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Instrumentation, monitoring and physical modelling of high-speed line

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Instrumentation and monitorization of sectors in high – speed lines

by
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ANNEX : Velocity and acceleration histories obtained at the top of the form layer for ALTARIA (TALGO) and AVE trains at 200 Km/h (November and December, 2003)
2 INTRODUCTION

One objective of the European FP5 project SUPERTRACK is the study of the midterm and long-term behaviour of ballast structures. To this aim a preliminary phase of monitorization of the high speed railway line, in operation between Madrid and Seville has been carried out.

Subsequently, as a project first phase, a permanent instrumentation of three sections was installed in the high speed railway line between Madrid and Zaragoza, at around K.P. 69+500 in the province of Guadalajara, before the line was open to traffic. The monitorization of settlements and static and dynamic pressures, by means of sensors located within the track structure and platform, would allow reproducing this behaviour at the laboratory installations. The instrumented sections have been provided with a control center and a meteorological station, presently in service.

The present report refers to the aforementioned instrumentation and monitorization works and it has been subdivided in the following sections:

▪ Monitoring of a sector of the high-speed railway line Madrid-Seville, in order to obtain the actions due to AVE and TALGO trains, and to predefine the transducer characteristics to be used in the line Madrid-Zaragoza.

▪ Instrumentation of three sectors (one in trench and the other two on embankment) at the Madrid-Zaragoza high speed line. One of the sectors on embankment has been reproduced at the track box in order to be able to study the short and midterm behaviour of the ballast structure under conditions of high speed railway traffic.

▪ Testing of the behaviour of the instrumentation installed at the three sectors of the real track, by means of a Diesel-Electric powered unit, with a total weight of 120 T circulating at speeds between 0 and 100 km/h.

▪ Monitoring of the instrumented track under the action of commercial trains of AVE and TALGO types, operating at 200 km/h, with the incorporation to the track of external sensors for determination of the dynamic loads and the movements of the rail and the sleepers.

3 MONITORING OF A SECTOR OF THE HIGH-SPEED LINE MADRID-SEVILLA

The objective of the measurements effected on the track, in 2002, was two-fold:

▪ Establishing the characteristics needed in the transducers to be installed at the high-speed line Madrid-Zaragoza.

▪ Determining the magnitude of the rail deformations, since this is the parameter used to operate the hydraulic system of self-control at the track box in the CEDEX testing station.

The section selected for those measurements was located at K.P. 103,400, within a straight stretch where the AVE reaches 300 km/h. Accelerometers, geophones and extensometric bands were fixed to different elements of the track structure. Accordingly, the following parameters were measured:

▪ Vertical component of acceleration at the rail base and at the sleeper.

▪ Rail strain at two sections, several meters apart.
Vertical component of the celerity of the surface wave at 4 points of the ground located in a perpendicular to the track.

Figure 3.1 shows two accelerometers, one at the rail base and the other at the concrete sleeper. Figure 3.2 shows an extensometric band used to measure the compressive strain at the rail web.

**Figure 3.1** Location of two accelerometers, at the rail base and at the concrete sleeper.

**Figure 3.2** Location of an extensometric band to monitor the strains of the rail
The analysis of results showed that the maximum vertical acceleration at the rail base, for a passing AVE, reached about 500 g, whereas it reached 25 g at the concrete sleeper, those values obtained for vibration measurements in “wide band”. However, if frequencies over 50 Hz are eliminated, the acceleration peaks are all less than 1 g.

Figure 3.3 and 3.4 illustrate the compressive and shear deformations at the rail web, and the flexural strains for the passage of TALGO and AVE trains, respectively.

**Figure 3.3** Compression and shear strains of the rail web and bending strains of the rail head and base for a passing Talgo train.
Figure 3.4 Compression and shear strains of the rail web and bending strains of the rail head and base for a passing AVE train.

4 INSTRUMENTATION OF A SECTOR OF THE HIGH SPEED LINE MADRID-ZARAGOZA

4.1 Location
One of the main objectives of the Project is achieving the measurement of loads and deformations at the real track structure, so that they can be fed at the track box, and the results compared with the real behaviour of the track.

