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Reducing vibration in Continuously Supported Track

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ABSTRACT

The Rossio tunnel was built in 1890 and connects the Campolide Station in the north of Lisbon with the Rossio Station in the urban city centre of Lisbon, with connections to the Metro network.
Due to structural problems in the tunnel this railway line was taken out of operation in October 2004 and because of its great strategic importance the track was rebuilt following completion of the necessary structural works. The Portuguese National Railway Network (REFER) selected a continuously supported fastenerless embedded rail system (CSFERS) from CDM range of track solutions.
There was demand for a high level of vibration isolation; for the "-10 dBV" zones so a soft CSFERS was chosen (COMFORT), whereas for the more sensitive areas a classic CSFERS (CLASSIC) system was installed in a floating slab track, using resilient mats from the CDM range to obtain a minimum reduction of 20 dBV.
The installed systems have been tested extensively in comparison with discrete supported rail and results show that the COMFORT system delivers extremely good vibration isolation performance whilst also delivering a far lower rate of corrugation than discrete supported rail.
This paper describes the installed solutions in Rossio tunnel, the vibration measurements taken and presents the results.
The Portugese national permanent way owner (REFER) was confident that a CSFERS system in COMFORT version would deliver excellent vibration isolation performance, even in areas without a floating slab, with the added advantages of fast installation and a multimodal platform inside the tunnel for easy evacuation and maintenance operations.

1. INTRODUCTION

In 1890, the Rossio tunnel was built to link the valleys of Avenida da Liberdade and São Bento in Lisbon, Portugal[1]. In this 2.6 km long tunnel, a railway line was constructed to connect two important railway stations, the Campolide Station in the north of Lisbon and the Rossio Station in the urban city centre of Lisbon, with connections to the Metro network.

Due to structural problems in the tunnel this railway line was taken out of operation in October 2004 and because of its great strategic importance REFER decided to rebuild the track following completion of the necessary structural works.. They opted for a continuously supported fastenerless embedded rail system from the CDM range of track solutions (hereinafter referred to as CSFERS) for the reconstruction of the railway line. Since February 2008 this rebuilt railway line in the Rossio tunnel has been in operation again and where the track was projected for 60 kph speed, trains are now running at 90 kph without any specific complaints.

2. TRACK CONSTRUCTION

For the renewal of the track section inside the tunnel, the CSFERS system was selected. See Figure 1 - typical cross section of floating slab track with CLASSIC CSFERS.

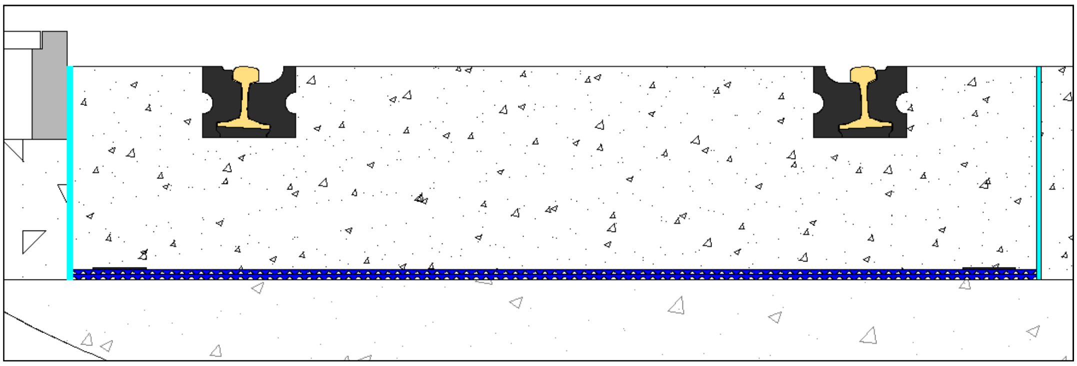

Figure 1: *Typical cross section of FST with Classic CSFERS*

According to REFER project specifications a "top-down" installation technique was mandatory as this technique provides good control of the alignment of the top of rail (TOR) level. This installation method also allows a high work rate, which was a very important parameter to REFER, considering the tight construction planning of only 5 months for 2.6 km platform of double track. Moreover, this high installation speed had to be reached in very difficult working conditions; the tunnel has just a single entrance/exit for the supply of all materials, there is no natural daylight and little fresh air inside the tunnel…Typical track design details: rail 60E1, track gauge 1668 mm., axle load 225 kN and design speed 60 kph (later changed to 90 kph).

