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Vibration Assessment on Reinforced Concrete Structure due to Heavy Trucks

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ABSTRACT

The vibration caused by the heavy truck is becoming a concern towards the cracking at reinforced concrete structure. This paper discussed the vibration of rigid heavy truck assessment at Masjid Jamek Kampung Bindu, Batu Pahat and be compared to the Department of Environment's guideline. This study was conducted using accelerometer device to get the vibration's acceleration reading. There were 13 channels of accelerometers were setup accordingly to get the peak value of acceleration which located at the near of podium, middle of the mosque and near the entrance of mosque. Test 1 had peaked at 49.96 mm/s^2 occurred at Channel 9, Test 2 had peaked at 69.64 mm/s^2 occurred at Channel 5 and lastly Test 3 had peaked at 27.51 mm/s^2 occurred at Channel 13. At the same time, peak velocity value also calculated using the equations. The values are 0.0795 mm/s, 0.1108 mm/s and 0.0438 mm/s, respectively. From the data obtained, a comparison with the acceptable road traffic induced vibration in building by Department of Environment (DoE) is established. Thus, all of the velocity value is considered safe as the findings are less than 1 mm/s, the recommend velocity limit for sensitive buildings.

1. Introduction

Malaysia's growing urbanisation, Irtema *et al.,* [1] said that on the other hand, has resulted in a rise in road traffic. There is an effect caused by the strong traffic, Beben *et al.,* and Jakubczyk-Gałczyńska *et al.,* [2-3] emphasized the traffic that is located adjacent to the reinforced concrete structure, specifically the mosque in this case study. Visitors who are visiting the mosque may feel the vibrations from the vehicles especially the heavy ones, making for an uncomfortable experience. Furthermore, due to the mosque's reinforced concrete construction, vibration absorption may be an issue. Tuan Chik *et al.,* [4] said that structures are frequently susceptible to two kinds of vibration: external vibration and internal vibration. The earthquake, traffic, wind load, and construction activities all contribute to the external vibration, while human activity, the use of machinery, and lifts

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all contribute to the inside vibration. Tuan Chik *et al.,* [4] also said the vibration in buildings is a continuous issue and a significant problem in urban areas because of the routine activities that take place there. In addition, Waddington *et al.,* [5] stated that most of the time, vibrations are annoying when they are too strong to be felt and Hunaidi *et al.,* [6] also stated the failure in a reinforced concrete structure usually caused by the vibration. Hence, the consideration of vibrations issue should not be taken easily.

As a matter of fact, the main objectives of this study are to examine the vibration wave on a mosque triggered by a heavy truck in the rigid vehicle category and to compare the vibration velocity to the Malaysian Department of Environment (DoE) guidelines. A severe vibration caused by heavy traffic could result in significant or minor damage to the reinforced concrete structure. This mosque lies near the village's main road, which is utilised by a high number of vehicles to reach Batu Pahat. Batu Pahat, as we all know, is a densely populated town. Accelerometer device has been used to collect the vibration data from the heavy trucks passed by the road. The accelerations value which was gained from the accelerometers were converted to velocity value for comparison to the DOE's Vibration Limits and Control purpose. The main research gap is all data gained will help the locals in accordance to provide the solution to the authorities as supported documents.

2. Literature Review

2.1 Reinforced Concrete Structure

Reinforced concrete is a type of concrete in which steel is embedded in the form of bars, rods, wires, cables, or a mesh to increase its compressive and tensile strength, as well as ductility. The reinforced concrete structure refers to the members or elements, such as beams, columns, slabs, walls, and foundations which consisting both concrete and steel bars as shown in Table 1.

Table 1
Reinforced concrete structure with its function

Structure	Function
Beams	Horizontal members carrying lateral loads
Column	Vertical members carrying primary axial load but generally subjected to axial load and moment
Slab	Horizontal plate elements carrying lateral load
Wall	Vertical plate elements resisting vertical, lateral or in-plane load
Foundation	Supported directly on the ground that spread the loads from the columns or walls

Reinforced concrete has excellent tension and compression strength, making it a popular construction material, stated by Naaman *et al.,* [7]. Kandasamy *et al.,* [8] also stated because of the long-lasting nature of reinforced concrete, the production cost of concrete is very low, making it a cost-effective material. Jipa *et al.,* [9] emphasized concrete's versatility is a result of its liquid state, which allows it to be used in a variety of formwork shapes. Other than that, Atkins *et al.,* [10] stated that reinforced concrete has a 100-year life span and is resistant to dissolved chemicals in water such as sulphates, chloride, and carbon dioxide. Concrete is an excellent choice for underwater and submerged applications such as dams and waterfront structures and it must have good workability, by Mohd *et al.,* [11].