A straight sector was then selected near Guadalajara, around K.P. 69+500 of the Madrid-Barcelona high speed line, comprising three zones, two on embankment, and the other one in trench. The geological formation, where the sector is located, is designated as “Paramo limestones”.

The embankment built at the sector is the highest in the zone, and it has been constructed to cross the so-called “Pilancones ravine”, with important longitudinal slopes (up to 40%). The
embankment materials have been obtained from trench excavations at the Paramo Limestone, and it includes fractions of clay from the limestone degradation.

Within the embankment, two line sections have been chosen for instrumentation, Section 1, reaching about 18 m height, and Section 2, to be modelled in real scale at the track box, reaching about 4 m height. Section 3 has been located within the trench zone. In order not to concentrate all the sensors at the same place, sections 2 and 3 have been divided into three subsections.

Figures 4.1 and 4.2 give perspectives of the instrumented sector. In Figure 4.3 a plan view shows the locations of the sections, and of the control center which includes a meteorological station.

4.2 Synthetic description of the instrumentation
The parameters to be measured in this sector are subsequently described along with some details of the devices employed.

Stresses at the bed layers: They are measured by means of total stress cells oriented along the three principal directions.

Contact stresses sleeper-ballast layer: They are measured in order to be able to establish the track system elasticity. Figure 4.4 shows the installation of a pressure cell under a sleeper.

Rail stresses: by means of extensometric bands flexural and shear stresses, produced by the circulating trains, are measured.

Permanent settlements and deflections caused by circulating trains: it was established to measure both the deflections (instantaneous) and the permanent settlements caused by the trains in the track structure and in the platform. The control of vertical movements of the track is made, as a function of time, both at the track structure and at the platform. The control of vertical track movements refers to both absolute movements of the track structure, and relative movements of the bed layers (ballast, subballast, form layers and platform). Figure 4.5 shows the installation of a displacement transducer to measure the relative movement sleeper-subballast.

Vibrations: Accelerations and velocities caused by the circulating trains have been registered at different locations (rail web, sleeper, subballast layer, form layer and embankment), for establishing, at each section, the transmitting vibrations and their corresponding frequency interval. Figure 4.6 represents the installation of an accelerometer at the subballast layer, and Figure 4.7 shows a boring between rails for geophone installation.

Temperature and water content: sensors have been installed to register the internal environment conditions of temperature and water content that may affect the track structure, in order to study their influence on the other control parameters.

Meteorological parameters: the evolution of environmental temperature, relative humidity, atmospheric pressure, rainfall intensity, wind speed and direction are registered at the meteorological station located at the control center of the instrumented sections.
Figure 4.1 Perspective of Sections 1 and 2 along with their connection boxes.

Figure 4.2 Perspective of Section 3 along with its connection box. Table 4.1 gives the types of control parameters existing at each one of the instrumented subsections.
Figure 4.3 Location of the three instrumented sections.
Figure 4.4 Pressure cells for vertical stress measurement at the sleeper base.

Figure 4.5 Relative displacement sleeper-subballast sensors (under the sleeper).
Table 4.1 gives the types of control parameters existing at each one of the instrumented subsections.
Table 4.1 Control parameters at the subsections of the experimental sector

