Advanced numerical methods to evaluate pavements response: comparison and parametric analysis

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Synopsis

In the last years, the mechanistic design methods in pavements field have become increasingly widespread. This has been possible thanks to the availability of field and laboratory test equipment, the material characterization of asphalt pavements and analytical computer packages. The mechanistic (analytical) methods have two steps. The first one consists in calculating the pavement "response", that is the stresses or strains in each pavement layer for all important combinations of loading and environmental conditions. This approach is also used in the backcalculation techniques for structural evaluation. The second step consists in the prediction of the "performance" through empirical relations between response and rate of deterioration.

In the simplest case which is still widely used today, the load is assumed to be static and the material is assumed to be linear elastic. The pavement is modelled as a multilayer structure of linear elastic material subjected to a circular, uniformly distributed load. A valuable contribution to this field has been given by modelling and finite elements analysis. In this way it is possible to consider the real dynamic road loads or the load impulse of a Falling Weight Deflectometer test and mainly the realistic behaviour of a given material. This paper is centred on the dynamic analysis with finite element modelling and with viscous elastic behaviour material. The comparison with static analysis and a complete parametric study show the relevance of this approach in the response evaluation, for both pavements design and the structural evaluation of existing pavements.

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INTRODUCTION

Evaluate pavements response, such as stress or strain, in each pavement layer is the first step in the design of these structures with mechanistic – empirical methods. The response values are used to predict distress from laboratory tests and field performance data. A correct tensional analysis is necessary also in the backcalculation techniques for a structural evaluation. The basic procedure is to measure the deflection basin that impulse loading devices cause and compare it with that computed. In the simplest case which is still widely used today, the load is assumed to be static and the material is assumed to be linear elastic. The pavement is modelled as a multilayer structure of linear elastic material subjected to a circular, uniformly distributed load. This approach, today, appears inadequate for different reasons.
The stress due to traffic load is of a dynamic type. Also neglecting the effect of the interaction of the wheel with the surface pavement, the load applied in a point of the road surface is of the impulsive type with frequency in function of the vehicle speed. Also in the FWD tests, the load transmitted to the pavement is similar to that exercised by the passage of one wheel. In the traditional analysis, even when a moving load is considered, the effect of inertia of the dynamic load is not considered. Moreover, in the modelling of the structure with the elastic multilayer (Theory of Burmister), materials are considered to have a linear elastic behaviour. The effect of linearity of the unbound materials can only be studied with a simplified iterative process. The elastoviscous behaviour of the surface layers in asphalt concrete is considered through an elastic analysis equivalent to values of the elastic moduli depending on the frequency of application of the load.
A valuable contribution in this field has been given by modelling and finite elements analysis. The finite element method (FEM) is a numerical procedure to obtain an approximate solution for an engineering structure. In this way it is possible to consider the real dynamic road loads or the load impulse of a Falling Weight Deflectometer test and mainly the realistic behaviour of material. In this paper, the axissymmetric formulation has been considered for pavement modelling.

CONVERGENCE TEST OF AXISYMMETRIC MODELLING

The FEM formulation used is an axisymmetric modelling approach. It assumes that the pavement structure has constant properties in horizontal planes and the traffic load can be modelled as a circular load. This choice can seriously limit the analysis, when the applied load has an asymmetric complex configuration (dual tyre configuration), but at the same time it requires a limited computational effort, similar to the one required for a plane - strain formulation. Given the objectives of this study, the decision to use a similar model for comparative analyses seems justified.
The accuracy of a FEM analysis depends on element size and type. The solution of an element can be approximated by a linear or quadratic interpolation function. In case of modelling of an indefinite structure like a pavement, the accuracy of a FEM analysis depends also on the ratio between height and width of the model considered. In this case, the result considerably improves by using infinite elements at both ends of the model.
The ABAQUS programme was used in this study as it is today's most complete code available for this kind of analysis. As this programme seemed rather complex, at least for the discretization of the structure and formulation of input data, a pre-processor compiled in Matlab has been realized to ease its use.
After defining some nodes of known co-ordinates on the horizontal surface and along the axis of symmetry, as well as the number of layers and their thickness, the pre-processor creates a mesh assigning the co-ordinates to nodes and the incidences of elements. The mesh is made up of rectangular elements with eight axisymmetric nodes (called CAX8 in Abaqus) and of infinite elements (called CINAX5R in Abaqus). After this model is geometrically generated, it is possible to visualize the resulting mesh and thus visually check its structure. A text file outside the programme contains the data concerning the arrangement of layers and the properties of the material (Young modulus, Poisson coefficient, density). Thanks to this file it is possible to modify the characteristics of materials and the number of layers without intervening in the programme. The pre-processor makes it also possible to identify the elements making up each layer and the nodes to restrain and to define the surfaces of the elements affected by the uniformly distributed load. The function of the load

