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RAYLEIGH WAVES AND HIGH-SPEED RAILWAYS

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1. Introduction

During the running of a train, vibrations always occur at the wheel-rail contact, among other things. Most of them are radiated to the surroundings in the form of noise, while some of them spread further through the construction of the railway track and the subgrade into the surroundings of the railway line. Currently, in the Czech Republic, the spread of vibrations around the railway track is being addressed with regard to their negative effects on human health in the affected area [1] [2]. Act No. 258/2000 Coll., On the protection of public health and on the amendment of some related acts, as amended, and subsequent decrees, focus on this issue. To reduce the spread of vibrations, various elements are built into the construction of the railway track, such as under sleeper pads or anti-vibration mats.

In connection with a large increase of train velocities, unknown problems began to appear, including the response of the soils forming the subgrade of the railway track to one of the components of vibrations generated by moving trainsets - Rayleigh waves. If the train velocity that generates the Rayleigh wave exceeds the so-called critical ground velocity, there is a resonance and a several-fold increase in the amplitude of the Rayleigh wave. The above measures to reduce the effects of vibrations are not effective against this phenomenon [3], [4]. The track response can only result in damage to the structures around the railway line (eg overhead contact line masts) or even train derailment [3]. The manifestations of Rayleigh waves from rail transport were first measured in 1997-1998 at the municipality of Ledsgard in Sweden. They occurred at a train speed of 200 km.h-1 on a track whose subsoil was made of clay. The measured amplitudes of the vertical deviations reached 15–20 mm [3].

This issue is becoming topical in the Czech Republic in connection with the preparation of the construction of high-speed railway lines with a considered maximum velocity for passenger trains of 320 km.h-1. In the years 2015 to 2017, a technical-operational study, Technická řešení VRT (Technical solutions of high speed lines), was prepared for the then Správa železnic s.o. (Czech Railway Infrastructure Administration), by SUDOP Praha a.s. This study comprehensively addresses the issue of high-speed lines in the conditions of the Czech Republic. Among other things, this study explicitly mentions the need to address the issue of Rayleigh waves [4].

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2. Waves

For the purposes of the analysis of wave propagation in a real environment, the environment is simply considered to be flexible, homogeneous and isotropic. In a homogeneous and isotropic environment, the waves propagate at the same velocity in all directions. Two independent types of waves propagate from the source to the environment - P-waves and S-waves (slower than P-waves). P-waves are characterized by the densification and dilution of particles in the direction parallel to the direction of wave propagation (it is a longitudinal wave). S-waves, on the contrary, are characterized by a change in the shape of the body perpendicular to the direction of wave propagation (it is a transverse wave) [7], [8]. In the vicinity of interfaces with significantly different elastic properties, such as soil-air, the course of wave propagation is very complicated. There is a new type of wave - surface wave, and there is a reflection and interference of the wave. For surface waves, we distinguish between Rayleigh and Love waves. In Love waves, the particles oscillate perpendicular to the direction of the waves in the horizontal plane. In Rayleigh waves, the particles oscillate in the vertical plane [7], [8]. The waveforms of all the above-mentioned waves are schematically indicated in *Fig. 1*.