2.2 Vibration

Free vibration refers to a type of vibration that occurs when a system experiences a change from its state of static equilibrium, according to Quanjin *et al.,* [12]. Vibration can be caused by a variety of sources, each of which causes a particular level of vibration in the environment. According to Proenca *et al.,* [13], the sources of vibration can be divided into two categories: internal and external sources. As for internal source, is coming from the inside of the structure. Huan *et al.,* [14] said that the mechanical and electrical equipment such as HVAC systems and generators, are contributing to the vibration inside the building. Human activities such as walking across the floor, hopping, or running, and other daily activity are included. In addition, vibrations of very lower frequency can be felt by occupants when chairs and tables move around in a room, by Hunaidi *et al.,* [6]. Meanwhile, external sources can be divided into three categories. First, the low frequency which occurs below 2Hz. Next, cause by single circumstances such as earthquake or strong winds. Tosi *et al.,* [15] indicate the earthquake frequencies typically range from 0.01 to 10 Hz meanwhile Fan *et al.,* [16] indicate the strong wind frequencies are around 30 Hz and lastly traffic vibration which the heavy vehicles with more mass than other vehicles, such as trucks and lorries.

2.3 Vibration Standard

Vibration standard provide guidelines to evaluate the maximum value of vibration to human response and building. It must be evaluated to ensure the level of vibration produced by the heavy vehicles. The guidelines are provided by Department of Environment (DOE) which can be applied for planning purpose, used in vibration impacts assessment [17]. Figure 1 shows the acceptable road traffic induced vibration in buildings.

Type of Building and Foundation	Recommended Vertical Velocity Limit, v_{max} [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 or friction piles	5

Fig. 1. Acceptable road traffic induced vibration in buildings

2.4 Accelerometers

Accelerometers used for measuring vibrations typically come in one of three different varieties. These are known as capacitive Microelectromechanical Systems, or MEMS for short. Others include piezoelectric and piezoresistive systems, according to Vasudev *et al.,* [18]. When picking an accelerometer type, the sensitivity, frequency acquisition, and noise are crucial aspects to keep in consideration. Shirefaw *et al.,* [19] mentioned that the choice is determined by the elements of the vibration that are to be monitored.

2.5 Heavy Vehicle

Rahman *et al.,* [20] said that roads and highways have long been recognised as crucial infrastructure for facilitating economic integration and cultural exchange over extended periods of time but the vehicles growing are contributing into traffic vibrations. It can be classified into four classes which are explained in Table 2.

Table 2
Classification of vehicles at Malaysia

Class	Types
1	Motorcycle
2	Passenger cars, taxis
3	Busses, light duty lorry, van
4	Heavy duty trucks

In Malaysia, Tuan Mood *et al.,* [21] suggested that a heavy vehicle is defined as one having a gross vehicle mass of more than 4500 kg and an unloading weight ranging from 7500 kg to 51,000 kg. The details of each vehicle category and loading is shown in Table 3 which represent the articulated vehicle, while rigid vehicles is shown in Table 4.

Table 3
Articulated vehicle with permissible weight [22]

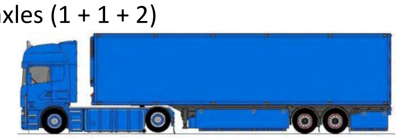
Category of articulated vehicle	Permissible weight
3 axles (1 + 1 + 1) 	26 – 30 tonnes
4 axles (1 + 1 + 2) 	27 – 37 tonnes
5 axles (1 + 1 + 3) 	27 – 39 tonnes

Table 4
The rigid heavy truck

Axles	Rigid heavy truck
2 (1+1)	
3 (1+2)	
4 (2+2)	

3. Methodology
3.1 Materials

Accelerometers, an IMC Data logger, and a wire connector were used in this study. These materials interact with one another to obtain the natural frequency without the need of force, also known as the ambient test. Figure 2, Figure 3 and Figure 4 shows the accelerometer device on the steel plate that is sensitive and need to be handled carefully, the IMC Data Logger and the wire connector.

