TRAFFIC VIBRATION DAMPING: THE INFLUENCE OF PAVEMENT MATERIALS CONSTITUTIVE MODELS

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ABSTRACT

Traffic-induced vibrations are a common source of environmental nuisance: they may cause discomfort to people, malfunction of sensitive equipment and damage to buildings. Interaction between vehicle wheels and road surface causes a dynamic excitation which generates waves that propagate in the soil and break up on the foundations of nearby structures.

The study of traffic-induced wave's propagation is very complex due to the number of variables involved and to the complexity of their relationships. Computer simulation is a possibility of a low cost "trial and error" approach; in this context it becomes a good answer to the question.

Many wave propagation problems can be solved using the widespread elastic material model, which is based on a linear and path-independent stress-strain law. However pavement materials have a much more complex behaviour, characterized by plasticity and viscosity features. So the search of reliable road pavement material models, easy to be defined and calibrated, becomes very important.

In this paper, by means of a finite differences technique, the authors developed a numerical analysis in order to evaluate the effectiveness of some pavement materials constitutive models in traffic-induced vibrations simulation. Their features have been determined, at the first step, by means of lab tests modelling, comparing numerical results and experimental data, and then by simulating a half-space containing the road pavement and the subgrade.

Keywords: road pavement, traffic vibrations, constitutive model

1. INTRODUCTION

Vibrations induced in buildings are a common concern to many cities around the world. Complaints are usually made by owners of residential homes about annoying vibrations in their structures as a result of heavy vehicles passing on adjacent roads, but they are also a problem regarding theirs long-term effect on historical buildings, especially those in weak conditions (Hunaidi O. & Tremblay M., 1997).

The phenomenon, in particular, is mostly caused by the presence of discrete irregularities on the road surface (e.g. potholes, cracks, uneven manhole covers), which lead to dynamic vehicle-pavement interaction forces that in turn generate stress waves in the supporting soil and eventually reach the foundations of adjacent buildings causing them to vibrate. Many factors affect nuisance levels: road conditions, vehicles weight and speed, soil stratification and properties, construction features.

The problem of traffic-induced vibration has been of concern for a long time: initial studies were reported almost 70 years ago and more recently numerous research works were undertaken around the world (Hunaidi O. & Tremblay M., 1997). They contributed significantly to identifying the nature of the problem and to clarifying its extents and effects. In many of them, vibration prediction methods were developed and remedial measures were also investigated. These include periodic maintenance of road surfaces, traffic flow and vehicles speed control, improvement of road sub-base and subgrade features, screening of vibration using in-ground barriers or building isolation systems. Most of these measures are usually considered not cost effective because of shrinking of municipal budgets. Consequently the problem continues to exist to this day and it is also believed that its complaints will increase in the future because traffic volumes and axle weights of heavy vehicles are enlarging. So the study of techniques for reducing traffic-induced vibrations becomes a primary requirement.

In this way numerical modelling can be very adequate for dealing with this particular problem, because, permitting a realistic description of the load-bearing behaviour of road pavements, can model the effects of many different external factors or structural parameters, which influence the traffic-induced wave's propagation. However, asphaltic materials represent a difficult medium to model because of theirs elastic, viscous and plastic behaviour, dependent from loading rate and temperature (Saad B., Mitri H. & Poorooshasb H., 2005). So the choice of a good numerical technique for simulating this problem is very important.

2. NUMERICAL TECHNIQUES FOR MODELLING TRAFFIC-INDUCED VIBRATIONS

In numerical modelling of traffic-induced vibrations continuous and discontinuous methods can be used (Jing L., 2003). The first require the division of the problem domain into a collection of elements of standard shapes (triangle, quadrilateral, tetrahedral, etc...) and imply that at all points in the system the materials cannot be broken into pieces. All points originally in the neighbourhood of a certain area remain in the same zone throughout the deformation process. These sub-domains must satisfy the governing differential equations of the problem and the continuity condition at their interfaces with adjacent elements. A discontinuous model, instead, is composed of distinct elements that displace independently from one another and interact only at contact points. The system behaviour is found by tracing the movements of the individual components. The Finite Element Method (FEM), the Boundary Element Method (BEM) and the Finite Difference Method (FDM) belong to the first group; the Distinct Elements Method (DEM) feels right into the second.

