

Study on Vibrations Produced by New City Rail of Cagliari

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Abstract. The vibrational impact of a city rail is a complex phenomenon, and an effective numerical prediction model has not been developed yet to describe the problem in a complete way. Vibrations induced by rail-way traffic depend significantly on mechanical characteristics of layers of soil underlying the track and type and conditions of rail superstructure. Finite Element Method (FEM) represent an interesting approach which can help to understand behavior and propagation of waves produced by vibration. This method gives trusted results; however, it must be calibrated correctly.

So, this paper presents a study aimed at estimating the forcing produced by light rail trains and the influence of the sediment soil in order to calibrate the FE model. The forcing was obtained by means of accelerometers that recorded accelerations on an active line.

Keywords: Sustainability · Vibration analysis · Finite Element Method · Forcing · Soil stratigraphy

1 Introduction

According to the UN World Urbanization Prospects 2018 dossier [1], today about 55% of the world population lives in urban areas. This percentage will reach 68% by 2050. The consequence of this phenomenon is that cities are, and will be even more in the future, centers of transport systems whose negative effects, such as congestion, air/noise pollution and road accidents are destined to grow.

The European Commission strongly recommends that European towns and cities of all sizes should adopt Sustainable Urban Mobility Plans (SUMPs) and developed guidelines in order to reduce externalities associated with transport sector [1]. Torrisi et al. [2] analyze these guidelines and the corresponding Italian one for the preparation of so-called "Piani Urbani della Mobilità Sostenibile" (PUMS) in order to provide essential elements for the critical assessment of best practices and the review of related SUMP.

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Today, the concept of sustainability is part of the broader concept of smart city and it is closely related to the concept of quality of life. Garau and Pavan [3] individuate a list of indicators to quantify the quality of life in Cagliari city. The indicators are grouped in sixth categories, one of them is "Use and Fruition", to this set is associated the quality and presence of services, accessibility, infrastructures, and mobility. So, public transport services play an important role in the sustainability of cities.

Quality of these services represents a fundamental aspect so that they can be perceived by citizens as a valid and functional tool for accessing the different areas of a city and for promoting a sustainable mobility. Passengers' viewpoint is a key tool in the monitoring of public transport quality. There are a lot of attributes to be measured (on-board and external), Barabino et al. [4] present criteria for the selection of attributes and the techniques of data collection based on the innovative concept of quality cycle. Another study focuses on the implementation of an Impact Score methodology which assesses the degree of perceived quality [5]. Perceived quality and expected quality by elderly users have been analyzed to highlight which are the most important attributes of a public transport service for over 65 years old passengers. Elderly represents that share of passengers who could benefit more from an efficient public transport system that meets their expectations [6]. Barabino develops an existing framework to automatically identify low quality vehicles and stops to help public transport managers to build systematically accurate monitoring plans and to increase passengers' satisfaction with the service [7]. Quality of travel experience can be also monitored by accelerations data detected on buses of a public transport system and related to the judgment of passengers [8, 9].

Accessibility is usually identified by people with the availability of an efficient transportation system because it provides the opportunity to access to several urban services to all categories of users [10]. It is no coincidence that general objective of UN's 2030 Agenda underlines the need to make cities smart [11], sustainable [12], inclusive and accessible by means, for instance, a suitable public transport system for all.

Numerous studies conducted in different cities have shown that accessibility can be improved by creating sustainable transport alternatives such as smart bike sharing systems, electric car sharing, public transport, and cycling mobility. This "Smart mobility" has several advantages including the reduction of city traffic congestion and therefore air/noise pollution, and the improvement of traffic safety [13]. An example of transition toward a smart, sustainable and green mobility is reported by Coni et al. [14]. From 2011, a new strategic plan was adopted by Cagliari city in cooperation with all its 17 municipalities which gradually led to sustainable and smart mobility. This plan provided using of Intelligent Transportation Systems (ITSs)'s technologies, improving routes and fleet buses, forbidding traffic cars in the historical center and promoting places and pedestrian areas, developing a network of cycle paths, supporting the use of car-sharing, car-pooling, bike sharing, electric mobility and completing and integrating tramway net-work. These actions have changed citizens' lifestyle: they started walking, running, cycling, using the public transport service, so discovering a different way to experience their city.