The straightforward installation method of the CSFERS system, using specially designed gauge support fixation equipment (GSF jigs), allows installation speeds of more than 100 lmst (linear meter of single track) per day per work front.

The contractor, using this system for the first time, managed to install 5000 lmst in only 5 months without any major issues. Another advantageous result of an embedded rail system, such as CSFERS, is the multi-modal platform, which is created inside the tunnel to allow access of vehicles in case of emergency or maintenance actions. Moreover, in case of hazard, people can be evacuated faster from the tunnel by cars or on foot, since sleepers and rails are no longer obstructing the exit route.

Figure 2: *Multimodal platform with embedded slab track in Rossio tunnel*

When the previous track system in the old tunnel was still in operation, REFER received many vibration complaints. As a result, REFER has carried out a detailed noise & vibration study of the tunnel and its surroundings in order to define track solutions capable of guaranteeing a max. vibration level in the neighbouring dwellings v-max-rms < 0.03 mm/sec, a limit commonly accepted in the acoustic community as a good vibro-acoustic comfort level. Based upon the study different zones have been defined, each with a requested level of vibration isolation. There are zones with a required isolation level of -10 dBV and more sensitive zones with a required vibration isolation level of -20 dBV. . For the "-10 dBV" zones, the CSFERS COMFORT solution has been installed, using a softer continuous rail strip to result in a track stiffness of approx. 25 MN/m/lmst. The more sensitive areas have received the stiffer CSFERS CLASSIC solution (approx. 50 MN/m/lmst), but in combination with a floating slab track using CDM resilient mats to obtain a minimum reduction of 20 dBV.

3. NOISE & VIBRATION MEASUREMENTS

An independent specialist consultant was asked to perform control measurements in the different track zones[2, 3].

Six measurement sections have been defined; a first section in the zone with direct fixations (S1) on a floating slab track, 3 sections in a zone with CSFERS CLASSIC on a floating slab (S2, S3 and S4) and finally 2 slab track sections with CSFERS COMFORT (S5 and S6).

In these measurement sections, the vibration and rail displacement levels during train pass-by have been measured, as well as the rail roughness levels and the receptance levels of rail, slab and tunnel invert.

These parameters have been measured twice, 7 and 70 days after installation of the track. A third measurement campaign is planned 700 days after installation in order to have an idea of the track long term evolution via logarithmically spaced time intervals

This paper presents a comparison of the obtained measurement results.

4. MEASUREMENT RESULTS

As a first parameter, the vibration level on both the tunnel invert and on the slab track has been measured with high sensitivity seismic accelerometers.

Table 1 shows the results of the measured LEQ and LMAX values for the six measurement sections 7 days and 70 days after installation.

The transit exposure level LEQ [dB] is defined as:

$$LEQ = 10\log\left(\frac{1}{T_p}\int_0^t \frac{v^2(t)}{v_0^2}\,dt\right) \qquad (1)$$

T being the measurement time in seconds, T_p the pass-by time of the train, v(t) the instantaneous vibration level in m/s and v_0 the reference vibration level of $1x10^{-9}$m/s. One must take in account that the trains are passing in the first and the last sections (closest to the stations) at reduced speed, resulting in higher values of T_p.
As an example, the LEQ (dB) vibration levels for the 6 measurement sections are put in a graph for comparison.
One can immediately notice the reduced vibration levels on the slab track in the last 2 sections, due to the absence of a floating slab. There is almost no difference in behaviour between the measurements 7 days and 70 days after installation.

