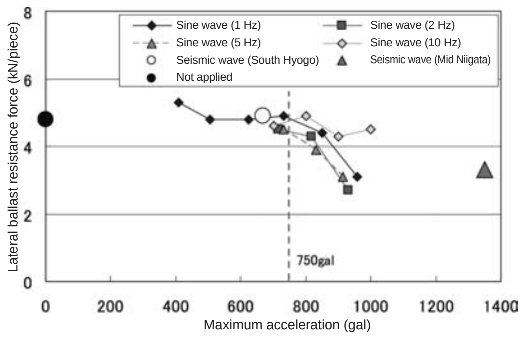


Fig. 9 Lateral Ballast Resistance Force per Frequency

4.3 Relationship Between Ballast Disturbance and Lateral Ballast Resistance Force Decrease

Fig. 10 shows the relationship between lateral ballast resistance force ratio and maximum acceleration. Lateral ballast resistance force ratio is obtained by dividing lateral ballast resistance force measured in each test condition by lateral ballast resistance force measured before the vibration.

The acceleration at which disturbance occurred on the shoulder and slope of ballast was around 600 gal. The acceleration at which lateral ballast resistance force ratio decreased to less than 1 was around 750 gal.

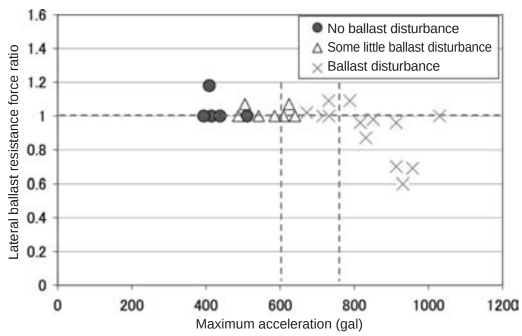


Fig. 10 Lateral Ballast Resistance Force Ratio and Maximum Acceleration

Based on those results, we have confirmed that the ballast shape and the lateral ballast resistance force have little dependence on frequency between 1 and 10 Hz. We also demonstrated that, in usual large-scale earthquakes, the shoulder and slope of the ballast would be disturbed at around 600 gal or more. Also, lateral ballast resistance force would start decreasing at around 750 gal where ballast disturbance would have progressed to some extent.

5 Summary

(1) The vibration acceleration at which ballast shape starts becoming disturbed is around 600 gal in the frequency range of 1 to 10 Hz, regardless of the frequency.

(2) Lateral ballast resistance force starts decreasing at around 750 gal in the frequency range of 1 to 10 Hz, regardless of the frequency.

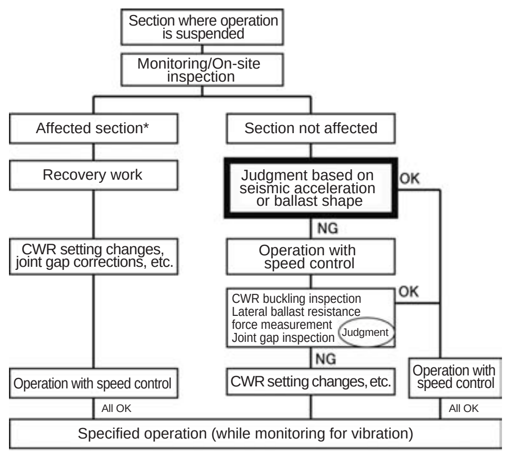
(3) As lateral ballast resistance force starts decreasing after disturbance of the shoulder and slope of ballast, the force is thought not to decrease significantly if the ballast shape remains unchanged.

In the present operation handling rules in the event of a large-scale earthquake, factors such as lateral ballast resistance force should be measured in all sections where the value exceeds the threshold in judgment by the SI value (an indicator of the vibration level of structures). This applies even if no abnormality is found in on-site inspections. As shown in Fig. 11, based on the threshold judgment of seismic acceleration quantified in this research or on ballast shape, the rule has been revised to require measurement only in the necessary sections. That has enabled efficient operation handling while securing safety.

6 Conclusion

We were able to successfully quantify by these tests the threshold value of the maximum acceleration that affects ballast. Still, in order to estimate the response acceleration on the track using existing seismographs, we need to examine attenuation according to the distance from the epicenter and amplification by viaducts, embankment and other civil engineering structures[4]. We need to identify the exact ballast shape in judgment on the change of ballast shape. In light of these issues, we are developing operation handling rules based on the findings of this research.

Finally, we would like to express our thanks to the Railway Technology Research Institute and Obayashi Corporation who have offered us cooperation and guidance.



* "Affected section" here is a section where trains cannot run due to large-scale ballast disturbance, etc.

Fig. 11 Proposal of New Operation Handling Rules in Event of Large-scale Earthquake

Reference:

1) Etsuo Sekine, Tatsuya Ishikawa, "Deformation Characteristics of Ballasted Track during Earthquake", RTRI Report, February 2005
2) Hiroki Hirao, Etsuo Sekine, "Vibration Tests of a Ballasted Track Model Using a Shaking Table Tester, Part 2: Ballast Resistance Force", Paper submitted for the 63th annual lecture meeting of the Japan Society of Civil Engineers, September 2008
3) Etsuo Sekine, Tatsuya Ishikawa, "Evaluating Seismic Resistant Performance of Ballasted Track by Cumulative Damage Model", RTRI Report, April 2006
4) Yutaka Nakamura; "Estimation of Seismic Movement Characteristics of Railway Embankment Based on the Measurement of Constant Microtremors", RTRI Report, July 1988