Seismic features of vibration induced by train^{*}

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Abstract

Based on schematically formulation of the vibrations induced by moving trains, this paper analyses the waveforms along the Datong-Qinhuangdao railroad in Northern China recorded in the suburban Huairou district of Beijing on March 8, 2003. It is illustrated that vibrations induced by train, except traditional recognized noises and interference effects, could be used as a seismic source to detect crustal structures with its advantage of abundant frequency spectrum, repeatability and no additional harm to the environment. It will bring lights to the traditional exploration seismology with the further studies of signal processing and interpretation methods, and related models and new observing systems.

Key words: vibration induced by trains; moving sources; seismic features

Introduction

Collisions can be generated continuously by the passage of trains due to the surface irregularities of wheels and rails. When a fully loaded train or freight with weight of thousands tons runs on deformed rails, it may induce strong vibrations. Such vibrations may transmit several kilometers to result in building damage. For instance, the famous Longmen Grottoes near the Luoyang city in China has been seriously damaged by the ground trembling by trains passing near it (<http://www.earthquake.net.cn/science/eerc/>), while in Italy, railroads were meticulously designed to avoid influence of ground trembling by trains on the ancient city of Venice and the leaning tower of Pisa. A large amount of research work on the damage and influence of vibration induced by running trains (VIRT) on buildings and structures have been done in Japan, Europe and USA in recent years, and the significant progresses in VIRT observation and simulation were made since 1970s (Gutowski, Dym, 1976; Melke, Kraemer, 1983; Okumura, Kuno, 1991; Heckl, *et al*, 1996; ZHAI, 2001; WANG, 1999; XIA, *et al*, 1999; Hung, Yang, 2001a). Okumura and Kuno (1991) studied the effects of various factors on railway noise and vibration through a regression analysis of field data obtained from 79 sites along 8 traditional railway lines in an urban area in Japan. Among the six factors they used to explain the vibration peak levels, *i.e.*, the distance, railway structure, train type, train speed, train length and background vibration, they found that the influence of distance was the greatest, but the influence of train speed (generally under 100 km/h) was not very significant. All this kind of researches focus on the response spectrum of constructions, and is conducted mainly with accelerometer measurements along railroads.

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Figure 1 Vertical recordings of VIRT at WPB Watts Point, BC, Canada (<http://www.pgc.nrcan.gc.ca/seismo/seismos/interpret.htm>) (a) and at Tanggu seismic station T23 of China (b)

semi-periodically recorded (Figure 1a) by a short period seismograph with a single component (S13) located at WPB Watts Point, British Columbia, Canada (49.657°N, 123.210°W, elevation 0.273 km). Another example (Figure 1b) is from Tanggu seismic station of China (39.05°N, 117.52°E), named as T23, deployed with a 3-component borehole short-period seismometer (FSS-3DBH) at the depth of 0.275 km. Almost former studies related to VIRT concentrated on its perturbation and harm, that is, concerning VIRT as a harmful noise and vibration source, but less investigation to take such kind of repeated exciting signal as an information source to inverse crustal structures. Ditzel, *et al* (2001) shows that VIRT could be expressed by terms of reflection and transmission properties of the stratified structure with modeling train as an oscillating point force (Figure 2). Up to now, however, it is impossible to identify the deepest layer VIRT may reach. The running train with wheel sets could be viewed as a sequence of moving point sources. Even more, no records about VIRT measured with distance of several kilometers perpendicular to the track are published until now. This paper brief summarized some theoretical and simulation results of VIRT. In order to further investigate the theoretical wave field with field experiments of VIRT, the present paper performed essential analyses of waveforms with a field measurement in suburban of Beijing along a heavy-load railway.