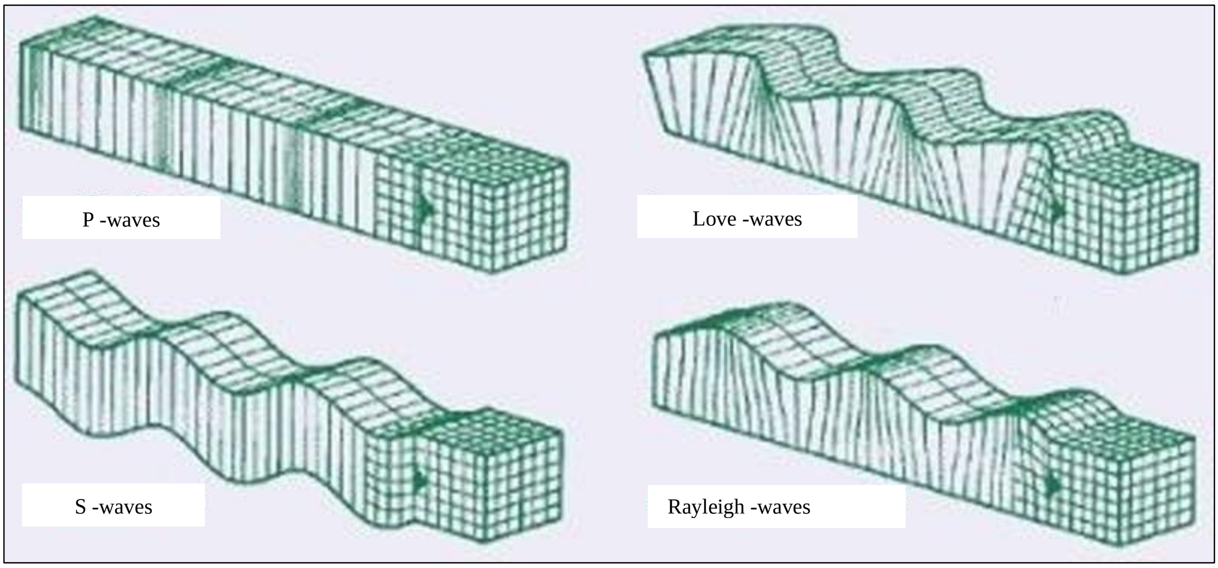

Fig. 1 – Diagram of waveforms [9]

3. Rayleigh waves

On a free surface, Rayleigh waves are manifested by a specific motion of particles, which describe a retrograde elliptical motion (counterclockwise). On the surface, the vertical deflection is about 1.5 times greater than the horizontal deflection [3]. The propagation velocity of Rayleigh waves is less than the propagation velocity of transverse (shear) waves. In terms of the total energy transmitted by the waves, 67% are transmitted by Rayleigh waves, 26% by S waves and 7% by P waves. This comparison shows that, from a practical point of view, Rayleigh waves are the most significant, even in terms of safety. The magnitude of the maximum deviation decreases with the increasing distance from the source, when the attenuation becomes more and more pronounced and the energy dissipation in the material continues [2].

The attenuation coefficient varies depending on the type of soil and its humidity in the range from 0.01 m-1 (uncompacted saturated soils) to 0.1 m-1 (compacted soils).

Rayleigh waves propagate almost exclusively in a layer with a thickness of one wavelength, so this wave is significantly attenuated with increasing depths. The wavelength of Rayleigh waves ranges from 5 m to 50 m [2].

4. Soils and critical soil velocity

If the velocity of the movement of the wave source (train) approaches or equals the so-called critical velocity of the ground, interference will occur, which is referred to as a ground boom. This phenomenon is physically similar to the sonic boom when the velocity of sound is exceeded. There is a several-fold increase in vibration intensity [3]. This can have a negative effect on the stability of the geometric position of the track, the stability of the subsoil, the foundations of nearby buildings and structures. In extreme cases, due to the phase shift of the vibrations and wave interference, the tracks may rise directly below the train axles. These dangerous manifestations only occur in a narrow range of train velocities. If the train velocity continues to increase after exceeding the critical ground velocity, these adverse effects gradually disappear [4], [6].

The critical velocity is the material constant of soils. Its size corresponds to the velocity of the propagation of Rayleigh waves through the soil. For soft clay soils, it is around 200-300 km/h, in very unfavorable conditions, it can be even lower. With the increasing stiffness of soils, their critical soil velocity also increases up to 600 km/h, or more for very hard subsoils. In the case of rocks, the critical soil velocity of the first thousand kilometers per hour is considered. In terms of low critical soil velocities, places with layers of fine-grained soils with high plasticity, ie layers formed by clays (MH, MV, ME) and clays (CH, CV and CE), appear to be the most problematic. They are especially risky if they are represented in strata of large thicknesses in the subsoil of railway tracks [3], [4], [10].

