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Influence of train-generated vibrations on embankment

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Abstract
Roads and railway lines are often constructed on different geotechnical structures such as tunnels, cuttings, and/or embankments. Three main parts are necessary to consider to evaluate vibration: the source of vibrations, vibration propagation path, and receiver of the signal. This paper describes a review of the influence of train-generated vibrations on an embankment and a building in the surroundings.
The first presented case study documents an interpretation of seismic signal in the frequency domain using wavelet transform. The algorithm, which we apply to the computation of the wavelet transform of the velocity component record, is based on the pyramidal algorithm, and the result of this procedure is used for an interpretation of data. The discrete wavelet transform was applied to the construction of a 3-dimension mapping of the time-frequency decomposition.
An example of the numerical model on the FEM method (the MIDAS GTS software) shows the vertical displacement of the embankment body during the movement of a train. The creation of these models is strictly based on the results of experimental seismological measurements. Then, the source of vibration is represented by a typical train/vehicle that runs on the nearest part of the railway/road at the most efficient velocity.

Keywords
Train-generated vibration, artificial seismicity, embankment, wavelet transform, FEM modelling

Introduction

Seismic loading is necessary to include in designs of structures in regions with seismic activity (natural earthquakes). Problems of vibration influence on structures and vulnerability of these are not usually solved in low seismicity areas. Therefore, artificial seismicity is necessary to take into account, although the maximum vibration amplitude is small as compared with the effect of natural earthquakes, especially in focal zones. For example, maximum velocity vibration amplitudes of artificial vibrations, excluding quarry blasts, reach 50.10^{-3} $m.s^{-1}$, while the amplitudes of earthquakes reach 400.10^{-3} $m.s^{-1}$ (according to International Standard ISO 4866-1990).

An embankment, in transportation, is a raised structure used especially to carry these lines or canals across a low-lying or wet area. Often, the material in embankments may contain much moisture. Thus, there is a risk that any slip may develop into a rapidly moving moisture-laden flow slide or mudflow (e.g. de Vallejo and Ferrer, 2002; Bell, 2004; Price, 2010). It is necessary to emphasize the fact that embankments during and after heavy rains are susceptible to damage due to vibrations. Also, vibrations may have a significant influence on the stability of this structure.

For issues related to the influence of artificial seismicity generated by traffic, we presented information in the papers Kalab et al., 2012; Kalab and Hrubesova, 2015; Kalab and Stemon, 2017. As regards basic literature that relates to the given topic, it is possible to mention books Thompson, 2009; Yang and Hung, 2009 or Al Suhairy, 2000. Common knowledge and theory are possible to derive from earthquake engineering studies (Towhata, 2008).

This paper describes a review of the influence of train-generated vibrations on an embankment and a building in the surroundings. Because this topic is very wide, only selected problems are discussed.

Main factors influencing vibration amplitudes

Three main parts are necessary to take into account to evaluate vibration: it means – the source of vibrations, vibration propagation path, and receiver of the signal (Fig. 1). It is necessary to point out the sound frequency domain – noise: wheel/rail interaction, brakes, wheel squeal on curves, horns and bells at grade crossings, diesel exhaust and fans (Meister, 2009, Lee, Griffin, 2013). However, this topic is not the content of the paper.

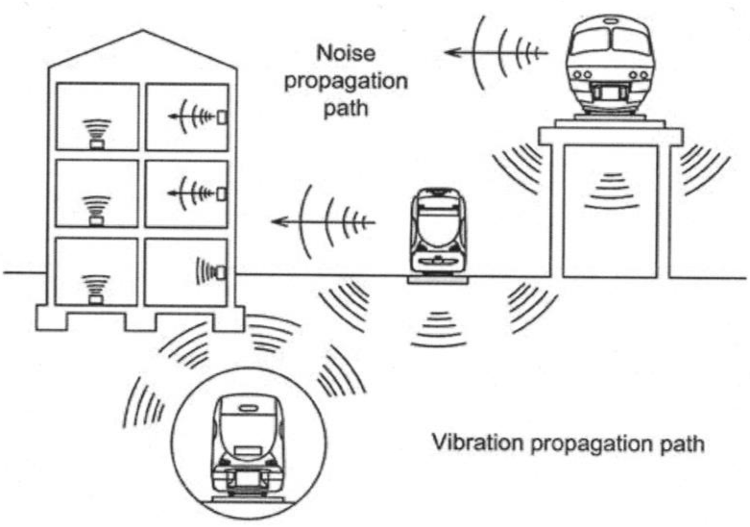

Fig.1 Rail traffic noise and vibrations (Lakusić, Ahac, 2012)