Fig. 2. Accelerometers on steel plate

Fig.3. The IMC Data Logger

Fig. 4. The wire connector

3.2 Methods

There are two methods to collect the data needed. A visual inspection method was chosen to get the heavy truck frequency data. According to Tuan Chik *et al.,* [23], visual inspection is described as the process of using the eye as the sensing mechanism from which a judgement regarding the condition of a unit to be inspected can be made, either alone or in conjunction with various aids. Meanwhile, Mirtaheri *et al.,* [24] explained the ambient vibration test has been utilised as an accurate experimental approach for full-scale structural dynamic identification. Dynamic characteristics such as natural frequency and mode shape can be obtained by using this test. As a result, an ambient vibration test was performed to obtain vibration readings from heavy trucks passing by the road beside the mosque. Before the test began, the position of the accelerometers was determined. This location is critical for obtaining the most accurate vibration reading result. Thirteen accelerometers were positioned in three rows and tested in three different ways. When the raw data is obtained, it is transformed to acceleration to establish the peak acceleration peak value for each test.

3.2.1 Heavy truck frequency

The counts of heavy truck passed by the road is important to seize the scope and were done by using visual inspection method. Figure 5 shows one of the heavy trucks passed by.

Fig. 5. Heavy truck passed by the road

3.2.2 Position of accelerometers

There are three sets of testing for each row of accelerometers, which all the device were placed inside the mosque. The ambient test was conducted for 5 minutes for each test. Figure 6 shows the layout of accelerometers placement. Hence, there are 13 accelerometers have been placed, which labelled as C1 until C13. Due to the device's high sensitivity, the accelerometers must remain static until the end of the test. The data logger was connected to a laptop running the IMC Wave software. This software collects information from the accelerometers that have been installed.

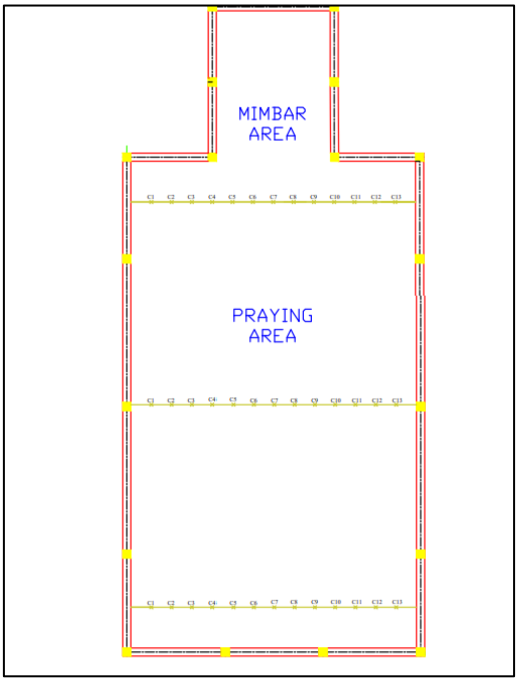
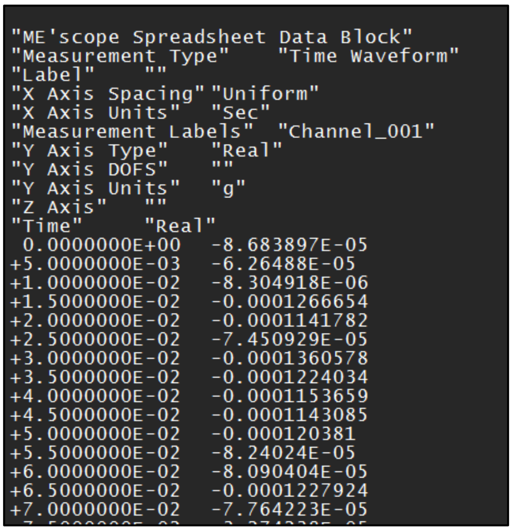


Fig. 6. Layout of accelerometers placement

3.2.3 Peak acceleration

The raw data received from IMC Studio software is converted to .txt format and manually added to Microsoft Excel for better analysis. Figure 7 shows one of the raw data in .txt format and Figure 8 shows the data that has been import to Microsoft Excel. When the data has been imported, the unit of raw data need to be converted to m/s^2 to find the acceleration. Therefore, the raw data are multiplied by 9.81 m/s^2 and multiplied again by 1000 mm to get the acceleration in unit mm/s^2. After that, by using maximum formula in Microsoft Excel, the peak value is determined.