As far as a public transport system is a fundamental aspect in the context of smart mobility and therefore in a smart city, however, often, the construction of new lines for public transport meet difficulties to be accepted by citizens due to the negative environmental effects produced by the passage of the convoys. In urban areas, the impacts generated by the passage of convoys, whether they belong to subway lines or terminal sections of railway lines, are closely linked to four distinct aspects: noise, vibrations, visual impact and the fracture of the territory urbanized. Situations of conflict can occur with the residents of the areas adjacent to the routes and disputes with local authorities accompany the entry into operation of the lines.

Therefore, in order to prove if this kind of public work is effectively sustainable from every point of view, it is necessary to verify a priori if its presence leads to a reduction of quality of life of those who live nearby; and, if it occurs, providing systems to contain its impacts to guarantee a good quality of life for all citizens including those who live or work near the line.

A lot of studies present interesting contributes on noise/visual impact and the fracture of the territory urbanized produced by a city rail conversely the issue of vibrations has not been particularly explored.

Çaty et al. and Mottahed J. et al. [15, 16] tackle the problem of track degradation on transition zone from ordinary ballasted track to railway bridges due to sudden stiffness changes and ballast vibrations. They both propose solutions with the use of Under sleeper pads (USP) and find that they provide an important decrease in ballast acceleration.

Other Authors focus the attention on the vibration effects in adjacent buildings. Mertens et al. [17] propose numerical studies to find the critical points of building design as well as the optimization process of the building structure to limit discomfort to residents on higher floors due to passing trains on a nearby tracks. Coulier et al. [18] investigate the effect of neglecting source-receiver interaction in wave propagation in the soil on the accuracy of numerical predictions. They employ a coupled finite element boundary element methodology, and they demonstrate that the dynamic axle loads can be calculated with reasonable accuracy.

Slab tracks are often used to reduce train induced vibrations. Kece, et al. [19] analyse the behavior of typical concrete slab tracks using a 2D Finite Element Model. They compare concrete slab track with a typical ballasted track and find that slab track more effectively reduces train-induced vibrations and track level displacements. Zhu et al. [20] developed a new vibration attenuation track (VAT) to mitigate vibrations at low frequencies based on an integrated theoretical and experimental study. They build a full-scale VAT which incorporates a floating slab track (FST) and the attached dynamic vibration absorbers (DVAs) with key parameters determined by the fixed-point theory and modal analysis technique. Computational and experimental results both demonstrate that the attached DVAs adsorb vibrations and significantly reduce subgrade vibrations in low-frequency range.

Coni et al. [21] study acoustical and vibrational impact of the city rail of Cagliari by FE Method and analyzed different vertical alignment solution to reduce or restrict it.

All research presented above use numerical models to simulate and study the vibrations produced by trains, so Finite Element Method (FEM) represent an interesting approach which can help to understand behavior and propagation of waves produced by vibration. However, it must be calibrated correctly to give trusted results. This aspect is often overlooked in the literature.

This paper covers this gap and presents a study aimed at estimating the forcing produced by light rail trains and the influence of the sediment soil in order to calibrate the FE model. The forcing was obtained by means of accelerometers that recorded accelerations on an active line. The stratigraphy of the soil has been reconstructed by means of surveys which have allowed a precise evaluation of the mechanical characteristics of the soil. The calibration of the FE model was carried out through a series of iterations, combining the mechanical characteristics of the soil and further accelerometric measurements taken in correspondence with the road area that will accommodate the future metro line.

The remaining paper is organized as follows. Section 2 describes the second section of the light metro of Cagliari. Section 3 presents the methodology adopted to calibrate FE model and, finally, Sect. 4 draws conclusions and research perspectives.

2 The Second Section of the Light Metro of Cagliari (Italy)

The second section of the light metro line of Cagliari (Italy) will develop for about two and a half kilometers and will connect Piazza Matteotti to Piazza Repubblica. Its alignment will be completely at grade with double tracks and will cross a highly urbanized area (see Fig. 1). Horizontal alignment will follow existing city street: Roma and Bonaria streets, then it will turn with a curve and keep on Cimitero avenue and Dante street.