In the early time, earth scientist already knew that VIRT could interfere with the seismograph records on earthquake stations near the railroad, and were adopted to design guidelines for site selection of seismic station (Willmore, 1979). There are express provisions in China that the seismograph station should avoid arterial railways (State Seismological Bureau, 1990; China Seismological Bureau, 2001). If the railway and seismometer lie on different geological regions or there are mountains or river valleys between them, the seismometers should be located at 3 km away from the railroad, otherwise, the distance between the seismometer and the railroad should be over 5 km. Nevertheless, some seismograph station still could record VIRT usually, both in China and other countries. For instance, VIRT is

Figure 2 Typical model of VIRT problem (modified from Yang *et al*, 2003)

1 Generalization of VIRT formulation and simulation

The problem of vibration induced by train through rail track, sleeper, rail pad and embankment to be considered is schematically shown in Figure 2, where a train moving at speed c is traveling along the z -axis on a homogeneous stratum surface. The external loading generated by a moving train is simulated as a moving load of frequency f_0 traveling with speed c along the z -axis on the surface (Yang, *et al*, 2003), *i.e.*

$$f(x, y, z, t) = \delta(x)\delta(y)\phi(z - ct)e^{i2\pi f_0 t} \quad (1)$$

where the exponential term accounts for the dynamic effect resulting from the rail irregularity or mechanical system of the vehicles, and $\phi(z)$ represents the loading function caused by the axle loads of all carriages of the train, which can be obtained as the superposition of the loading function $q_0(z)$ for each axle load shown in Figure 3. Here, the axle loading function $q_0(z)$ is determined from the deflection

Figure 3 Schematic of train induced loadings (Yang, *et al*, 2003)(图贴反了, 应转 180 度)

curve of an infinite elastically supported beam with a point load T applied on the surface. Assume the flexural rigidity of the beam to be E_I and the foundation stiffness to be s (N/m^2), the loading function $q_0(z)$ can be expressed as (Yang, *et al*, 2003; Hung, Yang, 2001b; Esvel, 1989):

$$q_0(z) = \frac{T}{2\alpha} e^{-\frac{|z|}{\alpha}} \left[\cos\left(\frac{|z|}{\alpha}\right) + \sin\left(\frac{|z|}{\alpha}\right) \right] \quad (2)$$

where α is the characteristic length of the beam

$$\alpha = \sqrt[4]{\frac{4E_I}{S}} \text{ (m)} \quad (3)$$

If the dynamical interactions of wheels and rails caused by different track junctions, oblate wheel and roughness rail are considered, we have to deal with very complicated coupling dynamical problems (WANG, 1999). There are some researches related to those problems in locomotive dynamics, rail dynamics and interaction of wheels and rails, but it is needed to further develop to be applied in real problems.

In a semi-infinite elastic space (Figure 2), each of the layer is characterized by its density ρ_n and by the compressional (P) and shear (S) wave velocities α_n and β_n ($n=1, 2, \dots, N$). For each of the n th layers, the equation of motion and the constitutive relation hold (Esvel, 1989):

$$\frac{\partial \tau_{ij}(w)}{\partial w_i} + \omega^2 \rho_n u_{ij}(w) = -f_j(w) \quad (i=1, 2, 3; j=1, 2, 3) \quad (4)$$

$$\tau_{ij}(w) = \lambda_n \delta_{ij} \frac{\partial u_k(w)}{\partial w_k} + 2\mu_n \frac{\partial u_j(w)}{\partial w_i} \quad (y_{n-1} < w_2 \leq y_n, n=1, 2, \dots, N) \quad (5)$$

where u is the displacement and τ the stress tensor. Furthermore, y_n is the n th interface, y_0 is the

free surface co-ordinate and w a position vector given by $w=w_1i_1+w_2i_2+w_3i_3$ and ω is the angular frequency of the Fourier transform. In equation (4), f_j is the loading force of a moving train given in equation (1).

Jones *et al* (2000) assumed that the railroad structure is modeled as a 2 m layer of weathered sandstone overlying the elastic half-space. With given Young's modulus, Poisson ratio and structure parameters of media density and velocities of P, S and Rayleigh waves for the elastic half-space, their simulation for 50 m×50 m area within the track showed quite different responses of the ground surface to loads at three frequencies for trains traveling at speed of 144 km/h. High levels of vibration may be expected to occur with higher frequency of excitation. With same oscillating frequency of the load to different structure parameters, however, different propagation effects of the ground surface can be generated by different train speeds. Waves of significant amplitude on the ground surface appear as the train speed approaches and exceeds the shear wave speed in the upper layer. The induced vibration has a low rate of decay with distance for the shorter wavelength wave (higher frequency).