5. Experimental work

The experimental work carried out at the Department of Railway Structures, the Faculty of Civil Engineering, Czech Technical University in Prague, focuses on research into the propagation of Rayleigh waves in the vicinity of railway lines in the Czech Republic. Due to the different geological structure of the territory of the Czech Republic, it is not possible to simply take over the results of research from abroad, but it is necessary to verify the correctness of the conclusions of foreign research in our conditions. It should also be noted that research into Rayleigh waves has not been completed yet, and there is an opportunity to contribute to international efforts to address this issue.

For a longer-term monitoring of Rayleigh waves in natural conditions in the Czech Republic, a locality situated at the 4th transit corridor near the village of Horusice close to Horusice Pond was chosen. The maximum line speed in the monitored section is 160 km/ h. In this section, the track crosses the shallow valley of the Bukovský Brook with a newly built relocation. The valley is crossed by a bridge, which is followed on both sides by an embankment approximately 5 m high, which gradually decreases with the distance from the object. The subsoil around the railway line in these places is formed by peat and clays to a depth of about 5 m. The locality also has a high groundwater level, which is located about 0.5-0.8 m below the surface. The measured profile is shown in *Fig. 2*.

So far, seven measurement campaigns have been implemented in the Horusice locality during the years of 2020–2022. The aim of the long-term measurement is to capture the changes in the subsoil response depending on different seasons and the changes in soil moisture in the subsoil.

Fig.2 – View of the measured profile (marked by sticks)

To measure Rayleigh waves, 8 geophones of the SM6 type with a natural frequency of 4.5 Hz were used, arranged in a laid-out measured profile (see *Figs. 2* and *3*). The use of this type of sensors was chosen on the basis of foreign experience. The geophones were mounted in a special plastic case with a mandrel and placed on the surface of the railway body and the surrounding area so that the upper surface of the plastic case would be at ground level. The measurement was controlled by a laptop, and the measured values were recorded using a data logger with a recording frequency of 2,000 Hz. The processing of the measured data used specialized Sigview software.