Seven stops are planned, including that called Repubblica which already exists:

1. Station stop/terminus;
2. City Hall stop (point km 0 + 414);
3. Darsena stop (point km 0 + 698);
4. Lussu stop (point km 1 + 076);
5. Bonaria stop (point km 1 + 429);
6. San Saturnino stop (point km 2 + 068);
7. Repubblica stop (point km 2 + 530)



Fig. 1. Second section of the light metro of Cagliari (Italy) and its stops

3 Methodology

Design, construction and entry into operation of light metro lines requires a quantification of the negative effects due to the transit of convoys. The wheel-rail contact causes a dynamic stress on the railway structure which generates the oscillatory phenomenon of the vibrations that propagate in the adjacent ground. Therefore, the acceleration spectrum will be influenced by numerous factors such as the railway superstructure, the tracks and the mechanical characteristics of the soil crossed. In addition, small imperfections in the wheel and rail surfaces cause sudden changes of contact forces, which in turn cause the rail to vibrate. Vibrations propagate mainly vertically, but the interaction with the ground and buildings allows the development of significant movement components also horizontally.

The main difficulty is that vibrations evaluation must be analyzed ante operam, so it is necessary to estimate the forcing produced by light rail trains and soil characteristics. In Fig. 2, a simple framework for calibrating FE Model is presented. The study starts measuring accelerations produced by train on the active line Repubblica Square – Gottardo. Also, accelerations produced by buses that pass today in correspondence with the road part that will host the future rail area were collected. On this area, surveys and deflectometric tests were carried out for the geotechnical characterization of the soil. With these inputs, the finite element analysis was conducted with a series of iterations aimed, firstly, at calibrating the FE model and, secondly, at returning the distribution of vibrations consistent with that obtained by accelerometric measurements.

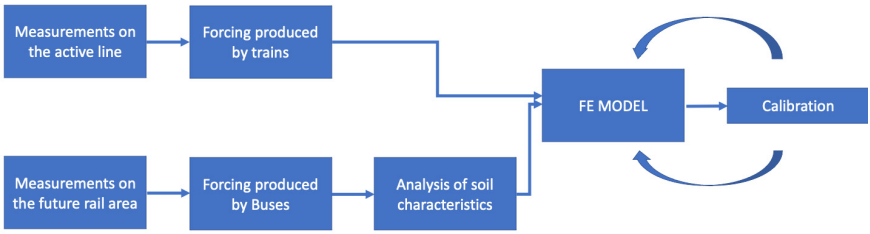

Fig. 2. Proposed framework for calibrating FE model

3.1 Measurements on the Active Line

Components x, y and z of accelerations produced by trains were collected along the active line Repubblica square-Gottardo; the accelerometer was placed between Cincinnato street and Attilio Regolo street, at a distance of 3.30 m from the rail. On visual analysis, rails appeared even and clean. Four passages were evaluated, two towards the Gotthard and two towards Repubblica. Component z assumed the highest values. In Fig. 3, the measurements relating to this axis are shown.

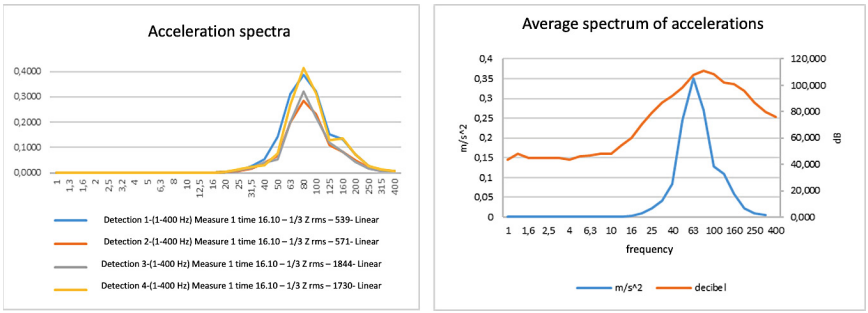

Fig. 3. Results of the surveys carried out on the Gottardo Repubblica line

Figure 3 shows that the phenomenon is dominated by the distance from the source, reducing exponentially with it and how different events have a similar response if evaluated to the same distance. For the above reason, the average spectrum is considered to reconstruct the forcing and calibrate FE models.

