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SYNOPSIS: Increasing demands on speed increase, higher axle on transportation overdimensional and havy loads cause simultaneous increase of unfavourable traffic effect on the structures of railways and on the train-induced ground vibration, respectively. This paper examines the residual problems of ground-borne vibration, the vehicle and track features which might be responsible for generation, how it is propagated, and how it might affect. A few of experimental results which have been obtained during studies made on Slovak Railways (ŽSR) are presented in the paper, too.

INTRODUCTION

The operation of modern railways has been attended by an increase in train speed, train weight and wagon axleload. At the same time greater attention is being paid to track quality. The changes in vehicle and train requirements has been matched to some extend by developments in track design. There seem nevertheless to be a few scattered complaints by wayside residents of vibration due to the passage of trains. The main aim of this paper is to point out the related problem of the vibration caused by traffic on surface railways, a subject which has been treated very little up to nowdays.

VIBRATION GENERATION PROCESS

The structures of the practical railway has many features which are capable of supplementing the basic stress field beneath the train. Any unsteady riding of the vehicle such as bouncing, rolling, pitching and yawing must result in additional fluctuating forces on the track structure. Recognized defects such as eccentric wheels, unbalanced wheels and wheelflats may also contribute to ground disturbance. The track itself does not provide uniform support: the rails, themselves of fixed length, are supported on sleepers placed at regular intervals, and the sleepers are in turn surrounded by and rest upon stone ballast. This ballast bed may by its very nature provide a somewhat variable support, and voidage below the occasional sleeper is a well known fault. All of these track features can be expected to contribute to the stress field present in the ground below and beside the train, and hence contribute to the vibration disturbances which propagate to the wayside. Clearly some of these will produce a purely local effect in the case of isolated features, while others will provide a regular pattern moving with the train.

The extend to which these features promote vibration can be expected to depend on the speed of the train and the weight of the vehicles within it. The static weight of the train provides the basic stress field due to the train, while the unsprung masses and the suspension characteristics of the vehicles, allied to their speed, will determine the extend to which track and rolling stock characteristics enhance this stress field. The experimental evidences point out the impacts from the weels passing over the rail joints have significant influence on ground vibration transmited from railway to nearby regions and the spectral characteristics of the ground-borne vibration can be significantly dependent on: (i) a unit train of identical vehicles produces ground vibration at frequencies which are related to wagon length; (ii) vibration which are produced by passing steady wheel load over the discrete support provided by sleepers. This effect is independent on inertia effects; (iii) vehicle vibrations (innertia effects); and (iv) track irregularities.

WAVE PROPAGATION PROCESS

Once transient stress variations are produced in the ground below the track, they will propagate away from the track as ground-borne vibration. A variety of modes of vibration are possible within the ground, and the principal types are the following: (a) compression waves, with particle motion being an oscillation in the direction of propagation; (b) shear waves, with particle motion being an oscillation in a plane normal to the direction of propagation; (c) Rayleigh's waves, which are surface waves, with a particle motion generally elliptical in a vertical plane through the direction of propagation. In the ideal case when the ground is homogeneous the compression and shear waves propagate in all directions away from the source, and hence suffer substantial geometric attenuation, as well as losses due to the damping properties of the ground. The Rayleigh's waves, being surface waves, do not suffer the same geometric attenuation, but are still subject to loss by damping. In practice the ground is far from homogeneous; it may well be stratified, and possess discontinuities. In such a case additional modes of vibration can propagate along the interfaces of strata, and mode conversion from one type of wave to another may be encouraged. The various mode have different propagation velocities. The compression waves travel at typically 1000 m/s, while the shear and Rayleigh's waves are much slower. Velocities for these seem typically to be about 200 m/s, but Rayleigh's waves have been reported as slow as 35 m/s, Hannelius (1978), although we have no experience of any so slow. The vibration energy is not shared equally among the modes. Because of different geometric attenuations, the Rayleigh's wave carries most of the vibration energy at significant distances away from the track, Miller and Pursey (1955).

