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MODELLING THE HIGH-SPEED TRAIN INDUCED DYNAMIC RESPONSE OF RAILWAY EMBANKMENT

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Abstract. FEM model (2D and 3D) to simulate dynamic deformations of railroad embankment and underlying soil is presented. Numerical modeling is performed for the railway embankment geometry used in Russian Federation. Loading conditions were corresponding to forces created by SAPSAN (Siemens Velaro RUS) high-speed train and TGV train. Since there was no possibility to experimentally measure displacements and accelerations inside ballast layer induced by SAPSAN train, the numerical model was validated using experimentally measured displacements and accelerations exited inside the railway embankment by cargo train traveling at several different speeds (20-120 km/h). The validated model was used in order to predict displacements and accelerations induced in the ballast layer by high-speed moving (50-315 km/h) SAPSAN train.

1. Introduction

Year 2009 new high-speed SAPSAN (Siemens Velaro RUS) trains were launched to run between St. Petersburg and Moscow – two largest Russian cities. 2010 the high-speed traffic was prolonged from Moscow to Nizhni Novgorod. The trains are running on embankments originally constructed for much lower speed traffic (up to 185 km/h) and the construction of a new separate carriageway for sole use of high-speed trains is being planned. The presented research was initiated by RZD (Russian Railroads) company in order to predict behavior of the present embankment under high-speed SAPSAN traffic. Another aim was to propose possible modifications of the embankment geometry and materials in order to make it more suitable for high-speed traffic [1].

The main objective of the study was to create a model being able to predict behavior of the embankment under SAPSAN train traveling at different velocities. The results were also compared to ones received using loads corresponding to French TGV train. Since the computational facilities were limited, there was no possibility to perform dynamic 3D modeling of the process. In order to overcome the difficulty, static 3D solution was compared to static 2D solution for embankment cross section [2-6]. As a result a procedure to reconstruct correct 3D solution from 2D computations in static conditions was proposed. It is supposed that the same procedure can be used in order to reconstruct 3D solution from 2D model in dynamic situation. As Russian standards are mainly limiting maximum displacements within the embankment, the analysis was mainly focused on displacements appearing in the embankment in a result of a load induced by a train.

2. Static modeling

Deformations of embankment in static conditions (standing or slowly moving train) were studied in 3D (ANSYS) [13] and 2D (ABAQUS) [14] formulation. Figure 1 shows the ANSYS 3D model (inter tie periodic). Figure 2 is giving computed quasistatic displacements for wheel load equal to 125 kN (12.5 tons). On this stage all embankment components are modeled as linear elastic materials with properties given in Table 1.

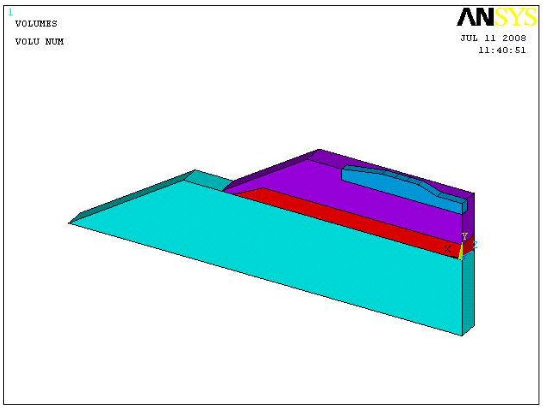


Fig. 1. 3D ANSYS model (inter tie periodic).

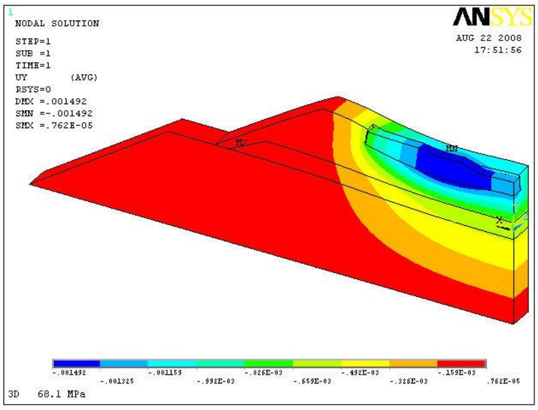


Fig. 2. Vertical displacements for wheel load equal to 125 kN.

