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In-situ measurement of railway-traffic induced vibrations nearby the liquid-storage tank

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Abstract. In this study, result of a field investigation of railway traffic-induced vibrations is provided to examine acceptability levels of ground vibration and to evaluate the serviceability of a liquid-storage tank. Free field attenuation of the amplitudes as a function of distance is derived by six accelerometers and compared with a well-known half-space Bornitz's analytical solution which considers the loss of the amplitude of waves due to geometrical damping and material damping of Rayleigh. Bornitz's solution tends to overlap vertical free field vibration compared with in-situ measured records. The vibrations of the liquid-storage tank were compared with the USA, Federal Transportation Railroad Administration (FTA) criteria for acceptable ground-borne vibrations and with the criteria in DIN 4150-3 German standard. Comparing the thresholds stated in DIN 4150-3, absolute peak particle velocities are within the safe limits, however according to FTA velocity level at the top of the water tank exceeds the allowable limits. Furthermore, it is intended to indicate experimentally the effect of the kinematic interaction caused by the foundation of the structure on the free-field vibrations.

Keywords: response of liquid-storage tank, railway traffic, in situ measurements, free field vibrations

1. Introduction

The environmental influences of ground vibrations induced by railway traffic in densely populated areas have become one of the main issues with the industrial advances in metropolitan society. Particularly, increase in train speeds and loads started to cause considerable disturbance to routine life of residences and fatigue type of damage to engineering buildings adjacent to railways (Rezvani *et al*. 2013, Li *et al*. 2015, Kim *et al*. 2015, Riedman *et al*. 2015, Bratov *et al*. 2015). However few in-situ experiments on train-induced vibrations have been conducted on special structures such as liquid-storage tanks (Xia *et al*. 2009, Cruzado and Letchford 2013, Cruzado *et al*. 2013, Park *et al*. 2016).

The major part of the train-induced ground borne vibration energy is transmitted to the nearby structures through their foundations by the Rayleigh waves. The increase in passenger transport with high speed as well as heavy-loaded freight traffics in railways may cause strong ground motions in intensively populated and industrialized areas. These vibrations when propagating through very soft soil deposits often result in considerable damage and unacceptable stress levels on railway-track and its neighboring residential areas (Jones and Block 1996, Peplow *et al*. 1999). Environmental vibrations induced by railway traffic generally have 4-50 Hertz (Hz) frequency content, depending on the speed of trains. This frequency range may cause malfunctioning of sensitive machinery, discomforting daily life of residents and even threating to the safety of structures with resonance effects (Krylov 1996, Massarsch 2000).

It is widely recognized that dynamic properties of the soft soil under the influence of the incident waves can amplify the ground motions significantly and alter the dynamic response of neighboring structures. The detrimental effects of environmental vibrations induced by continuous flows of the railway traffic and the countermeasures against these high level vibration problems have recently received more engineering interest for researchers in the world wide. Several scientists and engineers have been systematically investigated the train-induced ground borne vibrations, wave propagation mechanism, resulting environmental pollutions and vibration mitigation measures by way of numerical simulations (Celebi and Schmid 2005, Adam *et al*. 2000, Yang and Hung 2001, Lombaert *et al*. 2006, Yang *et al*. 2003, Celebi and Goktepe 2012, Adam and Estorff 2005), theoretical analysis (Vostroukhov and Metrikine 2003, Takemiya and Bian 2005, Senalp *et al*. 2010), and field measurements (Crispino and D'apuzzo 2001, Xia *et al*. 2009, Galvín and Domínguez 2009, Xia *et al*. 2005). Damage due to strong ground vibration to steel storage

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tanks can be various forms. Such as structural fatigue, “elephant=foot” buckling of the wall due to large axial compressive stresses, or sloshing liquid may damage the roof and the top of the tank wall, etc. Although it is well known that the acceleration amplitude levels of the environmental ground vibrations increase with train speed and reduce with the distance to the railway track, in-situ vibration assessment has very important role on evaluating key structures located close by railway lines.

In this paper, a field experiment was conducted to examine the influence of railway train-induced vibration on the liquid-storage tank and the surrounding neighborhood. Attenuation of free field ground motion measured with six high quality two component seismometers were used to verify the applicability of Bornitz’s analytical solution. The obtained results were then compared with the Federal Transportation Railroad Administration (FTA) criteria for acceptable ground-borne vibrations expressed in terms of root mean squared (RMS) velocity levels in decibels (FTA 2012) and with the criteria in DIN-4150 German standard, which a guideline for the assessment of structural vibrations concerning building damage (FTA 2012, DIN 4150-3 1999). The analysis were conducted for two component motion; horizontal and vertical and with two different speeds; 50 km/h and 70 km/h.