A further significant factor is that is that high frequencies are attenuated much rapidly than low frequencies, so that low frequencies dominate the spectrum at distances of more than a few metres from the source, Benčat (1986).
With the complication of so many modes of propagation, and the wide variety of geological conditions over which railways have to be built, it would not be surprising if trackside measurements at different sites produced a range of vibration values which bore no resemblance to each other. The experience which we have to date of vibration measurements in terms of vibration acceleration level (linear over the range 2 Hz to 1000 Hz) made on a variety of sites in Slovakia, yields just the confused picture to be expected. Both the levels of vibration and the manner in which the level decays with distance vary in a manner which has so far defied prediction. The only measure of consistency to date is that changing from one site to another does not appear to alter the rank order of vehicles in terms of their vibration generation characteristics.
The additional informations regarding to ground–borne vibration due to moving train have been reported e. q. Benčat (1992), Dawn and Stanworth (1979), Ford (1987), Fujikake (1986, 1987), Hannelius (1978).

EXPERIMENTAL RESULTS

The experimental tests have been performed in the test fields of the railways (ŽSR). The object of the experimental measurements was to find: (i) spectral characteristics of the components of the railway structure near the nearest rail joints and in the long distance from rail joints (rails, heavy concrete ties, ballast, roadbed and ground) by the power spectral densities $G_{xx}(f)$, $G_{xy}(f)$; (ii) the soil frequency characteristics expresed by the frequency response function $H(f)$ or by the gain factor of the response function $|H(f)|$, respectively; (iii) the Rayleigh's wave velocities v_R by the cross correlation function $R_{xy}(\tau)$ and then calculation the initial tangent shear modulus G_0, see also Benčat (1986); and (iv) the attenuation coefficients α from equation $\alpha = -(l_0 - l_x)^{-1} \cdot ln(k\, \sigma_d^0 / \sigma_d^x)$, where standard deviations σ_d^0, σ_d^x of amplitude vibration at the distance l_0, l_x from source of vibration are obtained from power spectral densities $G_{xx}(f)$, $G_{yy}(f)$, and $k = (l_0 / l_x)^{0,5}$ represents the effect of geometrical dispersion, Benčat (1986).
As shown in Fig. 1 in the railway track of ŽSR line many pickups were attached to the rail, the ties, ballast and wooden piles driven into the roadbed and ground and the accelerations of the vibrations were recorded using portable notebook computer (PC/386) with software and hardware facilities. The records obtained in the field were investigated by using a frequency analyser BK-2131 and PC/386; additional information of the field tests see Benčat (1992). In Fig. 2 results of one of the spectral and correlation analysis of the accelerations of the vibrations induced in the rail, the tie, roadbed and ground are shown.
The dimensions of the track and ground were as follows: welded rails – 50.0 kg/m, m length, tie – prestressed concrete tie, weighing 250 kg; tie pad - rubber, thickness of 6 mm (elastic constant of 600 kN/cm); ballast - crushed stone with depth of 350 mm; roadbed – embankment of 250 cm and ground- clay of 50 cm ($\rho = 1982$ kg/m^3) and sandy gravel ($\rho = 2050$ kg/m^3) of 10 m with water level at 4.0 m beneath ground surface.
The results of the analysis of all the measurements are presented in detail see, Benčat (1992). This paper describes the results only of one of all performed experimental tests as an example of using the method described.

