Measurement and prediction of ground vibration from railway traffic

Mesures et prédiction des vibrations du sol induites par la circulation ferroviaire

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ABSTRACT: This paper examines the nature and magnitude of ground vibrations by railway traffic. These vibrations are generated by two main mechanisms: vibrations from the axle loads moving at constant speed, and vibrations from the inertia forces of the train caused by railhead irregularity. Results from the test runs in southern Sweden are used to validate a numerical simulation model developed for this study. The numerical model is used to investigate the effectiveness of stiff track structures in suppressing ground vibration by the two mechanisms.

RÉSUMÉ: Ce paper examine la nature et l'ordre de grandeur des vibrations du sol induites par la circulation ferroviaire. Ces vibrations sont générées par deux mécanismes principaux: les vibrations du chargement des axes se déplaçant à vitesse constante, et les vibrations des forces d'inertie du train engendrées par les irrégularités du profil des rails. Les résultats de tests effectués dans le sud de la Suède sont utilisés pour valider un modèle de simulation numérique développé dans le cadre de cette étude. Le modèle numérique est utilisé pour investiguer l'efficacité de structures de voie rigides permettant de supprimer les vibrations du sol dues aux deux mécanismes.

1 INTRODUCTION

Ground vibrations by railway traffic are generated by two prime excitation mechanisms: i) the quasi-static displacement caused by the axle load as the wheel moves along the track, and ii) the inertia forces due to the acceleration of the unsprung mass of the train as it rolls over the irregular profile of the railhead (Fig. 1). Rail irregularity profiles, have generally an erratic nature. Therefore, the associated ground vibrations tend to display a stochastic character. The moving load excitation, on the other hand, has a well defined function and the associated vibrations can be treated deterministically.

Most of the studies on train-induced ground vibration conducted until a few years ago have dealt primarily with vibration from the second mechanism because moving-load contribution to the total vibration was considered secondary. However, actual observations and measurements with high-speed trains have in the past several years revealed that one might observe remarkably large vibrations in soft soil sites from the moving-load excitation mechanism (e.g. Woldringh & New, 1999).

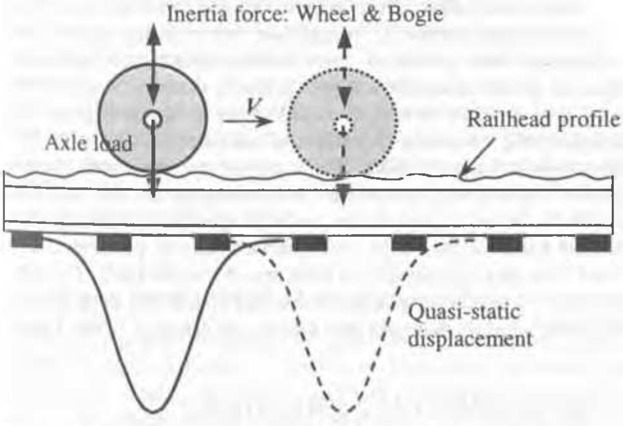

Figure 1. Schematic representation of railway excitation mechanisms

This paper presents typical measured ground vibration from railway traffic at a test site in Ledsgaard on the West Coast Line in southern Sweden. The paper also presents the corresponding numerical simulations using the computer code *VibTrain* (Kaynia, 1999). Vibrations from both moving load and rail irregularity are calculated separately and compared with the measurements. The objective is to highlight the conditions under which each excitation mechanism is dominant. In addition, the effectiveness of track stiffening for mitigating ground vibration is investigated numerically. The excitation mechanisms are again treated separately in this study.

2 EXCITATION MECHANISMS

2.1 *Quasi-static moving load*

Theoretical studies have shown that moving loads can produce ground vibration at high speeds. At low speeds, compared to the characteristic wave velocities of the medium, the ground response from a moving source is essentially quasi-static. That is, the displacement and stress fields resemble those for static condition but simply move under the load. However, as the speed of the load reaches the Rayleigh wave velocity of the ground, a situation reminiscent of the supersonic condition in aerodynamics, and characterised by large motions appear in the response. A number of measurements of excessive ground vibration at several sites in Europe, including those on the West Coast Line of Swedish Railway (Adolfsson et al. 1999, SGI 1999), have substantiated the theoretical findings. Such large motions raise concern about the running safety of the train and warrant appropriate countermeasures.