The Finite Element Method (FEM) is perhaps the most widely applied numerical method in engineering today, because of its flexibility in handling material heterogeneity and anisotropy, complex boundary conditions and dynamic problems. The principal FEM disadvantage remains the poor ability to represent the stress-strain behaviour of a system near the breaking point, because, being a continuum method, it doesn't admit the separation between adjacent elements.

The Boundary Element Method (BEM), on the other hand, requires discretization at the boundary of the solution domains only, thus reducing the problem dimensions and simplifying the mesh generation (Jing L., 2003). It enjoys greater accuracy over the FDM and FEM at the same level of discretization and is also a more efficient technique for fracture propagation analysis. However, in general, it is not as efficient as the FEM in simulating material heterogeneity, because it cannot have as many sub-domains as the FEM.

The basic technique in the FDM, instead, is the direct approximation of governing partial differential equations (PDEs) by replacing partial derivatives with differences defined at neighbouring gridpoints (Jing L., 2003). No local trial (or interpolation) functions are employed to approximate the PDEs in the neighbourhoods of the sampling points, as is done in the FEM and BEM. It is therefore more direct and intuitive technique for the solution of the PDEs. This also provides the additional advantage of simulation of complex constitutive material behaviour, such as plasticity and damage, without using global matrix equation systems, as in the FEM or BEM (Jing L., 2003). The conventional FDM with regular grids suffers from poor flexibility in dealing with fractures, complex boundary conditions and material heterogeneity. However, very significant progress has been made in the FDM with irregular meshes, which leads to the so-called Control Volume or Finite Volume technique (FVM) (Jing L., 2003).

The Distinct Element Method (DEM) for modelling a discontinuum, finally, is relatively new with the other approaches. Its essence is to represent the fractured medium as assemblages of blocks and solve the equations of theirs motion through continuous detection and treatment of contacts between them. The definitions of the mesh and of constitutive laws are replaced with description of the contact models and the particles packing (Cundall P. A. & Hart R., 1992). In DEM the initial stress state cannot be specified independently of the initial packing since contact forces arise from the relative positions of particles.

Starting from the comparison of the potentialities of numerical methods described above, in this paper the problem of traffic-induced vibration has been analyzed by FLAC code (ITASCA Consulting Group, 1993), based on the FVM/FDM scheme. Since the objective of this study is to evaluate the effectiveness of some pavement materials constitutive models in reducing traffic-induced vibrations, it was necessary first estimating theirs features. They have been determined by means of lab tests simulation on bituminous specimens, Marshall and creep tests, comparing numerical results and experimental data. In the second step, a half-space, containing road pavement and subgrade, have been modelled.

3. THE EXPERIMENTAL PHASE

3.1 Calibration of pavement materials constitutive models

To accurately calibrate the parameters of the pavement materials constitutive models, two tests have been simulated: a Marshall test and a creep test.

The first, geometrically modelled as specified in C.N.R. B.U. n. 30, consists in a cylindrical specimen of 100 mm diameter, inside two breaking heads (upper and lower) (figure 1). The steel upper breaking apparatus was moved down at a constant speed of 0.00085 m/sec. The specimen features have been defined on the base of a lab mixture of a wearing course asphalt concrete, and, to ensure low friction between sample and breaking heads, an interface was implemented. The test was simulated as the sample was at a temperature of 60°C. The Marshall test was tried on different material constitutive models, including Mohr-Coulomb, Maxwell and Burger, to underline the better response to real data. Their features, in particular, have been chosen in order to obtain predicted stability-flow curves similar to measured data. The results comparison is shown in figure 2 and table 1: all three material constitutive models exhibited behaviour very similar in magnitude and shape to the real one.

Every Marshall stability-flow curves show the same trend: a first elastic segment, in which load and displacement are linear-dependent, and a second one that is visco-plastic in Burger specimen, plastic in Mohr sample and visco-elastic in the Maxwell one.

