Intensity of Ground Vibration During the Passage of Trains: A Case Study

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Abstract

Continuous train induced ground vibration undoubtedly affects the health of nearby buildings and structures. This paper is based on the experimental study, carried out along the free field in the transverse direction of the railway track in-between Egoda Uyana and Koralawala railway station (a)to address the safety margin for the building construction and (b) to establish the relationship between the free field ground-borne vibration with the distance in the transverse direction from the railway track. The experiment was carried out by fixing 4 accelerometer devices at 4 locations (3 m, 6 m, 9 m & 12 m) in the transverse direction of the track and monitoring the effects of ground-borne vibration induced by the moving trains on the ground. The experimental data was verified using an additional experimental setup with vibrometer mounted on the ground at 3 m distance from the track centerline and the results have been verified. The data was measured for 27 moving trains in 5 days during the peak hour. In addition to the experiment, the soil properties of the location were identified using the lab tests. The experimental data states that the minimum safe distance to the dwellings from the centerline of the railway track when one train passes at a time is 9.8 m for the ground having similar soil properties and similarly safe distance could be found for other soil types and when two trains cross at a time.

1. Introduction

Although railway provides services to the passengers by functioning as a trunk in reducing the traffic towards the core of the city, the noise and vibration created by the motion of the trains can cause severe drawbacks which can cause immense disturbance to the community. Vibration from moving trains manifests itself in two main ways.

In some situations, people can feel it and it can be magnified by the resonance effect inside the building. Secondary effects include noise, radiation and disturbance of fixture and fitting (Suhairy, 2000)[1].

Vibration is generated in the system due to the passage of forces passing from wheel into track induced by several factors. These forces arise from the weight of the vehicle and irregularities/discontinuities at the wheel/rail interface and then propagate through the rail components to outwards from the track (Degrande & Schillemans, 2001)[2]. The wave energy dissipates and loses its strength when it propagates through the soil medium. The amount of energy dissipation strongly depends on the soil properties.

Figure 1: Experimental location

Lots of research have been done to study the effect of vibration generated by moving train. The field based experimental studies have been carried out to investigate the exact problem. Connolly et al., (2014)[3] carried out an experimental analysis of ground borne vibration created by high speed rail lines on various earth profiles such as at-grade, embankments, cutting and overpass. The results showed high vibration level at cutting and low vibration level at embankment. Also he has found that there is only a low (positive) correlation between the speed and vibration level. Hu et al, (2018)[4] investigated about the effect of ground vibration attenuation induced by heavy freight wagons on a railway viaduct. They have extended their research to assess vibration disturbance to the residents near the viaduct. The results showed significant ground and house vibration effect from a viaduct, and piers should be considered as sources of vibration. Chua, (1992)[5] presented an analytical procedure to examine the effect of ground borne vibration in houses due to subway rails. Sheng et al, (2004)[6] presented a theoretical model for a track and a layered ground, and the responses of the ground and track were studied under a moving harmonic and quasi static loads on the rails. Cai et al, (2010)[7] carried out a semi analytical investigation based on Biot's fully dynamic poro-elastic theory on the dynamic responses of the poro-elastic half space soil medium due to quasi-static and dynamic loads induced from a moving train.

2. Methodology

The experiment was carried out at a location in the middle of Egoda Uyana and Koralawella railway stations to have maximum speed at the location of experiment. A calm land, away from other sources of disturbances was selected to get high accuracy.

This experimental study is based on the following phases:

- Development of device to measure the ground acceleration
- Calibration of the device using an accepted method of calibration

- Field measurement of data
- Conversion of measured acceleration to peak particle velocity (PPV) using MATLAB
- Study and analysis of the results and establishing safe distance.

2.1 Experimental setup

In this experiment, two different experimental setups were used to take same measurements in-order to have high accuracy. (a) Measurements from calibrated vibrometer - ISEE Geophone was connected to the Instantel Micromate device which was kept firmly on a level ground and pressed "start". The readings of vibration PPV and root mean square (r.m.s) values were displayed on the screen and results were printed. (b) An electronic device is developed to measure and record the ground acceleration. This device is developed with MMA7455 type triaxial accelerometer to measure the ground acceleration, a memory chip for saving the data, real time clock for recording the time, and a power bank for the power supply. 4 devices of similar type have been made and fixed at 4 selected locations (3 m, 6 m, 9 m & 12 m) from the centerline of the railway track and readings were recorded. The topsoil of 150 mm was removed in the selected location and the soil was stabilized to avoid relative movement of loose soil and the device was fixed firmly to the ground.

