Ground Vibration Attenuation Measurement using Triaxial and Single Axis Accelerometers

A H Mohammad 1,* , N A Yusoff 1, A Madun 1, S A A Tajudin 2, M N H Zahari 3, T N T Chik 1, N A Rahman 4, Y M N Annuar 5
1 Faculty of Civil and Environmental Engineering, University Tun Hussein Onn of Malaysia, 86400 Batu Pahat, Johor, Malaysia
2 Research Centre for Soft Soil, University Tun Hussein Onn of Malaysia, 86400 Batu Pahat, Johor, Malaysia
3 EMC Centre, Faculty of Electrical and Electronic, University Tun Hussein Onn of Malaysia, 86400 Batu Pahat, Johor, Malaysia
4 Faculty of Engineering Technology, University Tun Hussein Onn of Malaysia, 86400 Batu Pahat, Johor, Malaysia
5 Faculty of Mechanical Engineering, University Tun Hussein Onn of Malaysia, 86400 Batu Pahat, Johor, Malaysia

E-mail: *adihizami@gmail.com

Abstract. Peak Particle Velocity is one of the important term to show the level of the vibration amplitude especially traveling wave by distance. Vibration measurement using triaxial accelerometer is needed to obtain accurate value of PPV however limited by the size and the available channel of the data acquisition module for detailed measurement. In this paper, an attempt to estimate accurate PPV has been made by using only a triaxial accelerometer together with multiple single axis accelerometer for the ground vibration measurement. A field test was conducted on soft ground using nine single axis accelerometers and a triaxial accelerometer installed at nine receiver location R1 to R9. Based from the obtained result, the method shows convincing similarity between actual PPV with the calculated PPV with error ratio 0.97. With the design method, vibration measurement equipment size can be reduced with fewer channel required.

1. Introduction

Peak particle velocity (PPV) for ground vibration monitoring is commonly used for ground vibration monitoring [1, 2]. PPV also is the standard measurement for control and disaster prevention method which usually applies in construction vibration control or vibration emission due to transportation especially railway transportation in several of recent regulation and guidelines [3, 4, 5].

To monitor PPV on ground surface, a single point monitoring can be conducted using a triaxial accelerometer. However, for vibration attenuation monitoring to determine the effect of vibration by distance from source, several sensors are installed on the ground along the wave path [6]. Unlike triaxial accelerometer which is using three channels of the data acquisition module, single axis accelerometer which using only one channel is preferred for vibration monitoring with limitation due to equipment size and number of available channel of the data acquisition device. This paper attempt to approach a method which can generally obtained more accurate attenuation of PPV using only a triaxial accelerometer with multiple single axis accelerometers.
This method can reduce the number of channel used on the data acquisition module hence reducing the size of the monitoring equipment.

2. Methodology

The method for this study is a combination of a simple data processing using obtained ground vibration monitoring data from conducted field test. Computer programme DEWESoftX2 was used to record the ground vibration data in time domain with 50 kHz sampling rate used. Conversion from raw acceleration data to particle velocity was processed real time using the single integration function within the software. Using the particle velocity from single axis and triaxial accelerometer, the conversion ratio from single axis, Z, to PPV was obtained which was used to create the calculated PPV from the single axis accelerometers. Finally, the calculated PPV and actual PPV was compared to observe the accuracy of the calculated PPV.

2.1 Peak particle velocity

The basic vibration level can be measure as vibration amplitudes in single or multiple axis X, Y and Z. The vibration amplitude also can be used with vibration criteria guideline for vibration control [7]. Ground-borne vibration is measured in term of Peak Particle Velocities (PPV), which is referring to the vectored sum of the maximum velocity component of vibration [8, 6]. By observing the vibration amplitude in three dimensions, the peak particle velocity can be determined using the equation [6].

\[ PPV = \sqrt{v^2_{x,\text{max}} + v^2_{y,\text{max}} + v^2_{z,\text{max}}} \]  

PPV value will always be higher than a single axis vibration reading. Evaluation using PPV will be much more accurate and provide more realistic value to be use for vibration monitoring and control especially in British Standard and Malaysia DOE Guideline.