Yang *et al* (2003) investigated parametrically the effect of soil properties on the transmission of vibrations due to high-speed moving trains with finite/infinite element approach. The parameters to be considered include the shear wave velocity, damping ratio and layer thickness of soils, train speed and vibration frequency of moving trains. They designed a mesh system to cover a width of 20 m and a depth of 10 m with different elements for the near and far field of the system. The simulation concluded that the soil damping has an important effect on the degree of attenuation, and the stratum depth is a key factor for vibration propagation. The rail structure could be determined based on the relationship (Yang, *et al*, 2003) of critical frequency f_{cr} , train speed c , vibration frequency f_0 of the moving loads and the velocity of Rayleigh wave C_R of the top layer

$$f_{cr} = \frac{f_0}{1 \pm \frac{c}{C_R}} \quad (6)$$

Because no waves can propagate outward with lower critical frequency (Yang, *et al*, 2003), the Rayleigh velocity C_R of the top layer in layered structure can be determined theoretically from the critical speed at the location near the source with $f_0=0$.

By expressing three-dimensional field in terms of reflection and transmission properties of the layers, the response generated by a moving train was computed numerically (Ditzel, *et al*, 2001) based on a representation of the wavefield in the slowness domain. The predicted vibrations from the theoretical model showed a good agreement with the data of the field measurement, and quite similarity with the recordings of traditional explosion. They also pointed out that vibrations due to an oscillating load could be observed at rather large distances, even if the train speed is smaller than the critical wave (Rayleigh wave) speed.

2 Analysis of experimental recordings

2.1 The field experiment

In order to explore the possibilities to detect the ground structures with the seismograph records of VIRT, we did a field observation in suburban of Beijing along a heavy-load railway from Datong city to Qinhuangdao city in the spring of 2003 with broadband and short-period seismographs.

Figure 4 Field observation system for vibration induced by running trains on March 8, 2003

The Datong-Qinhuangdao electric railway is a major coal transport route with a designed capacity of ten thousand tons. The frequent passages on the railway are freight trains (heavy-loaded from Datong to Qinhuangdao, but back with empty cargos), occasionally by locomotive engines and short-distance passenger trains. The freight train is possible to carry coals over 6 000 tons with its own weight more than 1 000 tons. The measurement field is located near Taipingzhuang village ($116^{\circ}41'E$, $40^{\circ}16'N$) in the suburban Huairou district of Beijing. Figure 4 shows the observation area ($116.68^{\circ}\sim 116.71^{\circ}E$, $40.26^{\circ}\sim 40.28^{\circ}N$) with a $NE124^{\circ}$ segment of the Datong-Qinhuangdao

railway in the southwest. There are two countryside pavements, but no public road across the measurement field, and it is rarely to see automobile passing the pavements during our experimental observation. There is a professional service station in Chawu with the distance of around 12 km to the experimental field. The passing speeds of the empty trains, the heavy freight train and the passenger train are about 60 km/h, 70 km/h and 80 km/h respectively because all trains must stop on the Chawu station for maintaining.

The observation sites of 00t and 08t (Table 1 and Figure 4) are cement ground surface, and others belong to excavated solid soil. Table 1 lists the sites where we deployed the seismographs and related observation parameters, in an order of the distance from the site to the railway. Two sets of broadband seismographs were used, including seismometers with band from 0.05 Hz to 20 s and 24-bit multi-channel digitized data acquisition recorders, and one set of JC-V100 short-period seismograph, including a seismometer with band from 1 Hz to 80 Hz and a 16-bit data acquisition recorders. The two sets of broadband seismographs are deployed alternately in different sites while vibrations induced by 2 or 3 passing trains are well recorded. Both short-period and broadband seismographs are fixed on site 00t more than 2 hours for comparison analysis.

