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Determining the effect of damping layers in flexible pavements on traffic induced vibrations

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ABSTRACT: This paper proposes a novel method to evaluating the effect of damping layers on traffic induced vibrations; it's based on the estimation of the Rayleigh damping coefficients of different layers to be implemented in a FEM of the pavement structure. Two commonly used methods to determining those parameters are compared and then an improved approach is introduced by considering natural frequencies of the pavement structure but without underestimating damping in the basic frequency range. In addition, a more reasonable method is proposed to calculating pavement structure vibration based on shear beam model. Finally, the results of in-situ FWD tests are used to validate the accuracy of the model; the comparison between simulation and FWD results demonstrates the accuracy of the proposed method that is acceptable.

Finite Element Model (FEM) to predict the effect of a damping interlayer with different damping properties on vehicle-road vibration reducing. The model was fine-tuned using implicit analysis in ABAQUS and validated by comparing with pavement response from Falling Weight Deflectometer (FWD) field test. The predicted and calculated deflections at sensor positions were in agreement.

1 INTRODUCTION

Traffic induced vibrations is a relevant issue in some European cities where heavy traffic is running close to buildings; the problem is particularly relevant when pavement surfaces are uneven like in the case of stone pavements or artificial bumps.

When measures of eliminating or limiting the excitation of the pavement aren't feasible, vibrations can be controlled by means of either an increase in structural damping or a variation in the natural frequency of the structure.

In order to account for damping and mass inertia effects, damping properties must be defined for all pavement layers in the model. The sources of damping could be an arbitrary damping factor, friction factor, or viscoelastic material behavior. Given that the asphalt layers are characterized by viscoelasticity, the structural damping is appropriately accounted for. However, the granular layers and subgrade are defined with elastic moduli values, which do not consider dissipation.

As far as damping effect, a popular scheme that is often consistent with experimental data is Rayleigh damping. This method considers the damping matrix [C] as the combination of the mass proportional damping and the stiffness proportional damping, which can be described as,

$$[C] = \alpha[M] + \beta[K] \tag{1}$$

where α is the Rayleigh coefficient for the mass proportional damping whilst β is the Rayleigh coefficient for stiffness proportional damping. The relationship between α, β and the fraction of damping ξ at circular frequency ω for one-degree-of freedom problem is given by the following equation:

$$\xi = \frac{1}{2}\left(\beta\omega + \frac{\alpha}{\omega}\right) \tag{2}$$

From Eq. (2), it can be conjectured that there is a relationship between damping and frequency whilst experimental results, specifically in soils, show the damping is mostly frequency independent in a limited frequency range that is typical of ground motion; outside of this range, high frequencies are filtered and an artificial high damping is introduced (Park et al. 2004). Consequently, the Rayleigh damping coefficients, α and β should be appropriately formulated in order to fit experimental results.

So far several researchers have tried to get meaningful values of Rayleigh damping coefficients α and β; in the specific case of Asphalt Concrete (AC) pavements, some Authors have defined damping coefficients for these layers too instead of considering viscoelasticity. Yoo et al. (2007) assumed α and β are proportional and inversely proportional to the natural frequency of the system, respectively. Wang et al.

(2009) applied the same method but assuming that α and β are constant and the natural frequency is changing for each layer. Zeng et al. (2005) assumed different α and β for each kind of pavement material. Al-Qadi et al. (2008) used viscoelastic material behavior for the AC layer, and hence there was no need to introduce additional structural or mass damping rules for that layer whilst, for the layers that were defined by elastic material behavior, α and β were determined from the i_{th} and j_{th} modes of vibration. However, from these results it's clear that structural damping in pavements isn't determined in a unique way but each author assumes different values with large differences.

In order to identify a common method to evaluating structural damping in pavements, a methodology to estimating Rayleigh damping coefficients is proposed. Two commonly used methods to determining the parameters are compared and then an improved approach is introduced. A more reasonable method to calculating natural frequencies of different layers is proposed, and finally simulations and experimental results are compared in order to validate the accuracy of the model.

2 FUNDAMENTALS OF RAYLEIGH DAMPING

2.1 *Determining Rayleigh damping parameters*

Typically there are two principal methods to determining damping parameters to be used in FEM analyses.

The first one was proposed and applied by Idriss (1973) in the QUAD4 software for geotechnical seismic analysis, where it is assumed that the contributions of mass and stiffness proportional coefficients are the same. In this way, α and β can be described as,

$$\alpha = \xi_1 \omega_1 \tag{3}$$

$$\beta = \frac{\xi_1}{\omega_1} \tag{4}$$

where ξ_1 is the damping ratio and ω_1 is the natural circular frequency of the system. The relationship between frequency and damping ratio is reported in Figure 1, and it results in an overestimation of damping in all frequency ranges, determining a lower dynamic response of the system.