2.2 Equipment setup

A combination of 4 channel and 8 channel data acquisition module with a total of 12 channel input was used for the field testing as shown in figure 1(a). Groundborne vibration monitoring should be carried out using accelerometers [3] (Bsi, 2014). Nowadays, the use of Piezoelectric (ICP) accelerometer is preferable by researcher for field monitoring or laboratory testing [9, 10, 11, 12]. For the research, ICP Accelerometer was selected for both single axis and triaxial accelerometer with sensitivity 10.2 mV/(m/s²) as shown in figure 1(b). The single axis accelerometer was used to measure vertical axis, Z-Axis, of the surface wave. While the triple-axis accelerometer measures the vibration in three dimensions, resulting more accurate PPV by combining all three directions of the vibration amplitude.
2.3 Testing location

The field test was conducted on soft ground in Research Centre for Soft Soil (RECESS). Research shows that the effect of soil material properties appeared to be a significant factor on vibration levels hence soil material properties should be included in vibration assessment calculations [13]. Similar condition can be seen through several researches conducted by other researcher where vibration traveling through soft soil with low vibration propagation velocity, tends to create higher amplitude compare with denser ground [14, 15].

2.4 Testing procedure

Nine points was monitored in the testing. As shown in figure 2, first receiver R1 was installed 0.1m from source and the next receiver, R2, was installed 0.4m from source, means R2 is 0.3m from R1. Receiver R3 until R9 was installed with 0.4m spacing along the wave path. Based from table 1, the triaxial accelerometer location was changed every test setup. Each test setup consist of with 3 repeated force excitation using steel hammer as shown in figure 3. The vibration was recorded using single impact vibration and each data captured in 5 second.

![Figure 2. Testing arrangement.](image)
Table 1. Triaxial and single axis sensor arrangement for all 9 test setup.

| Test setup | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 |
|------------|----|----|----|----|----|----|----|----|----|
| Setup 1    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 2    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 3    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 4    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 5    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 6    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 7    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 8    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |
| Setup 9    | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|            |    |    |    |    |    |    |    |    | T  |

Figure 3. Field testing for ground vibration attenuation measurement.
3. Result and discussion

The recorded data was transferred to MS Excel for further processing. Table 2 shows the maximum amplitude in term of particle velocity (mm/s) from single axis accelerometers, S1 until S9, and from a triaxial accelerometer, TZ, TY and TX. The excitation forces using the steel hammer were repeated three times for each test setup. Table 3 show the calculation of actual PPV using equation 1 based from data TZ, TY and TX taken from table 2. From table 3 also, the Z-PPV ratio was obtained by dividing the actual PPV with the Z-axis value, TZ, of the same accelerometer.

Table 2. Single axis and triaxial accelerometer raw data (a) data for Setup 1 to 5, (b) data for Setup 6 to 9.

(a)

| Accelerometer | 1     | 1     | 2     | 2     | 3     | 3     | 4     | 4     | 5     | 5     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| S1            | 50.75 | 64.92 | 49.87 | 53.91 | 58.03 | 47.26 | 41.46 | 32.92 | 33.24 | 32.04 |
| S2            | 2.95  | 3.42  | 3.11  | 3.13  | 3.23  | 3.29  | 3.23  | 3.32  | 4.04  | 3.63  |
| S3            | 2.32  | 2.47  | 2.31  | 2.32  | 2.35  | 2.34  | 2.34  | 2.31  | 2.27  | 2.25  |
| S4            | 1.77  | 1.97  | 1.82  | 1.80  | 1.78  | 1.71  | 1.85  | 1.79  | 2.02  | 1.77  |
| S5            | 0.44  | 0.43  | 0.52  | 0.44  | 0.45  | 0.49  | 0.43  | 0.46  | 0.45  | 0.50  |
| S6            | 0.50  | 0.46  | 0.40  | 0.44  | 0.39  | 0.38  | 0.33  | 0.47  | 0.41  | 0.35  |
| S7            | 0.65  | 0.75  | 0.71  | 0.71  | 0.75  | 0.71  | 0.72  | 0.72  | 0.83  | 0.72  |
| S8            | 0.51  | 0.47  | 0.47  | 0.46  | 0.44  | 0.44  | 0.41  | 0.47  | 0.49  | 0.38  |
| S9            | 0.31  | 0.34  | 0.31  | 0.30  | 0.29  | 0.30  | 0.30  | 0.29  | 0.33  | 0.27  |
| TZ            | 59.26 | 72.82 | 56.98 | 4.94  | 5.08  | 4.81  | 2.18  | 1.99  | 1.63  | 1.78  |
| TY            | 15.21 | 15.72 | 14.41 | 4.29  | 3.10  | 0.67  | 0.89  | 0.41  | 0.32  | 0.35  |
| TX            | 10.51 | 11.13 | 13.50 | 13.62 | 14.66 | 13.89 | 3.52  | 3.93  | 2.60  | 2.29  |