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"Measurement Type"     "Time Waveform"
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"X Axis Spacing" "Uniform"
"X Axis Units"    "Sec"
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"Y Axis Type"     "Real"
"Y Axis DOFS"     ""
"Y Axis Units"    "g"
"Z Axis"    ""
"Time"      "Real"
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+1.0000000E-02   -8.304918E-06
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+4.0000000E-02   -0.0001153659
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+5.0000000E-02   -0.000120381
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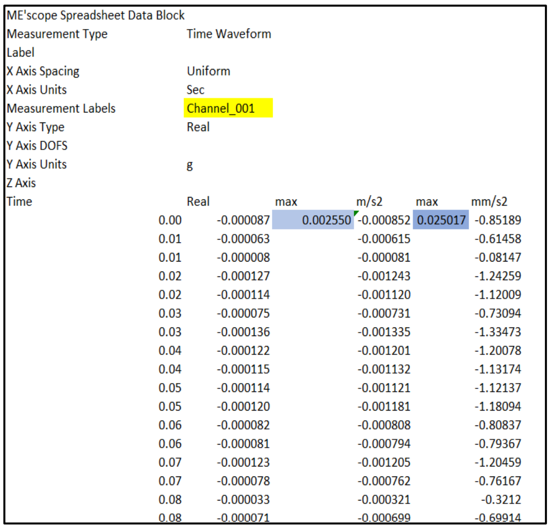
Fig. 7. Raw data in .txt format



ME'scope Spreadsheet Data Block						
Measurement Type		Time Waveform				
Label						
X Axis Spacing		Uniform				
X Axis Units		Sec				
Measurement Labels		Channel_001				
Y Axis Type		Real				
Y Axis DOFS						
Y Axis Units		g				
Z Axis						
Time		Real	max	m/s2	max	mm/s2
	0.00	-0.000087	0.002550	-0.000852	0.025017	-0.85189
	0.01	-0.000063		-0.000615		-0.61458
	0.01	-0.000008		-0.000081		-0.08147
	0.02	-0.000127		-0.001243		-1.24259
	0.02	-0.000114		-0.001120		-1.12009
	0.03	-0.000075		-0.000731		-0.73094
	0.03	-0.000136		-0.001335		-1.33473
	0.04	-0.000122		-0.001201		-1.20078
	0.04	-0.000115		-0.001132		-1.13174
	0.05	-0.000114		-0.001121		-1.12137
	0.05	-0.000120		-0.001181		-1.18094
	0.06	-0.000082		-0.000808		-0.80837
	0.06	-0.000081		-0.000794		-0.79367
	0.07	-0.000123		-0.001205		-1.20459
	0.07	-0.000078		-0.000762		-0.76167
	0.08	-0.000033		-0.000321		-0.3212
	0.08	-0.000071		-0.000699		-0.69914

Fig. 8. Imported data in Microsoft Excel

3.3 Equations

After getting the peak acceleration, the peak velocity can be determined by using the equations in the following:

$$v = \frac{a}{2\pi f} \qquad (1)$$

where, v = velocity; a = acceleration; f = frequency

$$f = \frac{1}{T} \qquad (2)$$

where, T = time taken for a complete cycle of vibration

4. Result and Discussion

4.1 Results

Because of an abundance of different kinds of heavy vehicles that use the major route, a visual examination was carried out to determine which kinds of big trucks are the most common. On Monday, this examination was carried out between the hours of 10 am and 12 pm. On the first day of work, inspection takes place at these hours for the following reason: since this time of day and hour is considered to be the busiest hour of the day. The results of the visual evaluation of the heavy vehicles are presented in Table 5. According to the findings, it is apparent a considerable number of huge vehicles, and more specifically rigid heavy vehicles with two axles, utilise this road. This type of vehicle is the most representative example of a heavy truck. As a result, the heavy rigid vehicle with two axles was chosen to serve as the scope of the study.

Table 5
Heavy trucks visual assessment

Types	Axles	Frequency
Articulated	3 (1+1+1)	5
	4 (1+1+2)	6
	5 (1+1+3)	1
	5 (1+2+2)	1
	6 (1+2+3)	2
	7 (1+2+4)	0
Rigid	2 (1+1)	132
	3 (1+2)	12
	4 (2+2)	1

The vibration data was gathered on Monday, November 7, 2022, between 10 a.m. and 12 p.m. The time and day were chosen based on the visual assessment made during the counts. As a result, for clarity, the vibration findings have been established based on the acceleration value. Figure 9 shows the acceleration readings for each channel in the three sets of testing. The graph can be used to calculate peak acceleration. The vibrations produced by passing vehicles influence the wave's direction. As shown in the graph, other types of vehicles, such as a car or motorcycle, produced a smaller wave, however the heavier truck produced a larger wave.