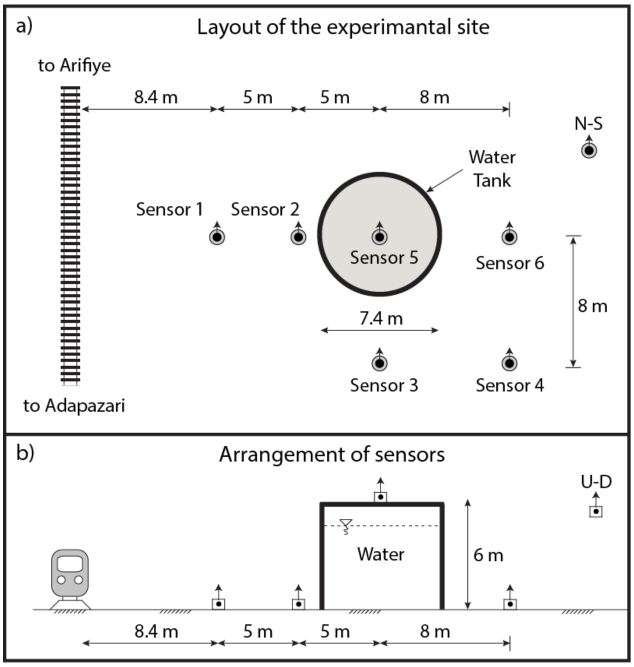

Fig. 1 Schematic demonstration of the measurement point a) Layout of the experimental site b) cross-section of the plan and employment of sensors on the ground and water tank

2. Description of the investigated environment and water tank

The structural response of the tank and ground borne vibrations are measured by using six accelerometers during the transit of the suburban trains in the Adapazari-Arifiye railway line, Sakarya City, Turkey. Seismometers are high quality Capacitive Force Micromachined accelerometer, which have 32-bit high resolution and have 120 decibel (dB) dynamic range with built in (Global Positioning System) GPS antenna and digital to analog converter. Sensors have been set to obtain 100 sample per seconds (SPS) which allow to analyze up to 50 Hz nyquist frequency. The measurement points for the free field ground motion are selected perpendicular to the train traffic at suitable distances from the rail track (Fig. 1). Accelerations of north-south horizontal and vertical component are recorded by data loggers inside seismometers.

Regular local trains passing 18.4 m apart from targeted storage tank between 50 km/h and 70 km/h speed everyday with about 50 minute intervals. Empty weight of trains is 1200 kN with total of four railroad car. The tank is being used by fire station as a backup water storage, built with flexible steel body and rigid concrete foundation sitting on a soft soil. 7.4 m diameter tank is filled with 5 m water.

The thickness of the steel is 0.01 m and the total height of the tank is 6 m (Fig. 2). The vibration measurement site consist of thick alluvial deposits that are transported by the Sakarya River. Surface soil of the area is very young Holocene soil developed in the recent 200 years (Arman and Gunduz 2005). There were some borings measurements available by municipally around the study area. According to test borings the soil profile is characterized as clay for free ground to 2 meter, clayey-silt between 2 and 8 meter and silty sand 8 meter to 15 meter. The water level is generally high to be about 1.90-2.00 m and it may come closer the ground surface in rainy season.

2.1 Data process

Records from the accelerometers are first base line corrected to zero and linear trends are removed if exist. The accelerometers time histories are filtered using band pass Butterworth between 0.4 Hz and 13 Hz. Then they are numerically integrated in order to obtain velocity time histories for both horizontal and vertical components (Fig. 3(a)-(b)). Frequency content of the signals are calculated using Fast Fourier Transform (Fig. 3(c)-(d)). Peak particle velocities and peak value of root mean velocities are calculated for each sensor.