It has become common to categorise moving-load problems as subseismic, superseismic, and transseismic, depending on whether the load speed is less than the Rayleigh-wave velocity of the ground, greater than the compression wave velocity, or intermediate between these velocities. Theoretical studies on this subject have revealed that the subseismic regime represents a quasi-static condition, whereas the transseismic and superseismic cases are characterised by large dynamic effects associated

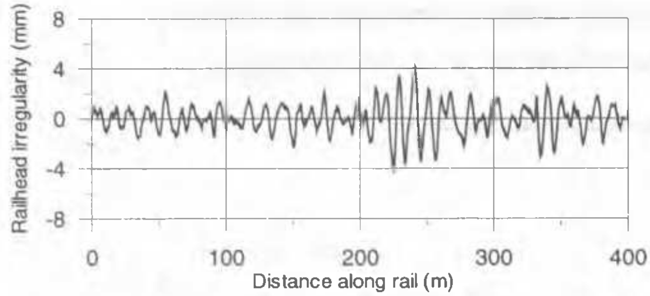

Figure 2. Typical rail irregularity profile at Ledsgaard test site

with the development of Mach lines and Mach surfaces in the ground response (e.g. De Barros & Luco 1994).

A number of numerical solutions have been presented in recent years that account for the presence of a track/embankment structure (commonly represented as a beam) over the halfspace model of the ground (e.g. Krylov 1995, Dieterman & Metrikine 1997, Lieb & Sudret 1998, Suiker et al. 1998). More recent models (Takemiya & Yuasa 1999, Kaynia et al. 2000, Jones et al. 2000, and Clouteau et al. 2000) have accounted for ground layering. The solution proposed by Kaynia et al. (2000) is used for the numerical modelling of track-side vibration in this study.

2.2 *Railhead irregularity*

Irregularity of the railhead and the wheel tread are important forms of track imperfection that have long been recognized as major sources of vibration by railway traffic. Railhead irregularity may be considered to cover wave-lengths from a few millimeters to 50 meters and more. Irregularities corresponding to short wavelengths, commonly referred to as corrugation and roughness, are essentially responsible for high frequency vibration and noise. Although the presented model is applicable to all ranges of irregularity wavelengths, this study is concerned only with those wave-lengths that are the main contributors to ground vibrations in the low and intermediate frequency ranges. Figure 2 shows an example of measured railhead profile at Ledsgaard that corresponds to wave-lengths in the range 1-20m.

A simple model is used in this study to derive the dynamic force that arises at the wheel/rail interface. The train vehicle consists of two components, the car body and the bogies. The car body is supported on the bogies by a secondary suspension and the bogies are supported on the wheel axles by a primary suspension. It is assumed that the secondary suspension uncouples the car body from the bogies and that the bogies and wheels act as a lumped mass moving rigidly on the railhead profile. The dynamic force is then simply the inertia force of the lumped mass as it accelerates up and down along the rail profile. Although derivation of more accurate wheel forces and their incorporation in the simulation model is straightforward, this simplified model is employed to minimize the number of variables.

3 NUMERICAL MODEL

The numerical model *VibTrain* (Kaynia, 1999) is used for the simulations performed in this study. *VibTrain*, is based on a substructuring scheme whereby the track-embankment structure is represented as a finite element beam, and the ground is represented by the Green's functions of layered half-space as proposed by Kausel & Roësset (1981). The two systems are coupled at a series of points along the ground/embankment interface where the compatibility conditions are enforced. Figure 3 shows schematically the elements of the calculation model.

