Review of Ballasted Track Destabilization on Shake Table Tests

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Abstract. Shake table tests have been used for a long time to understand the densification and fluidization of granular materials. While purely vertical shaking is quite unlikely to be found in vibration analysis when it comes to granular materials as soils, it has been found that the vertical vibration of railway bridge support structures can affect the fabric of the ballasted track on top. Starting from the experience at French railway lines with destabilizing track conditions on short bridges in high speed lines in the 1990s, various shake table test configurations have been used to investigate the destabilization of ballast at high acceleration levels. This article describes the effects of the variously investigated dynamic excitations of railway bridges on the ballasted track itself.

Keywords: Railway bridge dynamics, acceleration limit, ballast destabilization, shake table tests.

1 Introduction

1.1 Motivation

It is known from the dynamic calculations by the ERRI D214 Committee [1] that, despite compliance with the deflection criterion, vibration amplitudes of the bridge superstructure of up to 1.0 g are possible. In France, with the commissioning of the Paris–Lyon line, resonances occurred on some short bridges as a result of train crossings, which manifested themselves in signs of destabilization on the ballasted track. Visible vibrations of individual ballast stones were observed when trains passed over them. Ballast stones moved on the raised ballast shoulder, which led to a lateral track shift and presumably reduced the transverse resistance to the transverse displacement. Loosening, heavy abrasion, formation of longitudinal height and track alignment errors and even voided sleepers were the consequences. The subsequent measurements confirmed the resonance excitation of the superstructure. Acceleration amplitudes greater than 0.7 g were measured, whereby the destabilization of the ballast bed was significant. Some measured acceleration amplitudes were even higher, reaching 0.9 g [2].

However, the limit criterion of 0.35 g on acceleration prescribed in the design and reassessment codes, such as EN 1990 [3], is based on the destabilization of ballasted track, where Eigenfrequencies up to 30 Hz have to be considered.

1.2 Loading Scenarios

A train moving over a bridge causes a reaction of the track-bridge-system underneath the sequence of loads. In the event of significant vibration excitation, the bridge superstructure locally represents a vibrating shake table. The ballasted track, which is subjected to different preloads, is dynamically excited on this vibrating table (Fig. 1). This changes the vertical load transfer. Of particular importance, however, is the question of whether simultaneously acting lateral forces from the vehicle and rail temperature can be carried by the track.

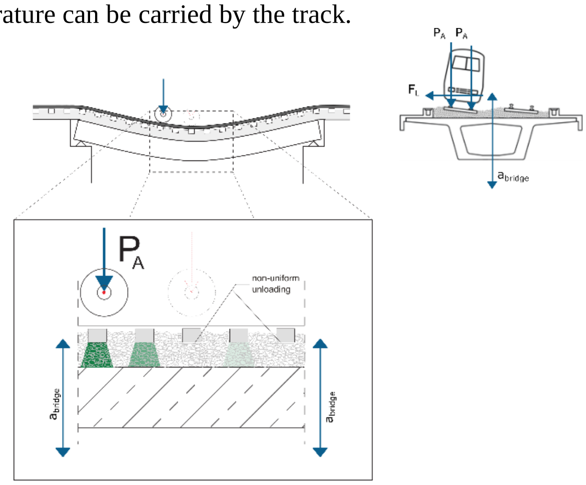

Fig. 1. (left) Section of the track of the bridge deck (right) Loads on the track on bridges.

The track on the bridge deck is usually confined between side panels similar to a test box. However also a sloped cross-section is possible (Fig. 2).

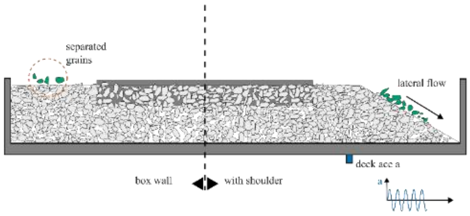

Fig. 2. Track section on bridge deck. Ballast particle movement and separation at high accelerations indicated.