2.2 Federal Transportation Administration criteria

Train induced ground vibration are non-continuous excitations. Decibel notations is adopted to measure vibration levels by Federal Transportation Administration (FTA 2012), although not accepted in many other country norms i.e., DIN 4150-3. FTA recommends calculation of the root mean square (RMS) amplitude to evaluate the signal which is a kind of smoothed vibration. RMS is computed by averaging the squared amplitude over a one second interval (red lines in Fig. 3(a)-(b)). Then, the velocity level (L_v) is calculated as a descriptor in decibels from velocity record using

Fig. 2 Investigated water tank and employments of sensors

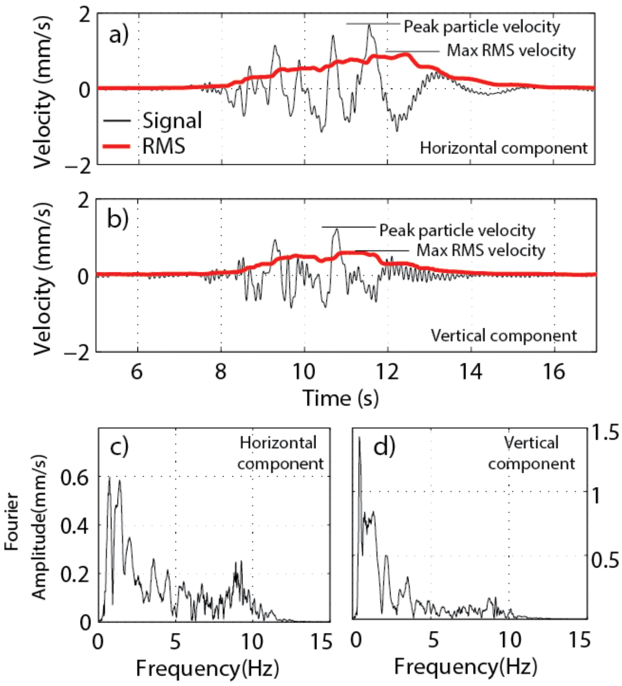

Fig. 3 Measured velocity time histories of ground vibration at 8.4 m (sensor 1) a) Horizontal b) Vertical components and frequency content of the signals c) horizontal d) vertical components

$$L_v = 20\log 10\left(\frac{v}{v_{ref}}\right) \tag{1}$$

where v is the max RMS amplitude in m/s and v_{ref} is the reference velocity amplitude (2.54×10^{-8} m/s).

FTA defines the maximum criteria levels for ground borne vibration in three land use category and event types (Table 1). Frequent events are described as more than 70 excitation events per day such as rapid transit rail systems. If it is less, it is considered to be infrequent events such as commuter rail systems. Investigated site was exposed to 38 events by the local train considered as infrequent event and defined as category 3.

Table 1 FTA Criteria for ground borne vibration impacts levels (in dB)

Land use category	Frequent events	Infrequent events
Category 1 : Buildings where low ambient vibration is essential for interior operations	65	65
Category 2 : Residences and buildings where people normally sleep	72	80
Category 3 : Intuitional land uses with primarily daytime use	75	83

2.3 German Norms on structural vibration (DIN 4150-3)

This standard defines the allowable structural response due to ground borne vibrations in terms of peak particle velocities. Guideline values of vibration velocity, v to be used when evaluating the effects of short-term and long-term vibration on structures are compiled in Table 2. Short-term vibration is defined as excitation which does not occur enough to cause structural fatigue and does not produce resonance in the structure. Long-term vibration is all type of excitation which is not covered by the definition of short-term vibration (DIN 4150-3 1999).

2.4 Bornitz's analytical solution

According to the Bornitz equation (1931) as stated by Amick and Gendreau (2000), the loss of the amplitude of waves due to spreading out (geometrical damping) and absorption of energy within the soil itself (material damping) is accounted by velocity amplitude of Rayleigh waves. The attenuation of the amplitude is a function of distance from the source and absorption coefficient dependent upon the type of propagation mechanism and soil.

We calculated the half-space solutions based on the Bornitz's analytical solution to validate the accuracy of Bornitz's approach. Therefore we illustrated the

Table 2 DIN 4150-3 guideline values for vibration velocity to be used when evaluation the effect of vibration on structures (in mm/s)