applied to the mesh is calculated by the programme so as to transform it in the load steps required by the Abaqus calculation code. .
Besides producing the above-mentioned data, the programme creates a text file which can define the model and the stresses according to the specific Abaqus requirements. Therefore, the use of the pre-processor allows the rapid change of any parameter in the model (i.d. nodes kind of load, layers and their properties) without having to modify the input file of the Abaqus calculation code.
Mesh size and model configuration are important parts of the finite element modelling, precise mesh refinement being necessary in regions of high stress intensity. To start with, the elements and their size had to be chosen accurately and the model size (height and width) had to be optimized. The results of the static analysis with linear elastic behaviour of materials have been compared to those of the multielastic layer (Bisar Programme).
The mesh reported in the figure 1 is formed by 8-nodes axisymmetric rectangular elements (called CAX8 in Abaqus) and by infinite elements (called CINAX5R in Abaqus).

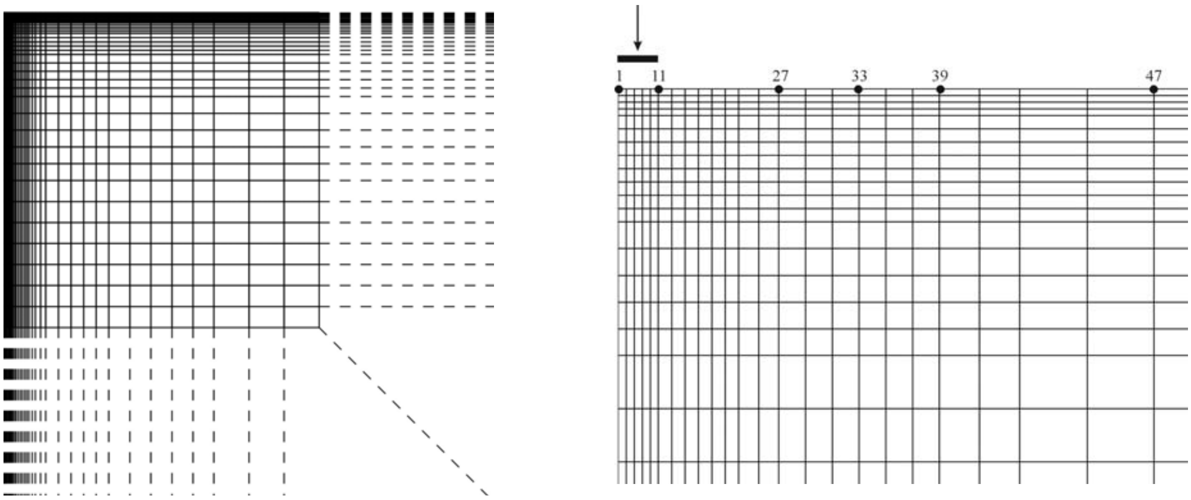

Figure 1 Axisymmetric model

This model was used to analyze a 4-layer flexible pavement having the physical and mechanic properties shown in Table 1 and subjected to a distributed load of 889,23 MPa with a circular area of r = 0,157 m.

Table 1 Pavement characteristics

LAYERS	THICKNESS [m]	ELASTIC MODULUS [MPa]	Poisson Ratio
Surface course	0,10	10000	0,35
Base course	0,15	7000	0,35
Sub base	0,25	800	0,40
Subgrade		90	0,45

The results of the static analyses assuming a linear elastic behaviour of materials and carried out by using the Abaqus programme have been compared to those of the Bisar programme which provides the exact solution of the multilayer according to the Burmister theory.
Figures 2 and 3 show the vertical and horizontal stresses which vary according to the depths obtained by the two methods. The differences measured are about 10 ÷15% which means they are acceptable for this study.

