Construction and Building Materials 92 (2015) 23–30

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Dynamic characterisation of a ballast layer subject to traffic impact loads using three-dimensional sensing stones and a special sensing sleeper

Akira Aikawa *

Railway Technical Research Institute, Hikari-cho, Kokubunji, Tokyo 185-8540, Japan

HIGHLIGHTS

- The author develops a sensing-sleeper to measure the load distribution on sleeper bottom.
- Dynamic response is precisely measured during a passenger express train operation.
- Spectral analysis evaluates the dependence on frequency regarding ballast behavior.
- The wave propagation phenomena in the ballast layer are simulated using a FEM model.

ARTICLE INFO

Article history:
Received 2 February 2014
Accepted 5 June 2014
Available online 4 August 2014

Keywords:
Railway track
Ballasted track
Field measurement
Impact loads
Strength
Attenuation
Spectral analysis
FEM
DEM

ABSTRACT

Spectral analyses, based on field measurement of dynamic response of the ballast layer subject to traffic loads, evaluated the dependency on frequency regarding attenuation effect and strength of ballast layer. The measurement was conducted by using high-performance three-dimensional acceleration sensors and a special sensing-sleeper, which was assembled to assess the dynamic response loads acting on the sleeper bottom at a wide frequency domain. The measured results confirmed that for impact-load components over 100 Hz, the ballast layer resists because of its high rigidity and can reduce the impact loads substantially. However, the ballast layer is almost non-resistant to the low-frequency load components, which are not reduced enough. The finite element vibration analysis of the ballast aggregate, whose ballast stones are expressed as a polyhedron model using a three-dimensional discrete element method, examines frequency characteristics up to high-frequencies and clarifies the stress distribution of the ballast and the wave propagation of the ballast stone.

1. Introduction

A ballast structure consists of compacted ballast rocks on a subgrade. The ballast layer has important functions of distributing and propagating the immense impact load from the train traffic throughout the sleepers, and of attenuating the loads. These important functions are accomplished through multi-contact mechanisms that take place among respective ballast rocks inside the tightly compacted discontinuous aggregate. The frequent passage of trains will trigger minute plastic deformations among the blocks, and the accumulation of such minute invisible gaps among them will gradually cause the looseness and subsidence of the ballast layer and the supporting bed. Therefore, the ballast requires periodic maintenance, which is an important subject of technical research. Recently, higher economic growth combined with reduced working hours, labour shortages, and a limited interval time for track maintenance have all created the need to introduce a new maintenance-saving track. Structural improvement of conventional tracks has been a technical subject.

During a train's passage at high speed, each ballast particle receives a dynamic load at low frequency (up to several tens of Hertz) because of axle load passage. Each ballast particle also receives an impact load at high frequency (from a few hundred Hz up to several tens of kHz) excited by the rolling contact mechanism between wheels and rails through the sleeper bottom. In the ballasted track, the transmission characteristics of the impact load in the aggregate of ballast grains affect the progressive plastic deformation because of the movement and the wear of ballast grains. The ballast's sharp corners lead to stress concentration and complex multi-contact stress distribution in a narrow area of blocks, which contributes to shearing resistance. Although grain abrasion, breakage, and movement are the main causes of ballast degradation, Lu and McDowell [1] explained that most ballast

* Tel.: +81 425737291; fax: +81 425737289.
E-mail address: aikawa@rtri.or.jp

http://dx.doi.org/10.1016/j.conbuildmat.2014.06.005

degradation is attributable primarily to corner breakage. However, load propagation characteristics inside ballast grains and between grains, in addition to deformation characteristics inside and among grains, remain unexplained.

To clarify the transmission characteristics of a dynamic load within the ballast layer, the author performed a fundamental examination of the attenuation characteristics and the strength characteristics of the ballast aggregate, especially regarding the dependency of these factors on frequency to traffic impact loads based on field measurement. Next, this paper describes newly developed techniques intended for a practical use regarding three-dimensional dynamic numerical model studies of a ballasted railway track. Results obtained are used to evaluate the dynamic behaviour of the ballast aggregate and to elucidate impact-load-induced wave propagation inside the ballast grains.

2. Measuring instruments

2.1. Sensing sleeper

In this chapter, the characteristics of the impact load generated by a passing train and the features of ballast behaviour against such impact load are extracted based on field measurement conducted at an existing railway track. Fig. 1 shows a special sensing-sleeper which was designed to assess the dynamic load distribution on the sleeper bottom, regarding a wide frequency range from a low frequency up to a high frequency of several 10 kHz. The sensing unit comprises a PC3-type mono-block concrete sleeper (which was most commonly employed in conventional ballasted tracks in Japan) fitted with numerous ultra-thin-type impact load sensors [2]. Attached to the sleeper's whole undersurface is a solid mass comprising 75 impact load sensors. Each impact load sensor has a main body and cover members. The main body including a piezoelectric film has solid cover plates on its both surfaces. The cover plates transmit impact load to the main body, which prevents breakage of the sensor itself from the impact loads of a running train. Each sensor can measure the load up to a maximum of 10 kN(s) per square (8 cm × 8 cm) in the frequency range from 0.01 Hz to several 10 kHz.