Table 1. Elastic properties of embankment components.

	Tie	Ballast	Subballast	Ground
E, MPa	30000	168	180	289
Poisson's coefficient ν	0.25	0.35	0.35	0.313
ρ, kg/m^3	2400	2135	2135	1960

The solution is compared to results of static 2D modeling for embankment cross section. 2D modeling was performed using ANSYS and after this the analysis was verified utilizing ABAQUS FEM package as it was used for the following dynamic analysis.

2D geometry for embankment cross section is given in Fig. 3. The central problem to solve in order to substitute full 3D model by a simplified 2D model consists in appropriate formulation of boundary conditions for 2D formulation. At first sight, one can think that the axial load (125 kN in our case) should be distributed over the area given by a contact area of a rail (0.15 m wide) and a tie (0.2 m wide). The results of 2D modeling received under this assumption are greatly different from the results of 3D modeling. A simple analysis is showing that the load from the train axis for 2D formulation should be distributed on the length equal to inter tie distance (0.54 m) and not the width of the tie. This is giving a reduction of load amplitude by a factor of 2.7. Figure 4 is comparing vertical displacements between 3D and 2D models.

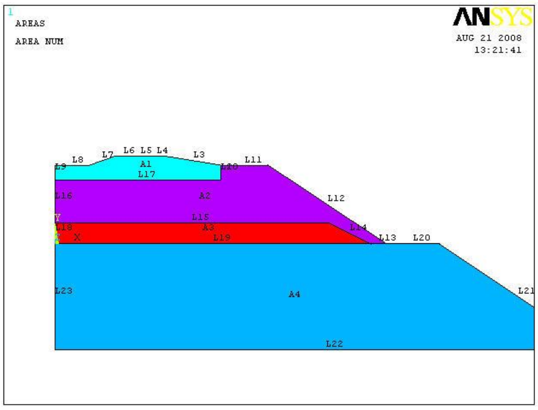
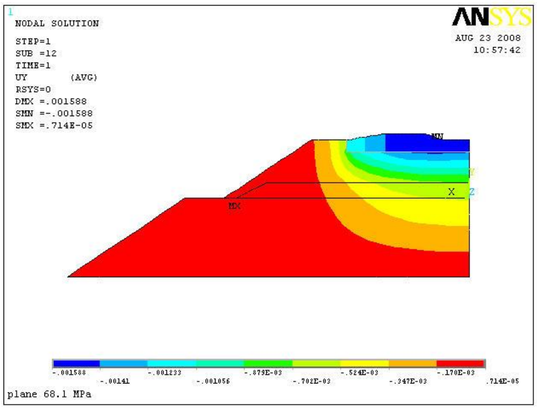
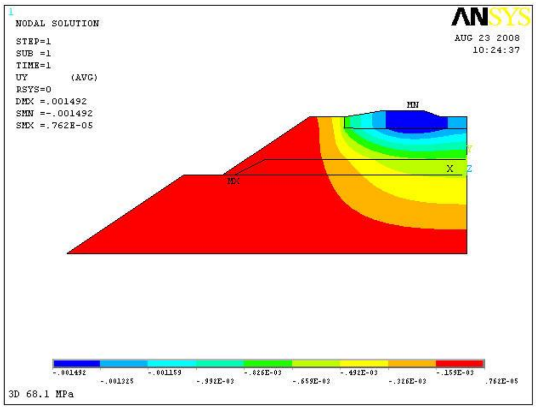


Fig. 3. 2D model geometry.