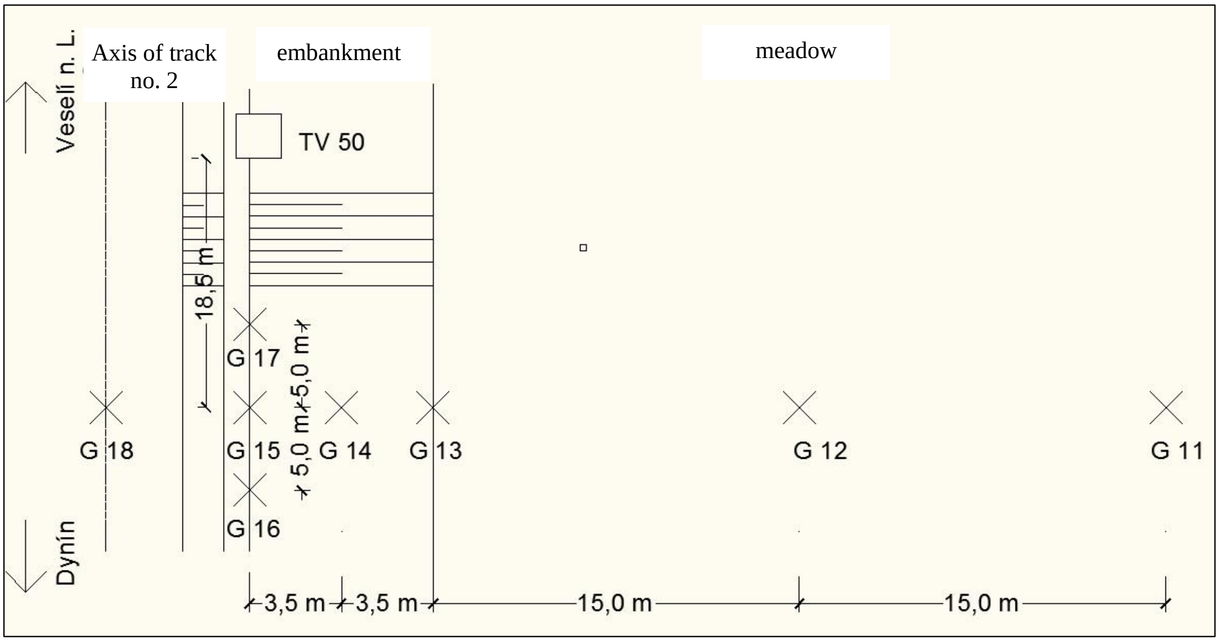

Fig.3 – Measured profile arrangement (points G11 - G18)

During each measurement campaign taking place between 8:30 and 15:00, the passages of all trains on both tracks were recorded. With regard to the higher velocity achieved by passenger trains and the low frequency of freight trains, the emphasis in the subsequent evaluation was mainly on passenger trains. These trains consisted of sets of express cars of a classic construction pulled by locomotives of the 242 or 362 series, the trains with a velocity of about 160 km/h were driven by locomotives of the 380 series. Due to the fact that the maximum deviations were recorded at the time of the locomotive's passage, the different numbers of cars in the sets were neglected in the detailed evaluation. The different weights of individual types of locomotives are also not considered, as the differences are minimal - the 242 series electric locomotive has a weight of 84 t, the 362 series electric locomotive has a weight of 86 t, and the 380 series electric locomotive has a weight of 88 t [11].

During the measurements, not only the response of the earth body to the passing trains was recorded, but also the seismic waves gradually excited by a light dynamic plate near all geophones. The obtained data are used in a follow-up study of the described issues - they serve as a basis for the creation of a mathematical model and for further research.

The following graphs (*Figures 4* and *5*) show some of the results of the measurements. The velocity of the passing trains is plotted on the horizontal axis, and the maximum values of positive vertical deviations are plotted on the vertical axis. For each measured case, a linear trend line was interpolated with a graph for easier interpretation of the measured values.