(b)

| Accelerometer | 6     | 6     | 7     | 7     | 8     | 8     | 8     | 9     | 9     | 9     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| S1            | 44.42 | 51.38 | 48.14 | 46.85 | 49.89 | 56.37 | 49.57 | 57.68 | 50.17 | 45.04 |
| S2            | 2.72  | 3.09  | 3.25  | 2.55  | 2.82  | 3.16  | 2.81  | 3.73  | 3.29  | 3.12  |
| S3            | 2.00  | 2.15  | 2.26  | 2.00  | 2.19  | 2.23  | 2.26  | 2.29  | 2.06  | 1.98  |
| S4            | 1.30  | 1.11  | 1.32  | 1.09  | 1.30  | 1.21  | 1.39  | 1.19  | 1.14  | 1.15  |
| S5            | 0.42  | 0.39  | 0.46  | 0.37  | 0.44  | 0.44  | 0.48  | 0.53  | 0.44  | 0.42  |
| S6            | 0.36  | 0.47  | 0.38  | 0.40  | 0.38  | 0.43  | 0.40  | 0.46  | 0.41  | 0.40  |
| S7            | 0.71  | 0.66  | 0.73  | 0.70  | 0.81  | 0.78  | 0.82  | 0.74  | 0.69  | 0.66  |
| S8            | 0.43  | 0.40  | 0.45  | 0.39  | 0.44  | 0.46  | 0.42  | 0.44  | 0.42  | 0.37  |
| S9            | 0.31  | 0.27  | 0.29  | 0.26  | 0.28  | 0.32  | 0.31  | 0.29  | 0.28  | 0.25  |
| TZ            | 0.46  | 0.49  | 0.49  | 0.96  | 1.05  | 1.04  | 0.46  | 0.52  | 0.47  | 0.19  |
| TY            | 0.47  | 0.38  | 0.53  | 0.37  | 0.39  | 0.40  | 0.28  | 0.20  | 0.24  | 0.15  |
| TX            | 0.47  | 0.43  | 0.46  | 1.56  | 1.62  | 1.66  | 0.87  | 0.84  | 0.78  | 0.37  |

| Accelerometer | 7     | 7     | 8     | 8     | 9     |
|---------------|-------|-------|-------|-------|-------|
| S1            | 57.68 | 50.17 | 45.04 | 46.94 | 51.83 |
| S2            | 3.36  | 3.12  | 3.36  | 3.57  |       |
| S3            | 2.44  | 1.98  | 2.15  | 2.44  |       |
| S4            | 1.39  | 1.15  | 1.20  | 1.39  |       |
| S5            | 0.53  | 0.44  | 0.42  | 0.41  | 0.49  |
| S6            | 0.46  | 0.40  | 0.38  | 0.40  | 0.46  |
| S7            | 0.74  | 0.69  | 0.66  | 0.71  | 0.79  |
| S8            | 0.44  | 0.42  | 0.37  | 0.38  | 0.47  |
| S9            | 0.25  | 0.28  | 0.25  | 0.25  | 0.31  |
| TZ            | 0.19  | 0.18  | 0.23  |       |       |
| TY            | 0.14  | 0.14  | 0.19  |       |       |
| TX            | 0.19  | 0.19  |       |       |       |
Table 3. Triaxial Sensor data processing for actual peak particle velocity (a) data for Setup 1 to 5, (b) data for Setup 6 to 9.