Ground bore vibrations are possibly transmitted through the ground from vibration sources such as heavy construction activities, railways, and roads to the structure. The transmitted vibrations could be enough to halt sensitive equipment operations and make occupants uncomfortable. It is considered unlikely that ground-borne vibrations cause structural damage (Huang et al., 2022; Types of loads, 2021). Figure 2 shows the source of ground-borne vibration and its transmission to the structure. This is a simple sketch; the geological environment usually consists of several subsurface layers of clays and sediments deposited on the rocks. Vibration records in small distances (near field) represent a simple pattern, and vibration records in longer distances (far field) contain several types of waves (for details, see seismological books, e.g. Shearer, 2019).

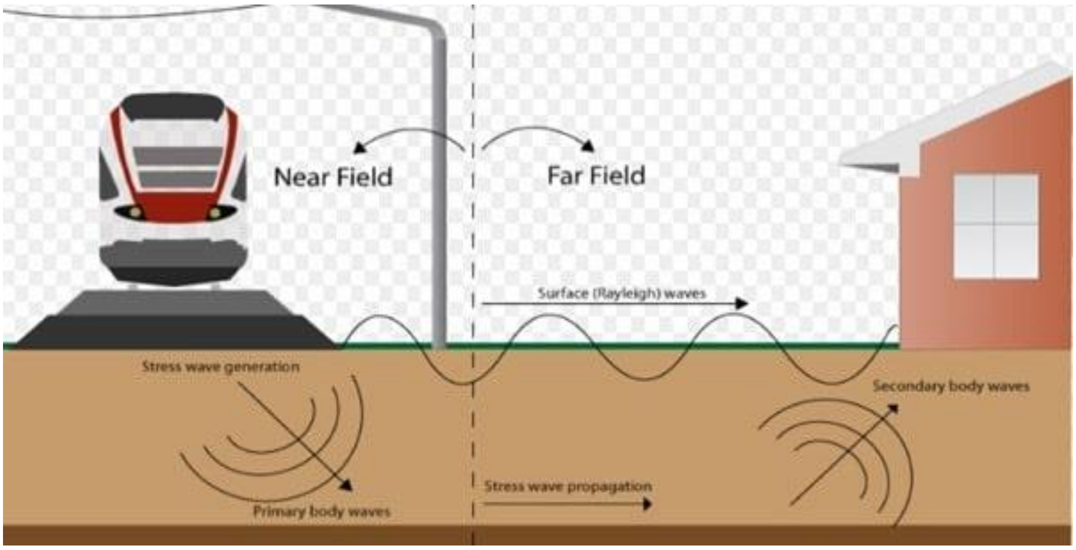

Fig. 2 Ground-borne vibration in buildings (Types of loads, 2021)

To discuss train-generated vibrations, many potential sources depending on the type of train are possible to determine. The main sources are summarized as follows (according to Meister, 2009):

- Vehicle suspension (primary suspension – wheel and/or truck mass deflect, secondary suspension – spring quality);
- Wheel type and condition (wheel defect, flat spot);
- Track surface (gap in track joint, running surface misalignment, corrugations in running surface);
- Track support system (resilient track fasteners, ballast mats, resiliently supported ties, floating slabs);
- Transit structure;
- Depth of vibration source (depth of ties, concrete pad, subgrade).
- Train speed also has a very significant influence on generated vibration amplitudes.