3.2 Measurements on the Future Rail Area

Measurements in Cimitero avenue were necessary to analyse the influence of the characteristics of the ground and how the vibrational phenomenon is attenuated with distance. In this case, forcings that determine the vibrations are those of the CTM and ARST buses that pass today in the road part that will host the future city rail.

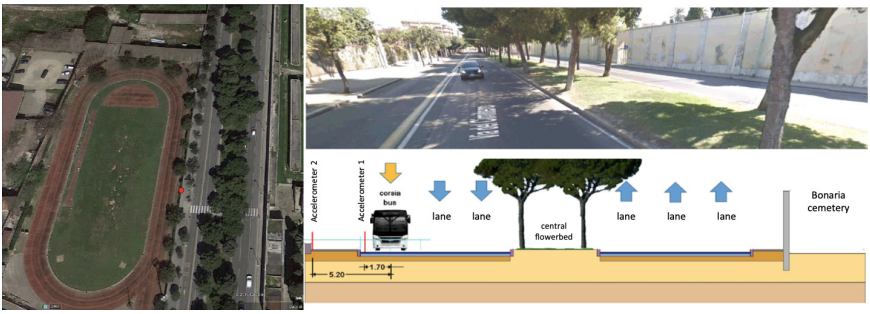

Fig. 4. Seat area of the new metro stage and measuring point in Cimitero avenue

The accelerometer was positioned on the RAI field side, first at a distance of 1.70 m from the center of the bus lane, then at a distance of 5.1 m (see Fig. 4).

The most significant vibrations were those relating to the ARST buses, at the Z axis.

Four passes were recorded from the accelerometer at 1.70 m, and five from the one at 5.1 m.

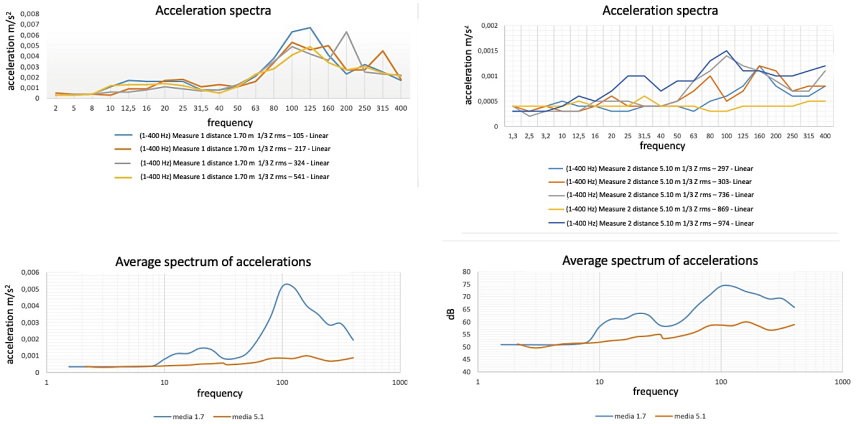

Fig. 5. Accelerations due to ARST buses

Figure 5 shows that the phenomenon is dominated by the distance from the source reducing exponentially with it and how different events have a similar response if evaluated at the same distance.

Also in this case, the average spectrum is considered for the reconstruction of forcings and the calibration of the FE models.

3.3 Stratigraphy of the Ground

The vibrations induced by railway traffic are a complex phenomenon and an effective general forecasting model, capable of describing this problem in a complete way, has not yet been developed.

Finite element calculation gives reliable results if FE models reproduce the different types of soils and materials and their mechanical characteristics. These are variable along the alignment, this affects the propagation of vibrations: rigid soils are linked to low damping values while low-stiff soils are highly damping and a lower transmissibility is connected to them.

A surveys campaign was carried out which provided stratigraphy of the ground for 10–20 m. Following parameters were collected for each layer:

- elastic modulus, longitudinal and transversal;
- poisson's ratio;
- internal friction angle;
- shear strength;
- cohesion.