(a)

| Accelerometer | Particle Velocity (mm/s) for each test setup |
|---------------|---------------------------------------------|
|               | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
| TZ            | 59.26 | 72.82 | 56.98 | 4.94 | 5.08 | 4.81 | 2.41 | 2.18 | 2.72 |
| TY            | 15.21 | 7.16 | 15.72 | 4.41 | 4.29 | 3.10 | 0.67 | 0.89 | 0.95 |
| TX            | 10.51 | 11.13 | 13.90 | 13.62 | 14.66 | 13.89 | 3.52 | 3.93 | 4.10 |
| PPV           | 62.08 | 74.01 | 60.72 | 15.14 | 16.10 | 15.02 | 4.32 | 4.55 | 5.01 |
| Z-PPV Ratio   | 1.05 | 1.02 | 1.07 | 3.07 | 3.17 | 3.12 | 1.79 | 2.09 | 1.84 |

(b)

| Accelerometer | Particle Velocity (mm/s) for each test setup |
|---------------|---------------------------------------------|
|               | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
| TZ            | 0.46 | 0.49 | 0.49 | 0.96 | 1.05 | 1.04 | 0.46 | 0.52 | 0.47 |
| TY            | 0.47 | 0.38 | 0.53 | 0.37 | 0.39 | 0.40 | 0.28 | 0.20 | 0.24 |
| TX            | 0.47 | 0.43 | 0.46 | 1.56 | 1.62 | 1.66 | 0.87 | 0.84 | 0.78 |
| PPV           | 0.81 | 0.75 | 0.86 | 1.87 | 1.97 | 2.00 | 1.02 | 1.01 | 0.94 |
| Z-PPV Ratio   | 1.76 | 1.54 | 1.75 | 1.95 | 1.88 | 1.92 | 2.22 | 1.94 | 2.00 |

As shown in figure 4, the obtained result of single axis PV from table 2, and triaxial PPV from table 3, was plotted into vibration attenuation chart. Significant difference between PV and actual PPV attenuation can be observe and these support why ground vibration monitoring should be monitor using PPV instead of PV in the regulation mentioned in section 1. Next, table 4 calculate the PPV from single axis accelerometers using the Z-PPV ratio obtained from table 3. Referring to attenuation chart plotted as shown in figure 4, both calculated and actual PPV value was compared.

Figure 4. Single axis particle velocity versus actual PPV from triaxial accelerometer.
Table 4. Calculated peak particle velocity data processing using z-ppv ratio (a) data for Setup 1 to 5, (b) data for Setup 6 to 9.

(a)

| Receiver | Peak Particle Velocity (mm/s) for each test setup |
|----------|--------------------------------------------------|
|          | 1      | 1      | 2      | 2      | 3      | 3      | 4      | 4      | 5      | 5      | 5      |
| R1       | 53.16  | 65.98  | 53.14  | 170.12 | 170.83 | 181.24 | 84.68  | 86.47  | 98.16  | 81.16  | 70.07  | 97.62  | 86.97  | 80.54  | 106.59 |
| R2       | 3.09   | 3.48   | 3.74   | 9.53   | 9.92   | 10.09  | 5.90   | 6.74   | 6.12   | 6.70   | 6.30   | 8.23   | 6.51   | 8.17   | 7.68   |
| R3       | 2.43   | 2.51   | 2.56   | 7.08   | 7.35   | 7.34   | 4.19   | 4.25   | 4.26   | 3.76   | 3.91   | 4.35   | 4.50   | 5.47   | 5.07   |
| R4       | 1.85   | 2.00   | 2.08   | 5.58   | 5.70   | 5.56   | 3.06   | 3.86   | 3.30   | 3.35   | 3.07   | 3.39   | 2.90   |        |        |
| R5       | 0.46   | 0.44   | 0.55   | 1.35   | 1.43   | 1.50   | 0.88   | 0.90   | 0.85   | 0.75   | 0.87   | 0.89   | 0.96   | 1.13   | 1.17   |
| R6       | 0.52   | 0.47   | 0.44   | 1.23   | 1.39   | 1.22   | 0.68   | 0.69   | 0.87   | 0.68   | 0.61   | 0.83   | 1.00   | 0.95   | 1.14   |
| R7       | 0.68   | 0.76   | 0.76   | 2.18   | 2.25   | 2.34   | 1.27   | 1.50   | 1.38   | 1.25   | 1.40   | 1.17   | 1.88   | 1.57   |        |
| R8       | 0.53   | 0.48   | 0.50   | 1.41   | 1.46   | 1.37   | 0.79   | 0.86   | 0.87   | 0.81   | 0.66   | 0.78   | 0.81   | 1.13   | 1.05   |
| R9       | 0.32   | 0.35   | 0.33   | 0.95   | 0.95   | 0.91   | 0.54   | 0.54   | 0.53   | 0.55   | 0.47   | 0.53   | 0.58   | 0.75   | 0.74   |