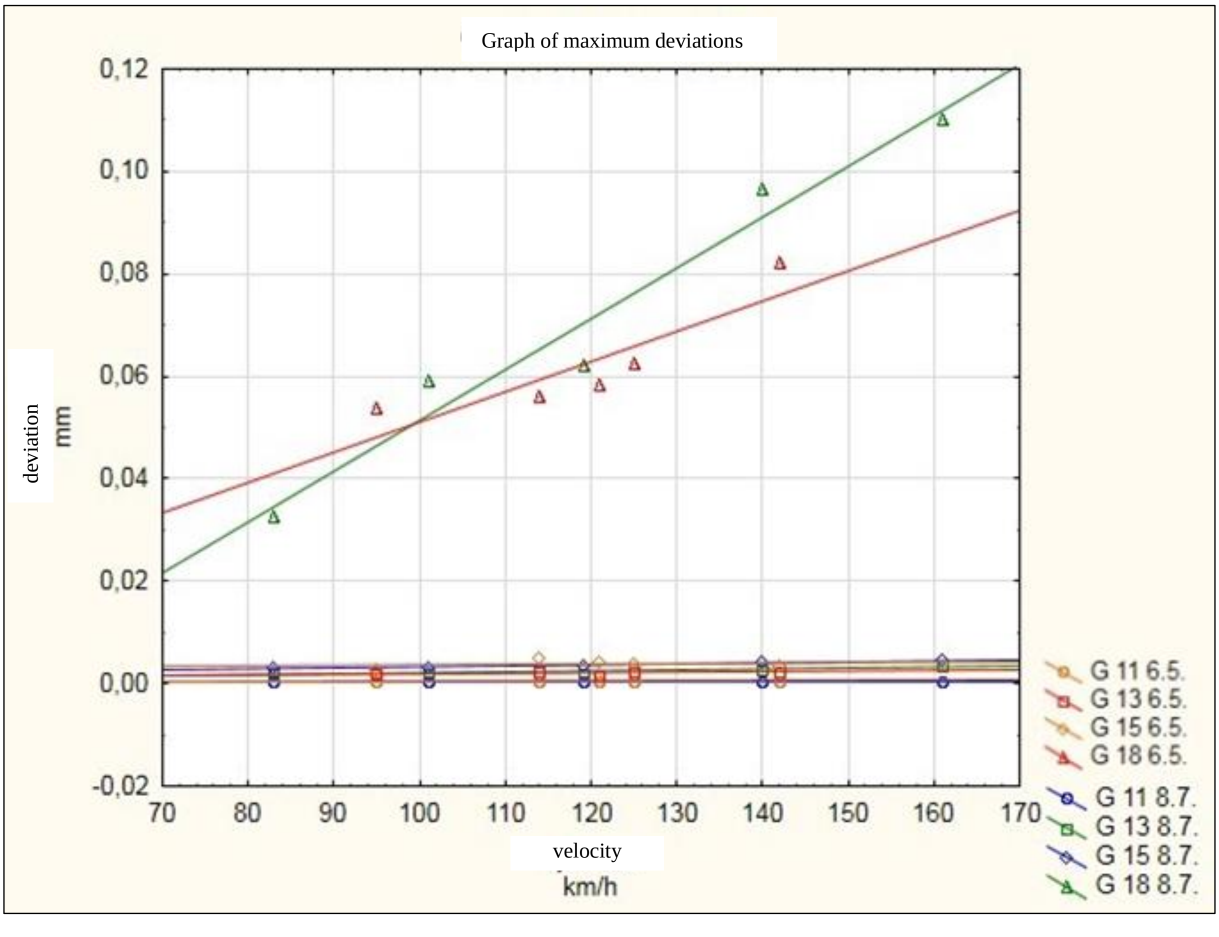

Fig.4 – Maximum positive deviations - all geophones

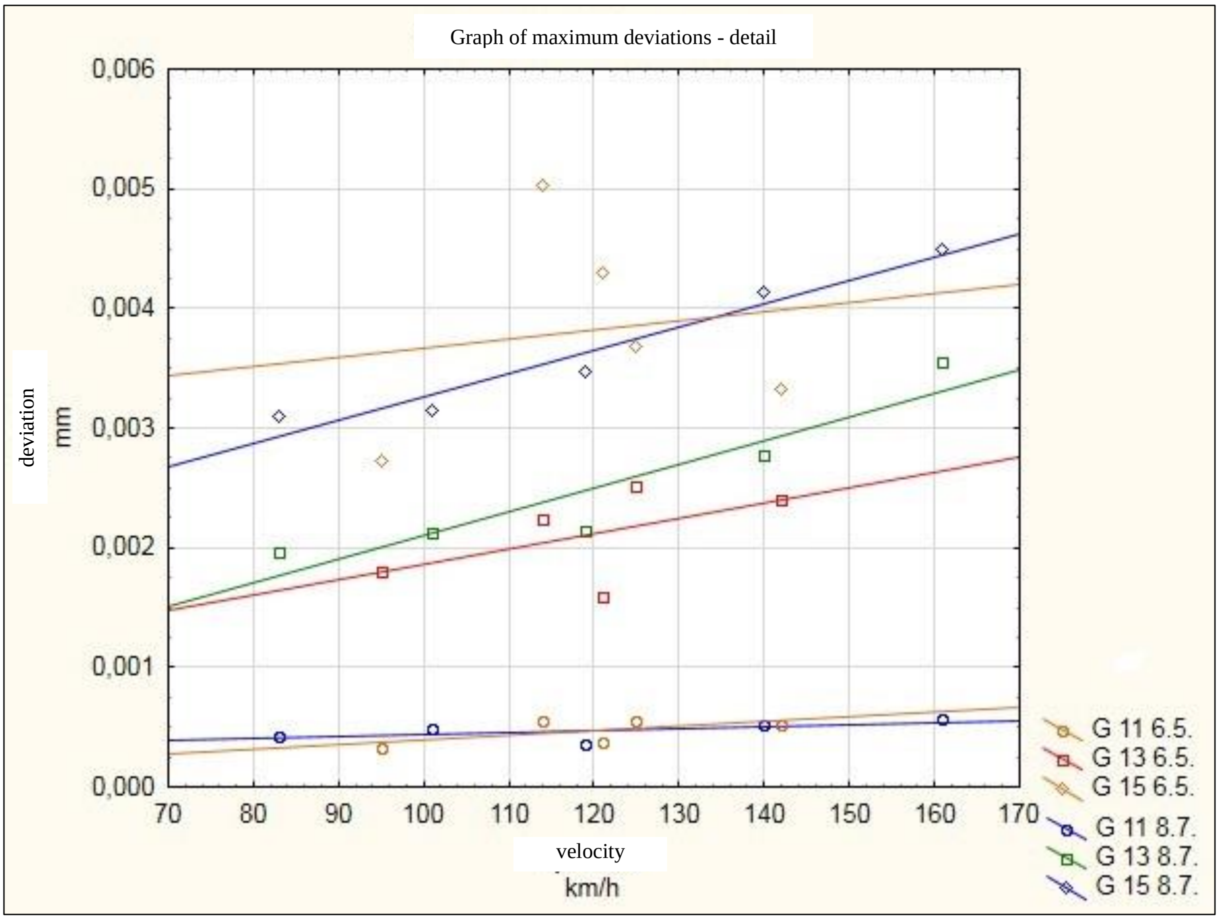

Fig.5 – Maximum positive deviations - detail for geophones G11, G13 and G15

The linear character of the interpolation corresponds very well to the whole range of the monitored train velocity. It is clear from the graphs that all the line slopes are of an increasing type, ie as the velocity of the trains increases, the size of the vertical deviation increases as well. Another characteristic feature is that the magnitude of the deviations in the monitored geophones decreases with the distance from the track axis. The largest difference in the magnitude of the deflection for neighbouring geophones was recorded between geophones G18 (in the track axis) and G15 (on the edge of the substructure subgrade), in the order of tenths of a millimeter. The difference in the size of the deviations between the G15, G13 and G11 geophones is in the order of thousands of millimeters. The significantly higher deviation values for the G18 geophone compared to the other geophones correspond to its location in the track axis. More detailed results have been presented in previous papers [12], [13].

6. Conclusion

The issue of Rayleigh waves is being monitored abroad with regard to the potential risks of negative effects on high-speed railways. In terms of behavior, this is a different phenomenon than the propagation of vibrations, which we are still used to address in the conditions of the Czech Republic.

In general, the risk that unwanted manifestations of Rayleigh waves cannot occur in some localities with problematic geology cannot be ruled out for the prepared sections of high-speed lines in the Czech Republic. Therefore, it is desirable to continue to pay close attention to this phenomenon due to its potentially significant harmfulness.

Based on the experimental measurements performed in the Horusice locality so far, the following can be stated:

- As the distance of the sensor from the track axis increases, the magnitude of vertical deflections decreases, while the decrease in the amount of deflection is not linear with respect to the distance from the track axis.
- As the train velocity increases, the magnitude of vertical deflections increases, with the increase in the magnitude of the deflections being approximately linear.
- The soil moisture in the vicinity of the railway track in individual measurement campaigns, or in different seasons respectively, differs only by units of percent. The effect of soil moisture on the size of vertical deviations has not been proven.

After all measurement campaigns in the Horusice locality, a comprehensive evaluation of the data will be started.

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