The vibration propagation environment is described as soils and rocks, soil layering, and/or rock layers. Physical parameters and characteristics of the soil/rock environment (represented path) are usually not at disposal. However, these geological characteristics of the environment between the source of vibrations and the studied place have a very important influence on amplitudes and other parameters of generated vibrations. Often, geotechnical and physical parameters of rock materials used for embankment constructions are known or obtained from different published studies and/or petrophysical databases (e.g. Zinszner and Pellerin, 2007). It means that preparing a simplified geological pattern with optimal physical parameters is usually possible. Depth of water table and frost depth is necessary to take into account, especially in the soil environment. The better the parameters are, the better the estimation of the vibration effect is performed, or the better results of numerical modelling are calculated.

After the vibrations propagate through the environment, the waves are recorded at the monitored point. Measurement methodology is dependent on a given point and the purpose for which the measurement is performed. For example, the vibration effect in a building is influenced by foundation type, building construction, location of a sensor in the building, and position of a sensor in the room. Even more complicated is the placement of the sensor when measuring in the field; it is recommended to remove grass under the sensor and compact the soil properly. However, a detailed methodology for the placement of the sensor in a building or field is not sufficiently defined. The parameters of the seismic channel and the seismograms must be chosen with great care so that the generated vibrations would be recorded in high quality and undistorted manner, both in time and frequency domains.

Analysis of train-generated vibration: Wavelet transform

The example presented below documents the character of train-generated vibrations. Common seismic instrumentation (GAIA seismic apparatus, made in the Czech Republic, Lennartz Le3D sensor, made in Germany) was used for field measurements: the frequency range of the seismic channel was 1 – 80 Hz, and the sampling frequency of the digital signal was 100 Hz. Measurement was performed in the surroundings of the trodden road that was located on the narrow embankment with a high of about 1.2 m.

The generated vibrations of about 20 trains were interpreted. The maximum measured vibration velocity value reaches almost 20 mm.s^{-1} on the railway tie. An example of a horizontal component (perpendicular to rails) of wave pattern recorded in the distance of 5.5 m is presented in Fig. 3. Almost linear attenuation of maximum vibration velocity is possible to detect up to a distance of about 7 m (value approx. 0.4 mm.s^{-1}); this attenuation is very strong. The effect of subsurface layers (wet clay) is more pronounced at greater distances (see Fig. 4) – which means on the plane on which the embankment was built. Frequencies in the records are possible to estimate using power spectra evolution within a moving time window. Prevailing maximum frequencies in the wave patterns were in the range of 5 – 9 Hz (Fig. 5). Maximum vibration values and character of attenuation curves in distances higher than 10 m are different, although local geological conditions are the same. It is possible to derive that only the speed of trains and their weights were different, and these factors influence recorded values.

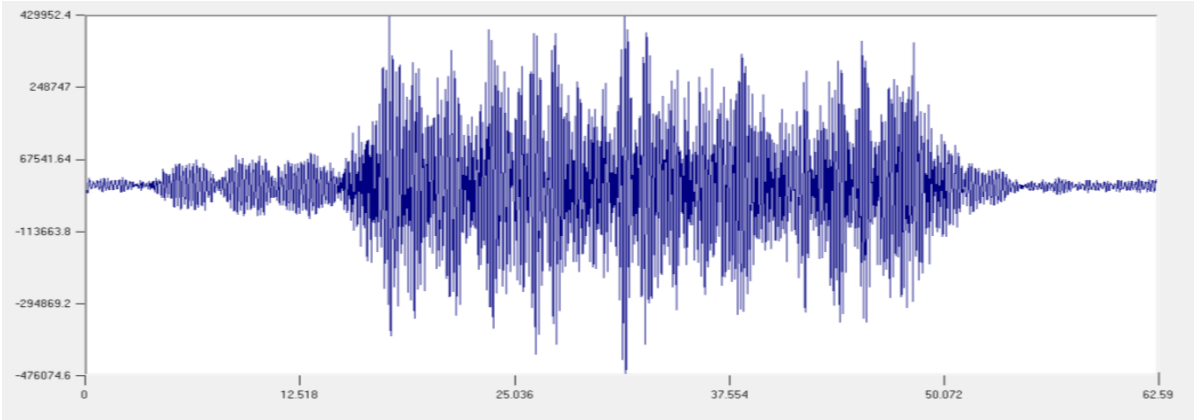

Fig. 3 Example of the horizontal component of the wave recording of the vibration velocity generated by the train (distance between railway and sensor was 5.5 m, maximum component velocity 2.3 mm.s^{-1} /in the graph in counts/; x-axis is relative time in seconds).