The basic idea behind the limitation of the acceleration amplitude has been resonance-like vibrations with frequencies below 20 Hz. However, it became apparent that bridge vibrations on real railway bridges do not always fit into this concept.

Andersson and Karoumi [4] presented an evaluation in which a distinction is made between a frequency content up to 30 Hz and up to 90 Hz (see Fig. 3). When taking up to 90 Hz into account, the acceleration amplitudes are at least twice as high and partly exceed the limit value of 0.35 g. In [5] large vibration amplitudes of the bridge deck around 60 to 80 Hz are shown. In another study the influence of the considered frequency range has been systematically analyzed [6]. The conclusion is that frequencies above 30 Hz can be significant in bridge deck excitation.

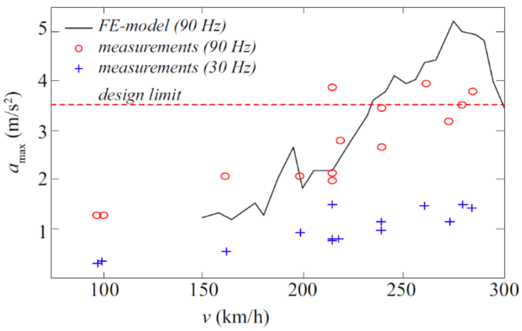

Fig. 3. Peak vertical deck acceleration during passage of the test train at different speed, comparison between experimental testing and simulation results, taken from [4].

Another issue is the distribution of the vibration amplitudes over the surface of the bridge. The initial idea for restrictions has been a vibration of a beam like structure in the first 3 bending modes. But as can be seen from Fig. 4. high acceleration amplitudes can be very local. Norris [7] concluded that isolated vibration peaks up to 1.0 g could be allowed for if they are very local.

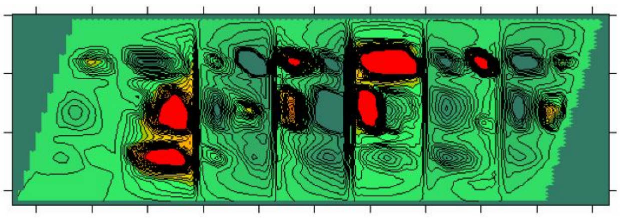

Fig. 4. Plot of bridge deck accelerations for a single time frame [7]. A red contour indicates vibration amplitudes above 1 g.

To summarize, the ballast track on dynamically excited bridge superstructures is represented by a track section in a box on a shake table. The loading of the track section is vertical and axial via the sleeper. The base case for bridge deck vibrations is a resonance excitation of vibration modes with low natural frequencies. In some cases also higher frequencies and individual local acceleration peaks are significant.

2 Material Behavior and Destabilization

The acceleration limit for railway bridge decks with ballasted track is prescribed to avoid track destabilization. Destabilization is an umbrella term for excessive deformation or negative impairment of the strength properties. The destabilization might also affect the dynamic characteristics (damping, stiffness) of the ballast bed. The base case for shake table tests is described in Fig. 5. A box filled with a loose ballast fabric is put on a shake table. When exceeding acceleration amplitudes of 1 g and above the loose ballast fabric sample densifies [8], [9].

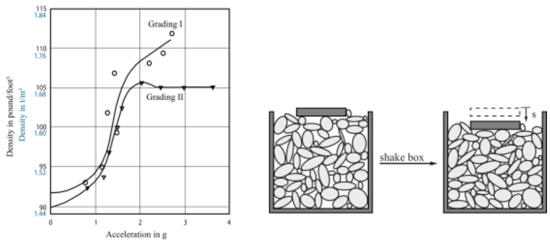

Fig. 5. Ballast densification in shake table tests for a loose sample (taken from [8])

Deformations in the ballast, rotation of particles and a fluidization will onset for accelerations close to or above 1 g. This can be understood from Fig. 6 for a sphere on a harmonically excited table. The sphere will only separate from the table if accelerations exceed 1 g. However, it needs to be noted that the sphere's lateral resistance is reduced for any increase of vibration starting from 0 g.