Hudson et al. (1994) introduced appropriate improvements to these shortcomings of using only the fundamental frequency to determining the damping coefficient, and adopted a different method in QUAD4M, the improved version of QUAD4.

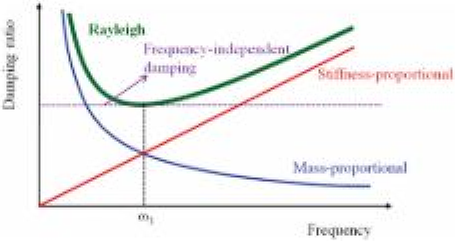

Figure 1. Relationship between damping and frequency by QUAD4.

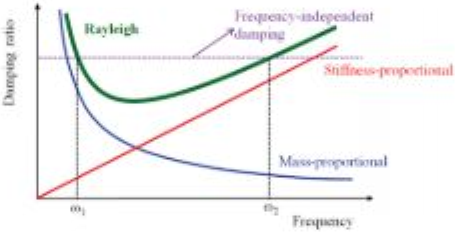

Figure 2. Relationship between damping and frequency by QUAD4M.

This method uses the first two natural frequencies ω_1 and ω_2 to determining the reference frequency for α and β; particularly, ω_1 is the first fundamental frequency, and $\omega_2 = n\omega_1$, where n is an odd number greater than ω_e/ω_1; ω_e is the dominant frequency. The coefficients alpha and beta can be determined by these relationships:

$$\alpha = 2\xi \frac{\omega_1 \omega_2}{\omega_1 + \omega_2} \tag{5}$$

$$\beta = 2\xi \frac{1}{\omega_1 + \omega_2} \tag{6}$$

As shown in Figure 2, this method can take into account both the natural frequencies and spectral characteristics of the structure, but underestimates the damping between ω_1 and ω_2 as well as overestimates damping outside the considered frequency range.

Most dynamic analyzes consider frequency ranges between ω_1 and ω_2, and hence it is very essential to improve the decoupling accuracy in such frequency range in order to make the damping ratio close to the frequency-independent one.

The frequency-independent damping ratio is given by,

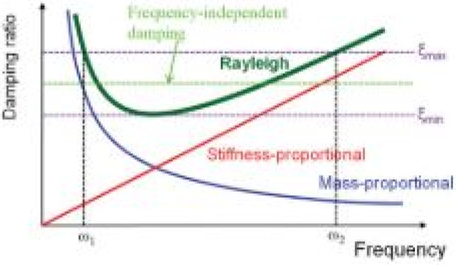

Figure 3. Relationship between damping and frequency by new method.

$$\xi_s = \frac{1}{2}(\xi_{min} + \xi_{max}) \tag{7}$$

In this way, the Rayleigh damping coefficients can be determined by making all the damping ratios (in the considered frequency range) close to the frequency-independent one, as shown in Figure 3.

2.2 *Determining the natural frequency of pavements*

As a multilayer system, a road pavement is consisting of finite layers over a semi-infinite subgrade. As the natural frequency is strongly dependent on thickness and modulus of layers, it assumes very different values for the finite and semi-infinite layers. Consequently, it seems more reasonable to estimate the natural frequency for each layer of a pavement structure. As far as the semi-infinite layer (subgrade) is concerned, the thickness is so large that the effect of finite layers on natural frequency can be disregarded. As a result of uncomplicated boundary conditions, it can be extracted directly from the FE model by ABAQUS.

However, for finite layers (surface and base layer), the support effect from the infinite layer is causing complicated boundary conditions so that it cannot be extracted directly. In order to solve this problem, an idealized shear beam model of the pavement is analyzed.

In this model, the pavement multilayer system is transformed in a layered system of shear beams, without considering the horizontal length of the different layers, as shown in Figure 4. Each shear beam is considered to be homogeneous and with the same cross-sectional area. The effect of the subgrade support on the pavement system is modeled by a shear spring that takes into account of the soil shear stiffness.

Correspondingly, the vibration shape functions of surface and base layers in the pavement model can be calculated by differential element method described in Figure 5 and the results are reported in Figure 6.

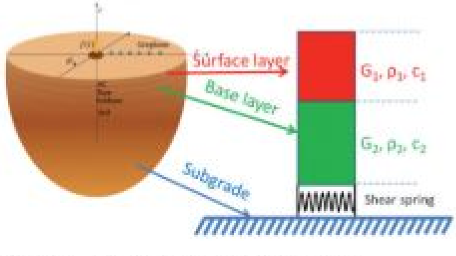

Figure 4. Shear beam model for pavement.

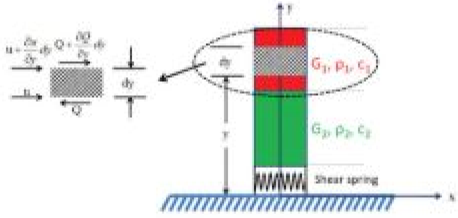

Figure 5. Infinitesimal segment section of one layer.

