Numerical Simulation of the Ground Response to the Tire Load Using Finite Element Method

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Abstract. Response of the pavement to the excitation caused by the moving vehicle is one of the actual problems of the civil engineering practice. The load from the vehicle is transferred to the pavement structure through contact area of the tires. Experimental studies show non-uniform distribution of the pressure in the area. This non-uniformity is caused by the flexible nature and the shape of the tire and is influenced by the tire inflation. Several tire load patterns, including uniform distribution and point load, were involved in the numerical modelling using finite element method. Applied tire loads were based on the tire contact forces of the lorry Tatra 815.

There were selected two procedures for the calculations. The first one was based on the simplification of the vehicle to the half-part model. The characteristics of the vehicle model were verified by the experiment and by the numerical model in the software ADINA, when vehicle behaviour during the ride was investigated. Second step involved application of the calculated contact forces for the front axle as the load on the multi-layered half space representing the pavement structure. This procedure was realized in the software Plaxis and considered various stress patterns for the load. The response of the ground to the vehicle load was then analyzed. Axisymmetric model was established for this procedure.

The paper presents the results of the investigation of the contact pressure distribution and corresponding reaction of the pavement to various load distribution patterns. The results show differences in some calculated quantities for different load patterns, which need to be verified by the experimental way when also ground response should be observed.

1. Introduction

Pavements are structures that are exposed to direct dynamic effects of the moving vehicles or other loads. Unevenness of the pavement surface has significant influence on the magnitude of the contact stresses on the tire-ground contact area and are the main source of kinematic excitation for the vehicle. The actual load amplitude is variable of time and frequency domain. The influence of the load effect depends on the deformation characteristics of the pavement layers, the velocity of the passing vehicle, number of repetitions and magnitude and shape of the contact pressure [1, 2].
The tire inflation pressure has also significant influence on the tire pressure distribution. The variation in the stress distribution in the contact area is caused by the flexible nature of the tire material and the construction and by the response of the ground. The investigation of these stresses is complicated by the influence of the other forces (acceleration, deceleration, centrifugal and centripetal forces) and other factors (unevenness of the pavement surface, dynamic behavior of the vehicle). Several studies investigated the stress distribution in the tire-ground contact area were carried out [3, 4, 5, 6]. The experiments show considerable effect of the tire inflation on the stress distribution. The tire configuration has also significant influence on the stress distribution when simple tire axle causes larger deterioration of the asphalt pavement than double tire configuration with higher axle load.

Recently, flexible asphalt pavements are replacing by the semi-rigid asphalt pavements in the engineering practice. The subbase layers of the pavement are designed as a bonded layer with higher stiffness. The pavement can then resist heavier load from traffic with the restricted impact on the permanent deformations and the occurrence and the development of the cracks. This type of the pavement is modelled in the presented study.

2. Setup and calculation procedure

The scope of the study is to investigate the role of the different load patterns of the single front axle tire of the heavy truck and the corresponding response of the pavement structure in terms of the pavement surface deflection, velocities and accelerations. The tire was selected due to the simpler approximation of the contact area to the circular shape for the axisymmetric analyses. Calculations were divided into two stages. Determination of the vertical tire contact forces was realized in FEM software ADINA as a first step. Calculated forces were then applied as a load on the pavement structure in FEM software Plaxis 2D.

2.1. Vehicle parameters

The input parameters for the vehicle model was determined according to the measurements of the fully loaded heavy lorry Tatra 815. The front axle and the rear pair of axles were separately weighted and the weight of these masses was then used as an input in the numerical model in the software ADINA to achieve the contact forces (table 1).

| m \( (\text{kg}) \) |  
|-------------------------------|---|
| Front axle                   | 5 200 |
| Rear axle pair               | 20 300 |
| Total                         | 25 500 |

For the analyses of the contact load patterns, the contact area of the tire was measured. The width of the footprint of the front axle tire was 23 cm and the length was 28 cm. Approximation to the axisymmetric model requires the transformation of the footprint shape to the circle with the equivalent area. Assuming rectangular shape of the original footprint, the radius of the equivalent circular contact area was \( r = 143 \) mm.

2.2. Pavement parameters

Pavement characteristics are based on the typical semi-rigid asphalt pavement composition. For the calculation purposes, dynamic values of the modulus of elasticity \( E \) of the materials were set (table 2). These values are larger than static inputs because dynamic loads cause smaller deformations when act only short period of time and the ground show apparently higher stiffness. Linear elastic material model was adopted for the pavement layers.
Table 2. Composition of the layers for the semi-rigid pavement.

| Material                                      | Designation | Thickness (mm) | Modulus of elasticity E (MPa) | Poisson's ratio |
|-----------------------------------------------|-------------|----------------|-----------------|---------------|
| Stone mastix asphalt                          | SMA 11      | 40             | 5500            | 0.33          |
| Asphalt concrete                              | AC 22       | 50             | 6000            | 0.30          |
| Asphalt concrete – subbase                    | AC 22 L     | 50             | 3050            | 0.33          |
| Cement bounded granular mixture               | CBGM C3/4   | 150            | 2000            | 0.22          |
| Graded aggregate                              | GA          | 150            | 400             | 0.30          |
| Subgrade                                      | S           | -              | 60              | 0.35          |

2.3. Calculations in software ADINA

For the simulations in the software ADINA, the half-part model of the lorry Tatra 815 has been selected (figure 1). 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 [7].