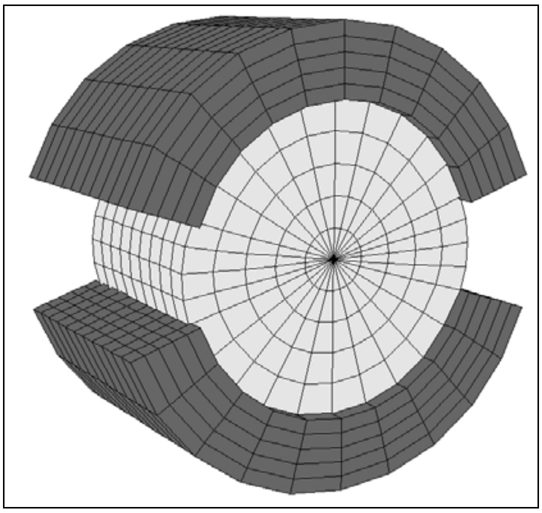

Figure 1: Marshall Test: Numerical Specimen

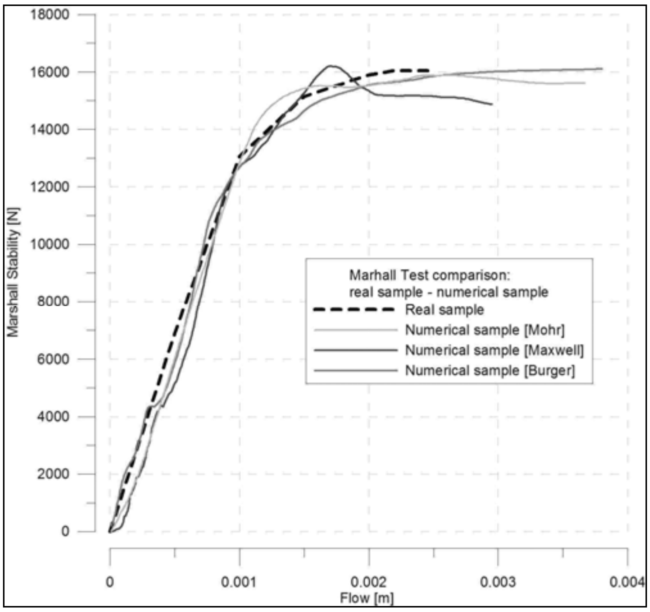

Figure 2: Marshall Test Results Comparison

Table 1: Marshall Test: Comparison Between Numerical And Lab Data

		Stability [N]	Stability Δ [%]	Flow [m]	Flow Δ [%]
Lab Sample		16050	-	0.0025	-
Numerical	**Mohr**	15900	0.935	0.0024	4
	Maxwell	16220	1.059	0.0018	28
	Burger	15925	0.779	0.0027	6

The Burger constitutive model showed the best behaviour on a quality level and also in the numerical comparison. So a creep test was implemented to calibrate its parameters. The numerical specimen, a cylinder of 100 mm diameter and 200 mm length, was created and loaded with a constant force of 200.000 Pa for a time of 500 s (figure 3). The tests were made at a temperature of 40 °C, in order to underline the worst conditions for the bituminous layers of the pavement model. In these conditions, in fact, the asphalt concrete layers lose great part of their elastic properties. The creep test has been calibrated according to results reported in the relevant national project, named “Set up of a performance catalogue of wearing courses for road pavements”, (research units of Potenza, Palermo and Bologna, 2001). The real specimen is made of M01 mixture (traditional wearing course asphalt concrete) and the creep curve is from the third sample (M01-3). The comparison between lab and numerical results in terms of creep deformation function (Jt) can be seen in figure 3 and table 2. The figure and the table report also the behaviour of a linear elastic material model, used later in the paper to compare the data collected from the pavement built with the Burger model.

