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Critical Review of Ground-Borne Vibration and Impact Assessment: Principles, Measurement and Modelling

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Abstract – The aim of this paper is to review the principles of ground-borne vibration induced by road traffic. Several researchers have studied the impact of ground-borne vibration on people, structure, and equipment, and developed guidelines or standards in order to indicate the threshold limit of damage and annoyance. Measurement of ground-borne vibration is a crucial aspect in ground-borne vibration studies that needs to be understood well. The reliability of the measurement is dependent on the accuracy of the data collected. Thus, discussion in this review paper proceeds on the types of ground-borne vibration modelling that can predict and explain the phenomenon.

Keywords: Ground-borne vibration, impact assessment, measurement, modelling

Introduction

Ground-borne vibration (GBV) is a term that is used to describe mostly man-made vibrations of the ground, for example, vibrations caused by air blast, construction work, mining, railway traffic and road traffic. Natural ground vibrations of the earth, on the other hand, as studied in seismology, is associated with different types of elastic waves propagating through the ground. They are normally associated with natural phenomena such as earthquake, tsunami, landslide and water waves in the oceans. These sources of GBV from man-made activities and natural phenomena create vibration energy and excite the nearby ground, creating vibration waves. These vibration waves are surface waves, mostly Rayleigh waves, bulk longitudinal waves and transverse waves (or shear waves) propagating into the ground depth. They then propagate through the various soil and rock strata to the foundations of nearby buildings and structures.

The basic principle of GBV and propagation path for a road system is illustrated in *Figure 1*. It consists of the source vibration, propagation path and the receiver, which may be people, buildings and structures (Hunaidi, 2000; Bahrekazemi, 2004). This paper focuses on ground vibration caused by the road traffic system.

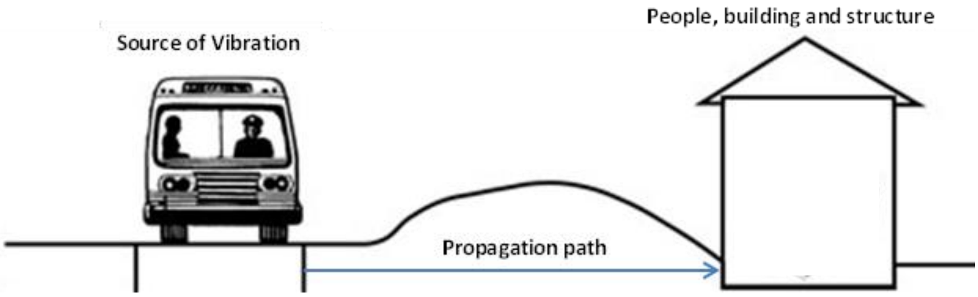

Figure 1: Illustration of propagation of ground-borne vibration towards buildings and structures

Impact of Ground-Borne Vibration

Once the GBV is generated by the source, it propagates through the soil-ground and is received by people, buildings and structures. This may, to a certain extent, affect and create problems to the people, structures and equipment.

Effect on people

People can be annoyed by ground vibration; Hunaidi (2000) reported that in Canada during winter when the topsoil is normally frozen, there are fewer complaints about ground vibration. During the spring thaw period, however, a higher number of complaints is reported. The thaw period is when the snow starts to melt, causing water levels to rise and subsequently increasing the ground vibration level. The ISO 2631 (1989) lists amplitude, duration and frequency content of vibration to be among physical factors which influence human response to ground-borne vibration. Other factors such as population type, age, gender and expectation are psychological. The vibration models output from the New Zealand Transport Agency (2012) recommends that 0.5 mm/s of Peak Particle Velocity (PPV) is a disturbance for residents inside a building. The primary effect of perceptible vibration is normally of immediate concern. However, secondary effects such as the movement of the building floors, rattling of windows, shaking of items on shelves or hangings on walls, can also occur even when vibration levels are below perception. These primary or secondary effects, or a combination of them, can lead to annoyance. Nevertheless, the degree of annoyance is dependent on the activities in which the people are involved at the time of disturbance (CDOT, 2013). This shows that the impact of ground-borne vibration on people is subjective, and may affect people differently depending on whatever activity they are doing.

Effect on structures

According to Hunaidi and Tremblay (1997), road traffic vibration is rarely the direct cause of damage to buildings and structures, but may contribute to their deterioration and may be the trigger to the damage. Ground vibration becomes an important issue when the buildings or structures concerned are heritage, cultural or historical sites which require protection and preservation. In Malaysia, such buildings or structures are especially found in Penang and Melaka, and also in some other states. *Figure 2* below shows buildings located by a roadway in Kuala Pilah, Negeri Sembilan.

