Computational Simulation of Dynamic Response of Vehicle Tatra T815 and the Ground

Jozef Vlček 1, Veronika Valašková 2

1 Department of Geotechnics, Faculty of Civil Engineering, University of Žilina, Univerzitná 8215/1, Žilina 010 26, Slovakia
2 Department of Structural Mechanics and Applied Mathematics, University of Žilina, Univerzitná 8215/1, Žilina 010 26, Slovakia

E-mail: j.vleek@fstav.uniza.sk

Abstract. The effect of a moving load represents the actual problem which is analysed in engineering practice. The response of the vehicle and its dynamic effect on the pavement can be analysed by experimental or computational ways. The aim of this paper was to perform computer simulations of a vehicle-ground interaction. For this purpose, a half-part model of heavy lorry Tatra 815 and ground was modelled in computational programmes ADINA and PLAXIS based on FEM methods, utilizing analytical approaches. Two procedures were then selected for further calculations. The first one is based on the simplification of the stiffer pavement layers to the beam element supported by the springs simulating the subgrade layers using Winkler-Pasternak theory of elastic half-space. Modulus of subgrade reaction was determined in the standard programme through the simulation of a plate load test. Second approach considers a multi-layered ground system with layers of different thicknesses and material properties. For comparison of outputs of both approaches, the same input values were used for every calculation procedure. Crucial parameter for the simulations was the velocity of the passing vehicle with regard to the ground response to the impulse of the pass. Lower velocities result in almost static response of the pavement, but higher velocities induce response that can be better described by the dynamic theory. For small deformations, an elastic material model seems to be sufficient to define the ground response to the moving load, but for larger deformations advanced material models for the ground environment would be more reliable.

1. Introduction

The transport structures are subjected to direct dynamic effect of moving load. The main source of kinematic excitation is unevenness of the pavement. They determine the magnitude of the contact forces induced by the vehicle to the pavement. The actual load amplitude is variable of time and frequency domain. The reliability of transport structures loaded by the heavy traffic needs a detailed analysis using vehicle-ground interaction model. The most important part of the process is to create a reliable numerical simulation and a proper computational model to describe the response of the ground to the vehicle loading [1, 2].

Several computing systems are available for the FEM dynamic analysis of this problem. Two models based on the dynamic theory of the moving load have been created. Model 1 (M1) has been created in ADINA software and Model 2 (M2) has been calculated in the PLAXIS system.
2. Description of the model elements
Particular elements of corresponding models M1 and M2 were assumed modular. Two main parts of the system lorry-ground have been a lorry with subsequent simplification to the dynamic subsystems and a half space representing the ground under the pavement surface. The module for ground has been created separately for each model M1 or M2 when module for vehicle has been identical for both models. For the simulations, the half-part model of the lorry Tatra 815 has been selected (Figure 1). Half-part model is usually preferred for 2D analyses as a combination of mass, spring and beam elements. A discrete model of the vehicle with finite degrees of freedom simplifies the mathematical solution of the problem. This assumption transforms partial differential equations to the ordinary differential equations [3].

![Figure 1. Half-part model of the lorry Tatra 815](image)

The main characteristics of the half-part model are defined by three diagonal matrices – mass \( \{m\} \), stiffness \( \{k\} \) and damping \( \{b\} \) matrices which contain experimentally measured values [4].

Matrices values for the lorry model have been determined:
\[
\begin{align*}
\{m\}_D &= \{m_1, I_{y1}, m_2, m_3, I_{y3}\}_D = \{11475; 31149; 455; 1070; 466\}_D, \quad [\text{kg, kg.m}^2], \\
\{k\}_D &= \{k_1, k_2, k_3, k_4, k_5\}_D = \{143716.5; 761256; 1275300; 2511360; 2511360\}_D, \quad [\text{N.m}^{-1}], \\
\{b\}_D &= \{b_1, b_2, b_3, b_4, b_5\}_D = \{19228, 260197, 2746, 5494, 5494\}_D, \quad [\text{kg.s}^{-1}].
\end{align*}
\]

The natural frequencies have also been determined:
\[
\{f\} = \{f_1; f_2; f_3; f_4; f_5\} = \{1.13; 1.45; 8.89; 10.91; 11.71\} \quad [\text{Hz}].
\]

The pavement has been modelled as a rigid surface. Pavement has been composed of the surface for acceleration with length of 15 m and the surface for deceleration also with length of 15 m (Figure 2).