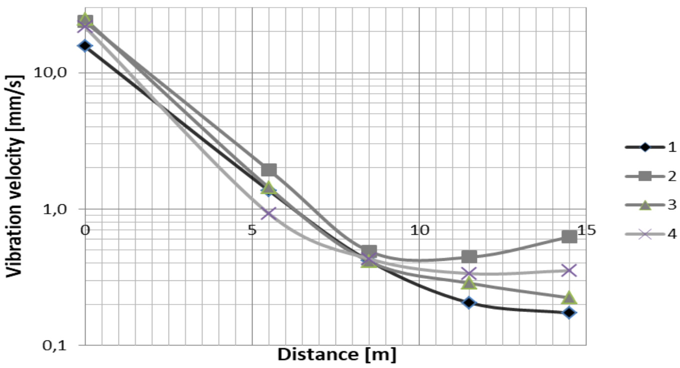

Fig. 4 Attenuation curves (vertical component) for selected data measured during this study. Curves: Train No. 1 is Pendolino, trains No. 2 and 3 are fast trains and train No. 4 is a local train.

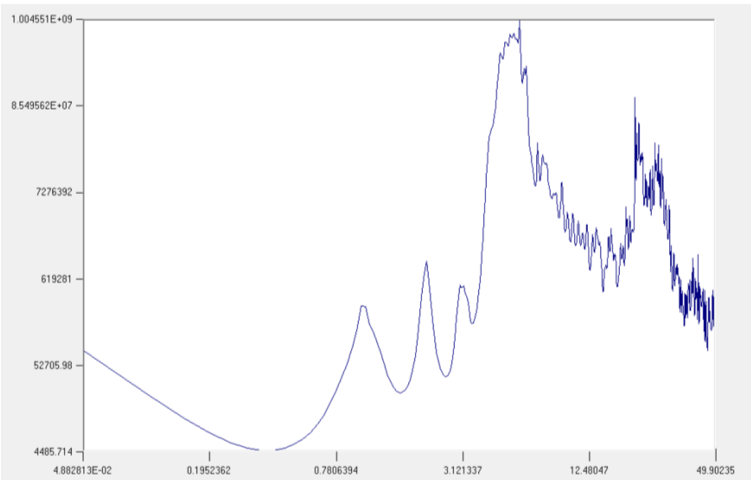

Fig. 5 Power (Fourier) spectrum of record on Fig. 3 (x-axis is frequency [Hz,] log-log scale)

Modern numerical methods play an increasingly important role in all fields of geophysics. These methods must also be used to interpret seismological data; fuzzy sets, fractal analysis, and wavelet analysis may be given as examples (e.g., Lyubushin et al., 2004; Ord et al., 2009; Telesca et al., 2011).

Wavelet transform (WT) is another type of digital data analysis in the time-frequency domain associated with conventional filtering. The mathematical theory of the WT was actively developed at the end of the 20th century (e.g., Klees and Haagmans, 2000). The first use of the wavelet transform in seismology was focused on data (signals) compression. A wavelet transform was also applied to smooth the recorded signals.

The algorithm, which we apply to the computation of the wavelet transform of the velocity component record, is based on the pyramidal algorithm, and the result of this procedure is used to interpret data. A discrete wavelet transform was applied to construct a 3-dimension time-frequency decomposition mapping.