<table>
<thead>
<tr>
<th>Instrumentation subsection</th>
<th>Control parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1B</td>
<td>Settlements and deflections, sleeper accelerations</td>
</tr>
<tr>
<td>S-2A</td>
<td>Compressive and shear stresses at the subballast layer</td>
</tr>
<tr>
<td></td>
<td>Rail stresses</td>
</tr>
<tr>
<td>S-2B</td>
<td>Settlements and deflections</td>
</tr>
<tr>
<td></td>
<td>Accelerations at rail, sleeper, subballast and form layer</td>
</tr>
<tr>
<td></td>
<td>Vibration velocities</td>
</tr>
<tr>
<td>S-2C</td>
<td>Vertical stresses at the contacts sleeper-ballast and ballast-subballast layers</td>
</tr>
<tr>
<td></td>
<td>Temperature and water content in subballast</td>
</tr>
<tr>
<td>S-3A</td>
<td>Compressive and shear stresses at the subballast layer</td>
</tr>
<tr>
<td>S-3B</td>
<td>Settlements and deflections</td>
</tr>
<tr>
<td></td>
<td>Accelerations at rail, sleeper subballast and form layer</td>
</tr>
<tr>
<td>S-3C</td>
<td>Vertical stresses at the contacts sleeper-ballast and ballast-subballast layers</td>
</tr>
<tr>
<td></td>
<td>Temperature and water content in subballast</td>
</tr>
</tbody>
</table>

4.3 Testing campaigns at the sector

The registered measurements obtained in this sector may be grouped in three different campaigns:
- April 2003. Test with a 120 T powered unit, including removable external instrumentation
- November 2003. Monitorization of commercial trains passing at a speed of 200 km/h, including removable external instrumentation.
- July-October 2004. Monitorization of commercial trains passing at a speed of 200 km/h, including removable external instrumentation.

April 2003
In relation to the first campaign (April 2003), ADIF (then GIF) provided a diesel-electric powered unit to be able to start studying the track, since the operations had not been started at the railway line. That unit had the following characteristics (see also Figure 4.8):
- Locomotive weight: 1180 kN
- Number of bogies: 2
- Number of axles per boggy: 3
- Weight per axle: 197 kN
- Distance between bumpers: 17 m
- Distance between boggy pivots: 9 m
- Distance between end axles of a boggy: 4,1 m

This first test aimed at verifying the performance of all the instrumentation placed within the sector, and at estimating the magnitude of some of the parameters to be monitored, so that the components of the measuring system could be properly adjusted.

We can point out the use of removable external sensors, essentially potentiometric systems for displacement registration, and a laser system for measuring the absolute movements of the rail. The latter includes an emitting element, fixed to a support embedded in the layers underlying the track structure, which aims at a receiver, fixed to the rail base. An essential
difference between both acquisition systems is that those of potentiometric type need to be rigidly fastened to a fixed base. In Figure 4.9 the laser system placed at Section 2A is shown.

Figure 4.8 Rumanian diesel-electric locomotive during the tests.

Figure 4.9 PSD Laser displacement transducer at section 2A: The emission unit is on a fixed base; the receiver is on the rail base.

Two types of tests were run, static and dynamic. The former consisted upon placing the front axle of the locomotive at the vertical of the different instrumented sections, and at the vertical of the sections in which removable external instrumentation had been installed. Figure 4.10 illustrates this procedure in Section 2, with indication of the locomotive positioning at the different subsections.
Since one of the objectives of the test was to obtain the displacements due to the static load of a wheel (98.5 kN), the effects of load interaction were interpreted by linear interpolation. The vertical displacements of the rail, due to a wheel load in Section 28, are shown in Figure 4.11.

Figure 4.10. Location of the locomotive for running the static test at Section 2C.
The dynamic tests were performed by allowing the locomotives to pass by at speeds ranging between 5 and 100 km/h. It was observed that up to 40 km/h the maximum displacement of the rail does not change (a constant value of about 1.9 mm was obtained) whereas from that speed up, a linear increase of the maximum displacement with the speed was obtained reaching a value of 2.4 mm at 100 km/h. This fact has been illustrated in Fig. 4.11bis where a linear variation of that displacement versus speed has been assumed for speeds higher than 40 Km/h.

**Figure 4.11** Vertical displacements of the rail due to a wheel load at Section 2B, as measured during the static test.

**Figure 4.11bis** Maximum absolute vertical displacement of the rail versus locomotive speed.
In relation to the instrumentation permanently installed within the track structure, the values registered at the different bed layers should be considered. The average values of the maximum pressures obtained are shown in Figure 4.12.