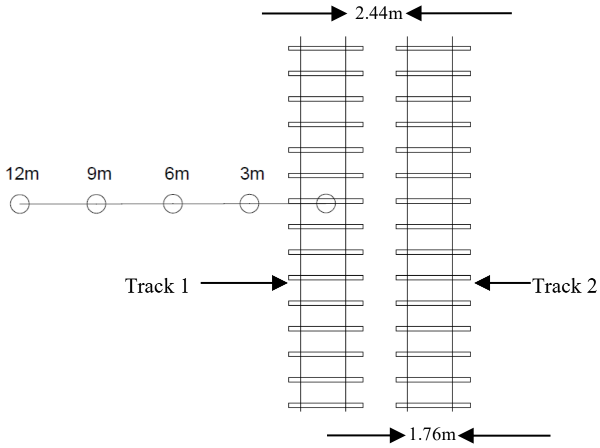


Figure 2: Detailed dimensions of the experimental components

2.2 Identification of soil properties

Vibration propagation greatly depends on the type of soil and soil properties. The soil at the experimental area was collected and sieve analysis was performed to identify the type of soil. Also, the borehole log of the location was collected from the Maintenance Division of Railway Department to identify the layered properties of soil.

2.3 Speed survey

The speed of each moving train was measured using manual method of speed calculation. A distance of 65m was marked on the railway track and the time taken by each train to pass the distance is measured. The speed is calculated from the survey results (distance travelled, and time taken to cross the distance) using the basic formula (1)

S=ut .... (1)

Here, S=Distance travelled

u=Speed of the train

t=time taken to pass the distance

2.4 Conversion using MATLAB coding

The MATLAB software was used to convert the experimental data in acceleration to peak particle velocity. Denoising techniques have been used to remove the noise signals recorded from the field. The actual data have been filtered using low pass and high pass filters from the field measurements.

2.5 Calibration of accelerometer device

Measurement was taken at the same location for the same train using accelerometer device and the calibrated vibrometer. The final results after converting the analog signal to PPV is compared with the results of the calibrated vibrometer reading.

Secondly, gravity calibration of the apparatus was done and ensured that the data is within the acceptable range of deviation.

2.6 Analysis of processed data

- The results from MATLAB coding is represented in graphical form for each train with their respective speed data.
- The variation of PPV in X, Y and Z directions of a specific train is discussed to show the variation of ground borne vibration with distance from the centerline of railway track.
- Identification of safe distance for the prevailing railway condition
- Prediction of safe distance for the future high-speed trains using the techniques of extrapolation

3. Results and Discussion

3.1 Soil investigation results

The particle size distribution diagram of the collected soil sample from the experimental location is summarized in Figure 3.

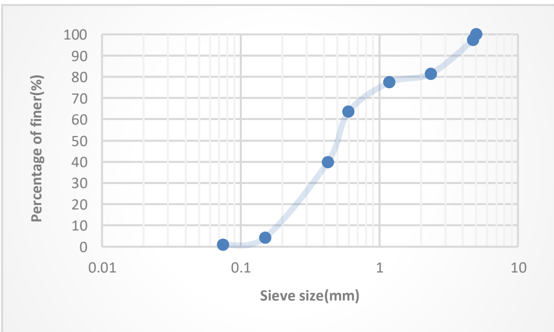


Figure 3: Particle size distribution of the soil sample - Dry sieve analysis

From the graph,

$D_{10} = 0.19\%$

$D_{30} = 0.34\%$

$D_{60} = 0.56\%$

$$Cc = \frac{D_{30}{}^2}{D_{60} \times D_{10}} = 1.086$$

$$\mathrm{Cu} = \frac{D_{60}}{D_{10}} = 2.95$$

According to the Unified soil classification system (USCS) the soil sample from the experimental location is classified as Poorly graded sandy soil. The moisture content of the soil sample was determined from the test results as follows,