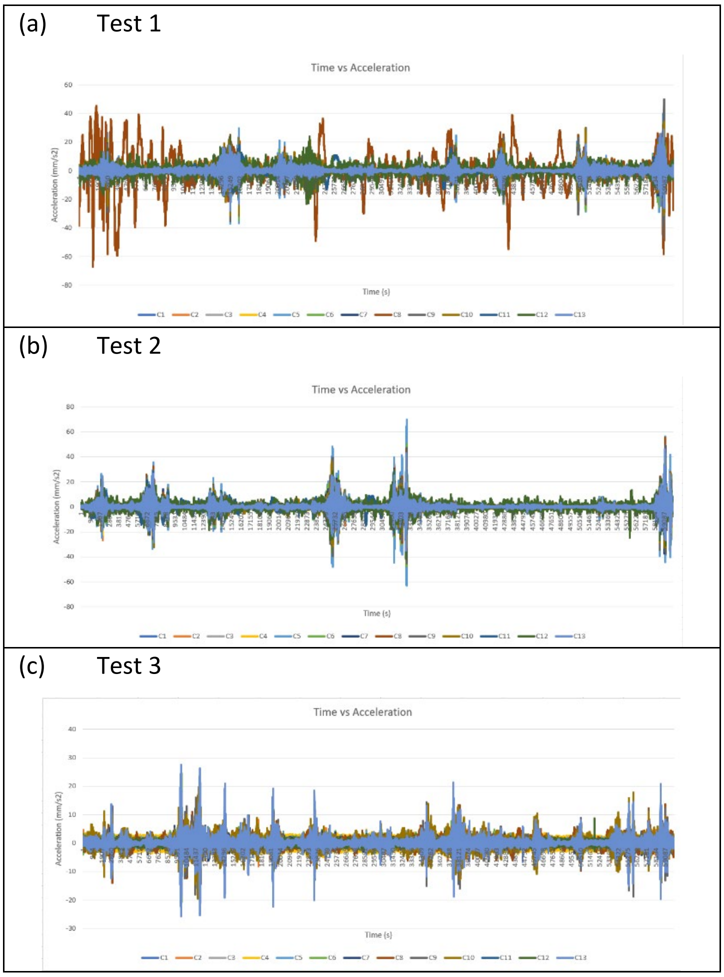


Fig. 9. Vibration assessment

The established graph was used to calculate the peak acceleration reading for each set. Test 1 has a high reading of 49.96 mm/s^2 at Channel 9. Meanwhile, the highest value for Test 2 at Channel 5 is 69.64 mm/s^2, and the top reading for Test 3 at Channel 13 is 27.51 mm/s^2. The maximal acceleration from each test is shown in Table 6, which was translated from unit g to m/s^2 and then to mm/s^2. Figure 10 illustrates the location of the peak channel.

Table 6
Peak acceleration

Test	Channel	Acceleration	
		(m/s^2)	(mm/s^2)
1	9	0.049958	49.96
2	5	0.069638	69.64
3	13	0.027509	27.51