Using of the spectral and the correlation analysis results of the track and ground vibrations and theretical analysis of the viscoelastic shear and Rayleigh's waves, Benčat (1986), the results regarding to the ground geotechnical parameters are as follows:
$v_R = 185.20$ m/s, $\alpha = 0.049$ m^{-1}, $G_0 = 75.10$ MPa. The complex moduli are given by

$$E^* = E_0 (1 + i\, \delta_E) \quad (1)$$
$$G^* = G_0 (1 + i\, \delta_G) \quad (2)$$

where E_0, G_0 = real components of complex moduli E^*, G^*, ($e.g;\ G_0 = \rho\, v_R^2 F_{RE}$), δ_E, δ_G = imaginary components of complex moduli E^*, G^* and represent the viscous properties of soil media. Damping parameters were obtained by approximate relationship between a coefficient of attenuation α and a wave length λ_R of the propagating Rayleigh's waves as follows $\delta_G = |\alpha| \lambda_R / \pi$, then: $\delta_G = 0.170$ and $G^* = 75.10 (1 + i\, 0.170)$. The calculation includes the data as follows: $\lambda_R = 9.30$ m, $\rho = 2050$ kg/m^3, $\nu = 0,35$.

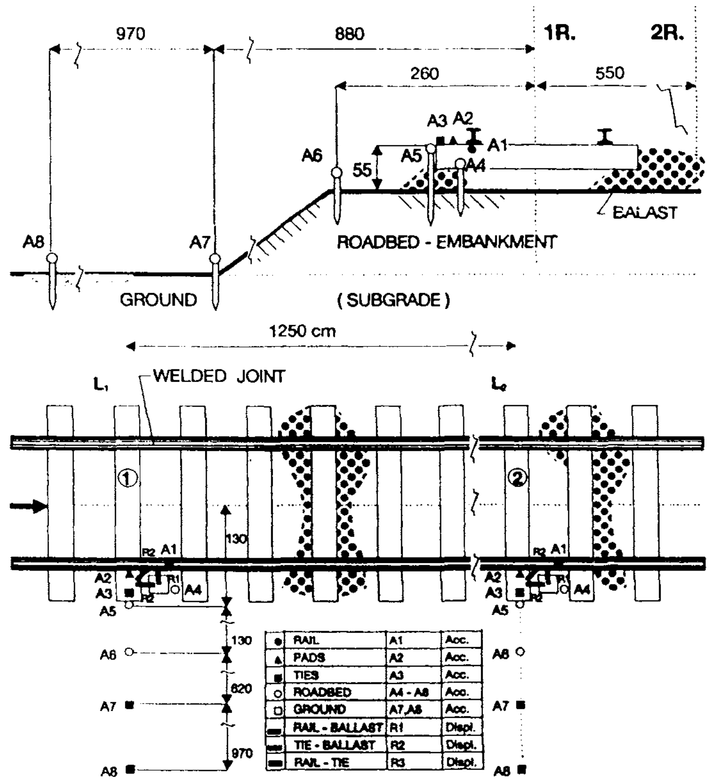

Fig. 1. Position of the Attached Pickups

SUMMARY AND CONCLUSIONS

From perfomed of the theoretical and the experimental analysis of the railway track and ground vibrations, the following summary and conclusions may be made:
- The results of the experimental measurements indicate that the analysis of random ground vibration due to railway traffic

means provides a useful and required information on the frequency spectral characteristics of ground vibration $G_{xx}(f)$, $G_{xy}(f)$; the vibration characteristic of soils $H(f)$; the surface wave velocities propagation v_R; the soil attenuation coeficients α; and damping parameters δ as well as the visco-elastic properties of soils, E, G, δ, E^*, G^*.