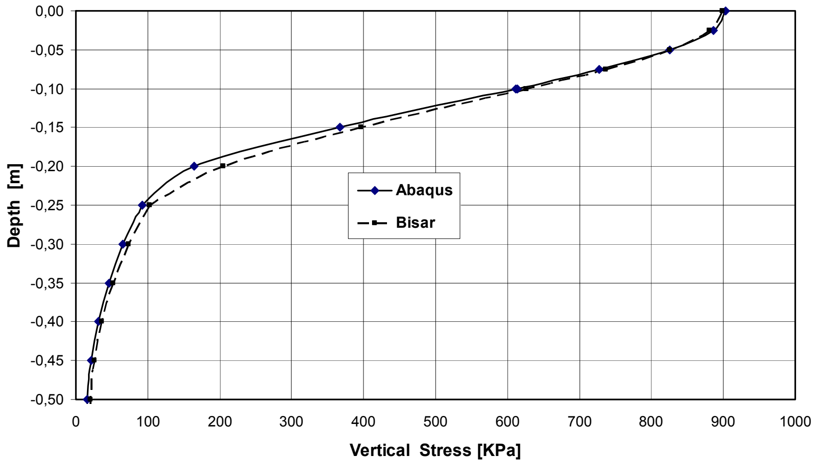

Figure 2 Comparison of analysis response

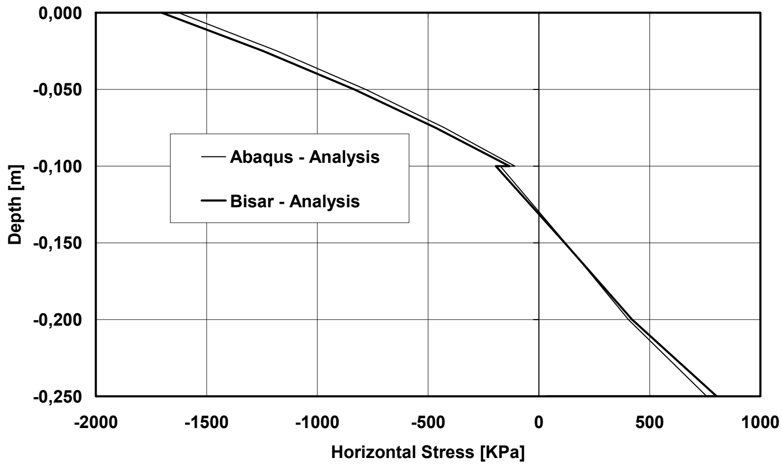

Figure 3 Comparison of analysis response

DYNAMIC ANALYSIS

A dynamic analysis is more accurate and physically more realistic than a static analysis. ABAQUS offers several methods for performing dynamic analysis of a problem in which inertia effects are important. Implicit direct integration is provided in the ABAQUS standard to solve the equation of motion.

$$M \times \frac{d}{dt}\left(\frac{d(u)}{dt}\right) + C \times \frac{d(u)}{dt} + Ku(t) = F(t) \quad (1)$$

where M, C, K are the mass, damping and stiffness matrices; u(t) ú(t) ü(t) are the displacement, velocity and acceleration vector of the finite element assemblage; F(t) is the external load vector.
Mathematically (1) represents a system of linear differential equations of second order. In direct integration, the equation is integrated using a numerical step-by-step procedure. ABAQUS uses the implicit Hilber Hughes – Taylor operator for integration.

For linear dynamic analysis several options are provided in the ABAQUS Standard to introduce damping. The Rayleigh damping has been used in this analysis. It is defined as a damping matrix formed as a linear combination of the mass and the stiffness matrices.

$$C = \alpha \times M + \beta \times K$$

In static analysis the equation of motion is considered with inertia and damping effects neglected.

$$Ku(t) = F(t)$$

The comparison between the static and dynamic analyses of the same pavement primarily aims at evaluating how inertia, the time a load is applied, the structural damping and the possible presence of an extremely rigid subgrade (bed rock) affect this kind of analysis.

Dynamic load

To simulate the moving loads of road traffic, a load of variable intensity has been assumed with time varying according to the function (haversine function):

$$F(t) = q \times \sin^2\left(\frac{\pi}{2} + \frac{\pi \times t}{\tau}\right)$$

The duration of the load τ depends on the speed v and on the radius of the load area. A reasonable assumption is expressed by

$$\tau = \frac{12 \times a}{v}$$

with a = radius of the area and v speed in m/s of the moving load.

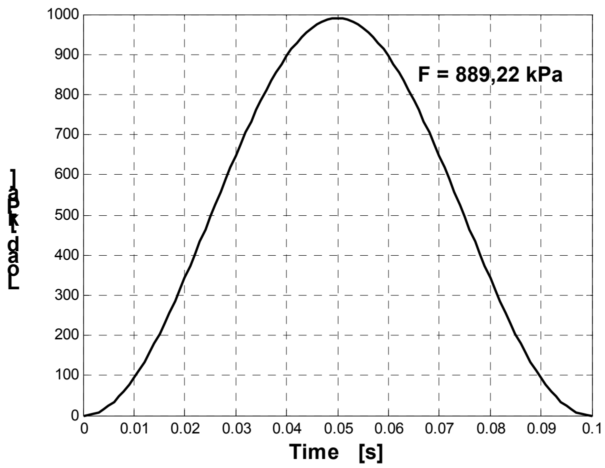

Figure 4 Loading cycle

The figure 4 represents pressure in function of time (load cycle) for a maximum load value of 70 KN applied on a circular area with a 0.315 m diameter. The peak pressure reaches 889.22 KPa. The duration of the load for a speed of 72 Km/h is 0.09 s.

As far as the loads of a dynamic test with Falling Weight Deflectometer are concerned, it is possible to simulate them with the same function but with a considerable shorter duration (20 ÷ 30 ms).