Line	Type of structures	Short-term vibration		Long-term vibration
		At the foundation at frequency of 1 Hz to 10 Hz	At the horizontal plane of highest at top of structures	
1	Buildings used for commercial purposes. Industrial buildings and buildings of similar design	20	40	10
2	Dwellings and buildings of similar design and/or occupancy	5	15	5
3	Structures that because of their particular sensitivity to vibration, cannot be classified under lines 1, and 2 and are of great intrinsic value (e.g. listed buildings under preservation order	3	6	2.5

applicability of analytical solution which takes account the loss of the amplitude of waves due to spreading out (geometrical damping) and absorption of energy within the soil itself (material damping) by velocity amplitude of Rayleigh waves. Bornitz, decrease in peak particle velocities, $\dot{u}$ from one point, a to another, b can be stated as

$$\dot{u}_b = \dot{u}_a \left(\frac{r_a}{r_b}\right)^{\gamma} e^{\alpha(r_a - r_b)} \tag{2}$$

where r is the distance from the source, γ is geometrical damping, and α is material damping coefficient which can be calculated as

$$\alpha = 2\pi f \xi / V \tag{3}$$

where f is the frequency of the source vibration, ξ is the damping ratio, and v is the Rayleigh wave velocity.

3. Results

Attenuation of the amplitude is derived as a function of distance from the train rail for free field vibration using records from Sensors 1, 2, 3 and 4 which are placed 8.4 m, 13.4 m 18.4 m and 26.4 m respectively. Results are calculated for two different train velocities 50 km/h and 70 km/h (Fig. 4 a-b). Horizontal peak velocities (black squares) attenuates faster than vertical peak (red squares) velocities. Bornitz's analytical solutions have been computed for each component and velocities for one meter intervals. Absorption coefficient dependent upon the type of propagation mechanism and soil are selected as Bornitz's recommendations. For the radiation damping (γ), 0.5 is assumed which suitable for point source type and surface wave. Damping ratio (ξ), is assumed to be 4 %. The frequency of source vibration (f), and the Rayleigh wave velocity (v) are determined as 13 Hz and 99 m/s, respectively. The Rayleigh wave velocity of 99 m/s taken into consideration for Bornitz solution is obtained from the site investigation. This value relates to the shear velocity. The frequency of 13 Hz is the maximum value of the frequency content for both horizontal and vertical vibration components at the nearest recording point to the vibratory source.

In general, the vibration level attenuates with the increase of the distance from the railway track, which is formulated for a point source by Bornitz. It could be seen from the distribution of the measured ground vibrations versus distance from railway site in Fig. 4, the level of ground velocities are magnified. There is a vibration-amplifying zone in the investigation site, which is about 15-20 m away from the railroad. This case can be explained by the scattering, diffraction and multiple reflection of the S waves in the soft soil between the bedrock and the ground surface. The occurrence of the magnifying zone is related to the depth of the bedrock and soil strata with different elastic properties. Bornitz's approach didn't take into consideration this important factor regarding soil stratification in the above mentioned formulation (see Eq. (2)).

Velocity levels in decibel using FTA standards are calculated. Attenuation of horizontal and vertical component of records with respect to distance have been shown in Fig. 5. The horizontal attenuation of ground vibration is faster than vertical motion. Velocity level exceed of 90 dB at the first sensor for horizontal component. For the two component under both train speed, level of velocity at sensor 1 (8.4 m) is higher than 83 dB which is the maximum allowable limit for infrequent events defined in FTA criteria. Rest of the free field sensors are under this limit except sensor 2 for vertical motion with the speed of 70 km/h. However amplitudes measured at the sensor 5 at the top of the water tank as 83.3 dB and 84.8 dB for the vertical which is above the standards and 79.7 dB and 78.2 dB for the horizontal component.

Although FTA considers max RMS values in terms of dB, DIN standards are given directly absolute peak velocity amplitudes in which considered more appropriate for evaluating the potential building damage rather than evaluating human response (FTA, 2012). Peak velocities of all records at all sensors are found less than 2.5 mm/s which is the minimum requirement for long-term vibrations. For short-term vibration, allowable thresholds are two times larger than the long-term vibration. Therefore, independent from short or long term effect, investigated water tank is in the allowable range with the measured peak amplitudes.

Finally two records from sensor 4 and 6 are compared in terms of variation in amplitude and frequency content. Sensor 6 is located at the other side of the water tank.