The motion of the axle loads is simulated by properly delaying the loads from node to node according to the train speed. To avoid the unnecessary computational efforts due to the high frequencies in the load variations, the bridging effect from the rails

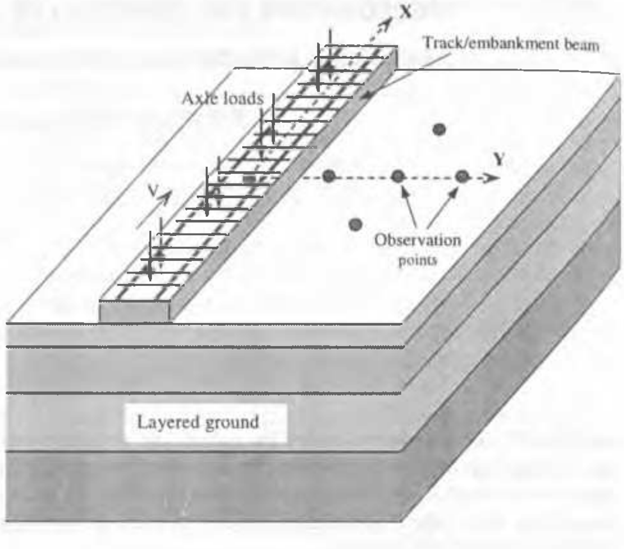

Figure 3. Elements of *VibTrain* calculation model

is used to broaden the time history of the loads. The load variation is simply taken as the variation of the reaction forces under the rail calculated from a Winkler model. All computations are carried out in the frequency domain, and the response time-histories are obtained by an inverse Fourier transformation. For a detailed account of the numerical model, see Kaynia et al. (2000). *VibTrain* has been validated against actual measurements of track displacements during Ledsgaard test runs. This paper will focus on track-side vibrations and the effectiveness of countermeasures.

4 FIELD TESTS

An extensive measurement program was undertaken by the Swedish National Rail Administration (Banverket) at a test site in Ledsgaard between Göteborg and Malmö. The test runs were performed using Sweden's X-2000 passenger trains. A total of 20 test runs were made with train speeds ranging from 10 km/h to 200 km/h and the motions of the track and embankment at several depths as well as the response of the nearby ground were recorded by a host of sensors. The measurements indicated a steady increase of track displacement with train speed. A three-fold magnification of track displacement was registered at 200 km/h. Detailed description of the instrumentation and results of the measurements can be found in Adolfsson et al. (1999).

As part of this investigation, a comprehensive site characterization program was undertaken to establish the soil profile and the geodynamic parameters of the soil layers and embankment. The soil investigation comprised in situ and lab tests as well as various seismic methods. In addition, because passages of the high-speed train produced considerable deformation and non-linearity in the embankment and ground, dynamic (cyclic) tri-axial tests were performed to establish the modulus degradation and damping curves for the soil and ballast materials at the site (Madshus & Kaynia, 2000). These curves, together with the estimated shear strains in the soil and embankment, were used to establish the equivalent-linear material parameters for the numerical simulations. Table 1 summarises the soil parameters derived from this calculation for train speed V=200 km/h. The embankment's bending rigidity, *EI*, for this speed was estimated at 80 MNm^2, and its mass per unit length was taken at 10800 kg/m.

5 MEASUREMENT AND SIMULATION

This section presents a number of numerical simulations of track-side ground vibrations measured at the Ledsgaard test site.

Table 1. Soil parameters corresponding to train speed 200 km/h

Soil layer	Thickness (m)	Density (kg/m^3)	Vs* (m/s)	Vp* (m/s)	Damping ratio
Crust	1.1	1500	65	500	0.063
Organic clay	3.0	1260	33	500	0.058
Clay	4.5	1475	60	1500	0.098
Clay	6.0	1475	85	1500	0.064
Half-space	--	1475	100	1500	0.060