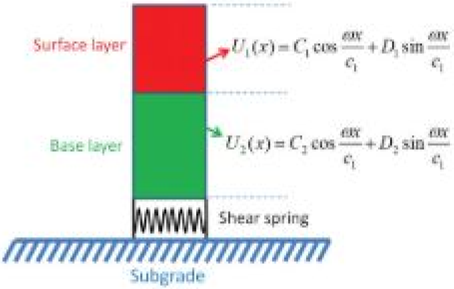

Figure 6. Pavement shear beam model.

The natural frequencies $\omega_1, \omega_2 \ldots \omega_n$ can be determined as the solutions of the system composed of these vibration shape functions, taking into account the boundary conditions.

3 FEM SIMULATION AND IN-SITU VALIDATION

3.1 *Description of the FEM simulation*

The dynamic analysis of a pavement structure can be solved in ABAQUS by using explicit or implicit

Table 1. Properties of pavement structure.

Layers	Thickness (cm)	Young's Modulus (MPa)	Poisson ratio	Density (Kg/m^3)
Surface layer	20.5	5680	0.3	2400
Base layer	22.5	660	0.3	2000
Subgrade	–	110	0.35	1500

Table 2. Damping of pavement layers.

Layers	Damping ratio	Alpha	Beta
Surface layer	0.05	89	2.5E-5
Base layer	0.03	3.2	0.0043
Subgrade	0.03	3.2	0.0043

integration method. In this paper, the implicit analysis is selected because of its stability and efficiency.

For this purpose, an axisymmetric FEM is developed; it assumes the pavement structure has constant properties in horizontal planes and traffic loads are modeled considering a circular footprint. The layer moduli, density and Poisson's ratio are back-calculated from FWD load tests and are shown in Table 1. The damping ratios are obtained by optimizing the values from Zhong et al. (2002). The damping ratios of various layers as well as the corresponding Rayleigh damping coefficients α and β are shown in Table 2 for the pavement layers.

3.2 *Comparison between numerical results and in situ FWD measurements*

The results of the FE model are compared with those of FWD tests. The recorded peak deflection basin and the dynamic response of sensors D1 (at the center of the loading plate), D5 (500 mm apart from the loading center) and D9 (1900 mm apart from the loading center) are used in this study as benchmarks to validate the FEM.

The numerical results of the peak deflection basin are completely overlapping to field, data as shown in Figure 7. Figure 8a, 8b and 8c compare measured and modeled deflection time histories at D1, D5 and D9, respectively. With the exception of a small magnitude difference at D1 and dephasing at D9, good agreements are achieved between measured and calculated deflection time histories under FWD load. As far as the magnitude difference is concerned, it can be explained considering that the FWD masses are interfering with pavement vibration. Theoretically speaking, the deflection time history should be a vibration curve along the pavement-air interface similar to the FEM

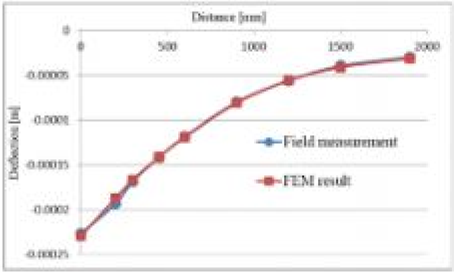

Figure 7. Deflection basin for field measurement and FEM result.

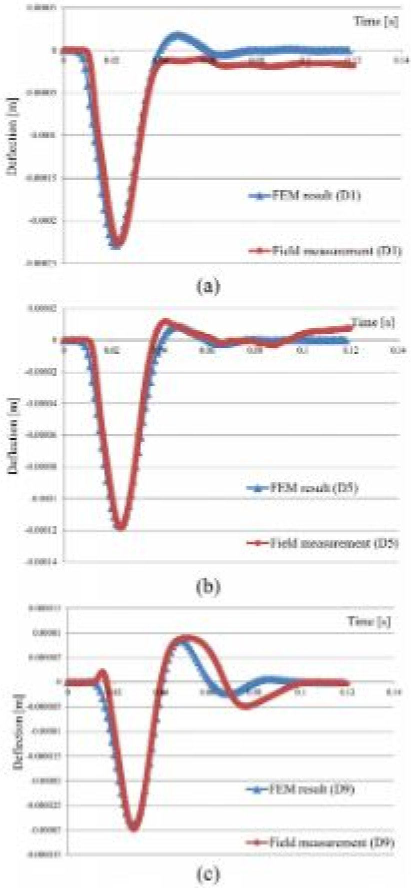

Figure 8. Deflection time histories of FEM results and field measurement at different points: (a) D1, (b) D5 and (c) D9.

result. For dephasing at D9, it can be influenced by the heterogeneity of pavement layers or subgrade. As shown above, these errors are considered acceptable for the developed method.