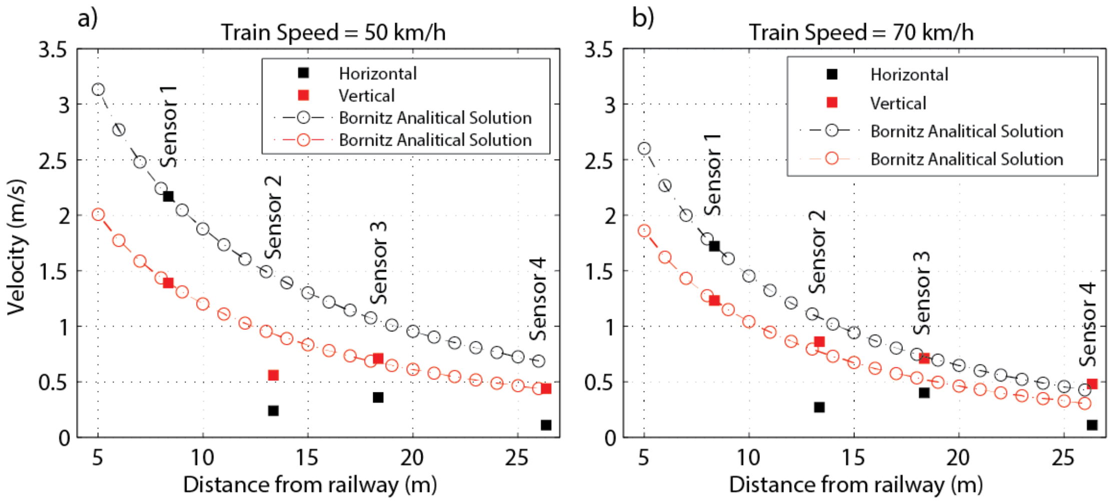

Fig. 4 Attenuation of measured peak velocity amplitude ratios and comparison with analytical solution a) 50 km/h b) 70 km/h train speeds

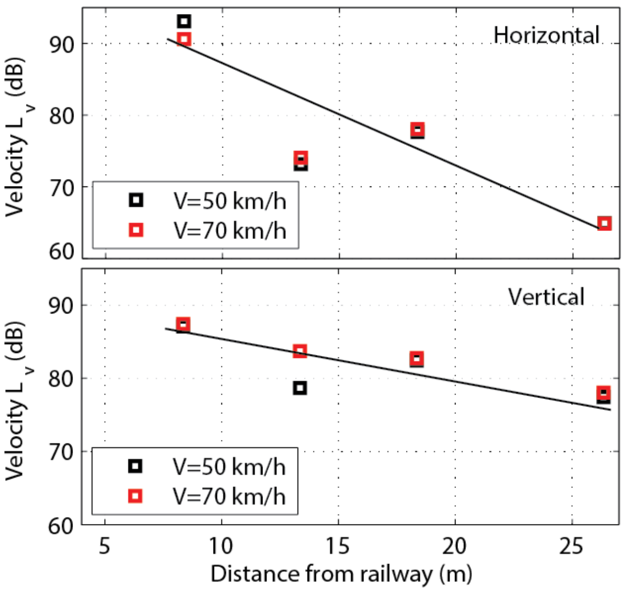

Fig. 5 Attenuation of peak RMS values in dB according to FTA, (2012)

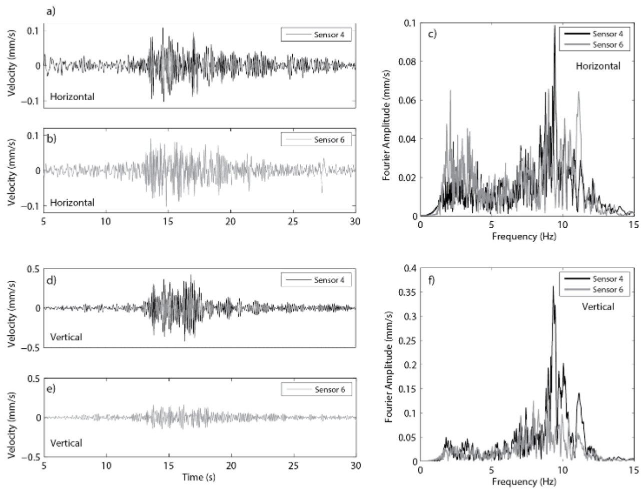

Fig. 6 Comparison between velocity time histories a) Horizontal component of Sensor 4 b) Horizontal component of Sensor 6 c) Comparison of frequency content of both sensors d) Vertical component of Sensor 4 e) Vertical component of Sensor 6, f) Comparison of frequency content of both sensors

Measurements show that the free field ground motion (Fig. 6(a)-(d)) are larger than Sensor 6 (Fig. 6(c)-(e)). Water tank reduced vertical the response of the surface vibration significantly compared to horizontal excitation. Furthermore, the existence of the water tank altered the frequency contents of the free field vibration.