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MATERIAL CHARACTERIZATION

Linear elastic material

In the simplest case, which is widely used today, the material is assumed to be homogeneous and isotropic linear elastic. Therefore only two parameters for one layer, the modulus of elasticity and Poisson's ratio, are needed to describe the stress- strain relation (constitutive equation).

Linear viscoelasticity

The behaviour of a viscoelastic material subjected to a simple shear test in which a time varying shear strain with small strain is defined by the relaxation function or by the corresponding creep function. The relaxation function is:

$$\tau(t) = \int_0^t G(t-s) \times \frac{d\gamma}{ds} \times ds$$

where G(t) is the shear modulus which characterizes the elastic response of material in function of time. This model is defined as a long term elastic model as the response tends to be constant in terms of stress when keeping the deformation constant for a long time. For t tending to infinity G tends to Go.

In a dimensionless form the expression is

$$\tau(t) = G_O \times \int_0^t g(t-s) \times \frac{d\gamma}{ds} \times ds$$

with

$$g(t) = \frac{G(t)}{G_O}$$

The ABAQUS calculation code assumes that the dimensionless relaxation modulus can be represented with a Prony series.

$$g(t) = 1 - \sum_{1}^{N} g_i (1 - e^{-\frac{t}{t_r}})$$

where N, g_i , ti, are constant values of the material.
By assuming for simplicity to stop the series to the first term, the expression is:

$$g(t) = 1 - g_i (1 - e^{-\frac{t}{t_i}})$$

for t tending to infinity, the expression becomes

$$g_1 = 1 - \frac{G_\infty}{G_O}$$

This mathematical law is the expression of the standard linear mechanic model represented by a spring in parallel with a Maxwell element.
In case of three-dimensional stresses, there are two viscoelastic functions with independent times too: the first expresses the viscosity response of the shear stress, the second the volumetric stress. In many applications the latter is neglected.
The ABAQUS programme offers three possibilities of implementing the viscoelastic behaviour of materials: direct specification of the parameters of the Prony series or by means of the data of a relaxation or creep test, the programme chooses the best Prony series to represent the rheologic behaviour. To evaluate the ABAQUS potential, a static creep test with mono-axial compression stress on 15 cm diameter and 8 cm high cylindrical samples was simulated. The figure 5 shows the FEM model. A constant 100 KPa stress is imposed during a first loading phase for 10 seconds followed by a recovery phase .
The figure 6 shows the trend of the instant deformation and the reversible viscous deformation during the loading and relaxation phases for two values of the long term elastic modulus, 10000 e 5000 MPa, and a material with a 0.8 G-ratio and t_1 = 1 s.

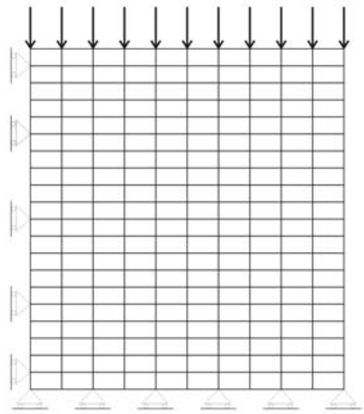

Figure 5 Creep test model

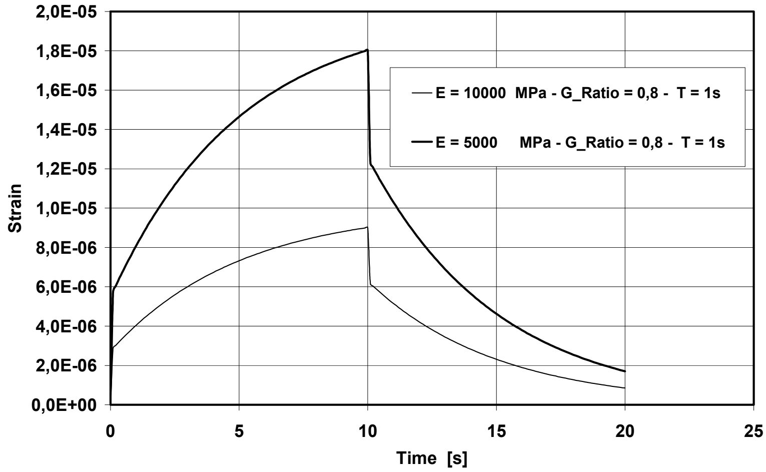

Figure 6 Simulation of creep test

COMPARISON E PARAMETRIC ANALYSIS

In this last section of the paper a comparison between dynamic and static analysis and a parametric study are conducted using the dynamic analysis procedure to assess the effects of several parameters on the dynamic pavement response: inertia, vehicle speed, material characterization, damping ratio, subgrade depth to bed rock. The structure examined has two layers of asphalt concrete, an unbounded mixed granular subbase and a subgrade, is schematized by means of the axisymmetric model of figure 1 and shows the physical and mechanical properties listed in the table 2.