Table 1: *Measured vibration levels in dB and mm/s for all sites after 7 days (D7) and 70 days (D70)*

time	parameter	measurement point SL: slab IN: invert	Averaged vibration level in dB re. 1e-9m/s for all sections					
			S1	**S2**	**S3**	**S4**	**S5**	**S6**
D7	MAX	SL	141	133	139	137	110	109
	MAX	IN	105	107	102	96.2	105	103
	LEQ	SL	132	124	132	130	101	102
	LEQ	IN	96.9	99	95.7	89.9	95.3	96.6
D70	MAX	SL	140	128	138	137	110	110
	MAX	IN	105	107	103	98	106	103
	LEQ	SL	132	120	132	131	102	103
	LEQ	IN	97.7	101	97	91.5	97.2	96.8
			Averaged vibration level in mm/s for all sections					
D7	MAX	SL	11.220	4.467	8.913	7.079	0.316	0.282
	MAX	IN	0.178	0.224	0.126	0.065	0.178	0.141
	LEQ	SL	3.981	1.585	3.981	3.162	0.112	0.126
	LEQ	IN	0.070	0.089	0.061	0.031	0.058	0.068
D70	MAX	SL	10.000	2.512	7.943	7.079	0.316	0.316
	MAX	IN	0.178	0.224	0.141	0.079	0.200	0.141
	LEQ	SL	3.981	1.000	3.981	3.548	0.126	0.141
	LEQ	IN	0.077	0.112	0.071	0.038	0.072	0.069

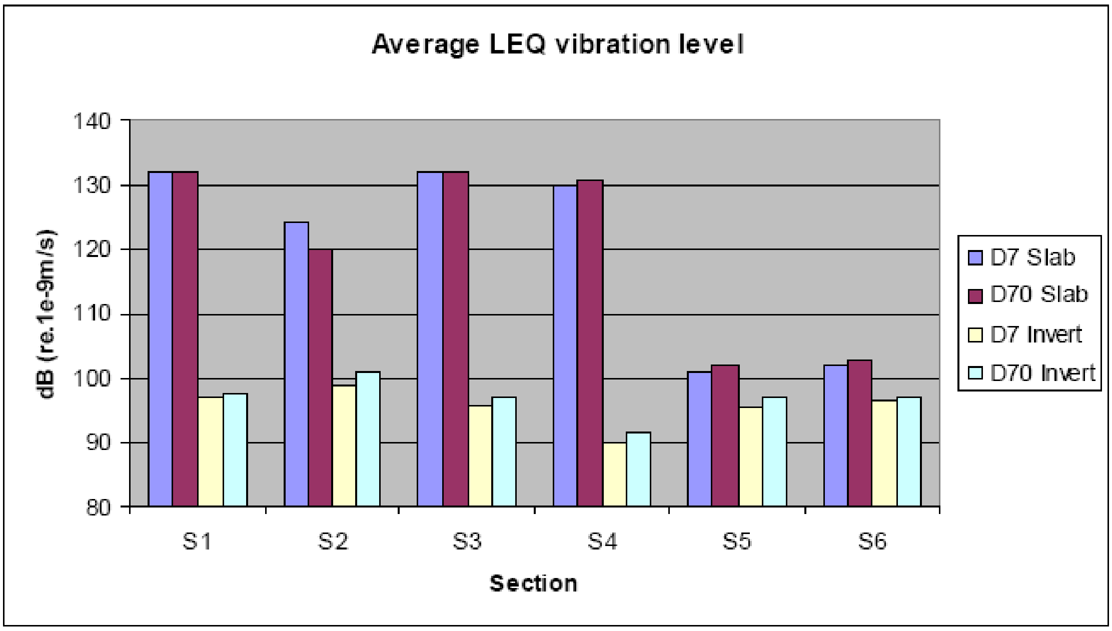

Figure 3: *Comparison of LEQ vibration levels expressed in dB*

The second parameter concerns the displacement of the rail, relative to the slab, which was measured during the train pass-bys using LVDT displacement transducers.
As shown in Figure 4 the vertical rail displacements vary between 0.6 and 1mm, whereas in Figure 5 the horizontal displacements only vary around 0.25mm. No significant difference could be noted between D7 and D70 measurements.
The highest horizontal displacement has been measured in section 1 for the direct fixation track system. Backed by some other measurement results from different track projects[4], it has been pointed out that embedded rail systems such as the CSFERS system have a better (or at least similar) lateral stability than direct fixation systems, taken into account the vertical stiffness of the system.