2D



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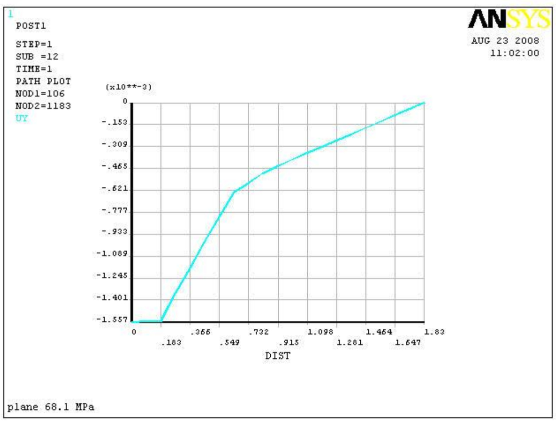
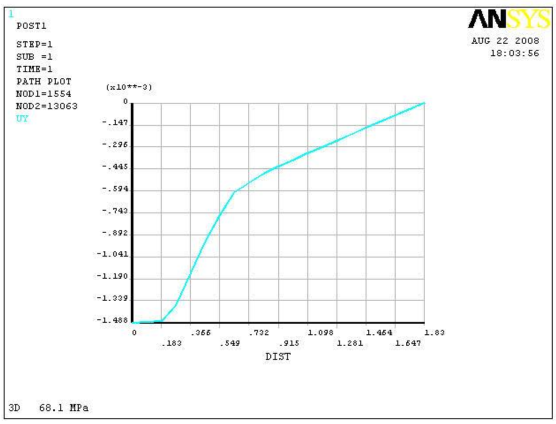


2D



3D

Fig. 4. Vertical displacements in the embankment (upper figures) and along the vertical line connecting the middle of the contact area and the bottom of the model (lower figures).

As testified by Fig. 4, vertical displacements appearing in embankment subjected to quasistatic loads can, with good accuracy, be predicted utilizing simplified 2D model. The same 2D model was created in ABAQUS FEM environment. The results received in ABAQUS are perfectly coincident with ANSYS results. Presumably for dynamic problems results received utilizing simplified 2D model will also be close to solutions that can be received solving full 3D problems.

ABAQUS 2D model for railroad embankment was modified in order to account for dynamic effects including possibility to apply time dependent load corresponding to moving train and account for propagation of elastic waves within embankment. The difficulty is connected with the bottom of the modeled zone (representing the soil under embankment). In reality this zone is practically infinite and the waves irradiated into the soil are not returning to embankment area (not accounting for smaller reflections from irregularities). Due to computational cost it is not possible to model large area and place the boundary at a distance that will guarantee that the waves reflected from this boundary will not return to the embankment within the computation time. The problem was solved by addition of "infinite" elements available in ABAQUS/Explicit on the bottom boundary of 2D model presented in Fig. 3. These elements (CINPE4) provide nonreflecting boundary conditions for the boundary they are placed on. The model was tested for a response after a single impact on the tie (corresponding to the single train wheel passing the tie) and it was found that ABAQUS/Explicit CINPE4 elements in conditions of the solved problem are reflecting less than 3 % of the signal that is coming to the boundary that they are placed on.

3. Study of dynamic response of the railroad embankment

The constructed model was used in order to study the dynamic response of the railroad embankment to SAPSAN trains moving at different velocities. The load applied to the developed 2D model was given as a force changing in time applied to the tie on the line where the contact with rail is taking place [7-8]. The load time shape is given in Fig. 5.