Using these data, the stratigraphy shown in Fig. 6 was reconstructed:

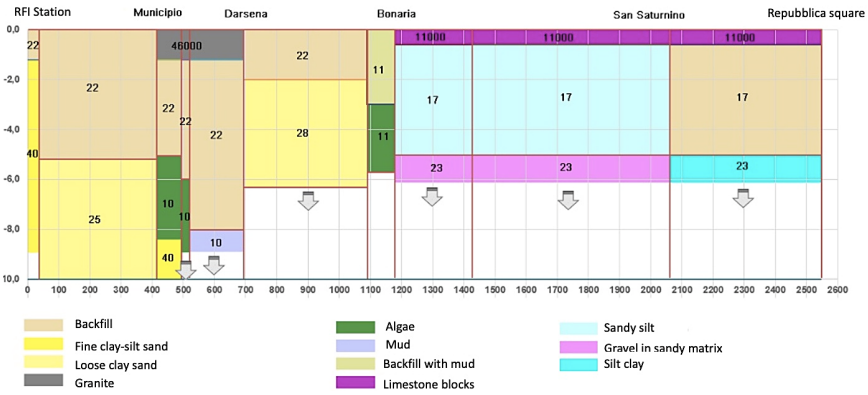

Fig. 6. Schematic representation of stratigraphy of the ground along the line Matteotti square – Repubblica square

It can be seen how the deep layers are made up of low-rigid and highly damping soils, while there are 2 sections, between the Municipio-Darsena and Bonaria-Repubblica

stops, which have high stiffness values due respectively to the granite block paving and concrete slabs.

The geotechnical parameters reported refer to the value on a point scale, in particular the stiffness is assessed without taking into account the fracturing and segmentation of the granite paving that makes up the road pavement.

It was therefore necessary to reduce these values, this can be done arbitrarily or through deflectometric measurements.

For a correct evaluation, the second option was chosen, carrying out deflectometric measurements conducted with the Falling Weight Deflectometer (FWD) on the stone pavement of Roma street.

The FWD test is a non-destructive investigation method used to measure the structural properties of a pavement in situ. The test consists in measuring the vertical deflection of the pavement induced by an impulsive load generated by the fall of a mass on a plate placed on the surface layer of the superstructure. The applied load is measured through a load cell positioned at the circular plate. The deformations induced by the load are measured by means of a series of geophones positioned along different points lying on a horizontal alignment, so as to be able to identify the deflection basin produced at the moment of impact of the mass. The deflection values are subsequently obtained by integrating the acceleration signal recorded by each individual geophone with an accuracy of 0.5 ± 1 μm.

Coni et al. [22] propose an experimental approach to assess the vibration damping using the FWD. The instrumentation, well known in road pavement analysis, can reproduce the force impulse of train wheel and collect the oscillation value along 2.10 m (Fig. 7).

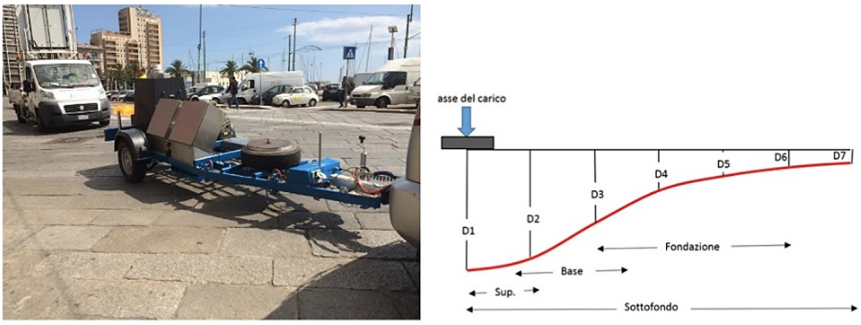

Fig. 7. The Falling Weight Deflectometer and the representation of the deflection basin

Data related to the measurements of the deflection basin and the measurement of the applied peak load are processed with the "backcalculation" system [23–25] to evaluate the stiffness modules of the individual layers of road pavement.

The module of granite paving found was much lower than that extracted from the geotechnical report.

Therefore, a new schematic stratigraphy was developed, as shown in the following image (see Fig. 8) to use in FE modeling.