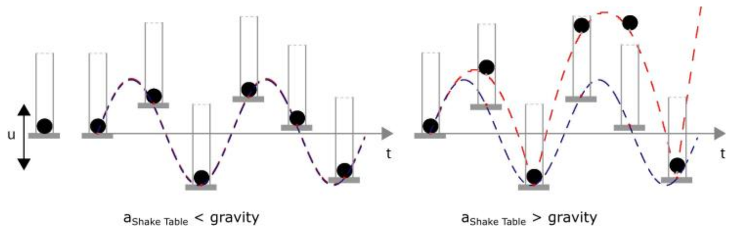

Fig. 6. Sphere on a shake table for harmonic vibrations with acceleration amplitudes smaller (left) or larger (right) than gravity.

The effect of the base excitation of a granular fabric on a shake table has been observed in various tests set-ups, see Fig. 7. Mogami and Kubo [10] mounted a shear device on a shake table and found the shear resistance to be strongly dependent on the acceleration amplitude (while the excitation frequency was of minor importance). Barkan [11] described experiments where a sphere was pushed into a sand filling fluidized by vibration. The sphere moves into the soil at a constant rate. What can be proven by these experiments is that the strength of a granular material is reduced by base vibrations up to a fluid like behavior.

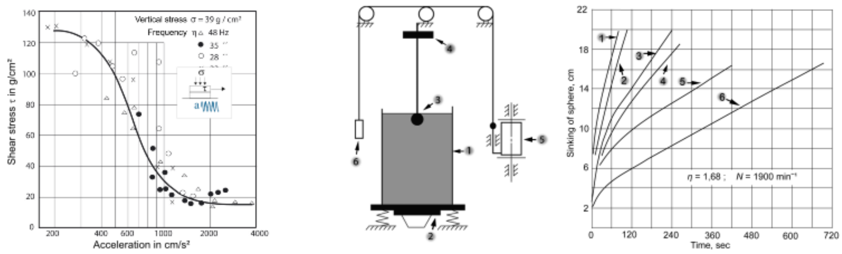

Fig. 7. Left decrease of shear resistance on a shake table with increasing acceleration levels A figure. (right taken from [10])

3 Shake Table Tests on Ballasted Track Destabilization

This chapter describes tests with sections of ballasted track.

3.1 Differentiation from experiments on dynamic characteristics

When analyzing the vibrations of dynamically excited short bridge superstructures, the prediction of the dynamic characteristics (stiffness, damping) of the individual bridge types in interaction with the ballasted superstructure is a major challenge (see e.g. [12]). In this respect various test rig experiments have been performed as outlined in [13], [14], [15]. Tests and measurements at bridges also indicate that the dynamic properties differ for high acceleration amplitudes [16]. Another tests scheme considers the track-bridge behavior during earthquakes (e.g. [17]). Reference is made to these tests, but they are not the subject of this article.

3.2 Eigenmodes and Transfer Behavior

For any dynamic testing it needs to be considered if rate effects are significant. The tests by Gaskin and Powell [8] and especially Shenton [18] (cyclic triaxial) do not show a frequency dependency of a ballast fabric on a material level.

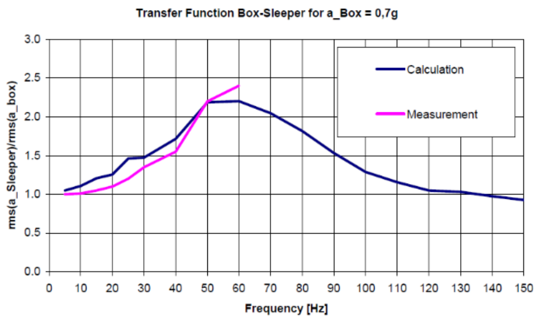

Fig. 8. Measured vs. calculated (assembly of DEM spheres) transfer function. From [19].