Figure 2: Buildings located by a roadway in Kuala Pilah, Negeri Sembilan

Crispino and D'Apuzzo (2001) conducted a series of measurements of road traffic-induced vibrations in a heritage building in Naples, using a modified Watts' formula for the determination of the vibration variation due to vehicle type, speed and road roughness. Their findings indicated that all acquired data exceeded the ISO 2631's perception threshold for Peak Particle Velocity (PPV). The Department of Environment of the Ministry of Natural Resources & Environment Malaysia (2007) published a set of guidelines for Vibration Limits and Control in the Environment. *Table 1* shows the recommended tolerable vibration induced by road traffic in buildings.

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Table 1: Tolerable vibration induced by road traffic in buildings (Department of Environment, 2007)

Type of Building	Recommended Vertical Velocity Limit Vmax (mm/s)
Especially sensitive buildings, and buildings of cultural and historical value	1
Newly built buildings, and/or foundation of a foot plate (spread footings)	2
Buildings on cohesion piles	3
Building on bearing piles and friction pile	4

Apart from road traffic, construction activities and mining industries also generate ground vibration and have the potential to damage buildings and structures. The damages caused may be structural damage, such as the cracking of floor slabs, foundation, columns, beams, or wells, or cosmetic architectural damage such as cracked plaster or tile (CDOT, 2013). *Table 2* shows the vibration criteria for different types of building use with frequency in the range of 8-80 Hz.

Table 2: ISO 2631 (1989) Vibration Criteria

Building Use	Vibration Velocity Level (VdB)	Vibration Velocity rms Amplitude (mm/s)
Workshop	90	0.8
Office	84	0.4
Residence	78day/75night	0.2
Hospital operating room	72	0.1

Effect on equipment

Ground vibration also has the potential to interrupt the operation of vibration-sensitive research and high technology equipment such as in hospitals and laboratories. Xu and Hong (2008) discovered that traffic induced ground vibrations disrupted high-tech facilities and found that the velocity responses of the high-tech building due to the traffic flow are larger than those due to a single heavy truck. Their study revealed that traffic induced ground motions obstruct the normal operation of sensitive equipment housed in the building. Examples of high technology equipment are optical microscopes, cell probing devices, magnetic resonance imaging (MRI) machines, scanning electron microscopes, photolithography equipment, micro-lathes and precision milling equipment (CDOT, 2013). The extent to which the equipment is disturbed depends on the type of equipment, how it is used and its support structure. For instance, equipment supported on suspended floors may be more vulnerable to disruption than equipment supported by an on-grade slab.

The author's own on-site research experience has shown that the measurement of ground vibration located less than 10m from road traffic shows the level of PPV to be normally more than 1mm/s, especially in soft ground areas. Most ground vibration levels in New Zealand and Malaysia are found to exceed the prescribed ISO level of both countries.

Measurement of Ground Borne Vibration

Basically, ground vibration can be measured in the unit of displacement (mm), velocity (mm/s) or acceleration (mm/s^2) of a particle velocity at site. The relationship between them is shown in the equation below:

$D = V/2\pi f$ and $a = 2\pi fV$ (DOT & Main Road, 2013)

Note: a = acceleration (mm/s^2)
D = displacement (amplitude) (mm)
V = particle velocity (mm/s)
f = frequency (Hz)

There are three components of the instrumentation for vibration measurement system, namely, the vibration transducer, the amplifier with gain control, and the recorder (Hunaidi et al, 1994; DOT & Main Road, 2013). The accelerometer is normally used for measurement of strong ground motion whereas the geophone is used to measure weak ground vibration. *Figure 3* shows the accelerometer used by Bahrekazemi (2004) and the seismograph used by the author.

Figure 3: Accelerometer installed at site-left (Bahrekazemi, 2004) and seismograph used by the author-right

Adnan et al. (2012) used an accelerometer in their study which collected vibration data 1m from the road shoulder. Azureen et al. (2013) and Idayu et al. (2013), on the other hand, used a seismograph to record ground vibration data near a road traffic in Lenggong, Perak, and Marang, Terengganu. This means that the suitability of the transducer selected, whether it is a strain gauge, geophone or accelerometer, depends on the frequency and vibration amplitude ranges that needed to be identified. The transducers are also selected based on their accuracy and the availability.