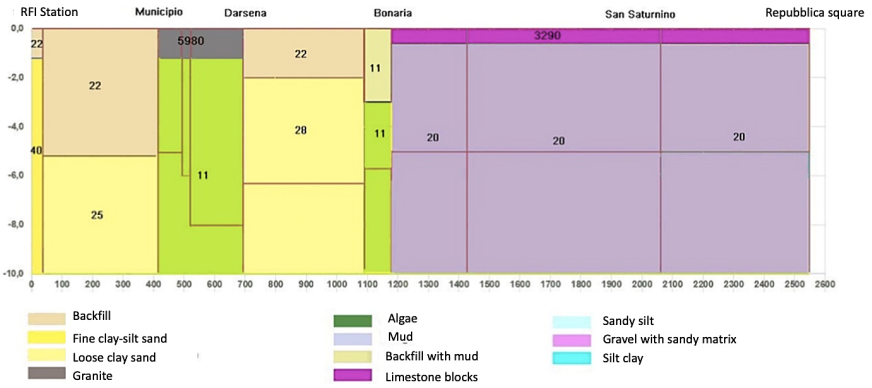

Fig. 8. Schematic stratigraphy used in Fe modeling

The schematization carried out led to the identification of 6 models:

- MODEL 1 from point 0.00 m to 36.50 m;
- MODEL 2 from point 36.50 m to 415.50 m;
- MODEL 3 from point 415.50 m to 693.50 m;
- MODEL 4 from point 693.50 m to 1088.50 m;
- MODEL 5 from point 1088.50 m to 1431.00 m;

for each of them a finite element model was created and processed with the Ansys software.

3.4 Finite Element Method

A two-dimensional model of the terrain was built with a dimension of 37.37 m × 10.0 m. The superstructure, the railway equipment, the base concrete plate and the reinforcement were modeled in detail by thickening the subdivision of the mesh in the vicinity of the forcing, constraints and geometric angularities (See Fig. 9).

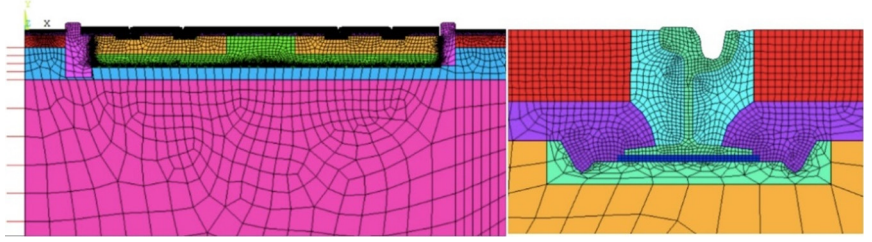

Fig. 9. Details of Model 6

Further FE modeling was carried out on the current situation of Cimitero avenue, and in a section of the Repubblica-Gottardo line for the estimation of forcings.

3.5 Model Calibrating

The calibration process is an iterative process, which consists in comparing the results obtained by the FEM with the real measurements.

In Cimitero avenue the measurements were taken at 1.70 m and 5.10 m from the bus axis, since the accelerometer cannot be positioned at the point of application of the load (under the bus wheel), a transfer function was used that it allows to reconstruct the forcing that causes the vibrations detected at a certain distance with the accelerometers.

An initial FE model was built, using stiffness values found with the geotechnical tests and the FWD tests. As a first approximation damping values from the literature were used. By applying a unitary forcing to the FE model at the points where the bus passes, the transfer function for each transverse abscissa is obtained as a response.

The forcing can be obtained by dividing the measured values by the transfer function and making a comparison.

At this point, the forcing was applied to the FE model and it was evaluated if there was a good correspondence between the average spectra and what was simulated. Otherwise, the damping values of the different materials are varied and the procedure is reapplied until a good result was found.