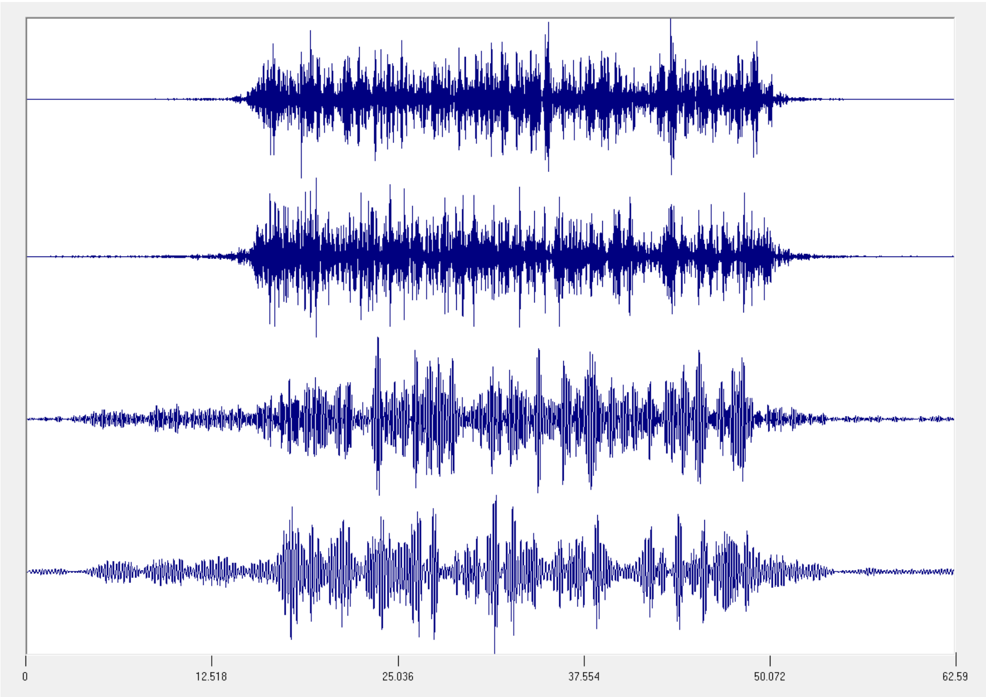

Fig. 6 Wavelet packet decomposition by orthogonal Daubechies wavelet of the order 20 of record in Fig. 3. Horizontal axis represents relative time [s]. Packet split levels: Tmin=0.02 s, Tmax=0.04 s; Tmin=0.04 s, Tmax=0.08 s; Tmin=0.08 s, Tmax=0.16 s; Tmin=0.16 s, Tmax=0.32 s. Vertical axes are normalized wavelet coefficients.

An example of the detailed interpretation of a recorded signal is presented in Fig. 6 and Fig. 7. Using Spectra_Analyzer software (made by Lyubushin, 2007), the recorded signal (see Figure 3) is decomposed into the defined number of packet split levels. These levels represent signals in given frequency/period ranges. The orthogonal Daubechies wavelet of the order 20 is used to decompose our measured signal (Daubechies, 1992). Suitable wavelet order is found automatically by using the minimum entropy criterion (e.g., Lyubushin et al., 2004). After plotting each sub-level in scale, we can see the most important parts of the original signal depending on periods. The number of packet split levels is selected according to the aim of the following application. These decompositions enable selecting frequency range(s) with the most significant vibration effect to evaluate train-generated vibration. The individual levels are normalized to their maxima to make different waves clearer.