Weight of empty tray: $W_1 = 0.2185$kg
Weight of moist soil + tray: $W_2 = 6.2415$kg
Weight of dry soil + tray: $W_3 = 5.8245$kg

$$\text{Moisture content} = \frac{W_2 - W_3}{W_3 - W_1}$$

$$= \frac{6.2415 - 5.8245}{5.8245 - 0.2185} \times 100\%$$

$$= 7.4\%$$

3.2 Analysis of experimental data for a specific train travelling with 63.8 km/h

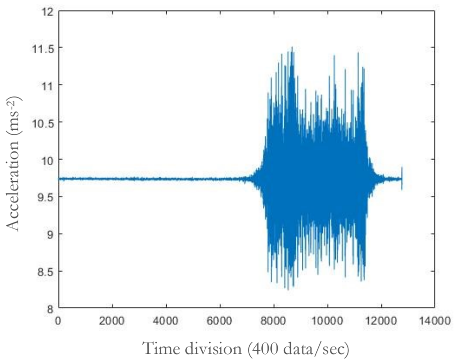


Figure 4: Measured free field vibration

The time history of vertical acceleration of experimental data is shown in Figure 4. The graph clearly states upto x=7000, the vibration sensed by the device is close to 9.81 ms^{-2}. The acceleration increases gradually from x=7000 and decreases after 8300. The increase from 7000-8300 states the approach of engine towards the location of data collection and the peak acceleration is obtained when the engine crosses the location of data measurement.

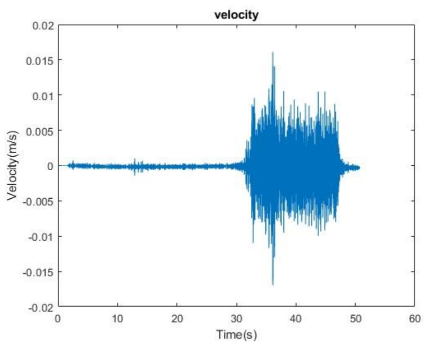


Figure 5: Time history of velocity in vertical direction

The ground acceleration created by the engine is higher than the train bodies. This experimental data is converted using Fast Fourier Transform (FFT) in MATLAB and the time history of PPV is shown in Figure 5. Velocities are obtained by the integration of acceleration after the removal of electrical noise and other noise factors. A low pass filter and high pass filter is used to derive the actual velocity variation due to vibration excitation.

3.3 Comparison of Measured data with the calibrated vibrometer reading

According to the experimental data, both instruments have given nearly similar readings. The error is less than 1 mm, which is fairly acceptable. Hence, the device data can be used for experimental analysis.

Table 1: Comparison of PPV measured from vibrometer and accelerometer device

Speed of train (km/h)	PPV (device) (mm/s)	PPV (vibrometer) (mm/s)	Deviation (mm/s)
63.8	16.098	16.02	0.078
38.9	5.13	5.281	-0.151
56.8	15.26	15.98	-0.72
77.7	17.588	17.64	-0.052
40.8	5.315	4.769	0.546

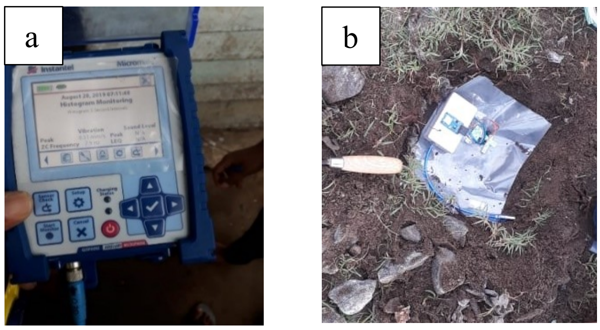


Figure 6: Field measurement – (a)Vibrometer, (b)Accelerometer device

3.4 Analysis of experimental data considering two trains of nearly same speed but difference mass

The details obtained from the Department of Railway stated that the mass of a car body of train is 35 tons and mass at maximum service condition is 76 tons. Two trains with nearly same speed was identified on a day of experiment, one carrying massive crowd and the other one is comparatively empty. These two trains were compared assuming all other parameters are constant. The train traveling in 77.7 km/h is identified as heavy train and 77.5 km/h is empty train. However, there is not much difference in the PPV variation obtained. Hence mass is not considered as the major influencing factor in this experiment.