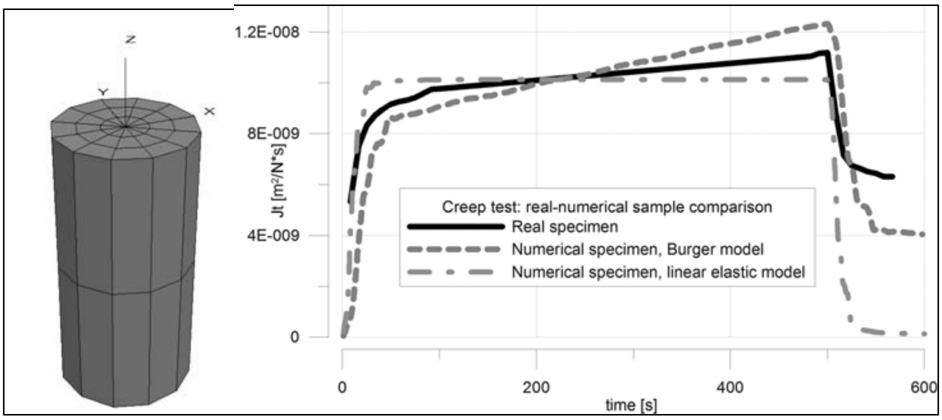

Figure 3: Creep Test, Sample and Results Comparison

Table 2: Creep Test: Comparison Between Numerical And Lab Data

	Time [s]	**50**	**100**	**500**	**560**
Jt	**Lab Sample**	9.16 e-09	9.76e-09	1.11e-08	6.31e-09
[m^2/Ns]	**Numerical Sample Burger model**	8.62e-09	9.07e-09	1.23e-08	4.18e-09
Jt Δ [%]	**-**	5.90	7.07	10.81	33.76
Jt [m^2/Ns]	**Lab Sample**	9.16 e-09	9.76e-09	1.11e-08	6.31e-09
	Numerical Sample Linear elastic mod	1.01e-08	1.01e-08	1.01e-08	1.62e-10
Jt Δ [%]	**-**	10.26	3.48	9.90	XXX

The Burger model implemented was, on a quality level, quite satisfying. A better precision should be appreciable in post-load phase. However, a visco-elasto-plastic material model is under study at the moment, in order to achieve a better accuracy.

3.2 The pavement dynamic loading response

The pavement model represented a single road lane, 4 meters wide and 10 meters long. Its layers were modelled on the basis of advices seen in C.N.R. B.U. n. 178, in particular referring to reserved lane pavements. These are specialized pavements that lie for the most part in urban and densely built areas and are subjected to frequent passages of heavy buses. The chosen type of pavement is the 8F, a flexible structure. Its thickness and assembly are shown in figure 4.

Under the pavement 2.5 meters of subgrade were added, in order to avail suitable wave propagation. The model was simply supported on all faces except for the upper one, providing an effective tie-up (figure 5).

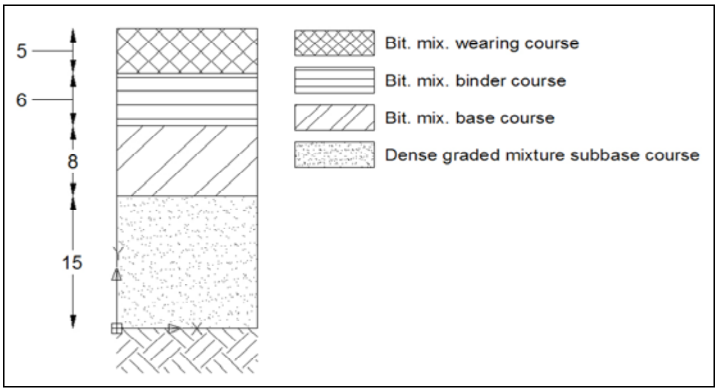

Figure 4: Pavement Layer Scheme, Dimensions In cm

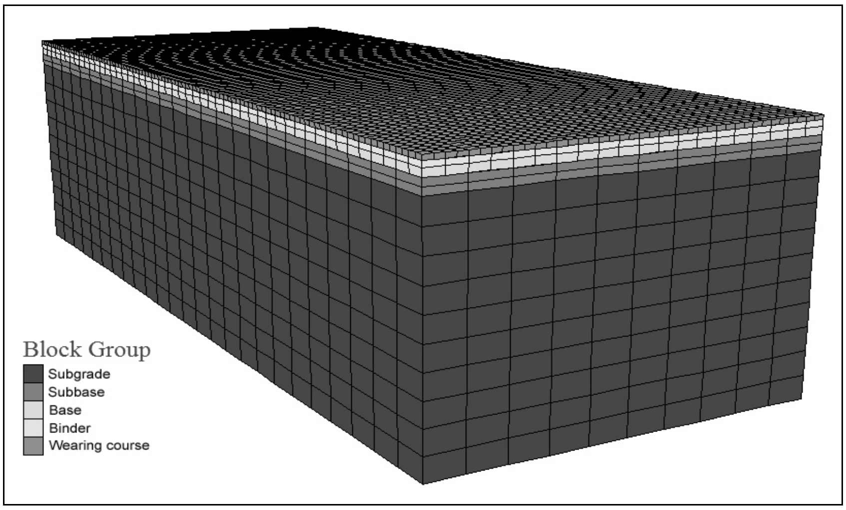

Figure 5: Pavement Model

For wearing, binder and sub-base layers the Burger visco-elasto-plastic model, defined in the first experimental phase, has been adopted (table 3).