![Figure 1. Half-part model of the lorry Tatra 815 and the scheme for the calculation in the software ADINA.](image)

The main characteristics of the half-part model are defined by the three diagonal matrices – mass \{m\}, stiffness \{k\} and damping \{b\} matrices, which contain experimentally measured values [7, 8]. Matrices values for the lorry model were determined:

\[
{m_D} = \begin{bmatrix} m_1 & I_{y1} & m_2 & I_{y2} & m_3 \\ I_{y1} & m_1 & I_{y2} & m_2 & I_{y3} \end{bmatrix} = \begin{bmatrix} 11475; 31149; 455; 1070; 466 \end{bmatrix}_D, \quad (kg, kg.m^2),
\]

\[
{k_D} = \begin{bmatrix} k_1 & k_2 & k_3 & k_4 & k_5 \end{bmatrix} = \begin{bmatrix} 143716.5; 761256; 1275300; 2511360; 2511360 \end{bmatrix}_D, \quad (N.m^{-1}),
\]

\[
{b_D} = \begin{bmatrix} b_1 & b_2 & b_3 & b_4 & b_5 \end{bmatrix} = \begin{bmatrix} 19228, 260197, 2746, 5494, 5494 \end{bmatrix}_D, \quad (kg.s^{-1}).
\]

The natural frequencies were also determined:

\[
{f} = \{f(1); f(2); f(3); f(4); f(5)\} = \{1.13; 1.45; 8.89; 10.91; 11.71\} \quad (Hz).
\]

The program ADINA allows to calculate the contact forces for the tire-pavement interaction as a result of the given vehicle characteristics. This was done by the simulation of the smooth ride of the truck at the constant speed of 40 km.h⁻¹ without any pavement unevenness. To exclude the influence of the ground deformations on the calculated forces, the pavement was simulated as a rigid beam with infinite stiffness. Generally, this static approach allowed us to determine the vertical contact forces as a result only of the mass distribution in the vehicle. Sum of the vertical axle forces for both truck halves is then equal to the overall vehicle weight as given in the table 1.

Calculated vertical force for the front tire reached 33.21 kN (the force \(P\)). Assuming measured footprint dimensions, the normal component of the vertical stresses is 516 kPa. This value is not far
from recommended inflation pressure given by the truck manufacturer for the front tires 500 kPa. Generally, it is assumed that inflation pressure is approximately equal to the tire pressure in the contact area, but this simplification cannot be adopted for every case [1].

Dynamic effects of the pavement unevenness in interaction with the vehicle are neglected because main scope of this paper is to investigate the load-pavement response. For this purpose, the knowledge of the static value of the load is sufficient because consideration of the dynamic effect of the load for the second step calculation in the software Plaxis 2D can be made only by the increase of the applied load. The same intensity of the load for each of the analyses allows the relevant comparison of the obtained outputs.

2.4. Calculations in software PLAXIS 2D
Second step calculation was done in the finite element software Plaxis 2D using dynamic module. The model was created axisymmetrically to avoid the obligation of the Rayleigh’s damping coefficients, which can be set to zero. The Newmark’s coefficients were set to default values [9]. With this simplification, it can be the problem simulated with the three-dimensional approach when only the geometry damping is adopted.

Figure 2. Scheme for the axisymmetric model in the software Plaxis 2D (not in scale).

The scheme of the numerical model is plotted in figure 2. Beside usual boundary conditions, additional absorbent boundaries were set to avoid the pressure rebound at the model edges. The mesh was further refined at the lines where load was applied. The measurement point was located in the center of the model on the pavement surface (figure 2).

Figure 3. Load patterns for the simulation in the software Plaxis 2D, a) point load, b) uniform load, c) trapezoidal load, d) cubic load.

The creation of load patterns went from the basic uniform load which was determined as a ratio of the contact force $P$ and the contact area ($\pi r^2$). This basic stress intensity $\sigma_v$ was given as a unit load "1"
(figure 3). Trapezoidal and cubical load patterns were created considering the condition of equal area of the load pattern $A = \sigma v \cdot r$ for each of them and were selected as an approximation of the real pressure distribution in the contact area [1, 3]. The load was applied as a harmonic load with time interval equal to the duration of the vehicle tire pass over the contact area at the velocity of 40 km.h$^{-1}$.

3. Results and discussions

Vertical deflection of the pavement surface, vertical velocities and vertical accelerations were investigated (figures 4 to 6). Point load caused for every case excessively large values of the quantities. Therefore, additional detail of the chart is plotted for another load patterns. The detail charts show some distinctions, especially between the trapezoidal and the cubical loads and the uniform load. Beside the point load, the uniform load causes slightly larger values of the quantities.

**Figure 4.** Vertical deflections of the pavement surface at the measurement point.

**Figure 5.** Vertical velocities at the measurement point.
Figure 6. Vertical accelerations at the measurement point.

4. Conclusions
The results of the analyses represent the preliminary outputs for further research of the tire-ground interaction mechanism when also stress-state of the ground will be investigated. Point load is evidently unsuitable for the tire load simulation because of unrealistic large induced displacements, velocities and accelerations. Uniform load (simulating normal tire inflation) gives similar results to other approximated patterns but still larger than the trapezoidal or the cubical load (overinflated tire).

The different load pattern should be analyzed to verify the exact influence of the tire inflation (and thus various stress distributions) on the ground response following the load effect on the surrounding structures. Fully 3D dynamic analysis is required to describe the pressure distribution in the tire-ground area, which is non-uniform and only part of it can be described by the axisymmetric approach.

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