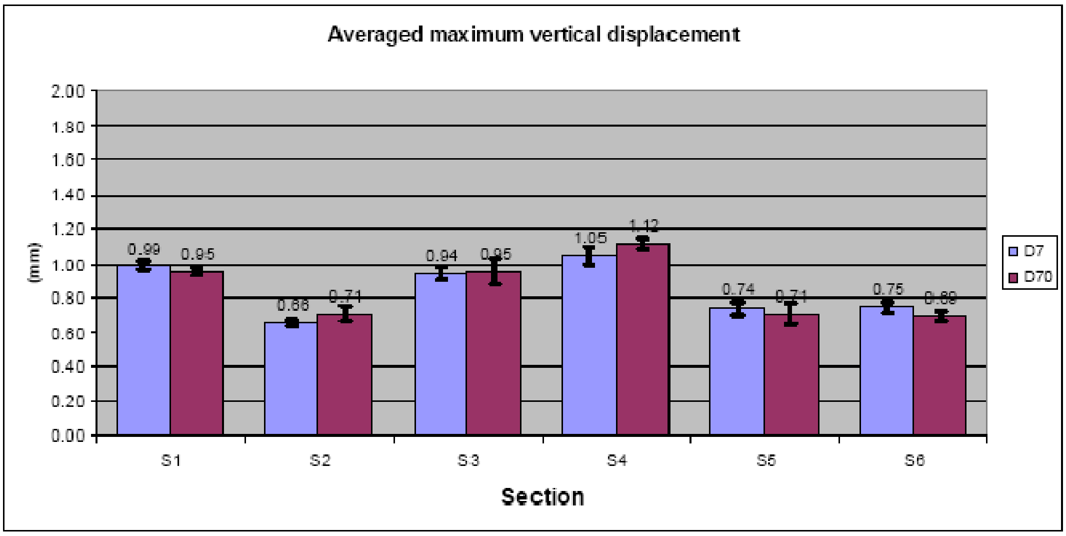

Figure 4: *Vertical rail displacement (mm) measured at D7 and D70*

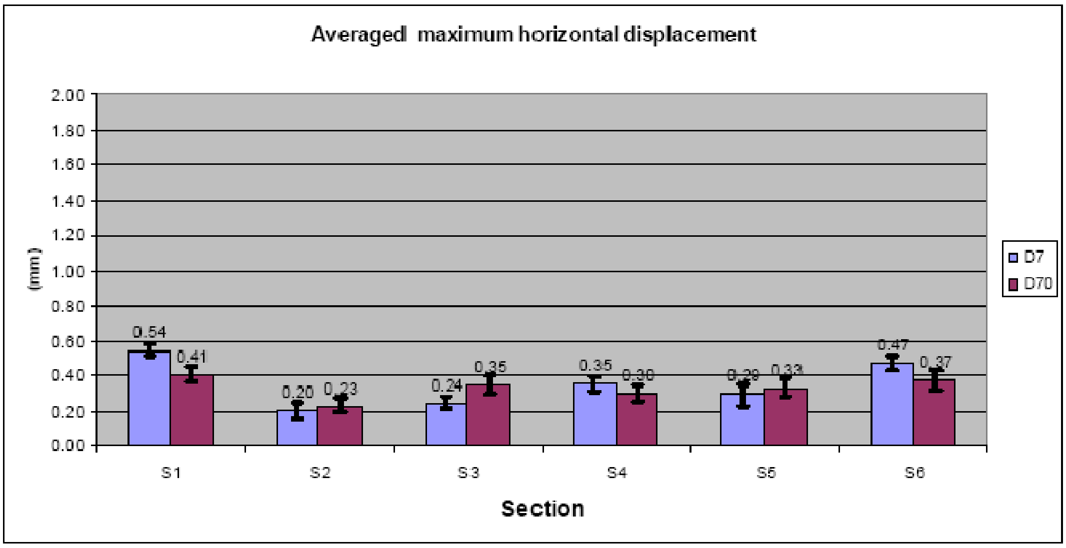

Figure 5: *Horizontal rail displacement (mm) measured at D7 and D70*

The third parameter was measurement of track receptance . Point mobilities on the rail, slab track and tunnel invert are determined by exciting them by an artificial impulse generated by hammer, instrumented with a load cell. In the same way, transfer mobilities from rail to slab track and from rail to tunnel invert have been determined. The following figures show some of the obtained results.