* Vs and Vp are shear and pressure wave velocities, respectively

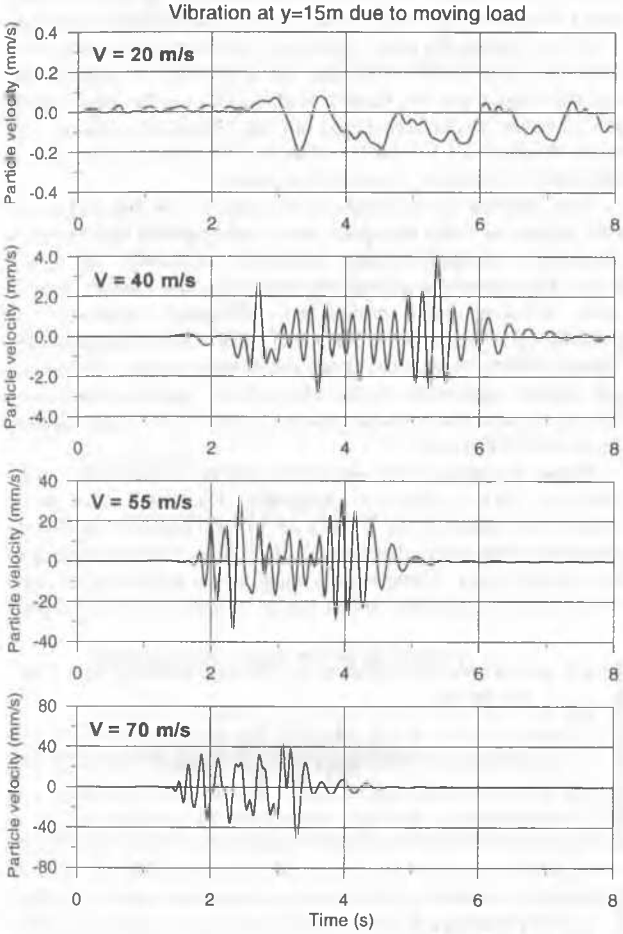

Figure 4. Simulated moving-load component of ground vibration

As will become clear shortly, at low train speeds, the ground vibration is primarily contributed by rail irregularity mechanism whereas at high speeds, that is in transseismic condition, it is the quasi-static moving load mechanism that dominates. For this reason, the ground motion components from the two excitation mechanisms are presented separately in the following. The same scheme is followed in assessing the effectiveness of stiffened embankment in reducing vibrations. In all the simulations, the same soil parameters given in Table 1 (corresponding to train speed of 200 km/h) is used. The reason for this choice is to provide a consistent basis in the sensitivity analyses. The lumped mass representing each axle of the train is assumed equal to 6500 kg. For the geometry and values of axle loads in X-2000 train see Kaynia et al. (2000).

5.1 *Ground vibration at low and high train speed*

Figure 4 displays the simulated quasi-static moving-load component of vertical ground vibration at 15m from the track for train speeds ranging from V=20 m/s (≈70 km/h) to 70 m/s (≈250 km/h). The figure reveals clearly the dramatic increase in ground vibration with train speed. (Note that the result for V=20 m/s is polluted by a spurious low-frequency component. The level of

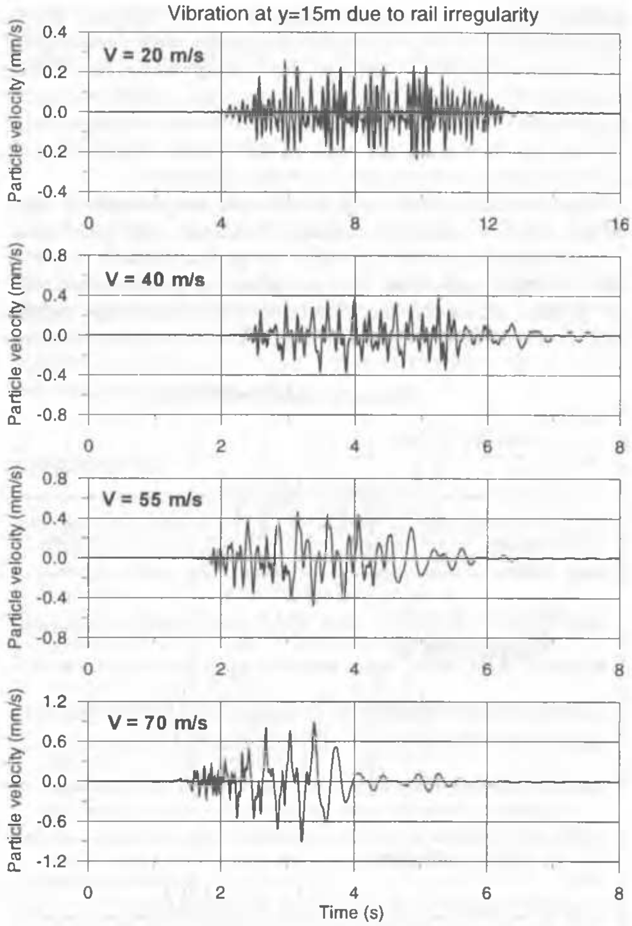

Figure 5. Simulated rail-irregularity component of ground vibration

vibration corrected for this artifact is about 0.1 mm/s.) Moreover, the vibrations corresponding to subseismic condition are largely low frequency whereas those corresponding to transseismic condition display higher frequencies.