However, the ballast layer and the assembly of track components are a dynamic system with Eigenmodes and associated amplification. Track measurements on bridges and test setups indicate that the base excitation amplifies to the track above 20 Hz and has some peak roughly above 60 Hz (see Fig. 8). This means that any bridge deck acceleration amplitude at frequencies above 20 Hz will be amplified.

3.3 Tests on Track Destabilization

Starting with an assignment from the ERRI D214 committee, various test configurations with a ballast track and a track grid of 4 sleepers on a vibrating table were investigated (Fig. 9, see [20].). Fig. 10. shows the transfer function from the shake table to the sleepers for configurations with different under ballast mats (UBM). Not unexpectedly, the UBMs are not a mitigating factor for track dynamics. Large particle movements were observed at the ballast surface for accelerations close to 1 g. Visually, the ballast layer looks completely intact until close to this threshold

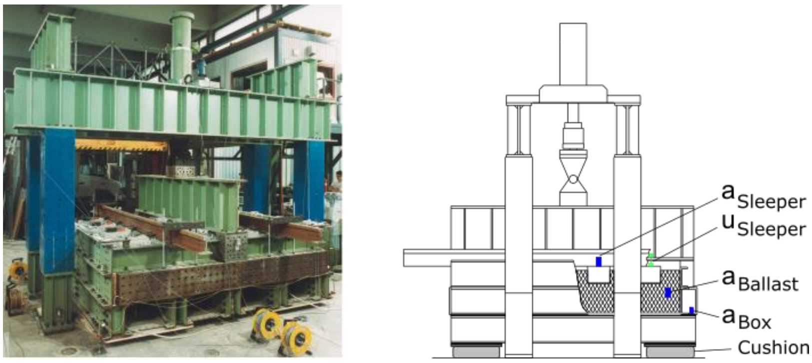

Fig. 9. Shake table test box with 4 sleeper rail grid.

The main function of the ballast superstructure is vertical and lateral load transfer. From a safety perspective, lateral resistance is of particular importance and is considered in the following. The track safety can be affected by a diminished resistance. Additional tests were carried out on a ballasted single B70 sleeper on the vibrating table, which was simultaneously loaded in the transverse direction by a force. Fig. 11 shows the accumulated lateral displacements of these tests for different acceleration levels and lateral preloads [21].

What can be observed (Fig. 12) is a creep like increase of lateral displacements of the sleeper. The magnitude of the lateral load and the amplitude of the accelerations determine the amount of creep deformations. The vibration-induced creep and the impact on the lateral stability of the track is described in more detail in [21]. However, it can be concluded that deformations of the track are affected significantly by acceleration amplitudes also below 1.0 g. The increasing deformations can impact the bearing capacity in terms of lateral stability.

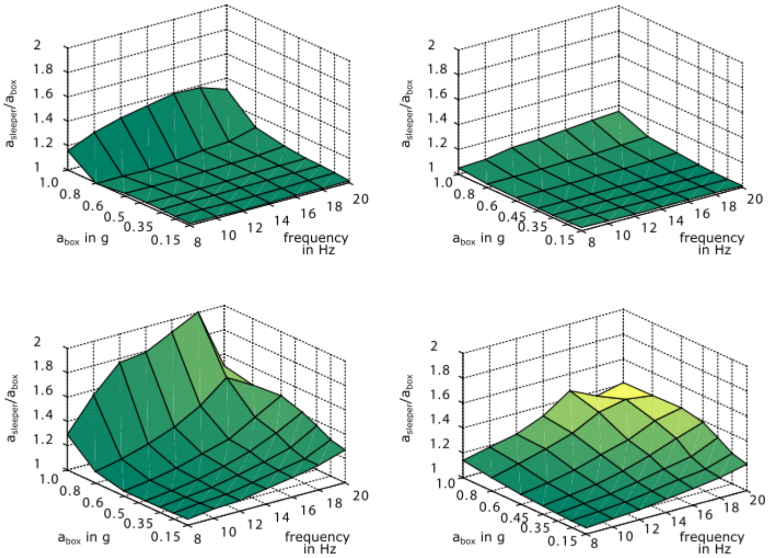

Fig. 10. Transfer function for different track-UBM-shake table assemblies at different frequencies and acceleration levels.