Table 2: Variation of PPV in Transverse, Vertical and longitudinal direction with speed

Train no	Start Time	Speed of train (km/h)	Distance from source of vibration (m)	PPV-(mm/s) Transverse	PPV-(mm/s) Vertical	PPV-(mm/s) Longitudinal	Maximum Frequency (Hz)
1	07:07:26	63.8	3	10.33	16.02	9.837	51-vertical
2	07:10:08	38.9	7.2	4.792	3.949	5.281	64-vertical
3	07:12:54	56.8	3	10.09	15.98	6.305	57-vertical
4	07:15:55	77.7	3	11.00	17.64	8.851	51-vertical
5	07:21:54	40.8	3	4.091	4.769	5.738	39-vertical

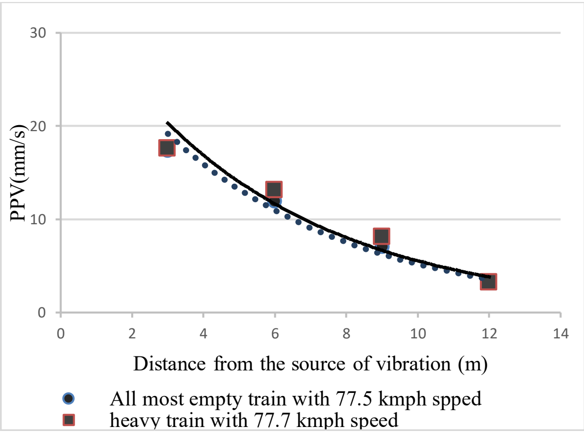


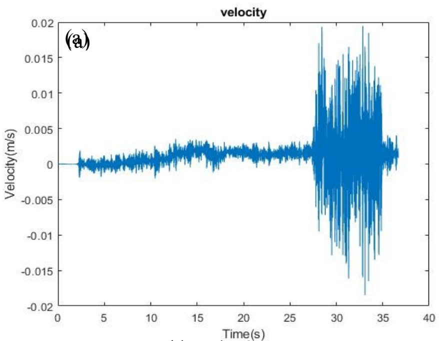
Figure 7: Influence of Mass in free field vibration

3.2 Analysis of variation with peak particle velocity in Transverse, Vertical and Longitudinal direction with speed

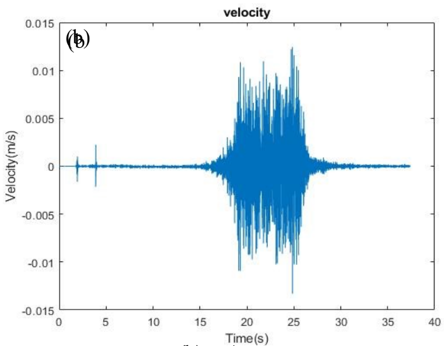
The calibrated triaxial vibrometer was kept at the experimental location and the following readings were observed. The readings were shown in Table 2 and graphical representation is shown in Figure 9.

Date of experiment – December 6,2019

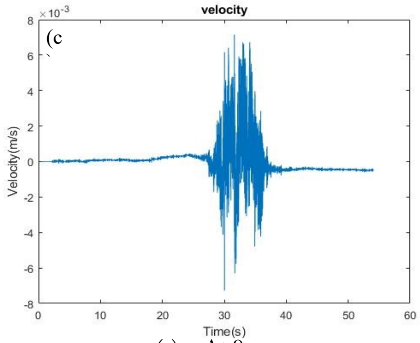
All other trains except 2nd train travelled in 3m from the location of measurement. The speed ascends in the order of train number 2 (lowest speed), 5, 3, 1, and 4 (highest speed). We can observe a gradual change of PPV with the speed change. The train with highest speed has high vertical PPV and low longitudinal PPV but the train with lowest speed has high longitudinal PPV and low vertical PPV.