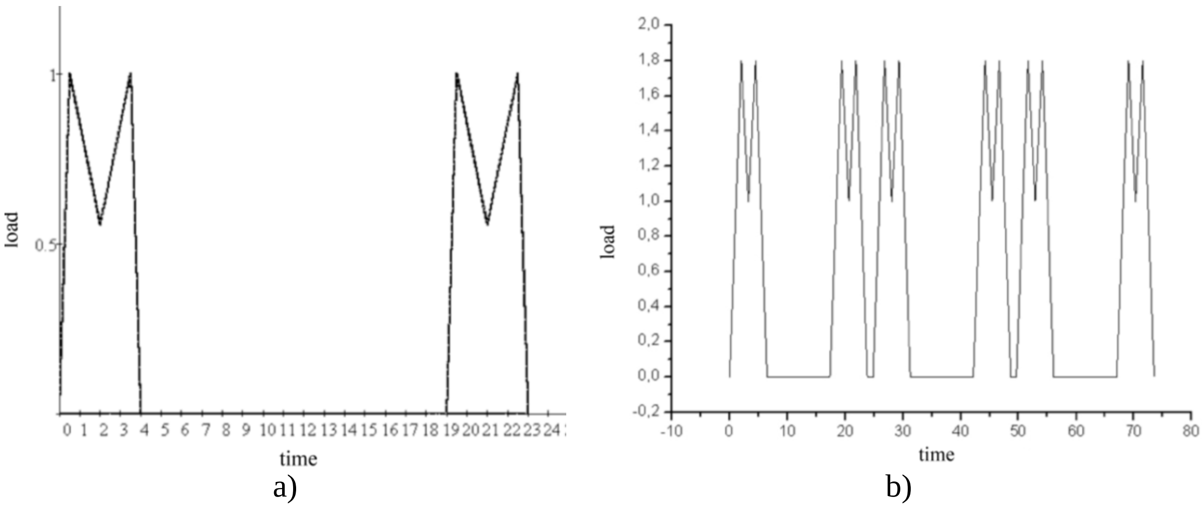


Fig. 5. Time shape of the applied load: a). TGV train; b). SAPSAN train.

Time between adjacent peaks in one loading cycle is equal to distance between the wheels in a train wheel pair divided by the train velocity. Time between loading cycles is equal to distance between the trains wheels pairs divided by the train velocity. Load amplitude is chosen from the correspondence to available experimental data. It is known that the load amplitude is also dependent on the train velocity [9-12]. This dependency can be measured (Fig. 6).

This dependency for load amplitude multiplier was used for all the following computations. Figure 7 is giving total vertical displacement history at the point of contact between the rail and the tie.

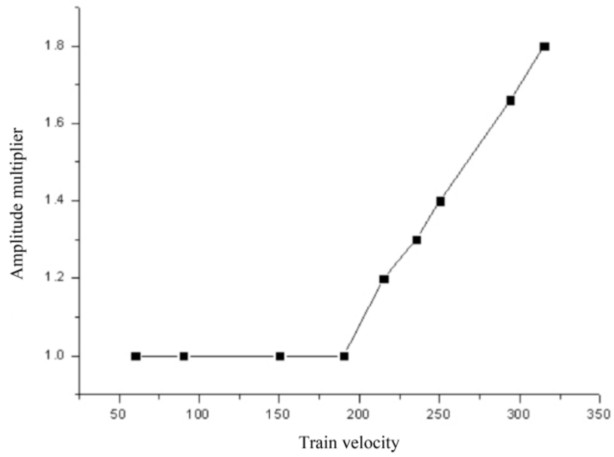
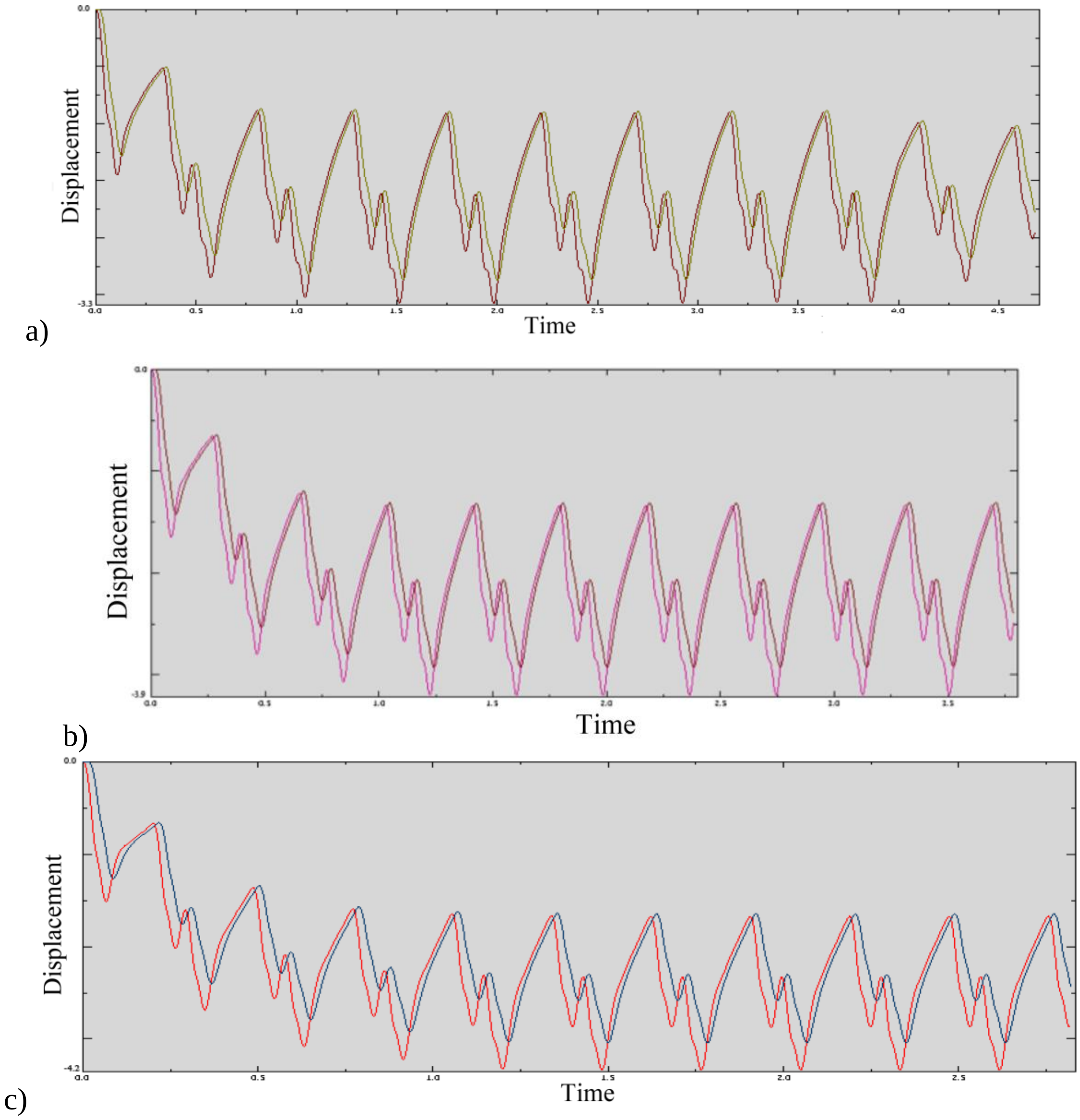