The corresponding set of results for the rail-irregularity component is presented in Figure 5. It is interesting to note that, compared to the previous case, the train speed has a relatively small influence on rail-irregularity component of vibrations. Moreover, the frequency characteristics of the motions vary more rapidly with the train speed. Comparison between the corresponding plots in Figures 4 and 5 shows that at low train speeds (subseismic condition) the rail irregularity is the main excitation mechanism whereas at high speeds (transseismic condition) the moving-load is the dominant excitation source. It should, however, be noticed that at low speeds, the moving-load is still responsible for low-frequency vibration.

The calculation of ground vibration from the rail irregularity is based on a measured rail profile. The results presented in Fig. 5 correspond to the first 200m profile shown in Figure 2. This stretch has been selected arbitrarily and does not necessarily coincide with the location of the measurement point. Therefore, a detailed comparison between the simulated and measured values is meaningless. One might instead compare the level of vibrations in the two sets. Geophone recordings at 15m from the track at a train speed of 20 m/s indicated vertical ground vibrations of about 0.4 mm/s versus 0.3 mm/s predicted by *VibTrain* simulations. A more detailed comparison is presented in the next section for a high train speed.

5.2 *Measured and simulated track-side vibration*

The Ledsgaard test runs provided a number of good quality recordings of track-side vibration at high train speeds. Figure 6 displays one set of such recordings at 7.5m, 15m and 22.5m from the track for a southbound train passage with a train speed of 200 km/h. Figure 7 displays the corresponding set of data simulated by *VibTrain*. Although the two sets exhibit somewhat different waveforms, they nonetheless have convincingly similar features and their magnitudes are in fairly good agreement considering the many uncertainties in model parameters.

In passing, it is interesting to note that the problem of large ground vibrations under transseismic condition is not just a local problem under the rail. The levels of ground vibrations are at least 10 times larger than what one observes under normal railway traffic. Moreover, the vibrations do not attenuate rapidly with distance. Obviously, such large vibrations cannot be permitted under normal operation. The design of suitable vibration countermeasure is thus inevitable for such conditions. Numerical codes that are validated against actual measurements provide valuable tools in design of countermeasures.