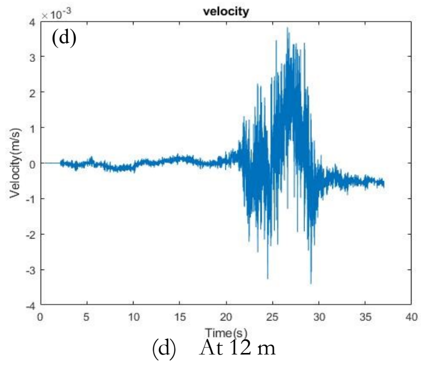
(a) At 3 m



(b) At 6 m



(c) At 9 m



(d) At 12 m

Figure 8: Time history analysis of vertical vibration of a specific train

Even if, the distance from the source is higher for train 2, similar pattern of PPV change can be observed in train 5 also.

Hence, we cannot always consider the vertical vibration to be prominent even if the applied loading is in vertical direction. The speed is also an important factor in determining the direction of maximum PPV.

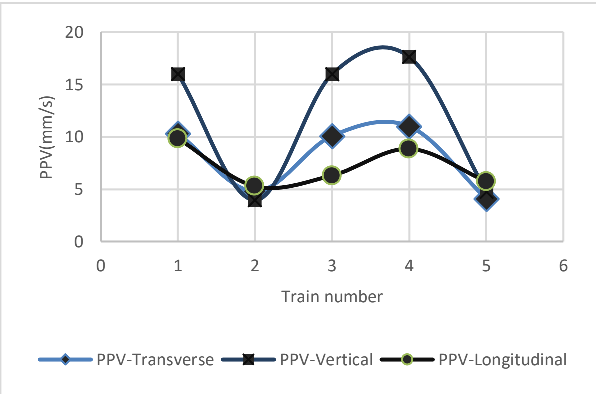


Figure 9: Variation of PPV in transverse, vertical & longitudinal directions

3.3 Analysis of experimental data considering the speed of the train

The figure 10 shows similar exponential variation of PPV with distance for the trains travelled in track 1. However, we can notice a clear deviation of the train travelled with the speed of 54.8 km/h from other patterns which can be considered as an error. The train with highest speed has generated highest PPV of 22.12 mm/s and train with speed 42.7 km/h has generated the lowest PPV of 9.89 mm/s.

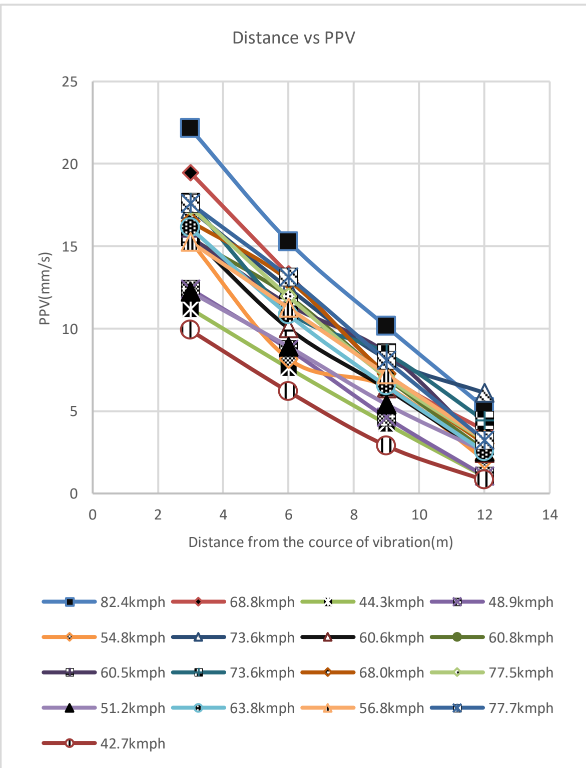


Figure 10: Variation of PPV with distance

But the train with 68.8 kmph has generated higher PPV value than the trains with 77.7 km/h, 73.6 km/h and 77.5 km/h. This might have been due to irregulates of the respective train.