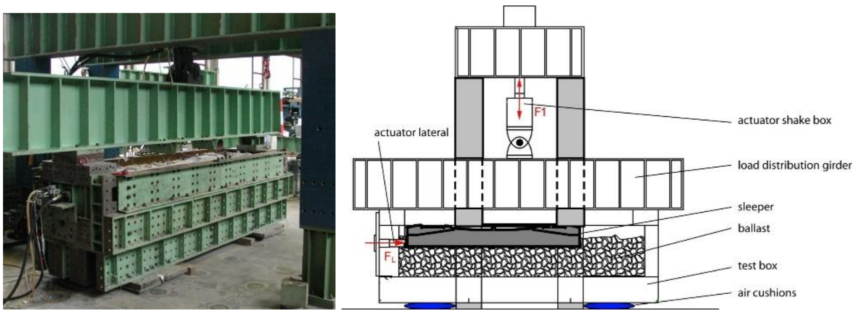

Fig. 11. Shake table tests for box with one sleeper and lateral force.

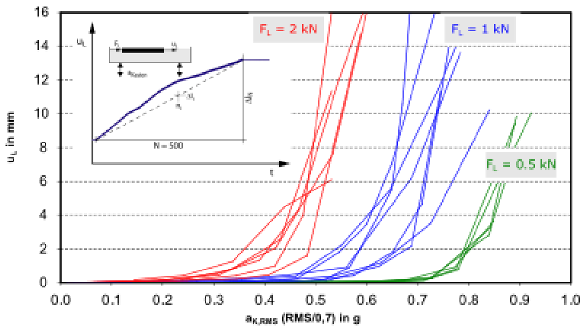

Fig. 12. Accumulated lateral sleeper displacement depending on lateral force and acceleration level for sequences of 500 vibration cycles.

The InBridge4EU project is currently investigating whether individual isolated acceleration peaks or excitations > 30 Hz do affect the deformation and strength of the ballast track. For this purpose, a new test rig with a vibrating table was set up (Fig. 13), with which a reduced sleeper in a ballast bed can be loaded vertically and/or laterally. Tests with a combination of vertical excitation of the vibrating table and lateral loading of the sleeper are shown below.

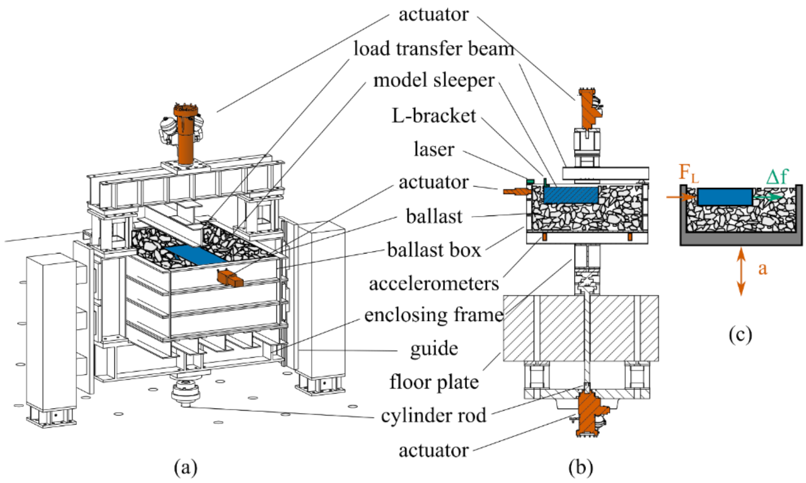

Fig. 13. Experimental setup for examining the vibration-induced creep due to lateral load and vertical vibrations (a) and longitudinal section (b). The quantities relevant for the tests are the lateral force F_L, the box acceleration a, and the lateral displacement Δf, as shown in (c).

