BALLAST VIBRATION MAKES NEW
DESIGNS FOR HIGH SPEED LINES ADVISABLE

Prof. Dr. Eng. Andrés López Pita
Polytechnic University of Catalonia

Thematic Structure: Requirement-oriented track design

Catch words = Ballast, vibration, high speed, deterioration, track

ABSTRACT

Railway lines have traditionally been designed according to tensional criteria, the maximum admissible value for each component being determined to avoid rapid deterioration. Nevertheless, increased speeds on newly constructed lines have shown that ballast vibration generated should serve as a new guideline for track dimensions.

1. INTRODUCTION

Railway infrastructure and superstructure dimensions were for a long time designed on the basis of the static action transmitted from vehicles to the track. The speed factor was taken into account by introducing a stress expansion coefficient obtained from statistical processing of results measured on numerous tracks and with different types of rolling stock.

It is true that at speeds of up to 160/200 km/h this method was shown to be satisfactory. This reality was perhaps represented by Prof. Eisenmann’s formula, which permitted quantification of the dynamic action on the rails of railway vehicles travelling at different speeds and on tracks with different resistance characteristics.

The reality is, however, that apart from purely static loads produced by a stationary vehicle and the dynamic loads normally produced by a vehicle moving at a constant speed on a superstructure of ideal quality, there may also be additional dynamic loads existing on the track or the vehicle itself.

Vibrations linked to the effect of vehicles are mainly caused by defects existing in the wheel-rail contact. Wheel contact involves a fluctuation in the force transmitted to the rail. This dynamic force is transmitted to the track and gives rise to the propagation of waves in the ground.

Existing experience in the introduction of high-speed commercial service lines in Europe in the last two decades reveals the rapid deterioration in ballast layers on some sections. This fact has been associated with vibrations generated by traffic on this material. A phenomenon which has not been dealt with much in technical literature.
With respect to the above, this study aims to contribute to analysis of this problem at a time when the Spanish railway authorities are planning to open a new Madrid-Barcelona high-speed line, with planned speeds in excess of 300 km/h.

2. **INITIAL ANÁLISIS OF THE BALLAST LAYER’S VIBRATORY BEHAVIOUR.**

With reference to the practical repercussions of oscillations acting on the railway superstructure, the main variable factors to consider are the oscillatory intensity and the frequency. With regards to the former, it should be pointed out that tests carried out at the Technical University of Munich in the sixties, showed that Prototype with increased running speeds a considerable increase in ballast layer oscillatory intensity was noted.

BIRMANN (1968) had already indicated, in fact, that the ballast layer, formed by granular elements and prone to friction and deformation, was subjected to an alternating stress through the sleepers when fast trains passed over, vibrating at a high frequency level. The German writer pointed out that, in spite of a certain cushioning effect being produced in the ballast layer, the stress could exceed a critical limit and destroy the equilibrium of the ballast’s granular structure.

This could, assuming axle loads of 16 to 18t. And travelling speeds in excess of 250 km/h, result in a classical type track, even with reinforced sleepers, being hard to use as a consequence of the vibration produced.

He also added that vibration tests carried out by DB at the end of the fifties had shown that the actual frequency of a normal track, under a load, was between 20 and 27 Hz. This level
would be close to that produced by the flexure waves when the bogie axles, with 3 m pitches, ran along the track at 300 km/h.

3 VIBRATIONS LEVELS IN BALLAST LAYERS ON COMMERCIALLY OPERATED LINES.

Concern about the vibratory reaction of ballast to high-speed traffic goes back to the 1970s, even though the first experience in high-speed line operations in Japan in the 60s had already shown the importance of this factor.

It was KATOH and KAREGAWA (1977) who pointed out the rapid deterioration of ballast on the Tokaido-Shinkansen line, noting the atomization of particles and a significant consequent increase in maintenance requirements. Among the main causes of the above phenomenon were:

1ª) The interaction between granular particles due to the high pressure and vibration the ballast was subjected to.
2ª) Repeated track-tampering operations which caused particles to break.

With relation to acceleration levels on the ballast layers, the above authors recorded the results shown in

![Fig 2 Test carried out in the Rolko tunnel](image)

<table>
<thead>
<tr>
<th>Train no.</th>
<th>6A</th>
<th>36 A</th>
<th>68 A</th>
<th>410 A</th>
<th>332 A</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velo City Kmh</td>
<td>175</td>
<td>187</td>
<td>200</td>
<td>200</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>Situation</td>
<td>Welded joint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Propotyptel It can be observed how, at speeds of between 175 km/h and 208 km/h, the acceleration levels were practically constant and were between 1 and 3g, according to the section of track considered.

With respect to the French experience, it should be remembered that, according to Prud’homme (1976), track superstructure and ballast components acceleration
measurements studied under a passing TGV 001 at different running speeds showed the values indicated in table 1. Ballast acceleration was measured between two sleepers and approximately 15 cm below their lower surfaces.

The French author carried out the following analysis with respect to the results from table 1.