Dynamic soil measurement

An important aspect in studying the problem of ground vibration is the dynamic properties of the soil. Within this parameter is the shear modulus of soil, G_{max}. Shear wave velocity (V_s) is a valued indicator of the dynamic properties of soil because of its relationship with G_{max} (Wair, et al., 2012). The relationship is given as below:

$$G_{max} = \rho \cdot V_s^2$$

Note: ρ = soil density

These dynamic soil properties can be measured in the laboratory or during field testing. The resonance column or the bender element test that is used in the laboratory can only measure at isolated sample locations and may not be representative of the entire soil profile. This is why field measurement has become the chosen method for estimating the soil's dynamic properties, with the advantage that it does not require undisturbed sampling. Among the geophysical methods for field testing are the spectral analysis of surface waves (SASW), multichannel analysis of Surface Wave (MASW), seismic refraction and seismic cross-hole test. The SASW test was performed by the author as shown in *Figure 4* to identify the dynamic soil properties of the shallow layers at one of the study areas.

Figure 4: SASW test performed at case study area

Modelling of Ground-Borne Vibration

In general, there are two purposes for developing the model, whether it is meant for explaining the GBV phenomenon or for predicting the GBV phenomenon. Models are useful and can be considered as significant when they help to solve problems and predict particular issues to do with real world phenomena. In GBV, a good prediction model is believed to have three basic principles or components of ground-borne vibration, namely, the source, the propagation path and the receiver. As mentioned earlier, the prediction model is dependent on the purpose of its development. If the prediction model is developed during the earlier or planning stage, before the road has been constructed, several significant factors such as vehicle speed and dynamic properties of the soil need to be identified. But, if the prediction model developed for evaluation of the impact after the road alignment has been decided, more detailed information is needed to develop the prediction model. There are three different types of GBV models which have been reviewed. They are: the simulation modelling, the semi empirical modelling and the empirical modelling.

Simulation studies

Xu and Hong (2008) simulated the traffic flow and vehicle distribution along a roadway by stochastic way and modeled the building by finite element method to explain the response of high-tech building equipment to ground vibration. Ju (2009) and Mhanna et al. (2012) also simulated the 3D vehicles moving on a road, road, soil and building irregularities by using finite element and validated their method with field experiment. The finite element model developed is found to be within acceptable accuracy when compared to the field experiment. Agostinacchio et al. (2014), in contrast, used the MATHLAB software to simulate the vibration phenomenon by generating the artificial road profile and dynamic load from different types of vehicle. Their simulation study evaluated the dynamic load from vehicle transfers to road pavements due to the generation of vibration by surface irregularities. The vibration stress level developed is a function of degradation of the road surface, speed and vehicle type for the purpose of designing and maintaining the road pavement.

Semi empirical studies

The semi empirical model is where the model relies to some extent on experimental measurement. Lak et al. (2011) studied the relationship between GBV, road irregularities and dynamic vehicle responses. Six roads with different pavement types were experimentally measured for the roads' unevenness and dynamic vehicle responses, supplemented with numerical predictions. The dynamic vehicle load is predicted from the 3D vehicle model based on measured road unevenness. Then the free field vibration is predicted from computed dynamic vehicle load based on the road transfer functions. Tuan Chik et al. (2013) performed the structural response of a multi storey building when subjected to GBV induced by road vehicles. Measurement conducted at site was used as an input to be analysed using the ANSYS and MATHLAB dynamic software. The vibration level achieved in the building by using overseas generic criteria guidelines is found to be above ISO level and within acceptable limit.

Empirical studies
An empirical study conducted by Watts (1990) predicted annoyance and PPV at a building foundation by regression analysis. For annoyance prediction, traffic vibration at 50 sites with various site factors was collected. Factors included the number of heavy goods vehicles (HGV), the distance of the house façade from the nearside kerb, the unevenness index and the speed of vehicles. The maximum vertical PPV 6m at a building foundation was found as follows:

$$0.028.a.(v/48).t.p.(r/6)^x$$

Note: a = max height/depth of surface defect (mm)
v = speed of heavy goods vehicles (km/h)
t = ground scaling factor
r = distance of the foundation from the defect (m)
x = power coefficient that defines the damping of the vibration with the distance.
p = wheel track index for the heavy vehicle

In order to check the accuracy of the predicted model developed, the measurement and predicted result are compared and found to be in good agreement, as shown in *Figure 5*. The prediction equation developed by Watts (1990) is only useful in determining whether there is any ground vibration problems existing from the road surface defect.