Table 3 Constitutive Models Materials Features of the Bituminous Layers

Layer	Constitutive model	Parameters
Wearing course	Burger model	Bulk modulus = 600 MPa Density = 2200 N/m^3 Maxwell spring parameter = 4e8 N/m Maxwell dashpot parameter = 7e11 Ns/m Kelvin spring parameter = 3e8 N/m Kelvin dashpot parameter = 1e12 Ns/m
Binder course	Burger model	Bulk modulus = 300 MPa Density = 2200 N/m^3 Maxwell spring parameter = 3e8 N/m Maxwell dashpot parameter = 6e11 Ns/m Kelvin spring parameter = 3e8 N/m Kelvin dashpot parameter = 9e11 Ns/m
Base course	Burger model	Bulk modulus = 100 MPa Density = 2200 N/m^3 Maxwell spring parameter = 2e8 N/m Maxwell dashpot parameter = 6e11 Ns/m Kelvin spring parameter = 2e8 N/m Kelvin dashpot parameter = 9e11 Ns/m

The granular courses (sub-base and subgrade) were numerically modelled with a Mohr elasto-plastic constitutive model. The parameters used are reported in table 4 and are originated from previous laboratory and field experiences (Dondi G., Grandi F. & Vignali V., 2006).

Table 4 Constitutive Models Materials Features of the Granular Layers

Layer	Constitutive model	Parameters
Sub-base	Mohr model	Bulk modulus = 111 MPa Shear modulus = 73 MPa Friction = 34° Density = 1700 N/m^3
Subgrade	Mohr model	Bulk modulus = 33 MPa Shear modulus = 11 MPa Friction = 25° Density = 1700 N/m^3 Cohesion = 3000 Pa

The model was, in a first step, loaded statically only by its own weight, to achieve the settlement due to gravity. In a second step, the loading is made by four halves of contact patches, that simulate the rear axle of an urban bus (80 kN as for C.N.R. B.U. n. 178). The contact patches were assumed to be a circular area with a diameter of 210 mm, as reported on BISAR manual, approximated for modelling purpose to a square 200 mm wide. The difference in area between circle and square was kept in regard varying the pressure of the load on the surface, maintaining constant the overall 80 kN load. The rear axle of a heavy vehicle very often has dual wheels, so a total of four contact patches were modelled on the pavement. In figure 6 the vertical stresses generated by contact patches are shown. In particular, the figure underlines the intersection between the load diffusion solids given by the dual tires of the rear axle.

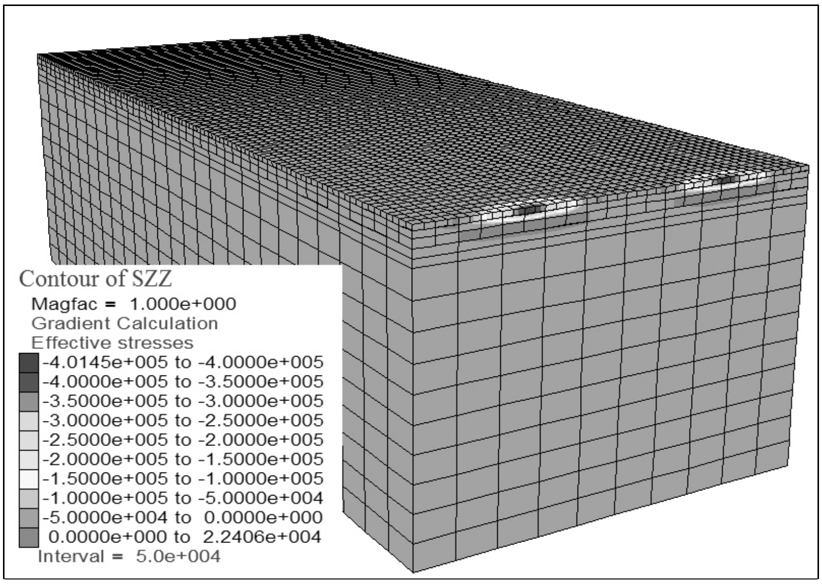

Figure 6: Pavement Model Loading Areas

The static loading value is dynamically applied to the model according to a half-sine function, calibrated to simulate a heavy vehicle passage on the pavement. Its form was chosen to achieve better dynamic calculation precision and implementation simplicity. In particular, the frequency of the trigonometric function was calculated basing on the typical urban bus speed of 36 km/h (10 m/s). The time exploited by the bus to pass through the contact patch is calculated in 0.02 seconds. In this time the loading function must load and unload the patch. So, the half-sine function (we considered only the positive part of a sine function) has a frequency of 25 Hz.