2.2 Time-domain features of VIRT

Figure 5 illustrated the three component seismograms for the passing locomotive engine on 13h30min and heavy-loaded train on 13h47min recorded at site 00t by short-period and broadband seismographs from 13h28min to 13h49min. It is demonstrated significantly the similarities and differences between locomotive waveform (less than 20 s) and heavy-loaded train's (more than 48 s). The essential resemblance of broadband and short-period VIRT recordings was clearly exhibited. The analysis in this paper only focuses on Z-component because of the satisfied similarities of three components and the significant amplitude of vertical vibration. The waveforms in Figure 6 show obviously that the signal noise ratio (S/N) of the ground shakings decreased with distance, although no recordings from the same heavy-loaded train. The S/N with several tens at the site of 3 m decreased to 5 at the site of 500 m, then to about 2 at the site of 2.15 km from the railway. There is definite automobile disturbance for the sites 006t ~ 008t, but the

Table 1 List of observation sites

Site	$\varphi_N(^{\circ})$	$\lambda_E(^{\circ})$	Distance between the site and the railway/m	Seismograph	Observing period h:min
00t	40.270	116.684	3	Short-period Broadband 1	11:24~16:50 11:24~14:10
01t	40.268	116.692	100	Broadband 2	11:50~14:42
02t	40.269	116.693	200	Broadband 1	14:40~15:35
03t	40.269	116.694	300	Broadband 2	15:35~16:03
04t	40.270	116.694	400	Broadband 1	15:54~16:45
05t	40.271	116.695	500	Broadband 2	16:41~17:00
08t	40.277	116.693	1 100	Short-period	17:15~18:50
06t	40.277	116.702	1 650	Broadband 1	17:30~18:30
07t	40.285	116.702	2 150	Broadband 2	17:30~18:30

Figure 5 Short-period (S) and broadband (B) seismograph records of the vibration induced by heavy-load trains at site 00t
Z denotes vertical component, E denotes EW component, N denotes NS component; SZ and BZ represent the Z component of a short-period and broadband seismograph respectively. The same labels are shown in Figures 6~9

amplitudes of the ground shakings in Figure 6b decreased slowly at far field (1.1~2.15 km). The length of the shaking wave increases distinctly with the distance from the railway according to waveforms recorded at sites 00t and 01t for the identical heavy-loaded train. The experimental data, however, are insufficient to give a certain relationship of waveform length with receiver distance because it is closely related to the length and load of train, even to train speed. The peak particle velocity (PPV) about 1 200 $\mu\text{m/s}$ observed at site 00t for heavy-loaded trains with speed about 70 km/h is nearly a half of PPV 2.5 mm/s obtained at 6 m from the track by Degrande and Schillemans (2001) from free field vibration measurements during the passage of a Thalys high speed train (speeds varying between 223 km/h and 314 km/h). It is confirmed the interdependent relationship between the vibration scale and the length, weight and speed of train in some way.

Using the reference velocity value of $v_0=10^{-2}$ $\mu\text{m/s}$ suggested by Esveld (1989), the calculated PPV values in Figure 6 are 101.6, 84.1, 84.6, 81.6, 85.6 and 70.9 dB for sites 00t to 05t, and

the notable 60~80 dB responses for sites 06t to 08t with stated mixture noises.

Figure 6 Records of the vibration induced by heavy-load trains at different sites
(a) The beginning record time was labeled in the top-left of each channel; (b) The beginning time is 18:00:00

2.3 Spectral features of VIRT

The Doppler effects of classical physics appear significantly in vibration signals induced by moving train as a multi tremble source. In Figure 7, the distinct discrepancy is showed in the frequency spectral curves of the forward and backward propagating waves, ahead and behind of the locomotive engine respectively. When the train comes to the seismograph, the peak value of high frequency is greater than it moves gradually away.