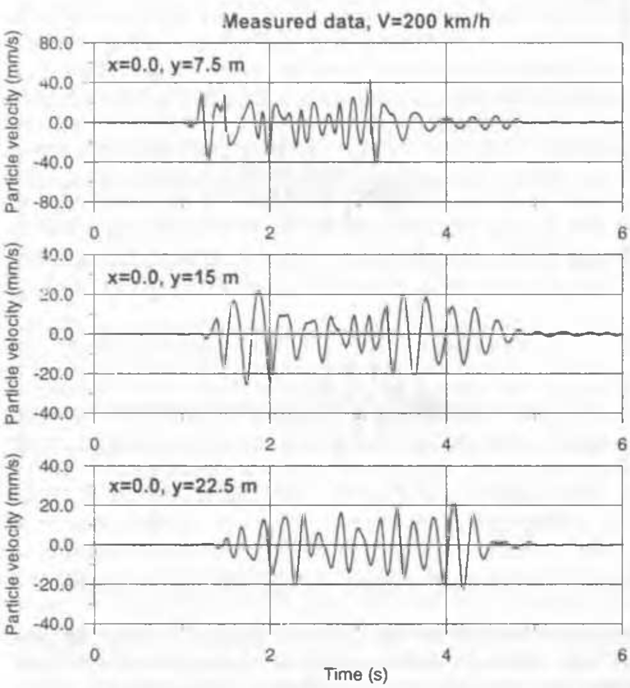

Figure 6. Measured track-side vibration for train speed 200 km/h

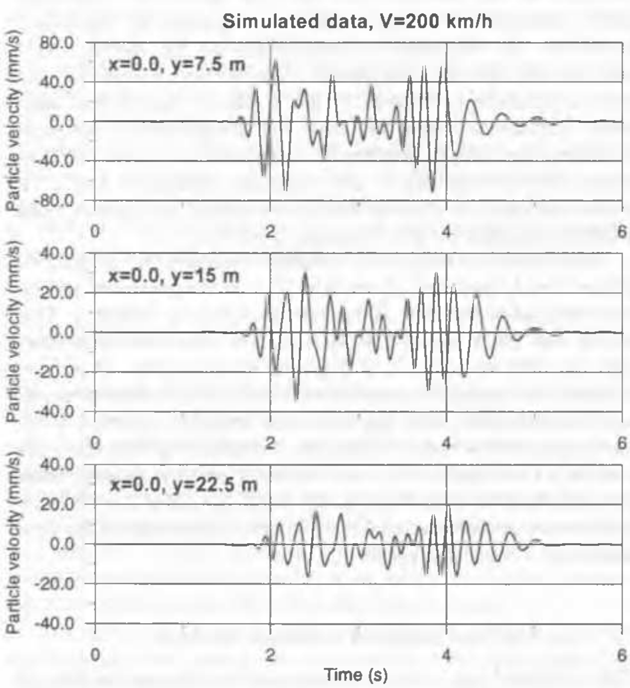

Figure 7. Simulated track-side vibration for train speed 200 km/h

5.3 *Vibration countermeasure*

The idea of using a stiff plate under the track for vibration mitigation has been tested both numerically and experimentally (e.g. Stuit 1994, Jones 1998). These studies have generally shown that stiff plates, typically of concrete with thickness of about 0.5m, can reduce the track vibrations; however, they seem not to have any appreciable influence on track-side vibrations. Numerical simulations by Kaynia et al. (2000) on the effectiveness of stiff beams under high-speed railway lines have confirmed the same observations for track vibrations. No attempt was made in that study to consider track-side vibration.

This problem is revisited in this section. To this end, track-side vibrations from the quasi static moving-load and railhead-irregularity mechanisms are simulated separately for a stiff track. This provides a basis for assessing the performance of track stiffening under normal and high-speed conditions. The simulations are carried out for a stiff track with bending rigidity, EI=800 MNm^2, that is ten times the previous value. This bending rigidity represents a concrete plate of approximately 0.4m thickness under the embankment considered in the calculation of the results in Figures 4-7.

Figure 8 presents the simulated ground vibrations at 15m from the track by the rail irregularity excitation. The results cover train speeds from 20 m/s to 70 m/s and can be directly compared with their counterparts in Figure 5 corresponding to the ordinary track. These results suggest that stiffening the track (to the extent considered in this study) may have only a marginal

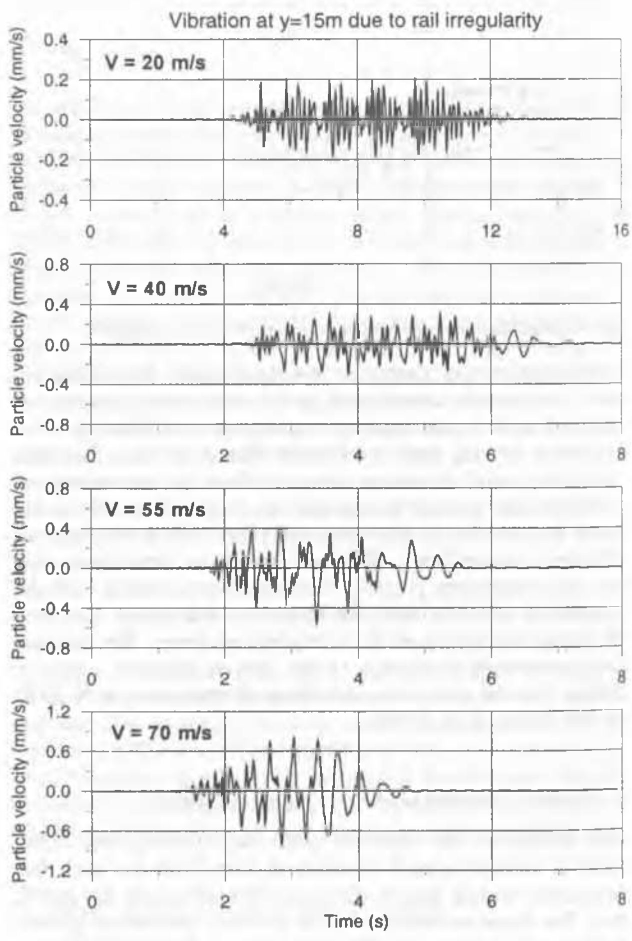

Figure 8. Simulated rail-irregularity component of ground vibration for stiff track