The result obtained after several iterations is the following (Fig. 10):

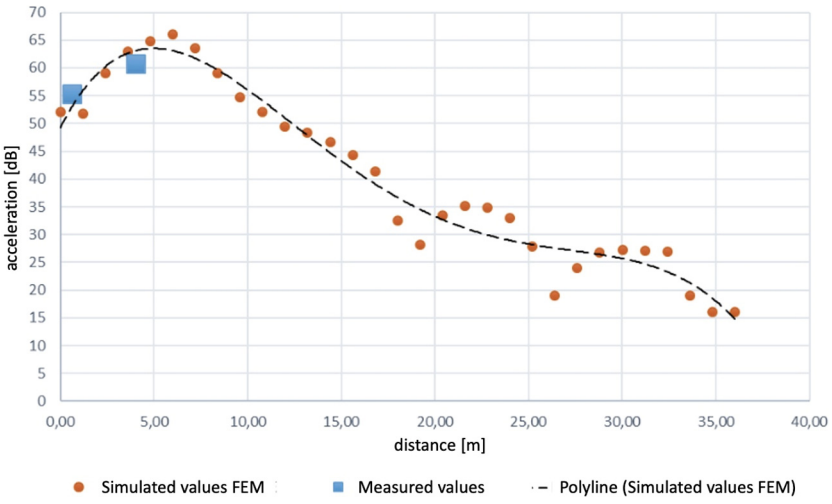

Fig. 10. Results of model 6 calibration.

The good correspondence between the measurements and what was simulated show effectiveness of the calibration method.

3.6 FE Simulation Results

The evaluation of the post-operam vibrational state was iterated for each different stratigraphic profile along the track, for each frequency component between 1 and 315 Hz,

evaluating the vibrational levels in terms of accelerations. The load conditions were represented by simultaneous presence of 4 forcing at the 2 tracks, corresponding to the real forcing due to the passage of the light rail and obtained through measurements on the current line.

The following graph (see Fig. 11) shows the transverse distribution of the acceleration levels of each model, each of these lines represents a logarithmic sum of the levels relating to frequencies from 1 to 315 Hz in third-octave bands.

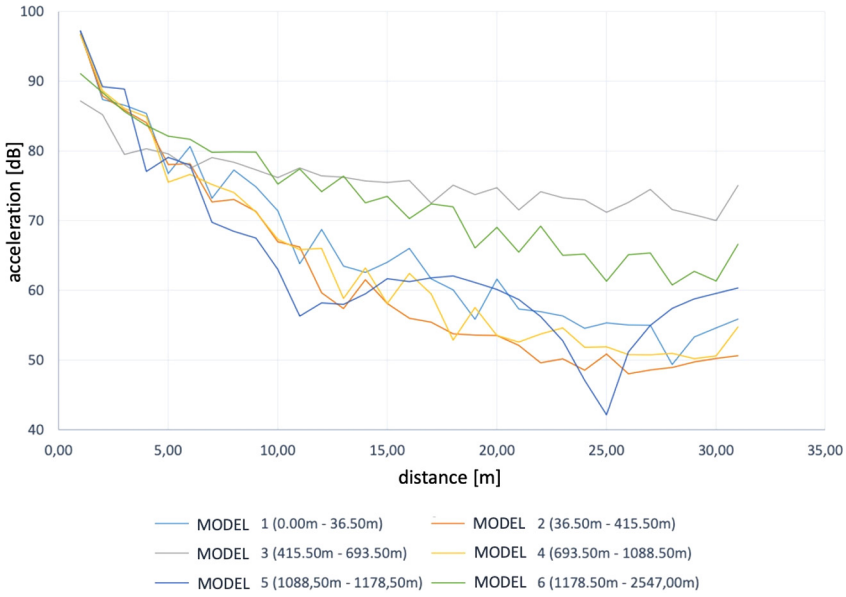

Fig. 11. Transverse distribution of the acceleration levels of each model

It can be seen how model 3 and model 6 have the highest acceleration values, this is linked to the presence of rigid stone paving in Roma street and concrete slab pavement in Dante Street a few meters from the line.

3.7 Mitigation Interventions

Three possible mitigation interventions were considered:

- insertion of anti-vibration mats;
- insertion of an inertial element;
- construction of a trench;

and they were applied to model 6 because the acceleration levels were greater than the limits set by Standard.

The presence of these mats is foreseen under the slab between the bedding mortar and the surface layer of the ground, furthermore they must be interposed in interference

with manifolds and ducts and in any situation in which rigid elements are interfered under the armament and its support.