4 CONCLUSIONS

This paper proposes a novel method to estimating Rayleigh damping coefficients. Two commonly used methods to determining the parameters are compared and it can be noted that the QUAD4 method overestimates damping in all frequency ranges, resulting in a lower dynamic response; QUAD4M can improve the accuracy in the main frequency range, but still underestimate damping within this range. The improved calculation method can consider the natural frequencies of the pavement structure, resulting more close to the so-called frequency independent damping.

A more reasonable method to calculating natural frequency of different layers is proposed based on an idealized shear beam model. The FE model and in-situ field test results are compared to validating the accuracy of the method. Good agreement is observed between simulation and field in-situ results, demonstrating that this method can provide a more accurate basis for considering damping effects in FE modeling of pavement structures dynamic.

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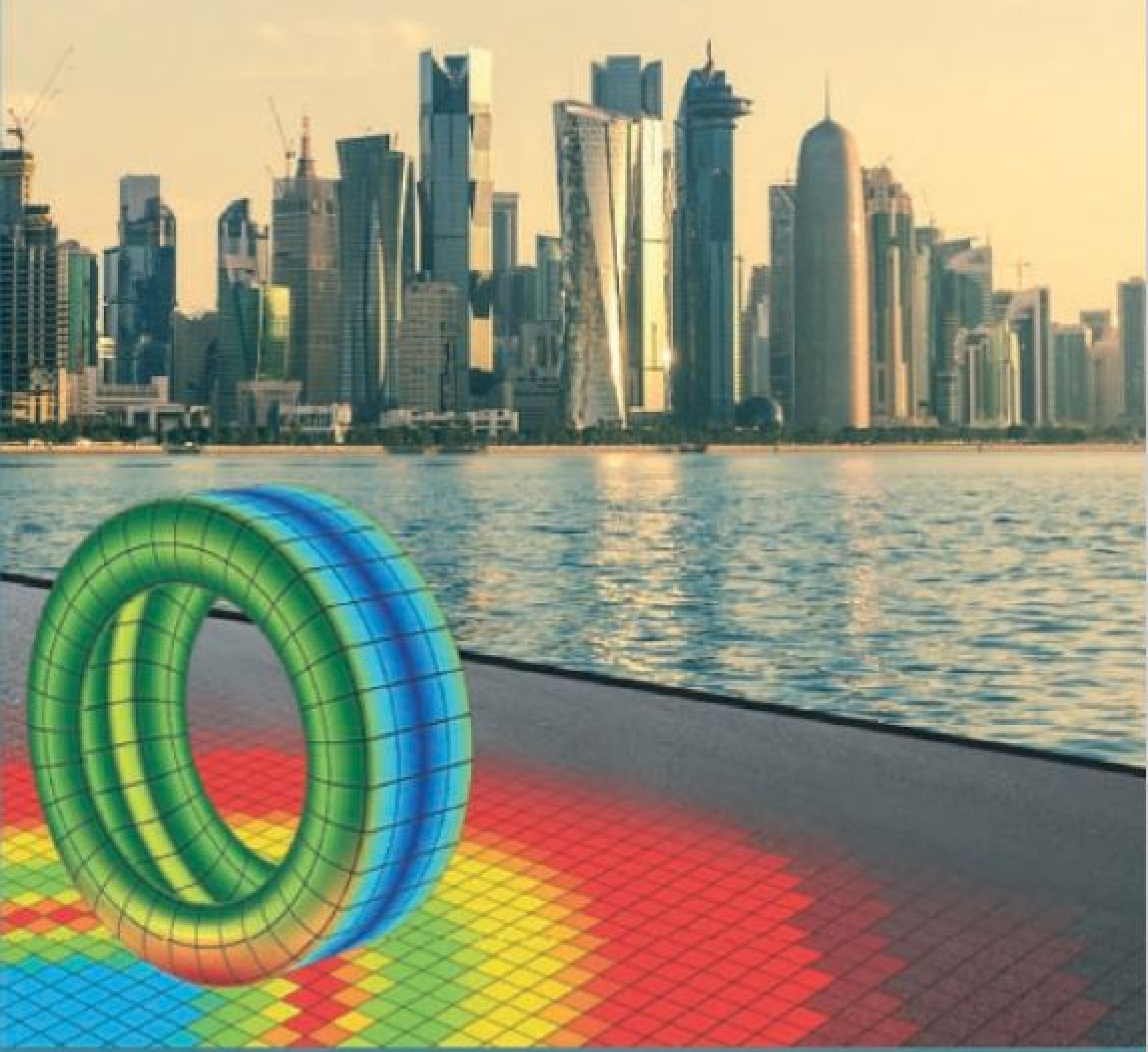

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