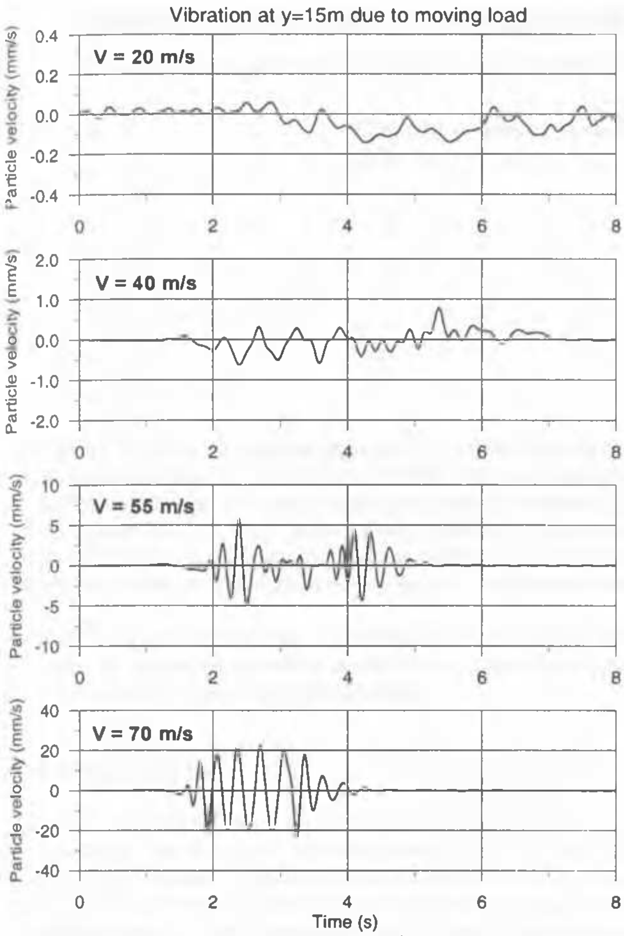

Figure 9. Simulated moving-load component of ground vibration for stiff track

effect in mitigating track-side vibrations at low train speeds for which the rail irregularity is the prime source of excitation.

Figure 9 presents the simulated ground vibrations at 15m from the track by the quasi-static moving load excitation. The results again cover train speeds from 20 m/s to 70 m/s and can be directly compared with those in Figure 4 corresponding to the ordinary track. Although a considerably higher reduction is achieved for this excitation (about 60%) the general level of vibrations are still so high that they may not be acceptable. However, based on these results, one may expect that a stiffer beam under the track provide a potential anti-vibration solution.

6 SUMMARY AND CONCLUSIONS

This paper presented results of numerical simulations by the computer code *VibTrain* for track-side vibrations under normal and high-speed railway traffic. To delineate the various features of induced vibrations, the components of ground vibrations from the quasi-static moving-load and railhead-irregularity excitations were calculated and presented separately. It was shown that the former mechanism is responsible for ground motions at high train speeds (i.e. transseismic conditions) whereas the latter has a more pronounced influence at low speeds (subseismic condition). The simulations compared well with the actual recordings of track-side vibrations during the 1997 Ledsgaard high-speed test runs in southern Sweden.

The numerical model was also used to explore the effectiveness of a stiff plate under the embankment for mitigation of track-side vibrations. The simulations suggested that the stiff-plate solution (of the order of 0.5m thickness) had only a minimal effect on reducing vibrations induced by the railhead irregularity and hence of little benefit at low train speeds. However, a much larger reduction was calculated for vibrations induced by the moving-load excitation at high train speeds (up to 60% for a 0.5m thick concrete plate). This may therefore provide a viable countermeasure for high-speed railway lines.

7 ACKNOWLEDGEMENT

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