In this case, differently from the case of the track movements, the pressures obtained for different speeds of the passing locomotive are not appreciably different.

![Figure 4.12 Vertical pressures measured at sections 2C (upper part) and 3C (lower part) for the passing locomotive. No speed influence was appreciated.](image)

**November 2003**

During the second round of measurements, in November 2003, commercial trains were passing, as the track had been opened to commercial traffic, with two different types of trains, AVE and TALGO, circulating at 200 km/h. The objective, intended in this case, was to obtain the displacements of the main components of the track structure at Section 2. Figure 4.13 shows a global scheme of the external instrumentation. The sleepers are shown numbered: sleeper number 6 corresponds to Section 2A; sleeper number 14 to Section 2B, and sleeper number 22 to Section 2C. The monitored parameters were:

- Absolute displacement of rail base, $(\delta_a)_R$
- Relative displacement of rail base with respect to sleeper, $(\delta_r)_{R-T}$
- Relative displacement of sleeper with respect to form layer, $(\delta_r)_{T-LF}$
- Velocities obtained at the form layer for different types of train

It was feasible to measure the absolute displacement of the rail base, since every subsection has a fixed base. At Section 2A (sleeper number 6) a PSD Laser displacement transducer was placed, whereas potentiometric displacement transducers were used at Sections 2B (sleeper
number 14), and 2C (sleeper number 22) (Figure 4.14). Potentiometric transducers were also used to measure the relative displacements of the rail base with respect to sleepers number 5, 6, 14 and 22 and of sleepers with respect to the form layer. The latter task was accomplished by means of a set of steel pikes driven to the top of the form layer (Figure 4.15).

**Figure 4.13** Schematic layout of the external instrumentation for the second test (Nov-03).

**Figure 4.14** Potentiometric transducer placed on a rigid structure for measuring absolute displacements.
Figure 4.16 shows the average values of the maximum vertical pressures measured at the box of the sleeper and at the ballast-subballast contact for commercial trains passing at a speed of 200 km/h.

Figure 4.15 Relative displacement transducers rail-sleeper and sleeper-form layer.

Figure 4.16 Average vertical pressures for commercial trains passing at speed of 200 km/h.
Table 4.2 gives a synthesis of results of maximum displacements, absolute and relative, of different elements of the track structure, at Section 2A, for commercial trains passing at a speed of 200 km/h.

**Table 4.2. Test with commercial traffic with trains at 200 km/h (Nov. 03). Summary of maximum deflections at Section 2 A.**

<table>
<thead>
<tr>
<th>Nº</th>
<th>HOUR</th>
<th>TYPE</th>
<th>$(\delta_{abs})_{Rail}$ (mm)</th>
<th>$(\delta_{rel})_{Rail-Sleeper}$ (mm)</th>
<th>$(\delta_{r})_{Sleeper-Form layer}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:11:30</td>
<td>TALGO</td>
<td>-3.137</td>
<td>-0.299</td>
<td>-2.768</td>
</tr>
<tr>
<td>2</td>
<td>11:26:06</td>
<td>AVE</td>
<td>-3.327</td>
<td>-0.252</td>
<td>-2.456</td>
</tr>
<tr>
<td>3</td>
<td>12:15:20</td>
<td>TALGO</td>
<td>-3.434</td>
<td>-0.343</td>
<td>-2.491</td>
</tr>
<tr>
<td>4</td>
<td>13:46:27</td>
<td>TALGO</td>
<td>-3.623</td>
<td>-0.339</td>
<td>-2.289</td>
</tr>
<tr>
<td>5</td>
<td>15:43:11</td>
<td>TALGO</td>
<td>-3.456</td>
<td>-0.231</td>
<td>-2.286</td>
</tr>
<tr>
<td>6</td>
<td>16:46:21</td>
<td>TALGO</td>
<td>-3.509</td>
<td>-0.333</td>
<td>-2.417</td>
</tr>
<tr>
<td>7</td>
<td>19:31:28</td>
<td>AVE</td>
<td>-3.570</td>
<td>-0.147</td>
<td>-2.488</td>
</tr>
<tr>
<td>8</td>
<td>21:26:44</td>
<td>AVE</td>
<td>-3.403</td>
<td>-0.211</td>
<td>-2.745</td>
</tr>
<tr>
<td>9</td>
<td>22:00:39</td>
<td>TALGO</td>
<td>-3.663</td>
<td>-0.309</td>
<td>-2.874</td>
</tr>
</tbody>
</table>