![Figure 2. The numerical model of interaction system for model M1](image)

Axle forces for both models M1 and M2 have been calculated: \( F_1 = 33.2076 \text{ kN} \), first wheel of rear axle \( F_2 = 47.1611 \text{ kN} \) and second wheel of rear axle \( F_3 = 47.1611 \text{ kN} \) (Figure 3).

Contact surfaces of tires have been considered as 0.25 × 0.20 m for each tire. Simplification of double wheels on the rear axles has been made as a substitution of two rectangular contact surfaces to one
circular surface with identical area. Similarly, contact surface of front tires has been substituted by the circular surface with identical area (Figure 3).

![Figure 3. Contact forces of the vehicle (left), contact surfaces of tires for models M1 and M2 (right)](https://example.com/figure3)

Contact forces calculated for the model M1 have acted in the centres of the contact surfaces and have implied the stresses on contact surfaces with peak intensities 664 kN.m\(^{-2}\) for front axle tires and 472 kN.m\(^{-2}\) for rear axle tires, respectively. The stresses have acted at the measurement point in the model on circular contact surfaces with appropriate diameters (Figure 4). The control point stays stable and the moving load is simulated as a change of the uniform load type following the tire pass and phases without the applied load representing the gap between the tires.

![Figure 4. Axisymmetric model for vehicle load and ground for model M2 (Plaxis)](https://example.com/figure4)

To simulate the effect of the moving load, a tire pass has been simulated as a harmonic load with maximums corresponding to the calculated tire contact stresses. The propagation of the time-load curve is plotted as a series of halves of sine curves with intervals of a monotonic run simulating the gap between the tires (Figure 5). Frequencies and time intervals for each part of the time-load curve have been selected following the vehicle speed of 40 km.h\(^{-1}\) for both models M1 and M2.

Pavement has been simulated as rigid asphalt concrete pavement on the cement bonded gravel material with subbase from compacted gravel (Figure 6). Elastic modulus for pavement layers has been considered dynamic, when load acts only for a short time interval and the response of the ground results is in very small deformations.
In this case, a numerical 2D model of the vehicle as well as pavement have been created using computer software ADINA. It offers the ability to define contact pairs between the elements of vehicle that ensured the interaction between the pavement and the vehicle. The calculation has been executed with submitted inputs of the lorry Tatra 815 as mentioned above.

For modelling M1, the pavement has been considered as a planar model according to the theory of the beam on the elastic ground. In the model, the upper 3 layers are considered as a beam with a total height \( h = h_1 + h_2 + h_3 = 40 + 50 + 50 = 140 \text{ mm} \), and a width in the cross direction \( b = 1 \text{ m} \). For these 3 layers, equivalent modulus of elasticity is calculated by equation (1):

\[
E = \frac{(E_1 \cdot h_1 + E_2 \cdot h_2 + E_3 \cdot h_3)}{(h_1 + h_2 + h_3)}.
\]  

For our case \( E = (5500 \cdot 40 + 6000 \cdot 50 + 3050 \cdot 50) / 40 + 50 + 50 = 4803 \cdot 5714 = 4800 \text{ MPa} \).

Moment of inertia of the cross section of the beam simulated asphalt concrete layers of the pavement is

\[
I = \frac{1}{12} b \cdot h^3 = \frac{1}{12} \cdot 1 \cdot 0.14^3 = 2.28667 \cdot 10^{-4} \text{ m}^4.
\]

Additional layers are included in the calculation as a Winkler elastic subbase. Ground modulus of reaction \( K \) has been calculated using as:

\[
K = 1.274 \left(\frac{p}{\gamma_p}\right),
\]  

and for this specific example, numerical value of \( K = 1.274 \left(\frac{0.07/0.00057149}{156.04549} \right) = 156.04549 \text{ MN.m}^3 \).