Fig. 6. Measured load amplitude multiplier as a function of train velocity



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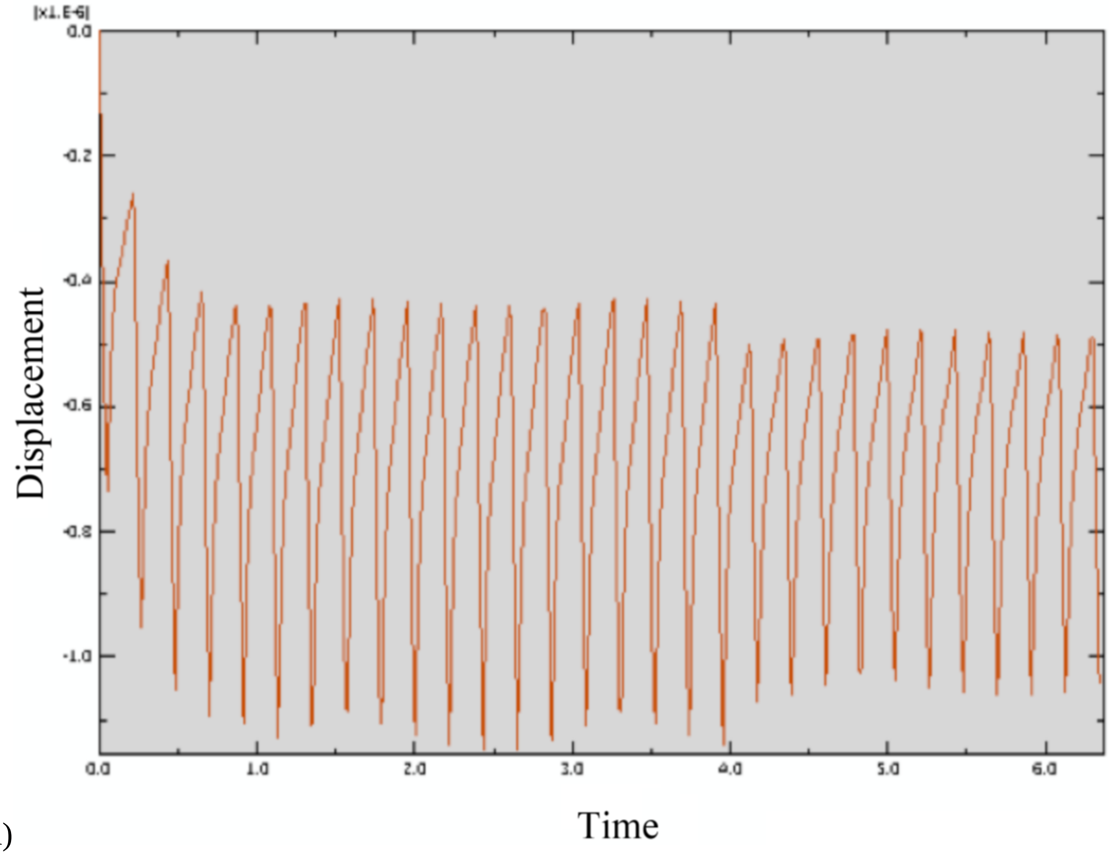