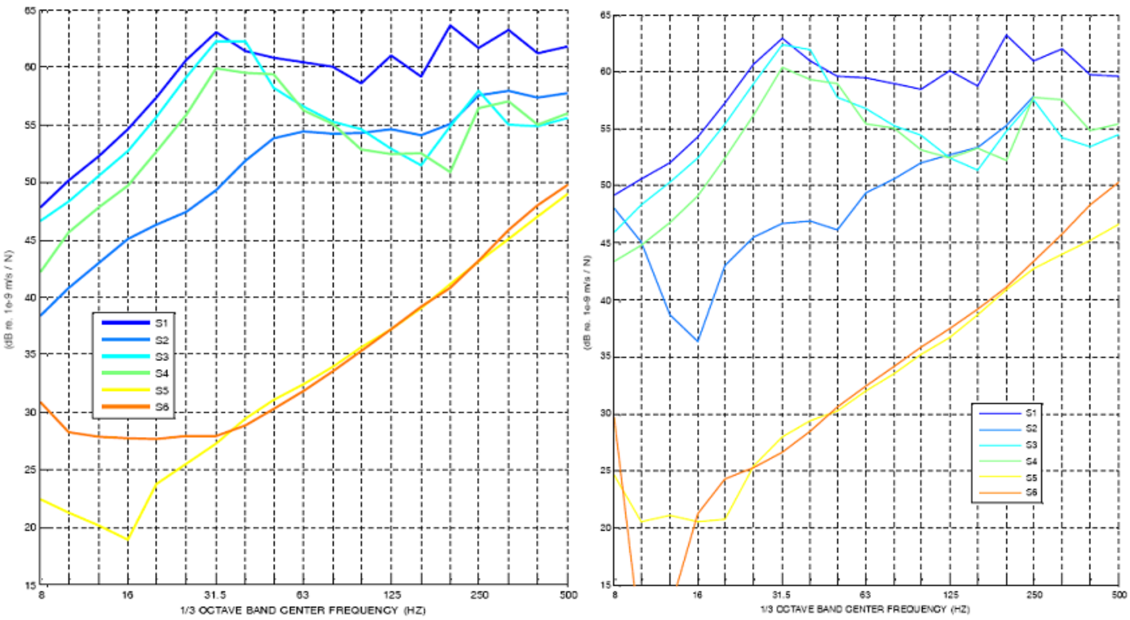

Figure 6: *Slab track point mobility at D7 (left) and D70 (right)*

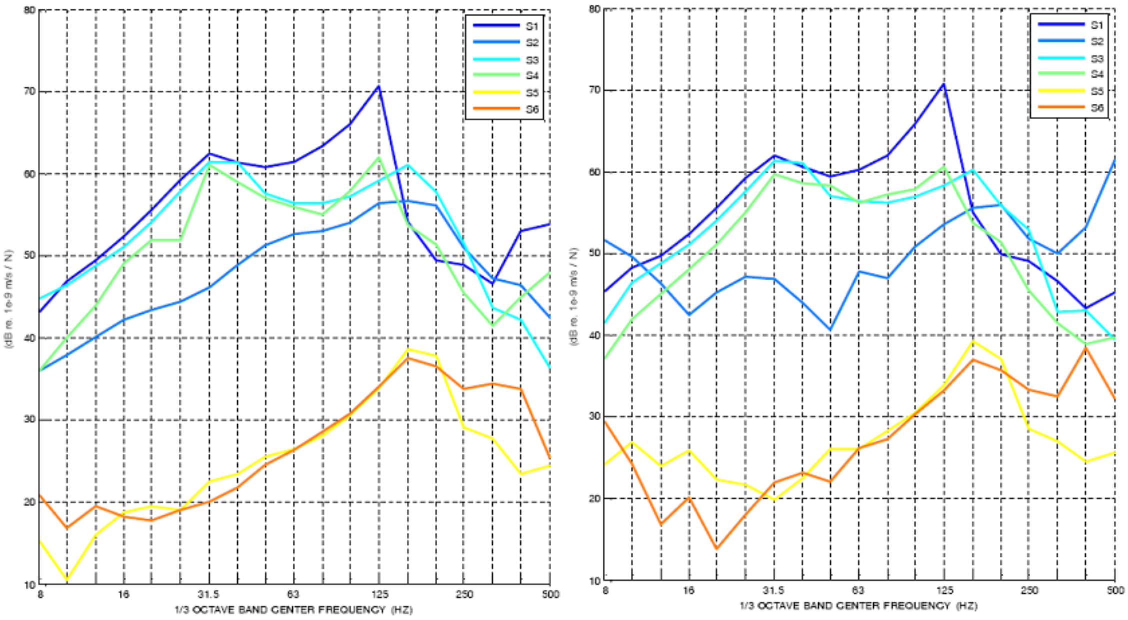

Figure 7: *Rail to slab track transfer mobility at D7 (left) and D70 (right)*

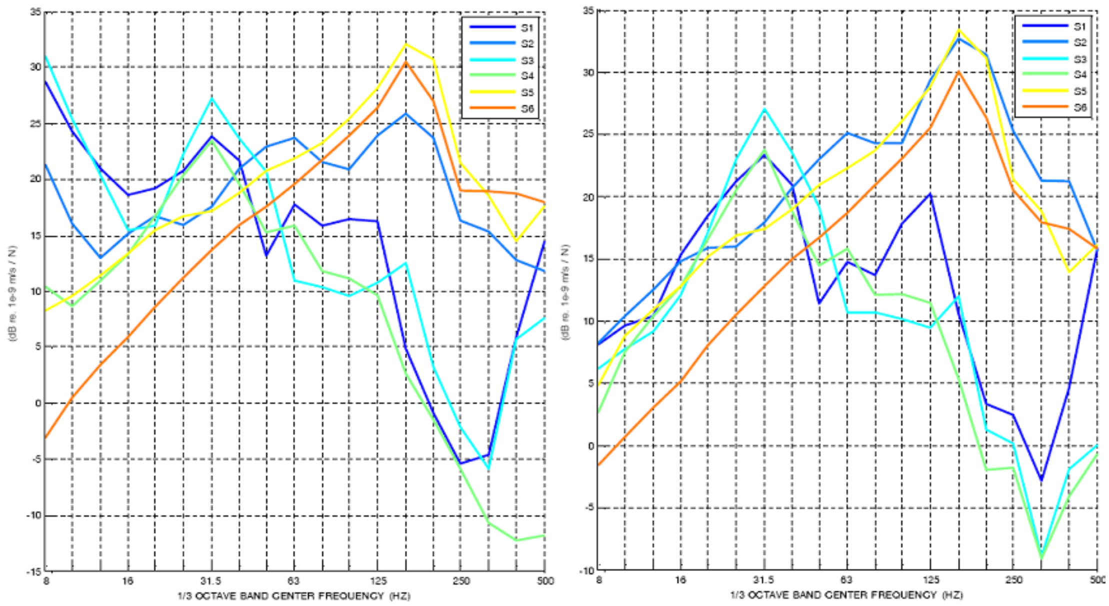

Figure 8: *Rail to tunnel invert transfer mobility at D7 (left) and D70 (right)*

From the above figures one can clearly see the difference between the sections with and without floating slab track. These measurements also point out that the floating slab track in section 2 is performing less well than the other floating slab sections. Visual control of this specific zone after the measurement program indicated the existence of some acoustic bridges between floating slab track to the lateral tunnel wall (being possibly the reason for the lower performance of the floating slab track in this specific area). The FST on resilient mats has a clear positive effect on vibrations at higher frequencies f>40 Hz or wavelengths < 62.5 cm at 90 kph, i.e. the rail roughness spectra that mostly are present in this type of traffic. For that reasons FST offers in any case a clear security that in case rail roughness gets worse, it will isolate vibrations.