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Table 2 Pavement characteristics

LAYER	THICKNESS [m]	ELASTIC MODULUS [MPa]	COEFF POISSON	Bulk Density [Kg/m3]	Damping
Surface course	0,10	10.000	0,35	2374	0 ÷ 0,05
Base course	0,15	7.000	0,35	2374	0 ÷ 0,05
Sub base	0,25	800	0,40	1766	0
Subgrade		90	0,45	1766	0

Inertia forces

To understand the effect of inertia forces (dependent upon acceleration) an initial comparison was made between the responses of the dynamic analysis, neglecting damping, and the corresponding static analysis. Figure 7 shows the trend of deflections on several nodes placed on the surface in function of time (time history). The load imposed for this first simulation corresponds to a vehicles' travelling speed of 72 Km/h and a time of application of the load of about 0.09 s. A slight reduction in vertical deformations can be observed via the dynamic analysis. The peak value of the deflection in correspondence of node 1 placed on the surface under the circular load is about 3% less than the statically calculated value. Moreover a shift can be observed in the peak values of deformations and the value of maximum load. Such a shift increases by moving further away from the centre of the load axis.

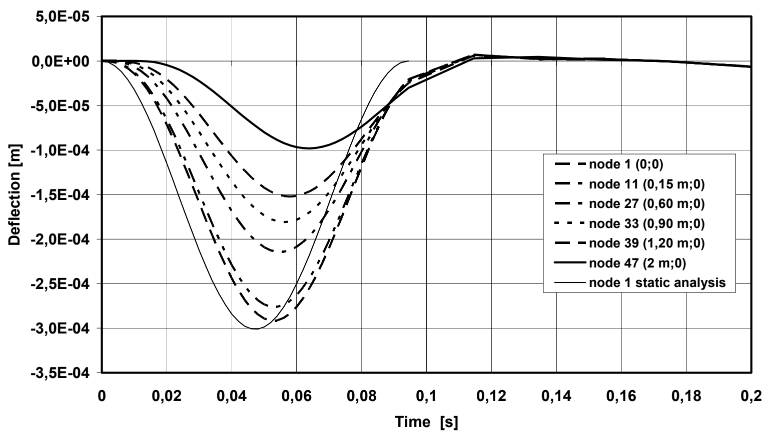

Figure 7 Calculated deflection histories

The comparison between the maximum values of the tensile traction of unbounded layers and the compression stress on the subgrade highlights an almost perfect superposition of their trends in function of time. An extremely small increase of 1% of the dynamically calculated maximum tensile traction is registered. The effect of the mere inertia forces, at least by a time of application of the load of 0.09 can be neglected.

Vehicle speed

The pavement was subjected to three different load impulse conditions: maximum pressure 889.22 KPa and time of application of the load of 0.18 s, 0.09 s and 0.06 s, corresponding to 36, 72, and 108 Km/h speed of the moving load. As far as maximum surface deflections are concerned, values decrease as the time of application of loads decreases. An 8% decrease is registered compared to the static analysis calculation for a time of 0.06 s . Moreover, the time history of surface deflection is slightly shifted compared to that of the applied load.

The comparison with the maximum stress tensile of bounded layers, which cause the deterioration of surface layers for fatigue, results in higher values when applying the dynamic analysis. The maximum difference registered is 2% for the shortest load impulse (maximum speed). The analysis of maximum vertical stresses in the subgrade reveals values which are nearly independent of the time of application of the load and identical to those obtained by the static analysis (table 3).

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Table 3 Comparison of the stress analysis

Speed	Dynamic Analysis				Static Analysis		
[Km/h]	Time [s]	σt max [kPa]	σc max [kPa]	Def max μm	St max [kPa]	Sc max [kPa]	Def max μm
36	0,094	709,30	-17,78	300,20			
72	0,048	714,56	-17,70	291,56	706,68	-17,76	301,07
108	0,032	719,34	-17,54	278,47			

Effect of material damping ratio

The introduction of a 0.05 damping coefficient for the asphalt concrete surface layers entails noticeable differences in the response of the dynamic analysis. As far as maximum deflections of surface nodes are concerned, values decrease by 5 ÷15% as the time of application of the load decreases (Fig. 8). Stresses follow a similar trend with even bigger variations: from 10% for the time of application of the maximum load to 35% for the shortest time (table 4). The dynamic analysis is extremely sensitive to even slight variations of this parameter, as could be expected.