4. Discussion of the analysis and experimental results

A broader review of the literature in this area where the effect of vehicle characteristics on ground and track borne-vibrations from railways is explained in (Kouroussis *et al.* 2014a). To ensure acceptable levels of ground vibration for residents living in the vicinity of freight railway lines is discussed by Waddington *et al.* (2015). Furthermore, various experimental research for train-induced vibrations are conducted across Europe and China (Xia *et al.* 2009, Auersch 1989, Branderhorst 1997, Adolfsson *et al.* 1999, Degrande and Schillemans 2001, Galvín and Domínguez 2009, Auersch 2010, Connolly *et al.* 2014, Connolly *et al.* 2015, Zhai *et al.* 2015). Several complex and more recent models regarding the effect of ground vibrations induced by high speed train pointing excitation and embankment modelling in the numerical approaches (Kouroussis and Verlinden 2013, Connolly *et al.* 2013, Hamdan *et al.* 2015).

The vibrations of the liquid-storage tank were compared with the standard of Federal Transportation Railroad Administration (FTA) and with the criteria in German Norm (DIN 4150-3). Former is the American criteria considering the ground-borne vibrations in terms of root mean squared velocity levels in decibels. Assessment parameters of FTA and DIN criteria's for structural damage and human response are different. According to brink stated in in DIN

4150-3, absolute peak particle velocities are within the safe limits. Even so, in comparison with FTA velocity level at the top of the water tank exceeds the allowable limits. Kouroussis *et al*. (2014b) compared these two standards by analyzing complex vibrations generated by railway traffic in order to present a relevant analysis of severity of each norm. They found greater vibration level in the vertical direction compared to the horizontal vibrations for a train speed of 30 km/h up to 20 m to the rail track. They concluded that assessment problem is complex due to contradictory recommendations by different guidelines.

On the other hand, it is observed from the free field measurements in the vertical direction that the rigid foundation of water tank becomes an obstacle for propagating surface waves generated by passing train. However, the same shielding effect is not examined for the horizontal vibration direction because of the discrepancy in spread of ground borne waves.

5. Conclusions

In this paper, a field experiment was carried out to provide to examine acceptability levels of railway traffic-induced environmental vibrations. The serviceability of a liquid-storage tank is also evaluated with regard to obtained measurements. During the transit of the suburban trains at variable speed (50-70 km/h) in the Adapazari-Arifiye railway line at Sakarya City, the structural response of the tank to the ground borne vibrations are measured by using six accelerometers. Attenuation of the amplitude as a function of distance and absorption coefficient dependent upon the type of propagation mechanism are derived. The applicability of a well know half-space solutions based on Bornitz's analytical approach which indicates for free field ground motions are investigated. The calculated analytical Bornitz's solution tend to overlap vertical free field ground motion depending on in-situ measured records. However the same relationship cannot be observed for the horizontal surface soil vibration because Bortnitz's solution cannot reflect the sharp decrease in amplitudes for sensors placed farther than 9 m from the dynamic source. There is a vibration-magnifying zone in the investigation field, which is located at 15-20 m from the railroad. This case can be explained by the dispersion of the S waves in the soft soil stratification. Bornitz's formulation didn't take into account this effect related to soil layers with different elastic properties. Therefore, this formula should be enhanced for such special cases that may be encountered in the field by considering the bedrock depth and the mechanical properties of the soil layers.

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References

Adam, M. and Estorff, O. von. (2005), "Reduction of train-induced building vibrations by using open and filled trenches", *Comput. Struct*., **83**(1), 11-24.

Adam, M., Pflanz, G. and Schmid, G. (2000), "Two- and three-dimensional modeling of half-space and train-track embankment under dynamic loading", *Soil Dyn. Earthq. Eng*., **19**(8), 559-573.

Adolfsson, K., Andréasson, B., Bengtson, P.E., Bodare, A., Madshus, C., Massarch, R., Wallmark, G. and Zackrisson, P. (1999), "High speed lines on soft ground. evaluation and analyses of measurements from the West Coast Line", Technical Report, Banverket, Sweden.

Amick, H. and Gendreau, M. (2000), "Construction vibrations and their impact on vibration sensitive facilities", *ASCE Construction Congress 6*, Orlando, Florida USA.