The average values of maximum displacements for Section 2 (S2A, S2B and S2C) would be:
- Absolute displacement of rail: $(\delta_{aR})_M = 3.5$ mm
- Relative displacement rail-sleeper: $(\delta_{R,T})_M = 0.3$ mm
- Relative displacement sleeper-form layer: $(\delta_{T,CF})_M = 2.6$ mm
- Absolute displacement of embankment: $(\delta_{aT})_M = 0.6$ mm

In relation to the measurements made of velocities at the form layer, examples of the results obtained from the geophone located in section 2 B at the top of that layer are given in Annex 1 for TALGO (ALTARIA) and AVE trains at 200 km/h. A large difference in maximum values of velocity is shown between ALTARIA and AVE trains, the former being almost 3 times larger than the latter. By deriving those signals with respect to time the acceleration signals have been obtained. In this case the maximum values of accelerations are almost the same for ALTARIA and AVE trains or slightly less for the former. With respect to energy spectra the AVE trains shows a higher energy content for higher frequencies than does the ALTARIA (TALGO) trains despite the fact that their operating speed is almost the same.
Finally, for the third test, carried out between July and October 2004, displacement transducers were used to measure relative displacements between different track elements, extensometric bands for moment and shear force determination were used at the rail, and accelerometers and geophones were placed at the rail and at the sleeper. The instrumentation was again complemented by a PSD Laser transducer for absolute displacement measurement at Section 2B. The main objectives of the test were:

- To measure the dynamic loads produced by the passage of the trains for replication at the track box.
- To measure the absolute displacements of the rail and the relative displacements between track elements.

Table 4.3 shows the different sensors used for this test. Figures 4.17 to 4.22 define their location at the 3 sections, including details of the subsections.

In order to illustrate this instrumentation, Figures 4.23 and 4.24 show its location at Sections 2B and 3C.

**Table 4.3. Test with commercial traffic with trains at 200 km/h (Jul-Oct. 04). Summary of sensors.**

<table>
<thead>
<tr>
<th>SECTION</th>
<th>DISPL. TRANSDUCERS</th>
<th>STRAIN-GAUGES (IN RAIL)</th>
<th>ACCELEROMETERS</th>
<th>GEOPHONES</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1B</td>
<td>POTentiometeR (R-S) + POTentiometeR (S-FL)</td>
<td>SHEAR + BENDING MOMENT</td>
<td>RAIL + SLEEPER</td>
<td>SLEEPER</td>
</tr>
<tr>
<td>S2A</td>
<td>-</td>
<td>SHEAR + BENDING MOMENT</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S2B</td>
<td>POTentiometeR (R-S) + POTentiometeR (S-FL) -- LASER (RABS) + POTentiometeR (R-S) + POTentiometeR (S-FL) + POTentiometeR (S-SB) + POTentiometeR (S-FL)</td>
<td>SHEAR + BENDING MOMENT</td>
<td>RAIL SLEEPER</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2C</td>
<td>-</td>
<td>SHEAR + BENDING MOMENT</td>
<td>RAIL</td>
<td>-</td>
</tr>
<tr>
<td>S3C</td>
<td>POTentiometeR (R-S) + POTentiometeR (S-FL)</td>
<td>SHEAR + BENDING MOMENT</td>
<td>RAIL + SLEEPER</td>
<td>SLEEPER</td>
</tr>
</tbody>
</table>
**Figure 4.17.** Instrumentation layout at Section 1B.
Figure 4.18. General layout of the instrumentation in Section 2
Legend

- Bending moment strain gauges
- Shear strain gauges

Figure 4.19. Instrumentation layout at Section 2A.
Figure 4.20. Instrumentation layout at Section 2B.
Figure 4.21. Instrumentation layout at Section 2C.
Figure 4.22. Instrumentation layout at Section 3C.
This has allowed to record a large number of dynamic actions produced by the real passage of trains at 200 km/h, for their reproduction at the track box. As an example, Figure 4.25 shows
the record of the dynamic loads produced by a train, obtained from the measurements of two extensometric shear bands separated 25 cm.