d)

Fig. 7. History of absolute vertical displacement at a point of contact between the rail and the tie.
SAPSAN train running at 190 km/h (a), 235 km/h (b), 315 km/h (c), granite ballast with elastic modulus of 150 MPa,
and 315 km/h (d), granite ballast with elastic modulus of 100 MPa.

The total displacement on the tie can be presented as a sum of two displacements: $\delta_{abs} = \delta_{def} + \delta_{avd}$, where δ_{def} is the deformation part of displacement found as a displacement difference between the displacement on the tie and the displacement on the bottom of the modelled area. δ_{avd} is presenting the movement of a big part of material surrounding the embankment as a whole. For the present analysis the interest is focused on the deformation part of the total displacement and it is shown in the Fig. 8 for train velocity equal to 315 km/h.

It was found that TGV train geometry (for same train velocity and axial load) is providing smaller displacements in the embankment as comparing to SAPSAN train geometry. Figure 9 is giving maximum displacement appearing in the embankment as a function of train velocity.

The main part of the maximum displacement change with velocity increase is provided by the increase of the load amplitude according to the experimentally measured dependency (Fig. 6). The smaller part of this change is given by wave processes within the embankment. Maximum displacements appearing in the embankment as a function of time, if one does not account for increase of the load amplitude for higher train velocities are given in Fig. 10.

The influence of the ballast material properties on maximum displacements was also studied. The received dependency for one of the train geometries (SAPSAN train geometry) and one of the train velocities (315 km/h) is given in Fig. 11.