Rail roughness measurements have been performed using the ATP-RSA[5] according to the ISO 3095:2005 standard, resulting in a slightly smoother rail surface at 70 days after installation, due to the polishing effect of the passing wheels. It will be interesting to monitor the rail roughness spectrum in time, to evaluate the effect of a continuous rail support on the corrugation growth. Figure 9 shows a typical example of such rail roughness measurements.

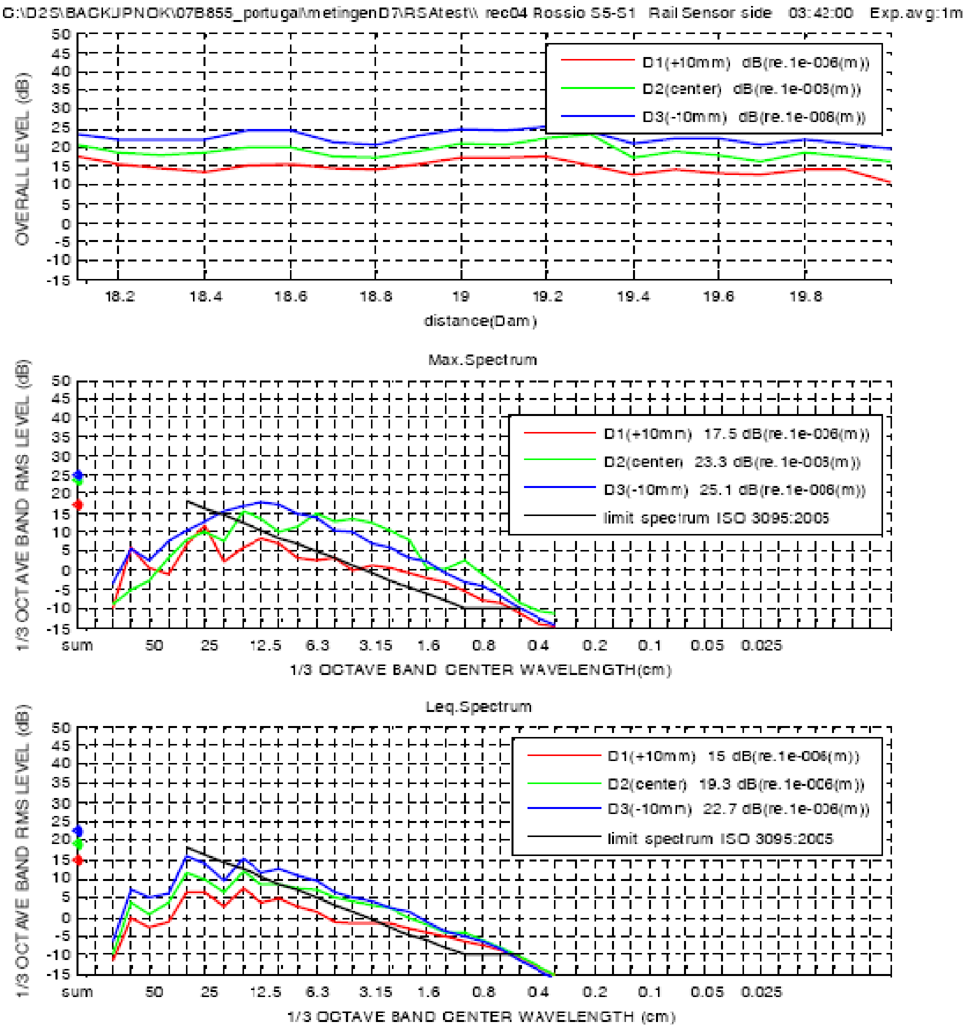

Figure 9: *Typical rail roughness measurement spectrum*

In three neighbouring dwellings above the tunnel, noise & vibration levels have been measured before the start of the operation of the train and then 7 and 70 days after the start of operation. These measurements were performed during the night between 23h00 and 01h00. Table 2 shows the obtained L_{Aeq} noise levels. No significant differences in noise level have been noted after taking the train line in operation, compared to the reference measurements.