3.4 Analysis of the variation in PPV when two trains crosses at the same time

Table 3: Variation of PPV in mm/s when combined effect of train crossing occur

Track no	From-To	Speed (km/h)	PPV-3m	PPV-6m	PPV-9m	PPV-12m
2	M-G	67.24	28.54	22.38	16.36	12.01
1	G-M	74.52				
1	G-M	82.38	22.12	15.28	10.12	5.21

The highest PPV reading is resulted from the vibration generated when two trains of 62.24km/h and 24.52km/h crossed at the same time.

Two trains with the velocities 67.24km/h and 74.52km/h crossed the point of experiment at the same time. The results of analysis showed that the free field vibration generated by this combined effect is much more than the individual effects with higher velocities. The equation of the graph is given by

$y = 38.959e-0.097x$ ……………………… (2)

where x = distance(m) and y = PPV (mm/s)

Hence, this effect should also be considered with different possible combinations which seems to be critical. The graph shows the measured free field vibration with another set of individual effect to make it easy to compare the variation.

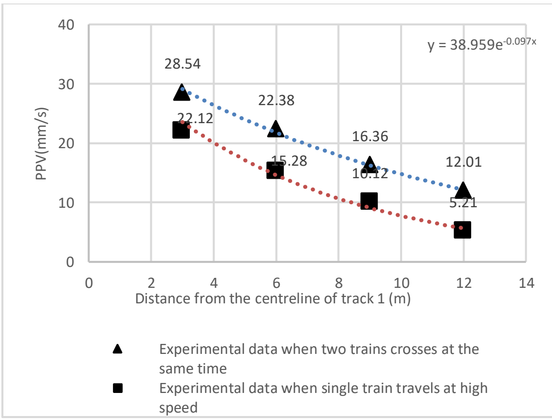


Figure 11: Variation of PPV for the passage of single train and two trains at the same time

3.5 Discussion

The results of this study show that the PPV of free field vibration in the location of experiment has exponential variation with the distance. The threshold peak particle velocity of buildings as stated in German standard DIN 4150-3 is shown in Table 4.

Table 4: German standards DIN4150-3

Line	Type of structure	Vibration peak particle velocity (mm/s)			
		Foundation frequency			Plane of floor of upmost storey
		Less than 10 Hz	10 to 50 Hz	50 to 100 Hz	Frequency mixture
1	Buildings used for commercial purposes, industrial buildings and similar designs	20	20 to 40	40 to 50	40
2	Dwellings and buildings of similar design and or use	5	5 to 15	15 to 20	15
3	Structures that, because of their sensitivity to vibration, do not correspond to those listed in lines 1 and 2 and are of great intrinsic value (eg buildings that are under a preservation order)	3	3 to 8	8 to 10	8

The measured frequency varies for every train. But most of it lie above 50Hz. Therefore, we are assuming the building foundation frequency is 50Hz even though there will be deviation.

The German standards DIN 4150-3 say, the dwellings whose foundation frequency is between 50 Hz – 100 Hz must possess PPV between 15 to 20 mm/s to reduce the damages caused to the buildings. Hence for a single storey dwelling, the allowable minimum PPV is 15mm/s. According to equation (2),

$$y = 38.959e^{-0.097x}$$
$$15 \text{ mm/s} = 38.959\times e^{-0.097x}$$
$$x = 9.839 \text{ m}$$

Hence when a combined effect of two trains crosses at once, the minimum safe distance is 9.8 m from the centerline of the track. But this event happens only once or twice a day. When considering the event of single train crossing, the maximum safe distance was 6 m from the centerline of the track. Similarly, safe distances for different types of buildings could be found using the above results to ensure the structural integrity of the building.

Here, mass of the train is not considered an utmost important factor affecting the PPV. The huge variation of mass creates only a very small deviation in PPV.

Vertical PPV is not always the maximum particle velocity. The speed of the train is an important factor deciding the axis of highest particle velocity in the free field.

This experiment could have been done in more locations with differing soil conditions and terrains. Using calibrated lab instruments for the experiment will further enhance the accuracy.

Also, numerical modeling and simulation with advanced FE codes can be done to predict the vibrations as the experimental investigation is expensive.

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