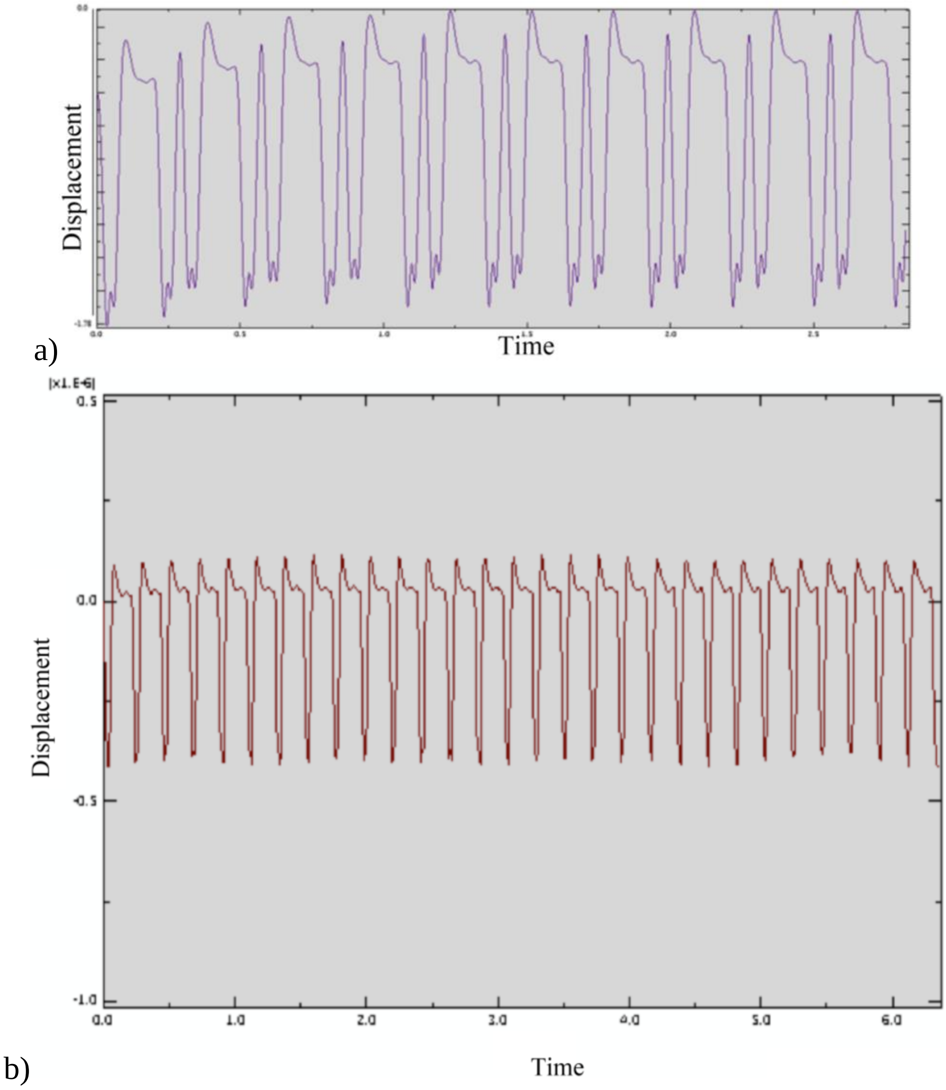

Fig. 8. History of vertical displacement (deformation part) at a point of contact between the rail and the tie.
a). SAPSAN train running at 315 km/h, granite ballast with elastic modulus of 150 MPa.
b). TGV train running at 315 km/h, granite ballast with elastic modulus of 100 MPa.

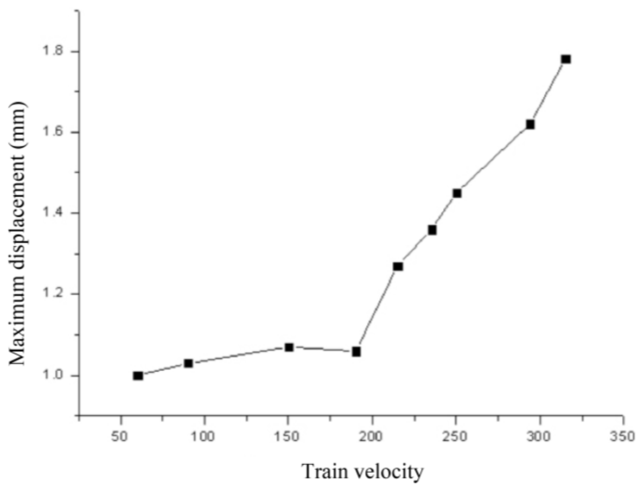

Fig. 9. Maximum displacement (deformation part) appearing in the embankment as a function of train velocity (SAPSAN train).

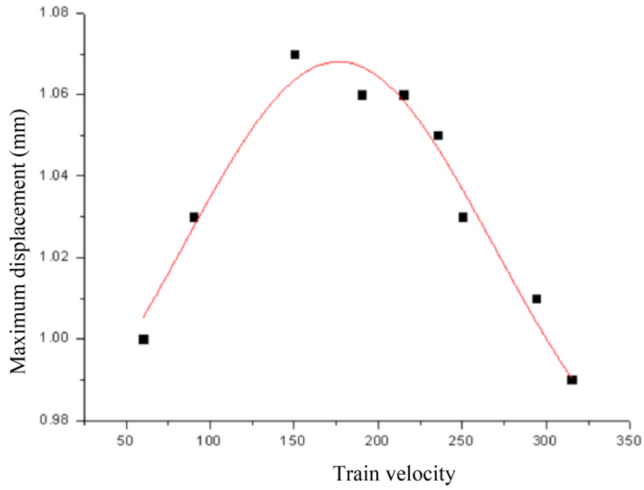

Fig. 10. Maximum displacement (deformation part) appearing in the embankment as a function of train velocity (SAPSAN train). Axial load is same for all velocities.