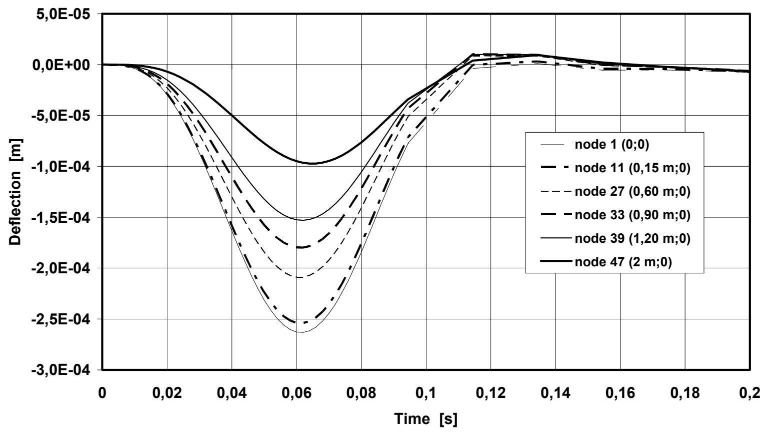

Figure 8 Calculated deflection histories

Table 4 Comparison of the stress analysis

Speed [Km/h]	Dynamic Analysis				Dynamic Analysis damping asphalt layer		
	Time [s]	σt max [KPa]	σc max [KPa]	Def max µm	St max [KPa]	Sc max [KPa]	Def max µm
36	0,094	709,30	-17,78	300,20	-15,82	624,24	284,79
72	0,048	714,56	-17,70	291,56	-13,63	523,29	263,74
108	0,032	719,34	-17,54	278,47	-11,67	449,17	235,23

Effect of subgrade depth to bed rock

These simulations intend to investigate the effect of the presence of a far more rigid layer right under the subgrade (bed rock). The five layers which make up the structure are made of linear elastic behavior material, without damping, having the physical and mechanical properties reported in table 5.

Table 5 Pavement characteristics

LAYER	THICKNESS [m]	ELASTIC MODULUS [MPa]	POISSON Ratio	Bulk Density [Kg/m3]	Damping
Surface course	0,10	10.000	0,35	2374	0
Base course	0,15	7.000	0,35	2374	0
Subbase	0,25	800	0,40	1766	0
Subgrade	1 ÷ 6	90	0,45	1766	0
Bed Rock		50.000	0,35	2400	0

The deductions based on the observation of figures 9, 10, 11 which show the vertical displacement of the surface node in correspondence of the load axis, in function of time are:

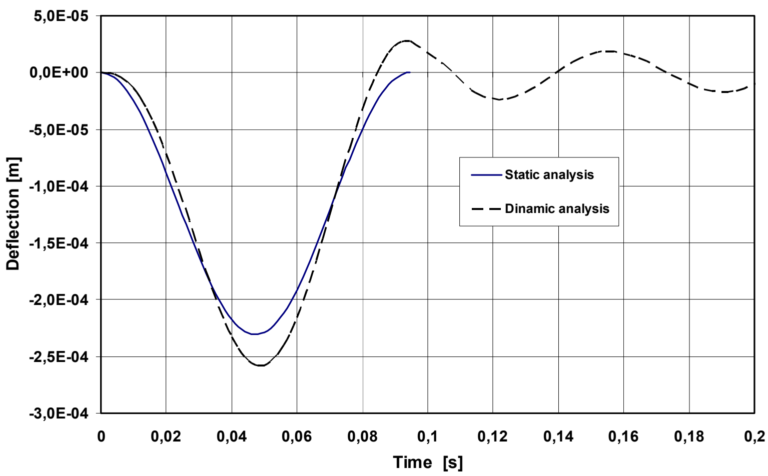

Figure 9 Calculated deflection histories at node 1

- The response (surface vertical deformation) shows a trend similar to that of the load but with a slightly shifted peak value (Fig. 9)

- The maximum amplitude of the displacement in the dynamic analysis, when there is a surface bed rock layer, increases as the depth of the bed rock increases (Table 7).
- The comparison with the static analysis reveals an anomalous behaviour of the structure, different from what was registered in previous analyses. Maximum deformations increase compared to the static analysis. Such a variation depends on the depth of the rigid layer. Given 0.09 s load time, the maximum increase, equal to 12 % is found when the bed rock is 4 m deep.
- With shorter load impulse time, the bed rock effect is less deep (Fig. 11).
- The depth of the bed rock layer also influences the response when the load is zero. An oscillatory deformation is observed, with a frequency which is directly proportional to the depth of the rigid layer (Fig. 10 e 11).

Table 7 Synthesis of the analysis

Bedrock [m]	Static analysis		Dinamic analysis		Diff. [%]
	Time [s]	Def. max [m]	Time [s]	Def max [m]	
-1	0,048	1,1305 10^{-4}	0,048	1,1352 10^{-4}	0,5
-2	0,048	1,7613 10^{-4}	0,048	1,7879 10^{-4}	1,5
-4	0,048	2,3052 10^{-4}	0,048	2,5808 10^{-4}	12
-14	0,048	2,8108 10^{-4}	0,052	2,9156 10^{-4}	6