A series of 13 virtual velocimeters was placed along the centerline of the model, to control the velocity values versus distance from the vibratory source. The Peak Particle Velocity (PPV) was measured as for UNI 9916:2004. PPV indicates the maximum value of the velocity vector magnitude.

Starting from results of former research works (G. Dondi, F. Grandi & V. Vignali, 2006), in which the bituminous layers have been simulated by elastic constitutive model, a comparison was made between it and the Burger one, in order to obtain a more dependable representation of the real phenomena. While, in fact, in static analysis Burger model is very reliable, an in depth study may be necessary to check the potentialities for dynamic analysis.

In table 5 a resume of material characteristics used in the elastic pavement model is shown. The subbase and subgrade layer maintain the same characteristics reported in table 4, to avail a correct comparison.

Table 5 Constitutive Models Materials Features of the Bituminous Layers

Layer	Constitutive model	Parameters
Wearing course	Linear elastic model	Young modulus = 1 GPa Density = 2200 N/m^3 Poisson ratio = 0.35
Binder course	Linear elastic model	Bulk modulus = 500 MPa Density = 2200 N/m^3 Poisson ratio = 0.35
Base course	Linear elastic model	Bulk modulus = 300 MPa Density = 2200 N/m^3 Poisson ratio = 0.35

In figure 7 and table 6 the time domain analysis results are shown. The waveforms are very different next to the vibratory source, due to interference and reflection phenomena on the elastic model. The peak values, instead, are very similar next to the vibratory source, and very different far away from it, because of the lack of internal damping in the elastic model.

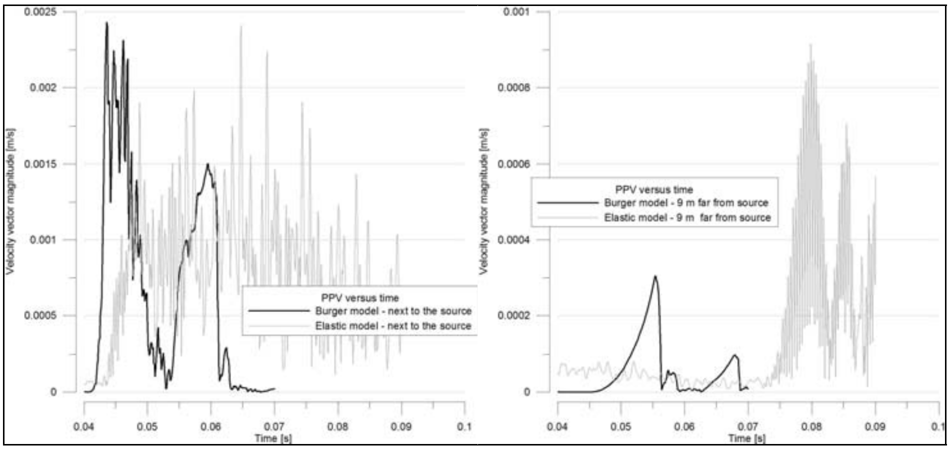

Figure 7: Time Domain Analysis: Next To The Source And 9 Meters Far

Table 6: PPV Comparison Between Elastic and Burger Pavements

	PPV (next to the source) [m/s]	PPV (9 m far from source) [m/s]
Elastic	0.00241	0.00092
Burger	0.00243	0.00031
Δ [%]	0.83	66.3

The damping analysis, in particular, was performed in two phases (figure 8):

- the first considered a comparison between the two pavements PPV values in function of distance, to evaluate their decreasing departing from the vibratory source;
- the second compared the results with the relative geometrical damping. It is a relative datum because it needs a known amplitude and distance value to be used as a benchmark. It represents the wave amplitude decaying along distance from a single-point vibratory source. The elastic pavement behaviour is very similar to the pure geometrical damping, due to the lack of a dissipative function implemented in the constitutive model, while the Burger pavement at a distance from the source continues to decrease its PPV values.