The value of the Young’s modulus in the calculation of the subbase considers the beam of width \( b \), then \( k = K \cdot b = 156.045 \text{ MN.m}^3 \).
Damping is introduced into the calculation through angular frequency of damping $\omega_b = 0.1 \text{ rad.s}^{-1}$. Ground for model M2 has been created as a multi-layered system using finite element method. Linear elastic material model has been selected for pavement layers. 3D analysis has been performed using axisymmetric model when observation point has been situated under the center of the corresponding contact tire surface on the axis of the symmetry. Only half of the ground in the cross section has been modelled to avoid the determination of the Rayleigh damping coefficients $\alpha$ and $\beta$. In this case, only geometric damping in the 3D half space takes place, given by the standard values of Newmark’s parameters and boundary parameters $C_1$ and $C_2$ [5].

3. Description of the calculation procedure
The vehicle moving on the pavement causes dynamic actions and corresponding ground response. These actions are described by the differential equation:

$$\begin{bmatrix} M \end{bmatrix} \dddot{u}(t) + \begin{bmatrix} C \end{bmatrix} \dot{u}(t) + \begin{bmatrix} K \end{bmatrix} u(t) = \begin{bmatrix} F(t) \end{bmatrix},$$  \hspace{1cm} (3)

where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices.

Newmark’s method is widely used to perform dynamic numerical simulation to solve the equations in time. This method is called implicit, because the solution at time $t + \Delta t$ is not explicitly determined by the state at time $t$.

As a result, the time is also discredited and the solution is given in a form of the functional values. It is also included for all defined geometrical points in every time step. The different value for the time step affects the quality of the obtained results. It is very important to choose the right value of the time step. ADINA is a commercial engineering simulation software program which is used in industry and academia to solve structural, fluid, heat transfer, and electromagnetic problems. ADINA can also be used to solve multiphysics problems, including fluid-structure interactions and thermo-mechanical problems. ADINA is the acronym for Automatic Dynamic Incremental Nonlinear Analysis [6].

For model M2, a cluster with corresponding material properties for every pavement structure layer has been set. Mesh in contact surfaces of tires and line along the axis of symmetry has been refined by 5 times. 15-noded elements for meshing have been selected. Vehicle has been introduced as a uniform circular dynamic loading simulating tire contact surface and induced loading.

A series of calculation phases has been arranged, one for each tire pass and for gap between tires. Time interval $\Delta t$ for calculation phase has been calculated as a ratio of travel distance for tire pass or gap and vehicle speed of 40 km.h$^{-1}$.

4. Results and discussion
The vehicle Tatra 815 has been passed the control point on the pavement in a constant speed of 40 km.h$^{-1}$ during all simulations. The time step for the simulation is selected as 1/50 s for ADINA and $\Delta t / 250$ (s) for Plaxis as a default value. The following figure shows the displacements on the pavement surface with the constant speed of 40 km.h$^{-1}$.

Results show a good agreement of the outputs of both programs. Differences are observable in the magnitudes of calculated deflections of the pavement surface. Larger values are obtained in Plaxis software (Figure 7). The run of the deflections in ADINA is smoother without distinction of peaks for rear axles. These differences need to be verified by the experimental measurements to calibrate the input parameters of the model, especially damping characteristics.

Waving of the curve for Plaxis output between 1.5 and 2.0 second (Figure 7) is caused by the numerical integration during the calculation procedure and has no physical meaning.
5. Conclusions

The article shows that the use of FEM methods can give good results for numerical analysis of the problem. To achieve accurate results, the parameters of the numerical model should be verified by the experimental measurements with given boundary conditions. Then it can be determining wider range of the quantities that describe the phenomena of the vehicle movement on the pavement with consideration of the ground response related to the dynamic characteristics of the vehicle.

The plans for the next steps of research are to compare the results of numerical simulations with experimental measurements.

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