**Table 1. The accelerations measured on the passing of the CC 6500 Locomotive**

<table>
<thead>
<tr>
<th>ROLLING STOCK</th>
<th>SPEED (km/h)</th>
<th>THE AVERAGE ACCELERATION ON THE</th>
<th>BALLAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC 6500 Locomotive</td>
<td>140</td>
<td>200 g</td>
<td>0.8 g</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>12 g</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TGV</td>
<td>245</td>
<td>15 g</td>
</tr>
<tr>
<td></td>
<td>245</td>
<td>300 g</td>
<td>300 g</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>350 g</td>
<td>350 g</td>
</tr>
<tr>
<td>Source: PRUD’HOMME (1976)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) At 140 km/h the accelerations measured with a locomotive type CC 6500 are somewhat less than those for a TGV travelling at the same speed.

a) At 300 km/h the ballast accelerations are almost twice as much as at 140 km/h, whilst those for the rails and the sleepers do not increase a great deal. Maximum values have not been compared in any case and it is only possible to record different orders of magnitude.

a) The increase in ballast acceleration is the aspect of most concern, since this could cause greater attrition of this material than that occurring on conventional lines.

He also added that on the Tokaido line Japanese railway authorities had noted considerable attrition of the ballast layer. To reduce this, especially in the case of track on concrete bridges, they had inserted rubber mats made from old car tyres between the concrete slabs and the ballast. Nevertheless, even if a certain reduction of ballast attrition had been observed on sections using these mats, it seems that this did not compensate the increased costs, given that the mediocre quality of the rubber would lead to its premature disintegration.

The combination of theoretical analysis and practical measurements enabled SATO (1978) to mathematically express the relationship of dependency between the track ballast layer bed and the conditioning factors according to the formula:

\[ \varphi = \beta \cdot \varphi_b \cdot y'' \]

where \( \varphi \) = the ballast layer bed
\( \beta \) = constant
\( \varphi_b \) = pressure on the ballast
\( y'' \) = ballast acceleration

With respect to the repeated track tampering operations, which according to KATOH and KAREGAWA caused the ballast particles to break, it is interesting to underline that, in accordance with H. MIYAMOTO (1995), even if the necessary operations on the Tokaido
– Shinkansen line to realign the track were initially carried out over 1000 km, this figure is currently just 33 km a year.

We should finally point out that, more recently, EISENMANN and RUMP (1997), in trying to analyse the causes of deterioration in track configuration on German high-speed lines, took a series of ballast layer behaviour measurements under the vibrations caused by traffic. In accordance with HAUSNER (1971), there is widespread consensus in using the “vibration speeds” factor as the most representative parameter for the effects produced on the ballast by oscillations which occur on the track.

The tests carried out by the aforementioned German authors showed that the level of vibrating speed in a vertical direction exceeds the corresponding speeds in a horizontal and transversal direction from the vehicle, being as much as four times greater in some cases. It is in any case possible to calculate the resulting vibration speed. The so-called effective vibration speed corresponding to a time period of 0.125 s. (DIN Standard 4150) was also assessed.

The main results obtained can be synthesized in figures
Prototype. In the first one the influence of the weight per vehicle axle on the effective ballast vibration speed can be observed. It can be seen that:
a) For axle weights of between 13t and 15t the vibration speed is about 18 to 19 mm/s.

b) For axle weights of between 19t and 20t the vibration speed reaches 21 to 22 mm/s.

In the second figure (3b), the effect of the vehicle speed can be analysed. It should be noted that for ICE (high-speed train) speeds in excess of 160 km/h, the vibration speed is close to 20 mm/s. This value is the norm for 200/250 km/h maximum speed with peaks of 24 and even 28 mm/s. Vibrations generated by goods trains on the other hand were around 10 mm/s.

It is interesting to note also that in track zones characterized by the existence of a transition between natural infrastructure and constructed sections, the vibrating level increased from 30% to 50%.

To what extent does the vibration speed influence deterioration in the ballast layer? According to Rump, by comparing the behaviour of similar materials to ballast, the latter should be able to withstand effective vibration speeds of between 10 and 15 mm/s. without the structured becoming unstable.

Taking these criteria as a reference, it follows that the greatest contribution to ballast layer deterioration would be caused by high-speed trains. Indeed, these generate, in accordance with the aforementioned, vibration levels of 20 to 25 mm/s, compared with vibration speeds of only 10 to 15 mm/s. caused by goods trains.

4. **THE CONTRIBUTION OF GRAULAR MATERIAL MECHANICS TO UNDERSTANDING THE VIBRATORY BEHAVIOUR OF BALLAST**

A study of existing technical studies shows that, until two decades ago, there was very little literature published on the behaviour of ballast when vibrated. In this respect it is useful to seek references on studies carried out on sand, owing to possible behavioural similarities of these two materials.