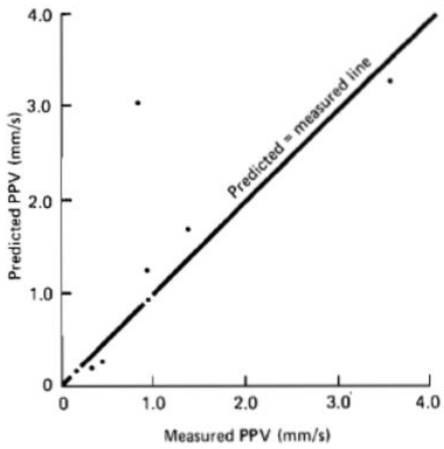

Figure 5: Predicted and measured vertical PPV at building foundations due to HGVS passing over road surface irregularities (Watts, 1990)

Long (1993) predicted the impact of vibration from a proposed highway to a residential area and evaluated vibration from the proposed ramp to the historical building. The measurement was taken at different distances from the highway, different topographic features and at the building pier using particle velocity sensors. The relationship between particle velocity and distance was found as follows:

$$\text{Log } A \text{ (mm/s)} = 0.9 - 1.25 * \text{Log } r \text{ (m)}$$

The empirical equation is valid for a distance of 30-300m only and the validation or significance of the relationship between vibration and distance was not proven or shown in the paper. Turunen-rise et al. (2002) introduced an empirical method for determination of statistical maximum velocity, $v_{w,95}$ or alternatively acceleration, $a_{w,95}$. The vibration measured is obtained as the 95-percentile of maximum weighted vibration velocities (or acceleration) from a minimum number of representative road and rail traffic events and validated by means of a Round Robin test. Their study provided relationships between different values of the new vibration exposure measure, v_{w95} in Norwegian and the strength of people's reactions.

Multiple linear regression models

Multiple linear regression models have been widely used by many researchers for prediction and explanation on a phenomenon, such as by Watts (1990), Basheer, (2001), Youd, et al. (2002), Jibson, (2007), Yimaz and Kaynar (2011) and Zhang, et al., (2013). From the literature, the prediction model by Watts (1990) is found to have used the multiple linear regression model to predict vertical vibration induced by road traffic, as has been explained in earlier. One example of multiple linear regression models for predicting ground-borne vibration induced by road traffic was developed by the author, and is shown in the equation below:

Vertical Vibration = 0.276 + 1.43 D/Vs - 0.0192 Ds + 0.00111S

Note: D = depth (m)
Vs = shear wave velocity (m/s)
Ds = Distance from vibration source
S = Speed of vehicle (km/h)

From the regression analysis, all independent variable D/Vs, Ds and S were significant for predicting vertical vibration where the *p*-value is less than 0.05, as shown in *Table 3*.

Table 3: Regression Analysis for Preliminary Model Predicting Vertical Vibration Model

Predictor	Coefficient	Standard error Coefficient	*T*-value	*P*-value	R-square
Constant	0.27641	0.01307	21.15	0.000	68%
D/Vs	1.4289	0.5140	2.78	0.006	
Ds	-0.0191970	0.0007406	-25.92	0.000	
S	0.0011077	0.0002283	4.85	0.000	

The analysis of variance (ANOVA) of the output is as shown in table 4. The *p*-value for models was less than 0.05, so the regression model was significant in predicting vertical vibration.

Table 4: ANOVA for Preliminary Model Vertical Vibration model

Source	DF	SS	MS	*F*-test	*P*-value
Regression	3	1.85025	0.61675	356.26	0.00
Residual error	514	0.88981	0.00173		
Total	517	2.74006			

The residual plots are the difference between the observed response value and the fitted response value. *Figure 6* shows the residual versus fitted values plot for the vertical vibration model. The figure shows that the points in the residual plot are scattered randomly at zero line. Therefore, no evidence of inconstant variance exists.

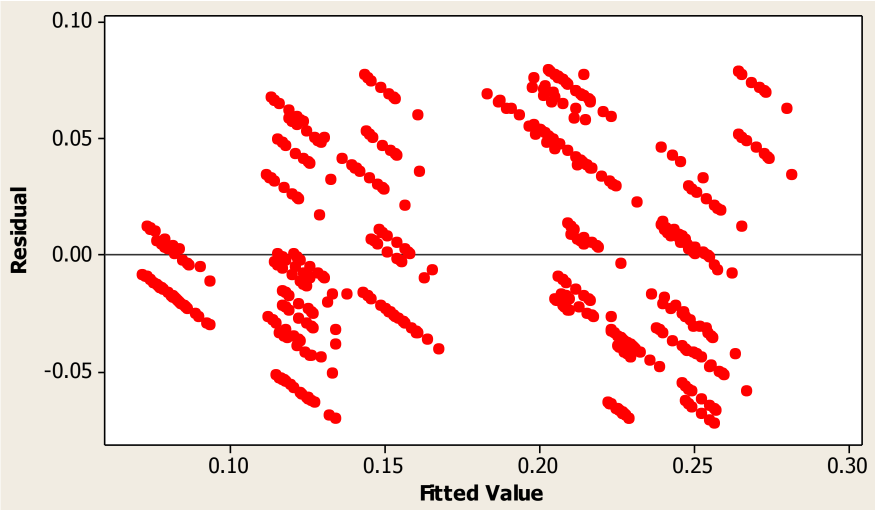

Figure 6: Residual versus fitted value for the Vertical Vibration model

The probability plot and goodness-of-fit tests, such as the Anderson-Darling and Kolmogorov-Smirnov normality tests, are used to check whether the residuals are distributed normally. As can be seen in *Figure 7*, the points are scattered closely along a straight line, which means that the residuals are normally distributed.