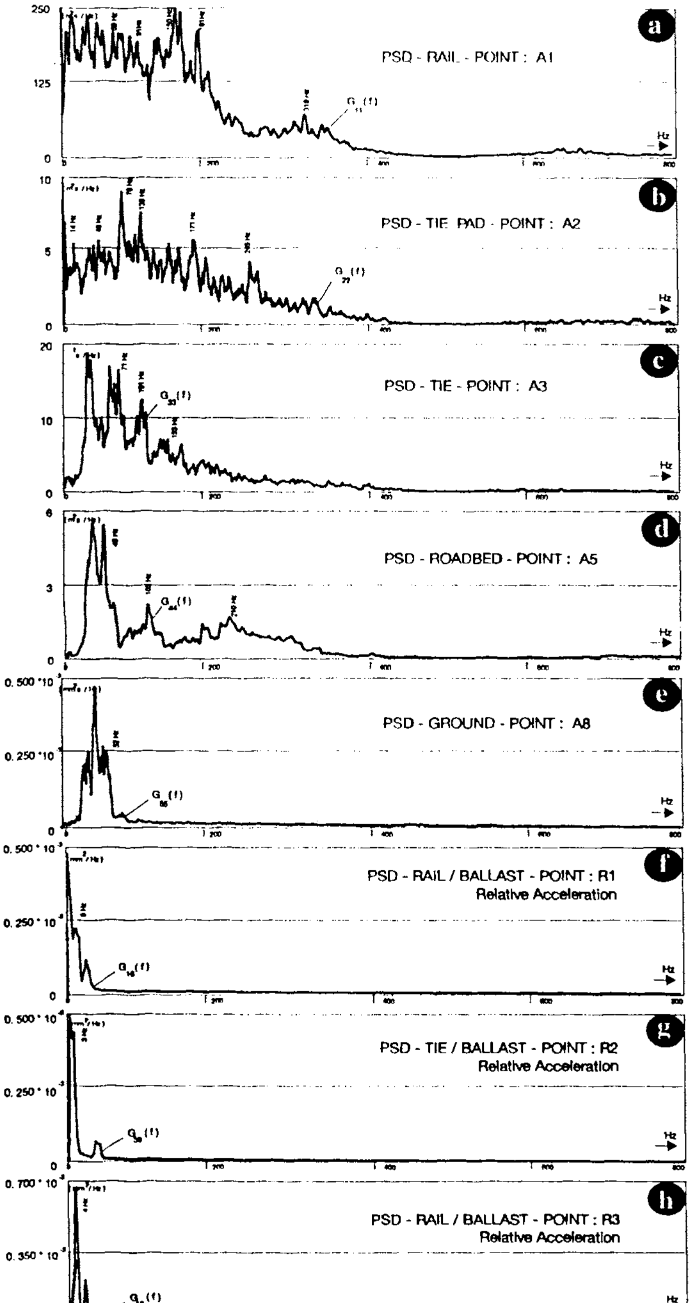

Fig. 2. Power Spectral Densities (PSD) of the Vibration Accelerations in Diferent Points of the Railway Structure and Adjacent Ground Due to Trains of 100t Bulk Carriers of Granular Materials, (70.0 km/h)

● From the spectrum analyses of the accelerations of the vibrations induced in the rail, the tie, the roadbed and the ground we can observe that the second peak is found at frequency of 80.0 Hz, Fig 2a (near the welded rail joint) but in Figs 2b, 2c the second peak can not be found at the same frequency. In comparison of these figures we see that the accelerations of the vibrations with lower frequencies induced in the rail are transmited to the ties and the roadbed with little damping, but the vibrations with the frequencies over 120.0 Hz are transmited downwards with large damping coefficient.

● Power spectral densities (PSD) of the ground transmited Rayleigh's waves indicate higher damping in the higher frequencies e.q. over 80.0 Hz. It proves the visco-elastic properties of the ground and roadbed, respectively. In the Fig 2d and 2e the peaks of the PSD are in the range frequencies from 20.0 Hz to 80.0 Hz, which indicates significant influence of the vibrations induced after the impulse into the track and ground.

● Experimantal and theoretical analysis, Ono and Yamada (1983), Benčat (1992), shows that three kinds of vibration are induced in the track and the roadbed by the application of the impulse. The first kind of vibration is the stationary vibration which continues with a constant amplitude and a fundamental frequency. The second kind is represented by the sum of the waves which propagate along the rail. This waves have the frequencies which are larger than the fundamental one and range in some intervals. The third kind is represented by the sum of the waves which propagate in the downward direction with various frequencies. The range of the frequencies is from the maximum value involved in the second kind to infinity. Experimental analysis has proved when the spring constant of the tie pads increases and bed materials become more softer, neither exist the first nor the second kind of vibration and only the kind of vibration is induced after the impulse.

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