![Graph showing dynamic loads](image)

**Figure 4.25** Dynamic loads due to a passing train from the results of the extensometric bands

A summary of the maximum dynamic values $Q$ measured under the passage of 153 trains of five different types are given in table 4.4.

In that Table the difference (in percentage), of the average, maximum and minimum values of $Q$ with respect the nominal static value (112-5 kN) are also given. It can be seen that the average values of $Q$ for the different trains are very close to the nominal static value.

The passage of 107 trains was used to record absolute displacements of the rail and sleepers at sections 2A, 2B and 2C. In Table 4.5 the type of trains recorded are identified for each instrumented section referring either to measurements made at the rail (designated by R) or at the sleepers (designated by T) at each section. Table 4.6 gives the maximum absolute displacements measured by laser beam technique at each section in the rail (R) and at the sleepers (T). It is worthwhile to verify that the sleepers may show higher displacements than the rails due to the fact that the former is a continuous steel beam and its connection with the sleepers is not rigid. The fact that the displacements of the rail and the sleeper are measured at different points of the sleepers, the latter being measured at the edge of the concrete mass, may also contribute to those results. From the upper part of the Table it can be concluded that the rail displacements produced by the passage of trains at 200 km/h are in the order of 2.5 mm. As an example of this type of measurements Figure 4.26 gives the absolute displacements of the rail under an Altaria (Talgo) train at section 2B.
Table 4.4. Dynamic maximum load values measured for 153 trains recorded during July-October 2003 (Percentage values refer to average, maximum and minimum values as compared with a maximum nominal static value per wheel of 112.5 kN)

<table>
<thead>
<tr>
<th>Type of train</th>
<th>Number of trains</th>
<th>$\text{Q}_{\text{AVERAGE}}$ (kN)</th>
<th>$\text{Q}_{\text{MAX}}$ (kN)</th>
<th>$\text{Q}_{\text{MIN}}$ (kN)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTARIA: L + 10 axles</td>
<td>94</td>
<td>112.674 (+0.15%)</td>
<td>133.899 (+19.02%)</td>
<td>102.233 (-9.13%)</td>
<td>6.155</td>
</tr>
<tr>
<td>ALTARIA: L + 14 axles</td>
<td>7</td>
<td>114.594 (+1.86%)</td>
<td>118.447 (+5.29%)</td>
<td>109.495 (-2.67%)</td>
<td>2.897</td>
</tr>
<tr>
<td>ALTARIA: L + 20 axles</td>
<td>10</td>
<td>110.823 (-1.49%)</td>
<td>117.973 (+4.86%)</td>
<td>104.819 (-6.83%)</td>
<td>3.577</td>
</tr>
<tr>
<td>ALTARIA: L + 13 axles + L</td>
<td>6</td>
<td>93.921</td>
<td>98.754</td>
<td>89.380</td>
<td>2.744</td>
</tr>
<tr>
<td>AVE</td>
<td>36</td>
<td>97.459 (+13.26%)</td>
<td>103.850 (+20.69%)</td>
<td>88.373 (+2.70%)</td>
<td>3.908</td>
</tr>
</tbody>
</table>

Comparing the values with those obtained in November 2003, when maximum displacements of the rail of the order of 3.5 mm were obtained under the passage of the same type of trains (see Table 4.2), it can be inferred that the high speed line Madrid-Zaragoza at the Guadalajara site has consolidated, increasing its dynamic track stiffness, after one year in operation.

Table 4.5. Trains used to measure maximum absolute displacement values. July 2004.