Arman, H and Gunduz, Z (2005), "Some geotechnical characteristics of Adapazari Region, Turkey", *Proceedings of the International Conference on Problematic Soils, Eastern Mediterranean University, Famagusta*, North Cyprus, May.

Auersch, L. (1989), "Forschungsbericht 155", Bundesanstalt für Materialforschung und-prüfung, Berlin, Zur Entstehung und Ausbreitung von Schienenverkehrserschutterungen-theoretische Untersuchungen und Messungen an Hochgeschwindigkeitszug Intercity Experimental.

Auersch, L. (2010), "Theoretical and experimental excitation force spectra for railway-induced ground vibration: vehicle-track-soil interaction, irregularities and soil measurements", *Vehicle Syst. Dyn. J.*, 48(2), 235-261.

Bornitz, G. (1931), "Über die Ausbreitung der von Groszkolbenmashinen Erzeugten Bodenschwingen in die Tiefe", Springler, Berlin, Germany.

Branderhorst, J. (1997), "Modellen voor het boeggolfprobleem bij hogesnelheidstreinen", Ontwerp en validatie met behulp van de resultaten van de proef Amsterdam-Utrecht, Master's Thesis, University of Twente, Enschede, Netherlands.

Bratov, V., Petrov, Y., Semenov, B. and Darienko, I. (2015), "Modelling the high-speed train induced dynamic response of railway embankment", *Mater. Phys. Mech.*, **22**, 69-77.

Celebi, E. and Goktepe, F. (2012), "Non-linear 2-D FE analysis for the assessment of isolation performance of wave impeding barrier in reduction of railway-induced surface waves", *Constr. Build. Mater.*, **36**, 1-13.

Celebi, E. and Schmid, G. (2005), "Investigation of ground vibrations induced by moving loads", *Eng. Struct.*, **27**(14), 1981-1998.

Connolly, D., Giannopoulos, A. and Forde, M.C. (2013), "Numerical modelling of ground borne vibrations from high speed rail lines on embankments", *Soil Dyn. Earthq. Eng.*, **46**, 13-19.

Connolly, D.P., Kouroussis, G., Woodward, P.K., Giannopoulos, A., Verlinden, O. and Forde, M.C. (2014), "Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils", *Soil Dyn. Earthq. Eng.*, **66**, 78-88.

Connolly, D.P., Costa, P.A., Kouroussis, G., Galvin, P., Woodward, P.K. and Laghrouche, O. (2015), "Large scale international testing of railway ground vibrations across Europe", *Soil Dyn. Earthq. Eng.*, **71**, 1-12.

Crispino, M. and D'apuzzo, M. (2001), "Measurement and prediction of traffic-induced vibrations in a heritage building", *J. Sound Vib.*, **246**(2), 319-335.

Cruzado, H.J. and Letchford, C. (2013), "Full-scale experiments of cantilever traffic signal structures", *Wind Struct.*, **17**(1), 99-123.

Cruzado, H.J., Letchford, C. and Kopp, G.A. (2013), "Wind tunnel studies of cantilever traffic signal structures", *Wind Struct.*, **16**(3), 59-67.

Degrande, G. and Schillemans, L. (2001), "Free field vibrations during the passage of a Thalys HST at variable speed", *J. Sound Vib*., **247**(1), 131-144.

Deutsche Norm, DIN 4150-3 (1999), "Structural Vibration: Part 3: Effects of vibration on Structures", Germany.

FTA - Feral Transit Administration Report. (2012), "High-Speed Ground Transportation Noise and Vibration Impact Assessment", USA.

Galvín, P. and Domínguez, J. (2009), "Experimental and numerical analyses of vibrations induced by high-speed trains on the Córdoba-Málaga line", *Soil Dyn. Earthq. Eng.*, **29**(4), 641-657.

Hamdan, N., Laghrouche, O., Woodward, P.K. and Mahmood, M.S. (2015), "Ground vibration reduction analysis using a frequency-domain finite element approach", *Constr. Build. Mater.*, **92**, 95-103.

Jones, C.J.C. and Block, J.R. (1996), "Prediction of ground vibration from freight trains", *J. Sound Vib.*, **193**(1), 205-213.

Kim, J., Kang, J.W., Jung, H. and Pack, S.W. (2015), "Effects of traffic-induced vibrations on bridge-mounted overhead sign structures", *Struct. Eng. Mech*., **55**(2), 365-377.