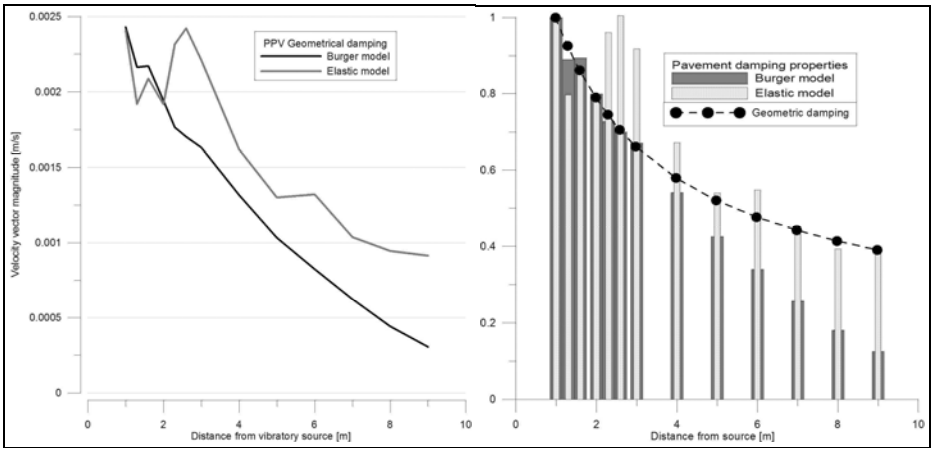

Figure 8: PPV Geometrical Damping And Damping Properties

Elastic model matched better the geometric damping curve in the far zone of the model, suffering interpherence phenomena near the vibratory sources instead. The Burger one exhibited a better behaviour in the proximity of the load, while the viscous nature of the material damped the long range wave propagation in comparison to the geometric damping curve.

In figure 9 the frequency domain analysis is performed, calculating the spectra by the Fourier transform. It underlined the great content of low frequencies in the spectra. This is a proper characteristic of traffic vibration waves (Cebon D. 1999), depending on suspension type, axle position, payload type and distribution and, last but not least, road profile.

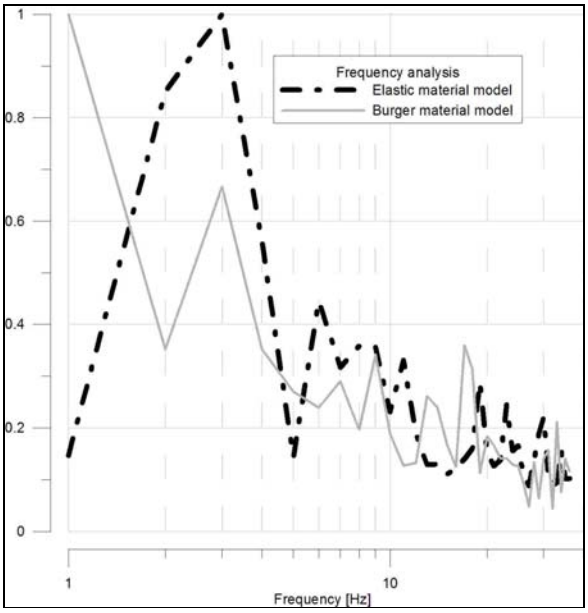

Figure 9: Frequency Domain Analysis

4. CONCLUSION

Based upon the developed research works the following concluding remarks can be stated:

- the elastic material constitutive model is suitable for a provisional study of wave propagation and vibration pollution analysis, for the determination of PPV values and of approximate frequency spectra. The waveform obtained in time-domain analysis is influenced by reflection and by interpherence effects. Moreover, some form of artificial damping has to be introduced adding uncertainties and parameters that need calibration;
- the Burger model shows a better general accuracy, at the price of a more difficult initial calibration and much longer computational times. In particular it should be more suitable for studying pavement with intrinsic damping properties, like those made with materials like crumb rubber asphalt. In addition to that, the better accuracy of material modelling allows the possibility of a more precise fatigue pavement design. In this way a more complete study of the traffic induced vibration phenomena with particular attention to the constitutive and geometric features of the pavement is under study at the moment;
- the choice of the material constitutive model is an important step in every numerical analysis and the sensibility of the engineer is essential to match resources and requirements;

- only the realization of a full-scale pavement in a test field instrumented with triaxial velocimeters will assure the correct model parameter calibration, accounting for damping and free field effects.

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