Of those works studied, one should emphasise the published results of D’Appolonia (1967) regarding the reaction of sand deposits placed on a vibrating table producing periodic vertical movements.
Prototype shows how sand compaction was relatively low up to acceleration levels of 1g, reaching maximum density when acceleration reached 2g. It was observed that at greater speeds density was reduced. From an initial density value close to 1.45 T/m³, it rose to a maximum of 1.7 T/m³, later falling to values below 1.67 T/m³.

One of the first studies on this subject was in fact carried out by MOGAMI (1953). Results obtained with sand showed that for acceleration values exceeding 2g, a reduction in compaction occurred for lower levels of acceleration. The influence of frequency in the process
Prototype. was, however, revealed.

In 1978 GASKIN et al. synthesized some of the studies carried out up to then by different authors. Those by SELIG (1963) and WHITMAN and PABLO (1968) in particular enabled them to state that if ballast reacted to vertical vibration in the same way as sand, a good base of information would exist for predicting the ballast layer’s behaviour when subjected to railway traffic.

On the basis of this reference, research carried out by GASKIN et al permitted fairly conclusive
Prototype confirmation of the parallel reactions to vibration of both types of material: sand and ballast.

In conclusion and as a synthesis of the tests carried out by the above authors, it can be stated that:

a) The main feature of vibration related to compaction of the ballast layer is peak acceleration.

b) The greatest increase in density occurs in the ballast with accelerations from 1 a 2g.

c) With a vertical pressure of up to 3.4 kg/cm\textunderscore{} no influence is observed in the relationship between initial density and acceleration. On the contrary, higher vibration acceleration values are needed to cause compaction of the ballast.

It should be noted that the initial ballast density considered in tests was around 1.4 to 1.5 t/m\textunderscore{}.

As is well known, the ballast is unloaded onto the track from hopper wagons and is compacted by tampering machines.

Studies of the compaction structure achieved in this operation were carried out in the sixties by BIRMANN and CABOS, using techniques with radioactive isotopes. The densities outlined in
 Prototype. were obtained in this way, with respect to the track’s transversal section.

The above authors also found that ballast density evolution under the action of traffic was that indicated in
Prototype, and in accordance with the results published in the framework of the ORE D-71 Committee.

It can be observed how the initial ballast density fluctuated between 1.54 and 1.72 T/m$^3$, depending on the test section considered. At the end of 7 months, in which time almost 4.5 million tons had passed overhead, a quasi-stabilisation in the degree of ballast compaction was observed, with respective values varying between 1.68 and 1.87 T/m$^3$.

It is extremely important to remember that, in the sixties, the maximum operating speed on commercial lines did not exceed 160 km/h (with the exception of some French sections where speeds reached 200 km/h). As a consequence, ballast layer consolidation was more the result of the continued action of the traffic in terms of pressure transferred and loads than of vibration.

It is also interesting to point out that the increase in ballast layer density coincides with an increase in its elasticity modulus. An approximate mathematical relationship between (E, $\gamma$) was given by RAFIROIU (1968) in the formula:

$$E_i = E_m \left[8.34 \left(\frac{\gamma_i}{\gamma_m}\right) - 7.34\right]$$

Where $E_i$ and $E_m$ are the elasticity moduli corresponding to the respective ballast densities $\gamma_i$ and $\gamma_m$. 
To conclude, we shall refer to MORGAN and MARKLAND’s results (1981), which confirmed that the application of acceleration values higher than 1g had the effect of destroying the previously stabilised ballast layer structure.

Of greatest interest were their tests and estimates in relation to ballast particle vibration according to the acceleration levels the ballast layer was subjected to.

**Fig. 9 The speed of the ballast particles with acceleration**  
(MARKLAND and MORGAN, 1981)

![Graph showing the speed of ballast particles with acceleration](attachment:image)

**Prototype**

**5 CONCLUSIONS**

The analysis carried out in this report has concentrated on ballast layer behaviour on a track subjected to a certain level of vibration.

Studies referring to its deformability have been carried out according to tensional criteria, attempting to determine the maximum admissible value to avoid rapid deterioration. Using this criteria track grillage components and the infrastructure were measured.

Increased operating speeds on newly constructed lines have nevertheless enabled it to be proved that vibration generated in ballast can affect its deterioration to a greater degree than the level of pressure which this granular material subjected to. It is necessary therefore to give detailed attention to this phenomenon.
Available experience in this field of sand behaviour subjected to vibration has guided similar studies on ballast. Current information seems to show that above a certain level of acceleration (1 to 2g.), a decompaction of the ballast layer occurs.

If these initial results are confirmed, it can be concluded that on high speed lines carrying mixed traffic, the main cause of track configuration deterioration would be high speed trains and to a lesser extent goods trains, as was initially thought.

One matter which remains to be resolved is the way in which new track design could contribute to reducing the deterioration in track configuration quality. Research is still in progress, but building more elastic lines, especially at the sleeper-rail contact points could be a good solution.

6. REFERENCES


LEYKAUF, G. Et al. (1998) *Schwingungsmessungen mittels schotter-mehrsteine*, ETR, 1