The sensor consists of thin metal plates attached to both sides of a thin piezo film, being the same structure as a condenser. As the structure has no internal resistance, no induced current by noise sources occurs even in the high-tension environment under train operation, thus enabling high-quality load measurement. Although a charge proportional to the impact load is output from both terminals, the digitization of charge output is extremely difficult. Accordingly, the charge from the sensor is usually converted into a voltage by the integration electric circuit attached to a sensor output terminal (charge amplifier). An impedance transformation circuit using a high-impedance OP amplifier is sufficient. Moreover, as this sensor also has good reactivity and the output voltage is as large as several tens of volts, the noise ratio to the maximum measuring load is as low as 0.003%. The sensor offers sufficient performance to measure the load characteristics of a high-frequency region.

2.2. Installation of sensors

Field measurement was performed on Tokaido Main Line in Japan over one month. The track-site installation was conducted in a straight section of the above-mentioned conventional railway line with 60-kg/m continuously welded rail over PC3-type concrete mono-block sleepers laying on 30-cm-thick ballast-bed over firmly tightened embankment. The size and the method of installation of the sensing sleeper were the same as those of sleepers currently used. Therefore, regarding the installation process, the work was completed easily by simply tamping and trimming the ballast after the existing sleeper was replaced with the sensing sleeper, which was then fixed with the usual fastening devices.

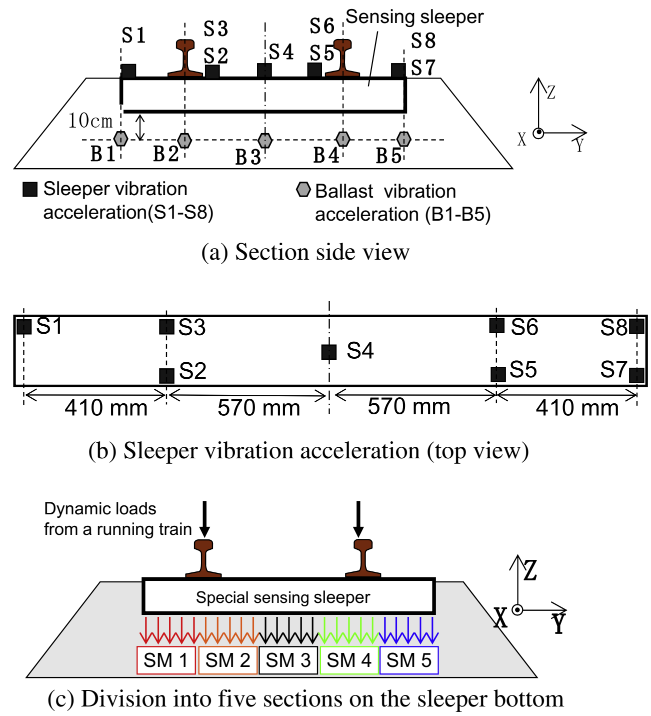

Fig. 2. Outline of in-situ measurements.

The dynamic response was measured for the following parameters: sleeper vibration acceleration, dynamic load distribution exerted on the sleeper bottom, and vibration acceleration of the ballast grains. Fig. 2(a) shows measurement points. For measurement up to the vertical third (w-shape type) bending mode of the sleeper, the sleeper vibration acceleration was measured at eight places (see Fig. 2(b)). The load exerted on the sleeper bottom was measured using a sensing-sleeper described previously. To compare the average load distribution by location along the bottom plane of the sleeper, the sleeper was divided into five sections, each section having 15 impact force sensors as portrayed in Fig. 2(c). Then a total measurement value was calculated for each section.

3. Measuring dynamic response under train operation

3.1. Sleeper deformation and load distribution on the bottom plane of the sleeper

The dynamic response was measured during a passenger express train operation. The linear amplitude spectra for loads exerted on the sleeper bottom, sleeper vibration acceleration, and ballast vibration acceleration are calculated. Fig. 3 presents an example of the measured results on the sleeper bottom to determine the dynamic stress generated by a passenger express train travelling at 122.7 km/h through the measurement section. The figure shows the relationship between the two-dimensional loading distribution characteristics on the bottom of the sensing

Fig. 1. Overview of sensing sleeper.