Kouroussis, G., Connolly, D.P. and Verlinden, O. (2014a), "Railway-induced ground vibrations-a review of vehicle effects", *Int. J. Rail Transport.*, **2**(2), 69-110.

Kouroussis, G., Conti, C. and Verlinden, O. (2014b), "Building vibrations induced by human activities: a benchmark of existing standards", *Mech. Indust.*, **15**(5), 345-353.

Kouroussis, G. and Verlinden, O. (2013), "Prediction of railway induced ground vibration through multibody and finite element modelling", *Mech. Sci.*, **4**(1), 167-183.

Krylov, V.V. (1996), "Vibration impact of high-speed trains effects of track dynamics", *J. Acoust. Soc. Am*., **100**(5), 3121-3133.

Li, Z., Li, S., Lv, J. and Li, H. (2015), "Condition assessment for high-speed railway bridges based on train-induced strain response", *Struct. Eng. Mech.*, **54**(2), 199-219.

Lombaert, G., Degrande, G., Kogut, J. and François, S. (2006), "The experimental validation of a numerical model for the prediction of railway induced vibrations", *J. Sound Vib*., **297**(3), 512-535.

Massarsch, K.R. (2000), "Settlements and damage caused by construction-induced vibration", *Proceedings of international workshop wave 2000*, Chouw N, Schmid G, editors, pp. 299-315, Bochum, Germany, Balkema, Rotterdam, 13-15 December 2000.

Park, J.H., Huynh, T.C., Lee, K.S. and Kim, J.T. (2016), "Wind and traffic-induced variation of dynamic characteristics of a cable-stayed bridge - benchmark study", *Smart Struct. Syst.*, **17**(3), 491-522.

Peplow, A.T., Jones, C.J.C. and Petyt, M. (1999), "Surface vibration propagation over a layered elastic half-space with an inclusion", *Appl. Acoust*., **56**(4), 283-296.

Rezvani, M.A., Vesali, F. and Eghbali, A. (2013), "Dynamic response of railway bridges traversed simultaneously by opposing moving trains", *Struct. Eng. Mech.*, **46**(5), 713-734.

Riedman, M., Sinh, H.N., Letchford, C. and O' Rourke, M. (2015), "Full-scale investigation of wind-induced vibrations of a mast-arm traffic signalstructure", *Wind Struct*., **20**(3), 405-422.

Senalp, A.D., Arikoglu, A., Ozkol, I. and Dogan, V.Z. (2010), "Dynamic response of a finite length euler-bernoulli beam on linear and nonlinear viscoelastic foundations to a concentrated moving force", *J. Mech. Sci. Technol*., **24**(10), 1957-1961.

Takemiya, H. and Bian, X. (2005), "Substructure simulation of inhomogeneous track and layered ground dynamic interaction under train passage", *J. Eng. Mech*., ASCE, **131**(7), 699-711.

Vostroukhov, A.V. and Metrikine, A.V. (2003), "Periodically supported beam on a visco-elastic layer as a model for dynamic analysis of a high-speed railway track", *Int. J. Solid. Struct.*, **40**(21), 5723-5752.

Waddington, D., Woodcock, J., Smith, M.G., Janssen, S. and Waye, K.P. (2015), "CargoVibes: human response to vibration due to freight rail traffic", *Int. J. Rail Transport.*, **3**(4), 233-248.

Xia, H., Chen, J., Wei, P., Xia, C., De Roeck, G. and Degrande, G. (2009), "Experimental investigation of railway train-induced vibrations of surrounding ground and a nearby multi-story building", *J. Earthq. Eng. Eng. Vib*., **8**(1), 137-148.

Xia, H., Zhang, N. and Cao, Y.M. (2005), "Experimental study of train-induced vibrations of environments and buildings", *J. Sound Vib*., **280**(3-5), 1017-1029.

Yang, B.Y. and Hung, H.H. (2001), "A 2.5D finite/infinite element approach for modeling viscoelastic bodies subjected to moving loads", *Int. J. Numer. Method. Eng*., **51**(11), 1317-1336.

Yang, Y.B., Hung, H.H. and Chang, D.W. (2003), "Train-induced wave propagation in layered soils using finite/infinite element simulation", *Soil Dyn. Earthq. Eng.*, **23**(4), 263-278.

Zhai, W., Wei, K., Song, X. and Shao, M. (2015), "Experimental investigation into ground vibrations induced by very high speed trains on a non-ballasted track", *Soil Dyn. Earthq. Eng.*, **72**, 24-36.

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