From the comparison between the results obtained with those of the model without mats, in a first approximation, there were not significant variations in acceleration levels. A more accurate analysis showed that the anti-vibration mats offer greater benefits for higher frequencies.

The second mitigation intervention concerned the insertion of an inertial element, extremely rigid with the aim of reflecting the waves towards the source.

A 15 cm wide concrete element was introduced and the effects evaluated modifying its depth and distance from the source.

But also in this case, the FEM analysis showed that the use of inertial elements does not have great effects on the reduction of the acceleration levels. A slightly better result was obtained by using an inertial element 4 m from the rail with a depth of 1.45 m with greater effects at low frequencies, but not significant. It is due to the presence of concrete slabs on the surface layer which prevent the formation of this discontinuity in terms of stiffness.

The third mitigation intervention consisted in the creation of an empty and extremely damping element. The construction of a 15 cm wide trench was simulated, and the effects were evaluated modifying depth and distance from the source.

Analyses were carried out for a distance of 4 m and 8.5 m from the external rail, and at the depths of 0.9 m and 1.5 m from the ground level.

With this solution, there is a clear reduction in acceleration levels. The benefit is greater at low frequencies and increases as the depth of the trench increases and with proximity to the source (see Fig. 12).

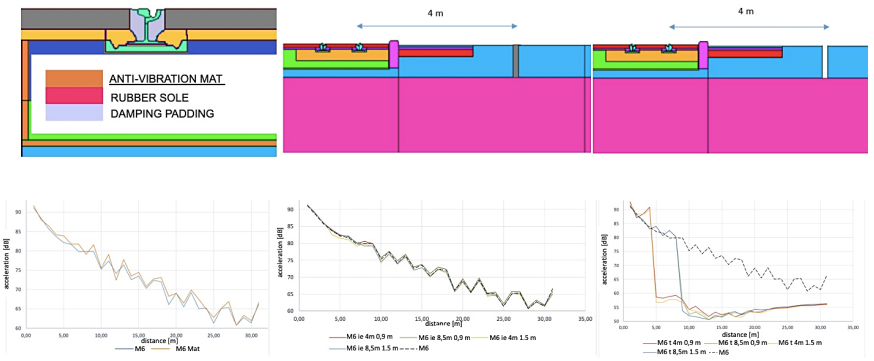

Fig. 12. Mitigation interventions and results

4 Conclusion

This paper presents a methodology aimed at estimating the forcing produced by light rail trains and the influence of the sediment soil in order to calibrate the FE model. The study overcomes the problem of the lack of a numerical model that can consider

all the factors that influence phenomenon as the characteristics of the materials and the tramway superstructure, rail, railway equipment, and the inhomogeneity of soil. From FE analysis it was found that the behavior of vibrations is strongly influenced by the dissipative capacities of the surface layer, in which the Rayleigh waves are concentrated, but also by the damping capacities of the other layers, found starting from literature values and then modified during calibration.

Model 3 and 6 showed higher acceleration values due to the high stiffness of their surface layer, due respectively to the granite paving and the concrete slabs. Model 6 needed mitigation measures because accelerations values exceed the regulatory limits. The authors proposed three solutions: anti-vibration mats, inertial elements and trenches.

Trench is a more effective intervention with a much greater effect than the inertial element, which begins to have significant benefits with a thickness of 40–50 cm, thus increasing costs. The trench is the intervention that guarantees better attenuation, but it limits are surrounding conditions.

The anti-vibration mat has a greater effect at high frequencies which rises increasing thickness.

Future investigations comprise the monitoring of some trial sections on the Light Metro of Cagliari, where different anti-vibration materials will be employed. Their outcomes will be monitored through FWD and sensors embedded in the subgrade. Works are starting in June 2021 and will finish in 2024.

Author Contributions. Conceptualization, all; methodology and formal analysis, Mauro Coni and Riccardo Murgia; introduction and literary review Francesca Maltinti and Mauro Coni; writing-original draft preparation, Francesca Maltinti; writing-review and editing Francesca Maltinti, Mauro Coni and Nicoletta Rassu; visualization, all. All authors have read and agreed to the published version of the manuscript.

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