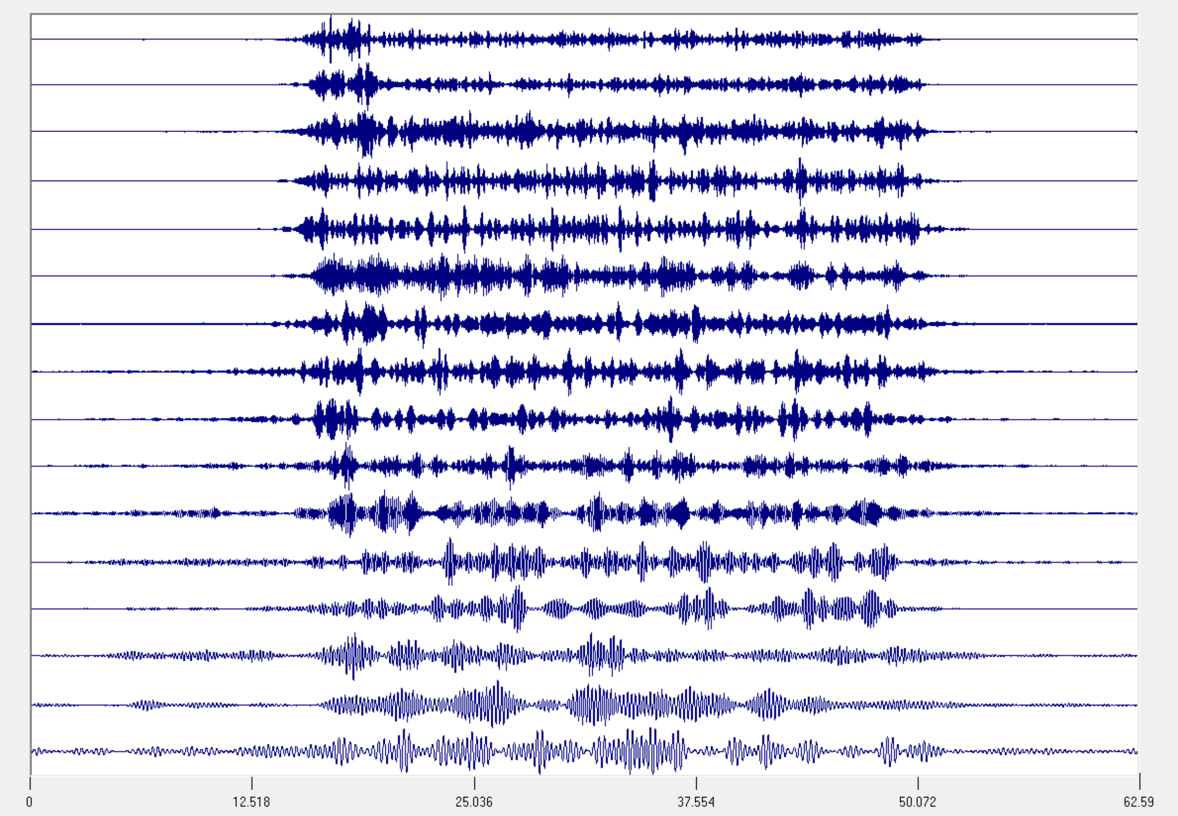

Fig. 7 Wavelet packet decomposition by orthogonal Daubechies wavelet of the order 20 of record in Fig. 3. Horizontal axis represents relative time [s]. Packet split levels: Tmin=0.02 s, Tmax=0.023 s; Tmin=0.023 s, Tmax=0.027 s; …; Tmin=0.26 s, Tmax=0.32 s. Vertical axes are normalized wavelet coefficients.

Numerical modelling: FEM

About 13.5 m high embankment represents an example of the model calculation of the dynamic response. The MIDAS GTS software (Finite Element Method) was used to construct the embankment; the length of the model is 50 m. A sketch of the model is presented in Fig. 8. Top-down layers in the model are defined especially by the elastic modulus of individual materials: A - structural layer (E = 23,000 MPa), B - reinforced layer (E = 130 MPa), C - upper part of the embankment body (E = 30 MPa), D, E, F - lower layers of the embankment body (E = 100 MPa), G - dusty soil (E = 20 MPa), H - weathered rock (E = 20 MPa), I - rock (E = 120 MPa). The natural oscillation analysis was performed to determine attenuation parameters (using analysis of eigenvalues and real effective mass).