Figure 7 Broadband record at site 00t induced by locomotive and its amplitude spectrum before and after the passage of locomotive

Figure 8 Amplitude spectra of the vibration induced by heavy-load trains at sites 00t and 01t

Figures 8 and 9 give the amplitude spectra of locomotive and heavy-loaded train showed in Figure 5. It is obvious that the frequency ranges recorded by short-period and broadband seismometers are nearly equivalent with mass frequency 1~20 Hz. The spectra from 3 seismographs in sites 00t and 01t all indicate that the vibration frequency of heavy-loaded train is about 8.2 Hz, and other distinguishable peak frequencies about 1.64, 3.27, 4.90, 6.54, 9.80, 11.44, 13.08, 14.71, 16.27, 17.98 Hz, and even at 30 Hz. Those peak values may reflect the resonance feature of multi carriages of the train or predominant frequencies correlated to crustal structure. Those peak frequencies affirmatively appeared in Figure 10 for power spectral density calculated with 1 024 and 4 096 points respectively. It is impossible to identify the passage of the individual carriages from our recordings as done by Degrande and Schillemans (2001) because the only one site is closed to the rail truck. Comparing Figure 5 with Figure 6a, however, it is implicitly exhibited the oscillation excited by the engine and individual carriage.

Figure 9 Amplitude spectra of short-period and broadband records induced by locomotive at sites 00t

Figure 10 Power spectral density of broadband record induced by heavy-load train at sites 00t

Due to the limitation of our experimental observation, we have not observed the vibrations in different sites induced by the same train. The variable background noise in different sites extends the difficulty to distinguish the likelihood body wave what may exist in the recording. It is impossible to analytically compare our recording with the vibration response to traditional explosive source, and it is very difficult to perform further analyses based on the simulating results given by Yang *et al* (2003) or Jones *et al* (2000). Nevertheless, our experimental investigation provides a foundational exploration to shallow crustal structures with VIRT as moving seismic sources and related theoretical simulations with real observational measurement in far field.

3 Discussion and conclusions

Our essential analyses and the published relative results are sufficient to confirm the advantage to use VIRT as a seismic source to detect shallow crustal structures. VIRT, as a new kind of trigger source, is repeatable and stable with no additional harm to the environment and broad frequency spectrum. VIRT will provide additional approach to the traditional exploration seismology with the further studies of signal processing and interpretation methods, and related models and new observing systems.

About VIRT theoretical analysis, the multi-point moving problem is the vibrations induced by the train wheels and transmitted downward with the railway tracks, sleepers and gravel embankment. It is involved in the complicated coupling processes of train, railway and stratum. The maximums of reachable depth and measurable distance of the VIRT must be investigated further. The foundational theory of VIRT and its applicable conditions should be quantitatively clarified. There are some referencable theories in the field of engineering vibration and railway engineering, and the models of finite moving source of earthquake rupture (ZHENG, 1979; Ben-Menahem, 1961; Ide, 2002) to offer favorable background to build up the theoretical models of VIRT multi-point moving sources. However, the problem of the VIRT affected by the varied loadings of train is almost not taken into account in the published studies (Ditzel, *et al*, 2001; Yang, *et al*, 2003; Hung, Yang, 2001b; Esveld, 1989; Degrande, Schillemans, 2001; Jones, *et al*, 2000). It should be paid more attention in the further study.

About the processing and analysis of VIRT signals, how to inverse effectively the crustal structure or shallow structure nearby the railway, even to obtain their changes related to medium property with the variation of tectonic stress remains unsolved. The correlative analysis in frequency and time domain may be a good beginning to develop new methods for VIRT signal processing. The frequency-dependent decompositions of VIRT to get significant vibration frequencies for different train speeds and loadings are a very important way to identify and distinguish further available VIRT information. The recognition and analysis of weak signals must be applied to increase the VIRT detectability according to our experimental data in 2.15 km distance to the railway.

Due to most researches focus on the damage and influence of trains, their field observational data are almost within distance of 100 m to the railroad. VIRT recordings at distance of kilometers and/or below ground surface are rarely delivered until now. We have collected the VIRT waveforms with slow attenuation at distances 1.1~2.15 km, although our data and the recordings in the 275 m borehole (Figure 1b) could not be confirmed that they contain reflected or converted waves from crustal interfaces now. However, as a brand-new research field to use VIRT as a seismic source to detect ground structures, new signal processing and interpretation methods and re-

lated theories must be developed, and the measurable instruments must be well designed to collect more VIRT data for thorough and detail investigations.

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