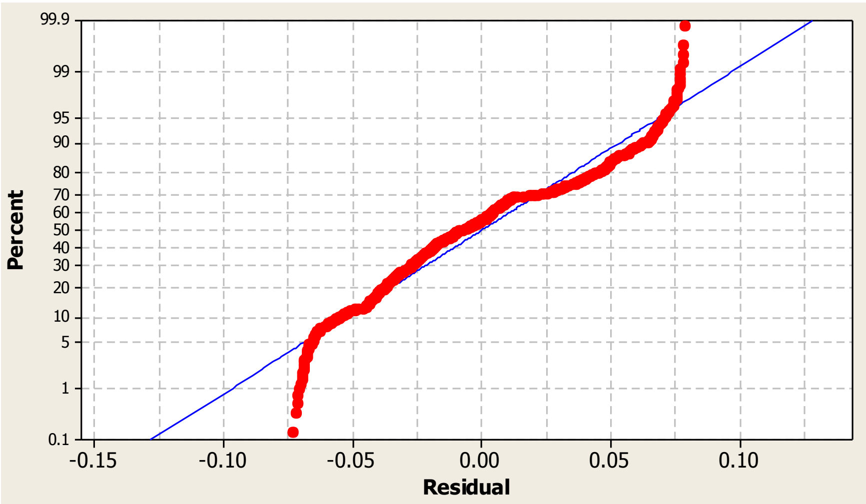

Figure 7: Normal probability plot of residuals for the Vertical Vibration Model

Figure 8 represents the relationship between the empirical values and the predicted values stated using a scattered plot. A 45-degree line is drawn in the graph where the points are close to the line. The points are found scattered along the 45-degree line, which means that the predicted value matched the empirical value. Therefore, the model can be accepted.

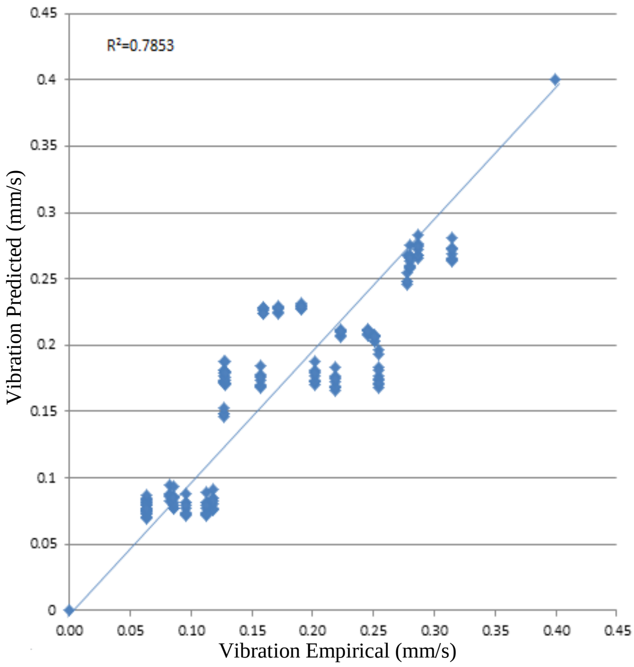

Figure 8: Predicted (Vertical Vibration) versus empirical (Vertical Vibration)

Conclusion

The aim of this paper is to review the principles, impact assessment, measurement and modelling of ground-borne vibration induced by road traffic. From the review of the literature, it is found that the impact of ground-borne vibration includes effects on the people inside the buildings, the sensitive equipment which may be affected by vibration, and potential damage to the buildings. In terms of measurement, proper techniques used for gaining and processing the data are highly dependent on the physical phenomenon of ground-borne vibration that produces the data. This also determines the desired engineering application for the study.

Several types of modelling approaches have been discussed and the models are only useful if they can solve problems and predict the best solution for the situation. It is hoped that this review can generate new research ideas, findings and approaches in predicting and explaining the ground-borne vibration phenomenon in Malaysia and other countries.

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