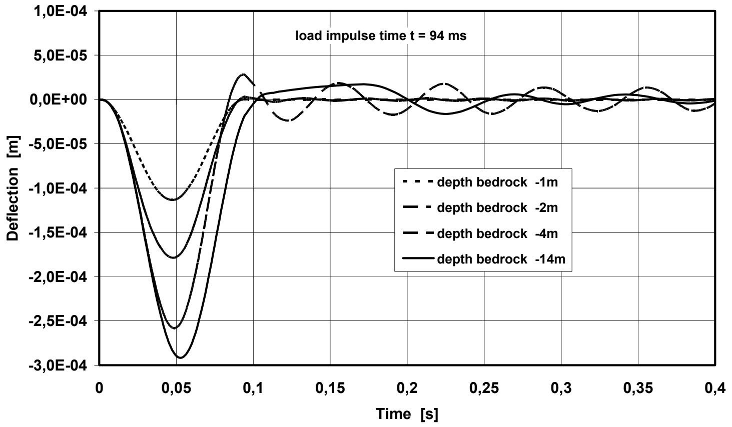

Figure 10 Calculated deflection histories at node 1

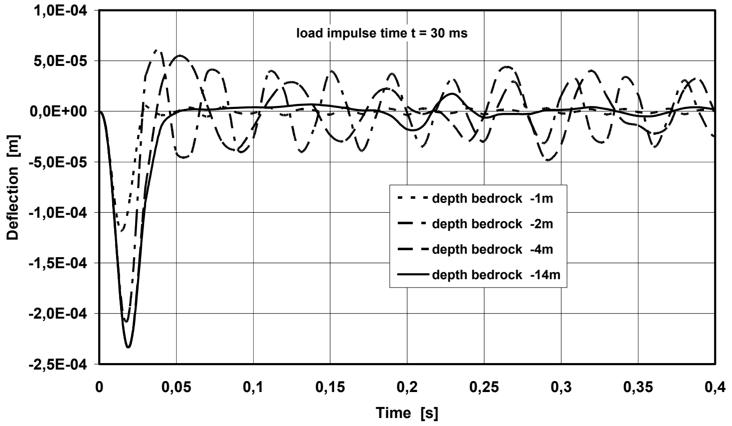

Figure 11 Calculated deflection histories at node 1

The introduction of damping in the first two layers and then in the unbounded ones modifies considerably the response, also when the load is zero (Fig. 12).

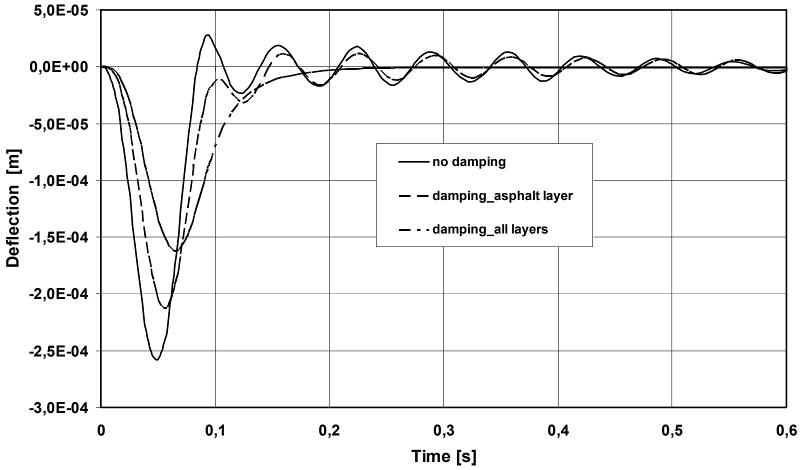

Figure 12 Calculated deflection histories at node 1

Effect of viscoelastic material

In this simulation, the asphalt mixture (surface course and base course) is modelled as a viscous elastic material and the time dependent properties are represented by instant shear modulus and long term shear modulus. The granular material, subbase course and subgrade are modelled using linear elastic material. For the dynamic analysis, also the damping coefficient and bulk density are included for all layers. Values of these parameters were obtained from the literature.

The applied load is always an impulse lasting 0.09 s. Three types of analyses have been carried out: static, dynamic without damping and dynamic with damping.

Table 8 Pavement characteristics

LAYER	Thickness [m]	Modulus [MPa]	Visco elasticity		Poisson Ratio	Bulk Density [Kg/m3]	Damping
			G-Ratio	T			
Surface course	0,10	5000	0,8	1 s	0,35	2374	0 ÷ 0,02
Base course	0,15	3500	0,8	1 s	0,35	2374	0 ÷ 0,02
Sub base	0,25	800	-	-	0,40	1766	0 ÷ 0,05
Subgrade		90	-	-	0,45	1766	0 ÷ 0,05