<table>
<thead>
<tr>
<th>Section</th>
<th>Number of trains</th>
<th>ALTARIA (10 axles)</th>
<th>Different ALTARIAS (1)</th>
<th>AVES</th>
<th>Specials or Locomotives</th>
</tr>
</thead>
<tbody>
<tr>
<td>L – 2 A - R</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>---</td>
</tr>
<tr>
<td>L –2 A - S</td>
<td>15</td>
<td>8</td>
<td>---</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>L – 2 B – R</td>
<td>34</td>
<td>18</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>L – 2 B - S</td>
<td>21</td>
<td>9</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>L – 2 C - R</td>
<td>1</td>
<td>---</td>
<td>---</td>
<td>1</td>
<td>---</td>
</tr>
<tr>
<td>L – 2 C - S</td>
<td>33</td>
<td>12</td>
<td>7</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>107</td>
<td>48</td>
<td>19</td>
<td>21</td>
<td>19</td>
</tr>
</tbody>
</table>

(1): ALTARIAS (14 axles), ALTARIAS (20 axles) o Locomotive + 13 axles + Locomotive.

Table 4.6. Average values of absolute maximum displacements measured with laser technique, in mm ($R =$ rail, $S =$ sleeper). In parentheses, number of recorded trains.

<table>
<thead>
<tr>
<th>Section</th>
<th>Number of trains</th>
<th>ALTARIA (10 axles)</th>
<th>Different ALTARIAS</th>
<th>AVES</th>
<th>Specials</th>
</tr>
</thead>
<tbody>
<tr>
<td>L - 2A - R</td>
<td>3</td>
<td>2.301 (1)</td>
<td>2.549 (1)</td>
<td>2.241 (1)</td>
<td>NO</td>
</tr>
<tr>
<td>L - 2B - R</td>
<td>34</td>
<td>2.481 (18)</td>
<td>2.467 (5)</td>
<td>2.448 (6)</td>
<td>2.621 (5)</td>
</tr>
<tr>
<td>L - 2C - R</td>
<td>1</td>
<td>NO</td>
<td>NO</td>
<td>2.022 (1)</td>
<td>NO</td>
</tr>
<tr>
<td>TOTAL</td>
<td>38</td>
<td>2.472</td>
<td>2.481</td>
<td>2.369</td>
<td>2.621</td>
</tr>
<tr>
<td>L - 2A – S</td>
<td>15</td>
<td>2.609 (8)</td>
<td>NO</td>
<td>2.687 (3)</td>
<td>2.894 (4)</td>
</tr>
<tr>
<td>L - 2B – S</td>
<td>21</td>
<td>2.563 (9)</td>
<td>2.318 (6)</td>
<td>2.438 (4)</td>
<td>2.498 (2)</td>
</tr>
<tr>
<td>L - 2C - S</td>
<td>33</td>
<td>2.447 (12)</td>
<td>2.221 (7)</td>
<td>2.410 (6)</td>
<td>2.712 (8)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>69</td>
<td>2.528</td>
<td>2.266</td>
<td>2.483</td>
<td>2.733</td>
</tr>
</tbody>
</table>
Figure 4.26 Absolute displacements of rail (after laser measurements) at Section 2B.

In relation to vertical pressures, Figures 4.27, 4.28 and 4.29 give dynamic records of vertical pressures at Section 2C, between ballast and sleeper, and between ballast and subballast layers, at the vertical of the external rail, at the vertical of the internal rail, and between rails, successively.

Figure 4.30 gives a synthesis of the average values of the maximum vertical pressures measured at the different layers of the track structure. The recorded values are in good agreement with those obtained in previous tests.

As an example of the dynamic response of the track, Figure 4.31 shows three geophone records obtained in the sleepers at Sections 1B, 2B and 3C respectively. It is worth to highlight the big differences obtained in the maximum celerity values of sleepers lying on 18 m high embankment, 3 m high embankment and natural ground.
Figure 4.27 Vertical pressures at the external rail vertical in Section 2C (upper part, contact pressures sleeper-ballast; lower part, contact pressures ballast-subballast).