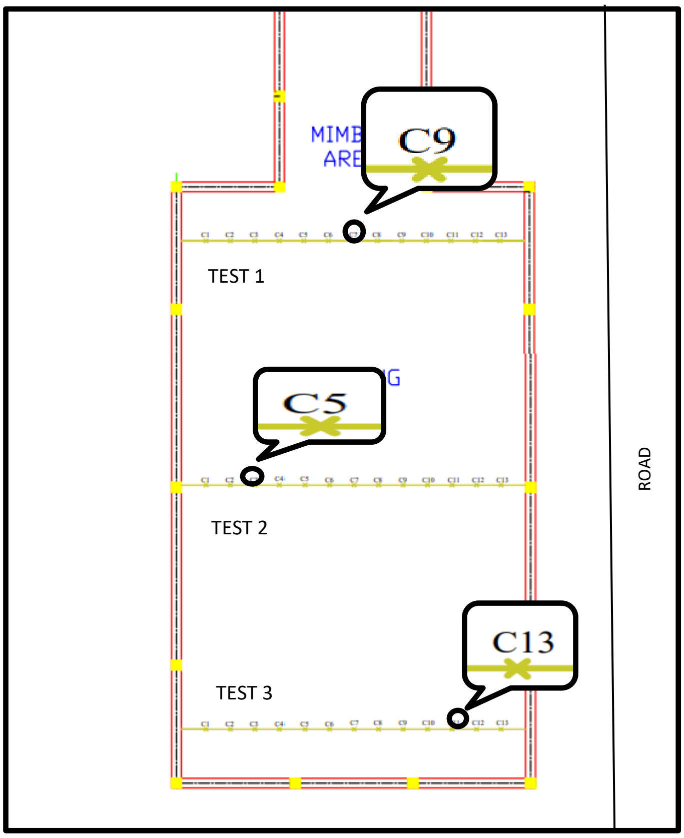


Fig. 10. The location of peak channel

The peak velocity of the reading can be determined using the equation after obtaining the peak acceleration. The peak velocity for each test is shown in Table 7. The calculation is detailed below. Calculate the frequency by using Eq. (1). The T value is coming from the time taken for one complete cycle of vibration.

$$T = \frac{0.005}{2} + 0.005 + \frac{0.005}{2} = 0.01\ s$$

$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{0.01} \\ &= 100\ Hz \end{aligned}$$

Calculate the velocity by using Eq. (2).

$$\begin{aligned} v &= \frac{a}{2\pi f} \\ &= \frac{49.96}{2\pi(100)} \\ &= 0.0795\ mm/s \end{aligned}$$

Table 7
Peak velocity

Test	Channel	Acceleration		Velocity (mm/s)
		(m/s^2)	(mm/s^2)	
1	9	0.049958	49.96	0.0795
2	5	0.069638	69.64	0.1108
3	13	0.027509	27.51	0.0438

The peak velocity is compared to the DOE-published criterion for permissible vibration generated by road traffic in structures. The vertical velocity limit in DOE is in mm/s, which is consistent with the estimated values. According to the standard, the limit is 1 mm/s. The peak velocity is clearly highest at Channel 5 of Test 2 with a velocity of 0.1108 mm/s, followed by Channel 9 of Test 1 with a velocity of 0.0795 mm/s and Channel 13 of Test 3 with a velocity of 0.0438 mm/s. Table 8 compares peak velocity with the standard.

Table 8
Comparison peak velocity with the standard

Date	Time	Test	Peak velocity (mm/s)	Acceptable road traffic-induced vibration by DOE (mm/s)	Criteria
07/11/2022	10 a.m	1	0.0795	1	Safe
	-	2	0.1108		Safe
	12 p.m	3	0.0438		Safe

4.2 Discussions

The environment may influence where the peak acceleration occurs. Channel 13 (C13), the final channel in Test 3, was found to have one of the highest acceleration values. This is because it is so close to the hump. This implies that when a large truck travels over a hump bridge, the pressure it creates induces a vibration that is also proportional to the speed of the heavy truck. As a result, increasing vehicle speed, especially for heavier vehicles, causes an increase in vibrations, according to Lu *et al.,* [25]. Channel 5 (C5) likewise recorded a high acceleration value. Galanti *et al.,* [26] point out that the centre of the floor is frequently where vibration peaks. As a result, considering C5's proximity to the centre of the floor, it is acceptable. The Channel 9 (C9) captured the peak acceleration value during Test 1, which can be estimated as the average of the C5 and C13.

According to Table 8, the peak velocity does not exceed the maximum amount of vibration that roads are allowed to induce in structures. As a consequence of this, the structure is unaffected by the traffic-related vibration that is induced by the passage of huge vehicles. Vibrations, on the other hand, may have an effect on the structure over the longer term, assuming that it is older than fifty years. Even if the velocity is low, it will still have a limited impact on the damages. The settling of peat soil may be another factor that contributed to the building's destruction. Visual inspection can be utilised to differentiate between shear cracks generated by settlement and non-structural cracks. Inference leads us to believe that the structure was continuously affected by the settling of peat soil.

5. Conclusion

As conclusion, the vibration assessment coming from the heavy trucks passing by the Masjid Jamek Kampung Bindu has resulted as safe according to the guidelines. The peak velocities data which coming from the peak accelerations data shows 0.0795 mm/s, 0.1108 mm/s and 0.0438 mm/s respectively are lesser than the acceptable road traffic-induced vibration by DOE which is 1 mm/s. To justify the relationship theory of vibration and speed as stated at discussion, a speed test should be considered, as stated by Lu *et al.,* [25]. Therefore, in order to obtain funds to complete the mosque's repair work, the villagers may use this study to support their submission of supporting documentation to the appropriate authorities.

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