(b)

| Receiver | Peak Particle Velocity (mm/s) for each test setup |
|----------|--------------------------------------------------|
|          | 6      | 6      | 6      | 7      | 7      | 7      | 8      | 8      | 8      | 9      | 9      | 9      |
| R1       | 78.06  | 79.12  | 84.09  | 91.20  | 93.21  | 108.37 | 110.26 | 111.81 | 100.53 | 104.81 | 115.57 | 112.45 |
| R2       | 4.76   | 4.76   | 5.68   | 4.96   | 5.29   | 6.07   | 6.25   | 7.23   | 6.59   | 7.26   | 8.27   | 7.75   |
| R3       | 3.51   | 3.31   | 3.95   | 3.89   | 4.11   | 4.29   | 5.03   | 4.44   | 4.13   | 4.61   | 5.29   | 5.29   |
| R4       | 2.28   | 1.71   | 2.31   | 2.12   | 2.44   | 2.33   | 3.09   | 2.31   | 2.28   | 2.68   | 2.95   | 3.02   |
| R5       | 0.74   | 0.60   | 0.80   | 0.72   | 0.83   | 0.85   | 1.07   | 1.03   | 0.88   | 0.98   | 1.01   | 1.06   |
| R6       | 0.63   | 0.72   | 0.66   | 0.78   | 0.71   | 0.83   | 0.89   | 0.89   | 0.82   | 0.93   | 0.94   | 1.00   |
| R7       | 1.25   | 1.02   | 1.28   | 1.36   | 1.52   | 1.50   | 1.82   | 1.43   | 1.38   | 1.54   | 1.75   | 1.71   |
| R8       | 0.76   | 0.62   | 0.79   | 0.76   | 0.83   | 0.88   | 0.93   | 0.85   | 0.84   | 0.86   | 0.94   | 1.02   |
| R9       | 0.54   | 0.42   | 0.51   | 0.51   | 0.53   | 0.62   | 0.69   | 0.56   | 0.56   | 0.58   | 0.62   | 0.67   |

Figure 5. Actual PPV versus calculated PPV.

Finally, the error ratio between calculated PPV with actual PPV can be calculated based from the attenuation equation from figure 5. Table 5 shows that the error ratio is 0.9738 which is very close to 1, proving the obtained calculated PPV is very similar with actual PPV.
Table 5. Calculation for error ratio.

| Condition   | Attenuation Equation | Using x = 0.1 m | Error ratio |
|-------------|----------------------|-----------------|-------------|
| Actual PPV  | $y = 3.2833x^{-1.371}$ | 77.1455         | 0.9738      |
| Calculated PPV | $y = 2.9976x^{-1.399}$ | 75.1231         |             |

4. Conclusion

As a result, the approach of using only one triaxial accelerometer with multiple single axis accelerometer can achieved similar PPV with very low error ratio 0.9738. From the result, the size of the vibration monitoring equipment can be reduced by using fewer channel for the sensors. Obtained vibration attenuation equation also can be used for further ground vibration analysis such as building damage prevention.

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