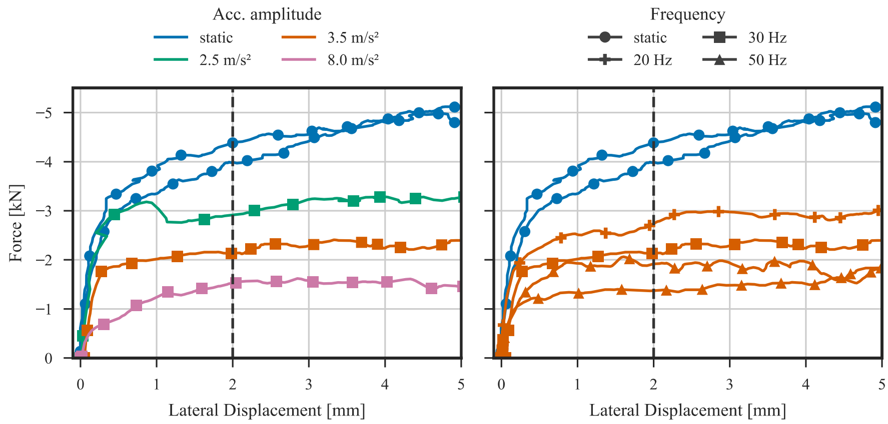

Fig. 14. Lateral resistance tests with varying acceleration amplitudes at a constant frequency of 30 Hz (left) and with varying frequency and constant acceleration amplitudes of 3.5 m/s² (right). Two lateral resistance tests under static conditions are shown for reference in each plot.

Fig. 14 shows the test results for the sleeper pushed laterally at a constant rate of 0.1 mm/s but at a constant vibration at the indicated acceleration level of the shake table. The decrease in lateral resistance even for amplitudes as low as 3.5 m/s² is remarkable. In addition, the influence of the excitation frequency on the lateral load-bearing behavior in the ballast bed was investigated. Fig 15 shows some scatter for frequencies from 20 to 50 Hz but a tendency towards a greater reduction in strength with higher frequencies. The frequently assumed hypothesis that frequencies > 30 Hz are less effective can therefore not be confirmed.

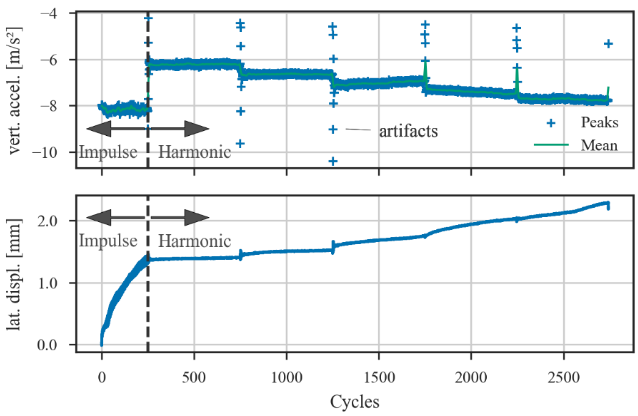

Fig. 15. Max. Peaks of the downward vertical box acceleration over number of cycles (above) and lateral displacement of the model sleeper (below). Constant lateral force F_L=1.0 kN.

Finally, Fig. 15 shows a sequence of 250 single pulses followed by a resonance like permanent excitation with a similar amplitude (see also [2]). It can be observed that also single pulses do affect the lateral deformations. Further investigations are currently being carried out.

4 Conclusion

The article provides an overview of the vibrating table tests for destabilizing the ballast bed on bridges at high bridge superstructure accelerations. Ballast in a vibration box only starts to fluidize with moving particles at amplitudes close to gravity. However, if an additional load is applied, it can be recognized that the strength is already reduced for smaller amplitudes and increased deformations are the result. More recent tests also indicate that the strength is reduced in the same way at excitation frequencies > 30 Hz. Nor can it be established that short acceleration pulses are less critical than longer, resonance-like excitation.

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