Table 2: *Measured L_{Aeq} levels in 3 houses above the Rossio tunnel*

Test Site	Obtained Results L_{Aeq} [dB(A)]		
	Reference Measurements	Measurements after 7 days	Measurements after 70 days
Largo da Oliveirinha, n° 4	34.9	36.9	38.6
Ruas das Taipas, n° 22	39.8	40.7	39.7
Ruas des Taipas, n° 32	43.0	45.7	47.6

Table 3 shows the vibration levels (in x, y and z-direction), which have been measured in the dwellings. Again no significant differences compared to the reference case have been noted after taking the train line in operation.

Table 3: *Measured vibration levels in 3 houses above the Rossio tunnel*

Test Site	Direction	Obtained Results V_{eff} [$\mu m.s^{-1}$]		
		Reference Measurements	Measurements after 7 days	Measurements after 70 days
Largo da Oliveirinha, n° 4	XX	3.65	3.65	4.03
	YY	3.67	3.75	3.72
	ZZ	2.36	3.85	3.79
Ruas das Taipas, n° 22	XX	4.11	4.33	4.23
	YY	4.73	4.11	4.18
	ZZ	4.23	5.07	5.73
Ruas des Taipas, n° 32	XX	4.35	4.74	4.34
	YY	5.17	4.36	4.23
	ZZ	4.23	4.61	5.17

Both the noise and vibration spectra show a lot of irregularities caused by the car traffic on the non-asphalted roads; which made the effect from the circulation of the trains on the noise and vibration levels almost unnoticeable.

From these results, it can be concluded that the train traffic in the renewed Rossio tunnel has no impact on the noise and vibration levels in the neighbouring dwellings. Apparently, this has also been confirmed by the fact that the number of complaints from local residents has decreased significantly since the finalisation of the track works.

5. CONCLUSIONS

Installation of CSFER technology in the Rossio tunnel has again proven its benefits, this time for a major main line application. The straightforward top-down installation method allows high speed installation. Other advantages, particularly interesting for this project, are: a) the creation of a multi-modal platform in the tunnel, providing accessibility for emergency or maintenance vehicles and b) the tuneability of the track support stiffness, by changing the rail strip or in combination with a floating slab to reduce the transmitted noise and vibration levels in the more sensitive areas.
The measurement campaigns have confirmed the efficiency of the taken mitigation measures such as the floating slab track. Besides a slight decrease in rail roughness level,

no significant differences have been noted between the obtained results at 7 days and 70 days after this track began operating.

This solution, which provides benefits both during and after construction, and in addition reduces transmitted noise and vibration to acceptable levels is surely positioned to provide a decent standard for future tunnel projects.

ACKNOWLEDGMENTS

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REFERENCES

1. L. Ribeiro e Sousa, J.V. Lemos, A. Sousa, F. Pinto, “Repair works and tests at the Rossio tunnel, Portugal”, ISRM 2003 – Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy, 2003.
2. Engenharia de Acustica e ambiente, “Tunel do Rossio, Monitorização na Componente Acústica e Vibrações”, Proc° 212/V/05, Relarorio Tecnico RT02-T03-v00, July 2008
3. D2S International, “Lisbon Metro, Tunel do Rossio, Evaluation of vibration, rail displacement and rail roughness levels over time (7, 70 and 700 days after installation)”, Measurement report B855/R01, June 2008.
4. Vincent Brasseur, Roger Kelly, Thomas Lorent, “Lateral stability fastener-less continuously embedded rail system CDM-Prefarail-GSF-60R2”, Internal report, January 2009
5. Tom Vanhonacker, “Accurate quantification and follow up of rail corrugation on several rail transit networks”, proceedings of Railway Engineering Conference, London, 2007.