Figure 4.28 Vertical pressures at the internal rail vertical in Section 2C (upper part, contact pressures sleeper-ballast; lower part, contact pressures ballast-subballast).
**Figure 4.29** Vertical pressures between sleepers at the external rail in Section 2C (upper part, contact pressures sleeper-ballast; lower part, contact pressures ballast-subballast).

**Figure 4.30** Synthesis of vertical pressures at different levels of Section 2C.
### 5 SUMMARY AND CONCLUSIONS

Measurements made in high speed lines constructed in Spain have served to:

- Assess the most appropriate type of instrumentation and sensitivity for the track box tests;
- Determine static and dynamic track stiffness in actual sections of one line and their evolution with time;
- Get vertical pressure distributions under the track for the daily traffic of trains;
- Set up a reliable laser beam system to measure absolute displacements of the rails;
- Determine the contribution of the different bed layers of the track to the total absolute displacements of the rails in one line instrumented internally;
- Differentiate the effect that the passage of different type of trains may introduce in the platform;
- Get track dynamic loads and displacement histories to be used as inputs in the track box tests;

![Figure 4.31](image-url) Geophone records at Sections 1B (upper part), 2B (middle part) and 3C (lower part).
Select and use easy to install external sensors such as geophones and accelerometers to get the dynamic response of the track.

The results obtained so far are important contributions to the knowledge of the behaviour of the track under the passage of high speed trains allowing to compare the difference between sections on embankments and in trenches.

The work has given insight on the problems associated with instrumentation of particulated media and has allowed to tune up the use of laser systems for determination of absolute movements on the rails. The combination of external and internal instrumentation has enhanced the use of different techniques for monitorization of dynamic signals resorting to small sensors easy to use in the railway field.

The main shortcomings encountered refer to the need of installing the instrumentation during the track construction to include it at different significant layers within the ground, the embankment and the track bed layers. There is also the need of placing the sensors at location where the ballasting operations in the track do not damage them.
ANNEX


V_{\text{MAX}} = 33.270 \text{ mm/seg} \quad V_{\text{MIN}} = -22.140 \text{ mm/seg}

FRECUENCIA (Hz)

MÓDULO TF

TIEMPO (seg)

\[
V_{\text{MAX}} = 33.270 \text{ mm/seg} \quad V_{\text{MIN}} = -22.140 \text{ mm/seg}
\]

\[
\text{ENERGÍA} = 92.516 (\text{mm}^2/\text{seg})
\]

$A_{\text{MAX}} = 0.728 \text{ g}$  $A_{\text{MIN}} = -0.469 \text{ g}$

FILTRO = 200 Hz

$A_{\text{MAX}} = 0.728 \, g \quad A_{\text{MIN}} = -0.469 \, g$

FILTRO = 200 Hz

ENERGÍA = 0.0219 (g² . seg)

- $V_{\text{MAX}} = 12.296 \text{ mm/seg}$
- $V_{\text{MIN}} = -17.181 \text{ mm/seg}$

\[ V_{\text{MAX}} = 12.296 \text{ mm/seg} \]
\[ V_{\text{MIN}} = -17.181 \text{ mm/seg} \]

\[ \text{ENERGÍA} = 39.623 (\text{mm}^2 / \text{seg}) \]

\[ A_{\text{MAX}} = 0.771 \, g \quad A_{\text{MIN}} = -0.625 \, g \quad (\text{FILTRO} = 200 \, \text{Hz}) \]

\[ A_{\text{MAX}} = 0.771 \, g \quad A_{\text{MIN}} = -0.625 \, g \quad (\text{FILTRO} = 200 \, \text{Hz}) \]

\[ A_{\text{MAX}} = 0.771 \, g \] \[ A_{\text{MIN}} = -0.625 \, g \] (FILTRO = 200 Hz)

ENERGÍA = 0.0504 \((g^2 \cdot \text{seg})\)