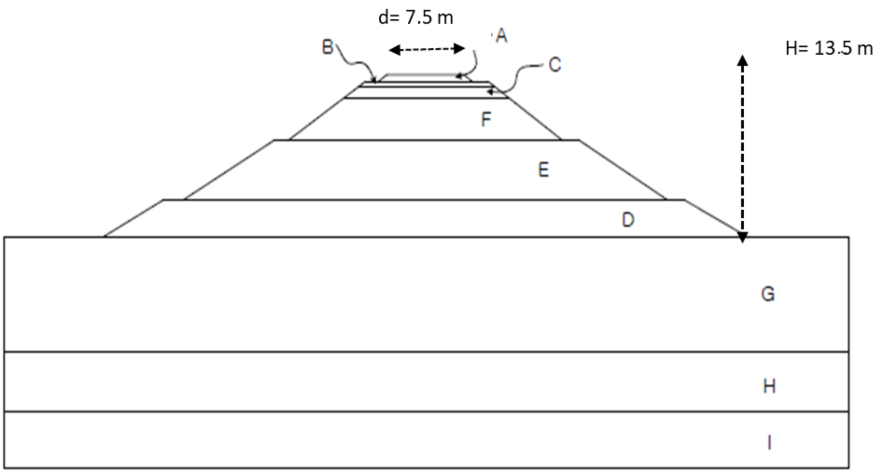

Fig. 8 Sketch of the model, A – I individual layers: description in the text (Kalab, Hrubesova, 2016)

This study used a train with a total length of 380 m and a weight of 700 t, representing 20 train cars. It means that the total number of wheels on both sides of the train is 92; impulse load from train passage was considered in nodes. A train speed of 162 km.h^{-1} was selected, and the beginning of the train reached the end point of the model in the time of 1.1 s. Examples of dynamic response calculation results are presented in Fig. 9 and 10 (Kalab and Hrubesova, 2016).

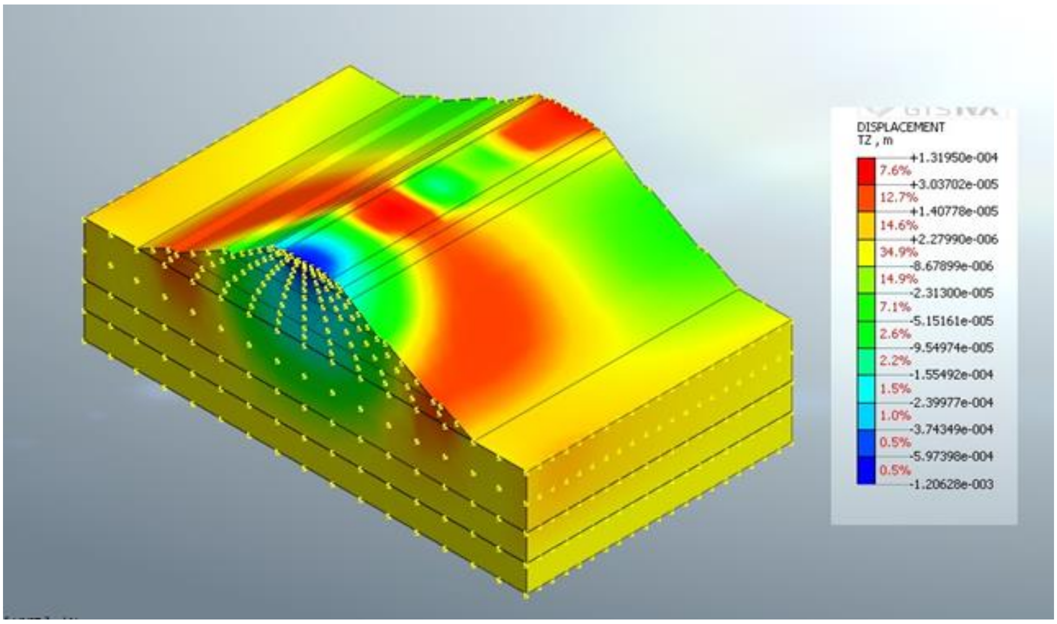

Fig. 9 Vertical displacement calculated at time 0.09 s, colour scale in m (Kalab and Hrubesova, 2016)