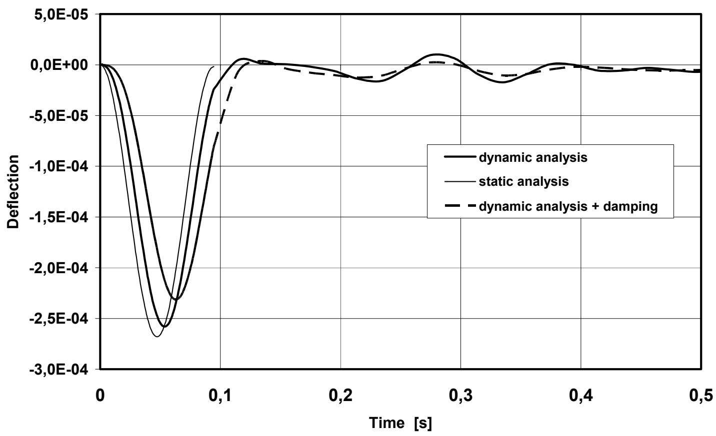

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Figure 13 Comparison of calculated deflection histories

The comparison between surface deflection trends in correspondence of the load axis (node 1) of static and dynamic analyses without damping reveals a decrease by 10 % in maximum values while stress responses remain practically unchanged. By introducing the dynamic analysis with damping of all layers, the differences between the maximum values of tensile traction in bonded layers and compression stress in the subgrade are evident: 20% (Fig. 14 e 15). Moreover the time history of stress show a shift and a considerably longer cycle.

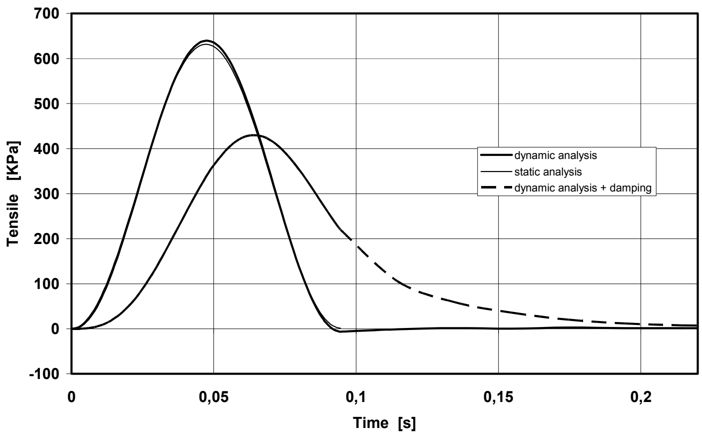

Figure 14 Calculated tensile stress histories

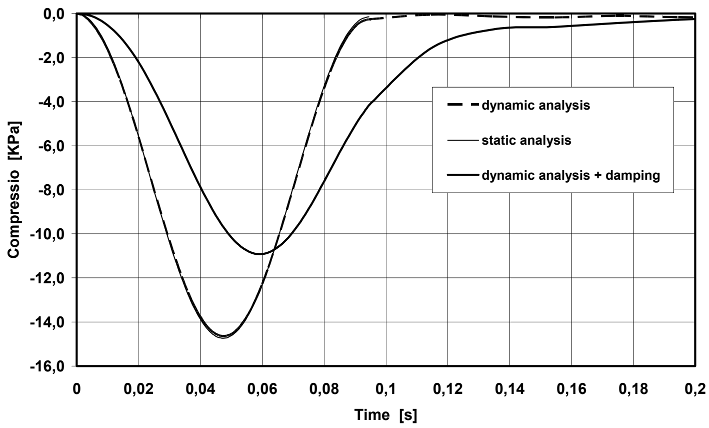

Figure 15 Calculated compression stress histories

CONCLUSIONS

The main objective of this study was to evaluate the efficiency of numerical analysis methods and in particular of dynamic analysis to evaluate the response of road superstructures to dynamic loads due to traffic. An accurate tensional analysis, taking the real behaviour of materials and the dynamic stresses imposed by the road loads into account, is of fundamental importance not only when designing roads, in which case the degradation conditions directly depend upon the stresses induced by the layers, but also when structurally evaluating in-situ pavements by means of the backcalculation technique.
A preliminary study was carried out to choose the type of model and its size and to define the mesh.
A comparison has been carried out between the static analysis of a pavement and the dynamic analysis by assuming the linear elastic behaviour of all materials of the layers. Considerable differences emerge especially in case of surface deflections in function of the time of application of the load, also by assuming a structure with zero damping. When a 0.05 damping is reasonably assumed for surface layers, the tensional response changes completely both in amplitude and phase compared to external stresses. The viscoelastic properties of the asphalt concrete layers can be easily described with the creep compliance function. The

dynamic analysis carried out for the time domain, does not entail considerable differences for a time of application of the load equal to that of road moving loads.
By means of the dynamic analysis it is possible to check the presence of for example a bedrock layer in the subgrade of the pavement. This might be extremely important in backanalysis techniques. Moreover, more information on the physical and mechanical properties of layers might be gained by using all the data coming from a deflectometer test and not only the peak value as usually happens in static analysis.

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