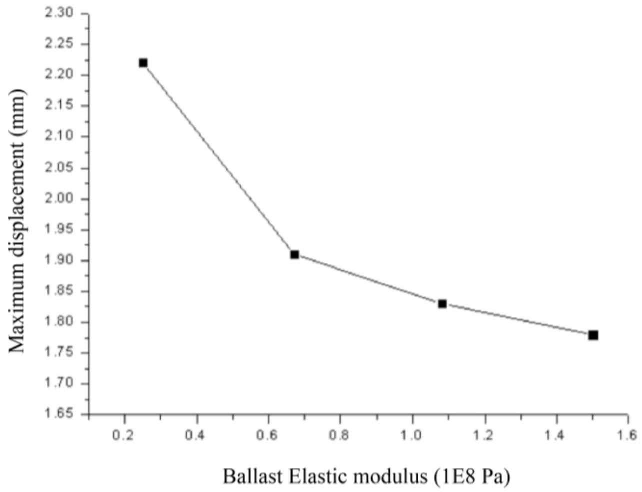

Fig. 11. Maximum vertical displacement (deformation part) as a function of ballast elastic modulus. SAPSAN train running at 315 km/h.

In order to validate the model experimental measurement of accelerations within embankment introduced by SAPSAN train passage was performed. Measured acceleration data is coinciding with modeling results (ex. Fig. 12) both qualitatively and quantitatively.

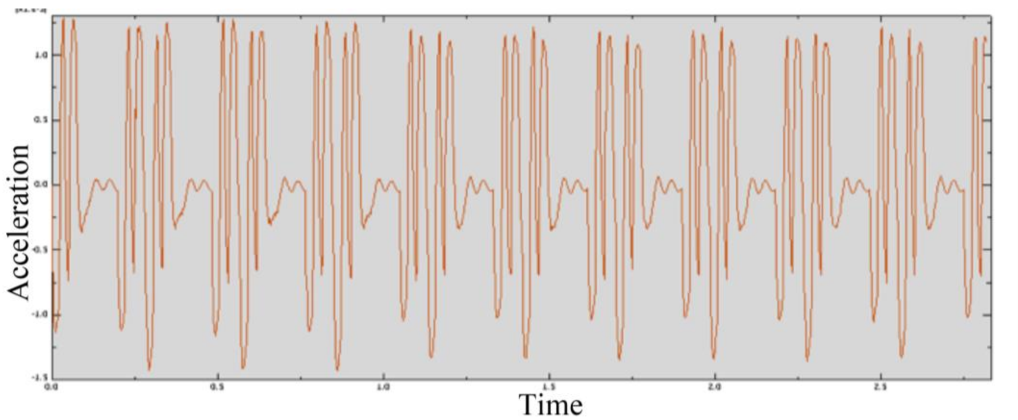

Fig. 12. Vertical acceleration history at a tie. SAPSAN train running at 315 km/h.

4. Conclusions

The constructed model was used in order to predict displacements and accelerations induced in the ballast layer by high-speed moving (50-315 km/h) SAPSAN train. Several different materials that can be used to form the rail track ballast were tested. Dependence of maximum displacements and accelerations observed in the embankment on properties of materials used to form the rail track ballast layers was evaluated. Dependence of maximum displacements and accelerations observed in the embankment on the velocity of the train was also studied. It was found that up to velocities of about 185 km/h maximal displacements and accelerations are not significantly growing with speed. For train speeds exceeding 185 km/h maximum displacements and accelerations are significantly dependent on the train velocity. In some cases displacements can exceed maximum possible displacements limited by Russian railroad safety standards. For example for 315 km/h maximum displacement is 1.8 times larger than the one for slow (50-185 km/h) moving train. Maximum displacements and accelerations of the railway embankment computed for SAPSAN train were compared to those computed for train geometry corresponding to French TGV high-speed train. It was found that TGV train passage excites smaller displacements and accelerations in the ballast layer as comparing to SAPSAN train (trains moving at the same velocity and having the same axle load).

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