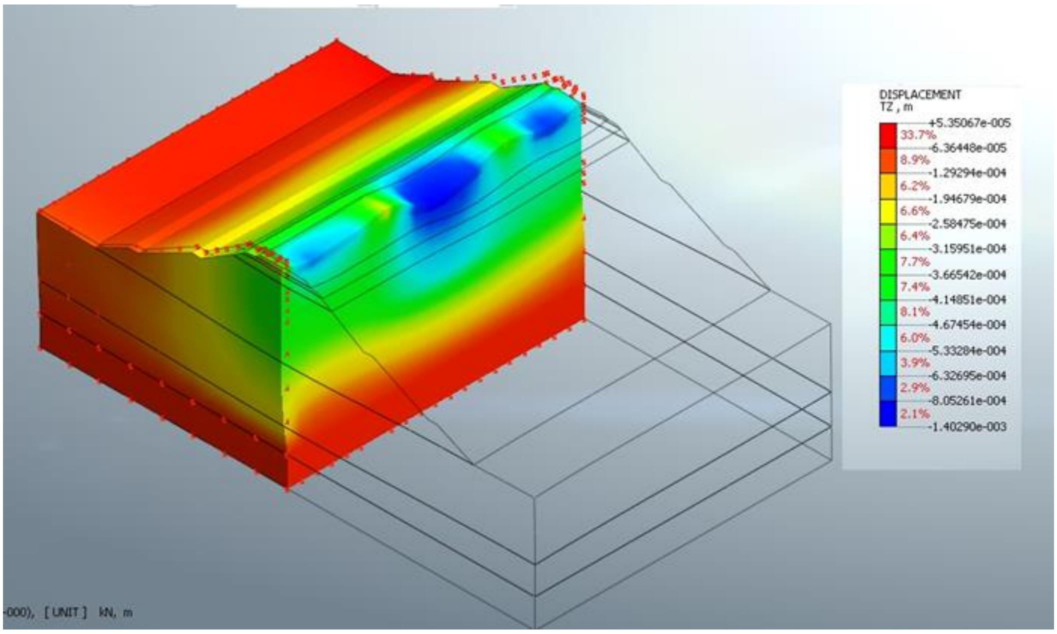

Fig. 10 Vertical displacement calculated at time 1.1 s, colour scale in m (Kalab and Hrubesova, 2016)

Discussion

The possible vibration effect in the surroundings of railway lines can be determined by experimental field measurements and/or numerical modelling of the given geological structures, vibrations, and also geotechnical structures and buildings (e.g., Yang and Hung, 2009; Thompson, 2009; Auersch, 2012; Thompson et al., 2019; Valaskova et al., 2015; Peng et al., 2022)

. A very special situation occurs if the railway lines are conducted after embankment. Analyses of the actual vibration measurements and the results from the numerical models have been performed in both the frequency and time domains.

Field measurement of vibration generated in the surroundings of a low embankment on which the railway is conducted shows different attenuation curves depending on the type of train. Differences are not documented on the slope of the embankment but mainly on the surroundings (Fig. 4). The first example also represents the use of wavelet transformation to interpret this real seismic signal. To compare individual split levels of decomposed signals (Fig. 6 and Fig. 7), it is possible to obtain information about the prevailing frequency range(s). This information is important for evaluating generated vibration on a building near railway lines and determining signal parameters for numerical modelling (source signal).

In the second case study, a 3D numerical model was performed using the MIDAS GTS software. The vertical displacements were obtained and presented graphically for two selected times (Fig. 9 and Fig. 10). The main aim, besides establishing 3D numerical model according to known characteristics and/or simplified situation, was the definition of the situation for predicting the values of vibration.

Conclusion

Field measurements and numerical modelling were carried out by many authors to obtain parameters of vibrations generated by moving cars/trains. The aims of those experimental seismological measurements represent three main tasks: determination of real amplitudes of generated vibrations, fitting of a numerical model, and searching of relations for prediction of vibrations (e.g. Al Suhairy, 2000; Hall, 2003).

The presented model of the vibration effects is based on the FEM calculation method - "Finite Element Method"; to obtain more detailed modelling results, the BEM method - "Boundary Element Method", is possible to use. The creation of these models is strictly based on the results of experimental seismological measurements. It should be considered and evaluated in all three parts of this process, it means the source of generated vibration, propagation path, and receiver parameters. In exceptional cases, replacing the dynamic calculation purposefully simplified field experiment is possible. Then, the source of vibration is represented by a typical train/vehicle that runs on the nearest part of the railway/road at the most efficient velocity.

This paper presents a short overview of factors influencing vibration amplitudes generated by trains. Two case studies document the need for detailed analyses, as these vibrations affect not only the embankment itself but also its surroundings.

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