AN INVESTIGATION OF TRAFFIC INDUCED VIBRATION EFFECT ON STRUCTURE AND HUMAN SENSITIVITY

By

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ABSTRACT

Vibrations caused by industrial activities such as piling, rock blasting, traffic, and vibrating machinery result as annoyance to human beings and generate possible structural damages. Therefore, vibration monitoring and analysis are required to predict the effects of the vibrations. In this project, measurement of the traffic-induced vibrations has been carried out by using the μMX system. The effects of traffic vibration have been evaluated by using some standard structural damaging figures and tables. Several factors might have contributed to traffic vibration levels, such as road condition, vehicle speed, vehicle weight, soil conditions, vehicle suspension system, and distance between the structure and the road. The characteristics of the traffic vibration in terms of the vehicle weight and distance to road center were discussed. For the first study, vibrations data were collected on different categories of vehicle. The results proved that the heavier the vehicle, the vibration level will be increased. For the second study, truck vibration data were collected with varying distances from the source. Then, the results were compared with the data of train motion induced vibration. The results showed that the trend of the peak velocity distribution graph for truck vehicle was similar with train motion vibration, even though the delivered energy between them was different. The results of this project can be used as a guide in predicting the effects of the traffic induced vibration to the nearby buildings and human beings.

ABSTRAK

Gegaran yang terhasil daripada aktiviti-aktiviti industri seperti pemacuan cerucuk, letupan kuari, trafik dan mesin gegaran akan mengakibatkan ketidakselesaan kepada manusia dan kerosakan kepada struktur bangunan. Dengan itu, satu sistem pencerapan dan analisis gegaran diperlukan untuk menganggarkan kesan-kesan gegaran. Untuk projek ini, sistem pencerapan gegaran trafik telah dijalankan dengan menggunakan sistem μMX. Selepas itu, kesan-kesan gegaran trafik akan dinilai dengan merujuk kepada gambar rajah dan jadual piawaian kerosakan struktur bangunan. Aras gegaran trafik boleh dipengaruhi oleh faktor-faktor seperti keadaaan jalan, kelajuan kenderaan, berat kenderaan, keadaan tanah, sistem ampaian kenderaan dan jarak antara struktur dengan jalan. Bagi projek ini, ciri-ciri gegaran trafik iaitu berat kenderaan dan jarak dari tengah jalan akan dibincangkan. Bagi kajian pertama, data-data gegaran akan dicerap daripada pelbagai kategori kenderaan. Keputusan membuktikan bahawa jika berat kenderaan semakin tinggi, maka aras gegaran akan semakin meningkat. Bagi kajian kedua, data-data gegaran lori besar akan dicerap dengan perubahan jarak dari punca gegaran. Selepas itu, keputusan akan dibandingkan dengan data-data gegaran pergerakan kereta api. Keputusan menunjukkan bahawa bentuk graf taburan halaju puncak bagi kenderaan lori besar adalah agak sama dengan gegaran pergerakan kereta api, walaupun penjanaan tenaga mereka adalah berbeza. Keputusan projek ini dapat digunakan sebagai garis panduan untuk menganggarkan kesan-kesan gegaran trafik kepada struktur bangunan dan manusia yang berhampiran.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Vibration is defined as any motion that repeats itself after an interval of time. It is a frequent problem which happened in buildings and its common internal sources are machinery, elevators, and the activities of occupants. External sources include construction operations, wind, rock blasting, road and rail traffic, and natural phenomena such as earthquakes. Vibrations induced by road and railway traffic are a common concern in worldwide. Occupants may complain about annoyance and building damage. Since that ground vibration give a lot of negative effect to the environmental and building structural, therefore engineers must play an important role to control the vibration level which generated by activities as discuss above to the satisfactory level. It is for this reason that survey study on ground vibration has been carried out.

1.2 OBJECTIVE

The objectives of this study are as shown below:

a) Introduce basic theory and concept on ground vibration especially induced by traffic vehicles, important parameter of vibration and method to analyze vibration frequency.
b) Introduce the traffic-induced vibration data measurement and analysis techniques.
c) Compare the vibration level which generated by different categories of vehicle.
d) Survey on the effect of traffic-induced vibration to the structural of building and human beings.
e) Compare the results of traffic induced vibration level with train motion vibration level

1.3 SCOPE OF PROJECT

1.3.1 Theory Part

First of all, concept on how traffic generates vibration, its important parameters of vibration and its influencing factors will be discussed. After that, basic theory about vibration wave which included types of waves, mathematical description of waves will be introduced. It will followed by estimation of particle peak velocity, method analysis of dominant vibration frequency and effects of dynamic loading. Next following step is involving the introduction of the operation system of Blastronics μMX Micro Monitor on how to obtain the data analysis of vibration waves from the site.

1.3.2 Measurement Work and Analysis Part

Site measurement is carried out to measure the data of vibration wave which induced by different categories of traffic vehicle. Categories of traffic vehicles which will be evaluated are motorcycle, bus, truck, lorry, and car. Data of vibration wave will be measured by using μMX Micro Monitor and it will then upload into the computer. After that, the data will be analyzed and make the comparison between them. Finally, survey will be held to check the effect of the traffic vibration to the building and human beings by using some standard structural damage and human sensitivity figures and tables.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Traffic-induced vibrations are a frequent concern around the world. Commonly, vehicles travel at various speeds on adjacent roads, resulting in annoying vibrations and possible structural damage. However, passenger vehicles rarely produce perceptible vibrations to cause significant structural damage. Generally, traffic induced vibrations are caused by heavy vehicles such as trucks and buses.

Traffic-induced vibrations are generated by road surface irregularities such as potholes, cracks, and uneven pavement joints. Dynamic interaction forces between the vehicle and pavement are created by these irregularities resulting in a generation of stress waves that travel through the adjacent soils. Vibrations produce damaging stress waves that quickly reach building foundations and causing them to vibrate. (Henwood, 2002)

Generally, road vehicle tends to produce vibrations with frequencies predominantly in the range from 5 to 25 Hz (oscillations per second). These predominant frequencies of the vibrations may contribute by several factors which included vehicle weight, vehicle speed, vehicle suspension system, road condition, soil type and stratification, distance of the road from affected structures and types of building.

2.2 HOW TRAFFIC GENERATES VIBRATION

Generally, vehicle contact with irregularities in the road surface (e.g. potholes, and uneven manhole covers) induces dynamic forces on the pavement and these forces will generate stress waves. The waves are transmitted through the pavement to the sub-structure or through the sub-soil to buried or even adjacent structures and causing them to vibrate. Traffic vibrations are mainly caused by movement of heavy vehicles such as buses and trucks. Passenger cars rarely induce vibrations that are perceptible in buildings.

When a bus or a truck strikes an irregularity in the road surface, it will generate an impact load and an oscillating load directly to the pavement due to the subsequent "axle hop" of the vehicle. The impact load generates ground vibrations that are predominant at the natural vibration frequencies of the soil whereas the axle hop generates vibrations at the hop frequency. If the natural frequencies of the soil coincide with any of the natural frequencies of the building structure or its components, resonance will be occur and vibrations will be amplified. (Hunaidi, 2000)

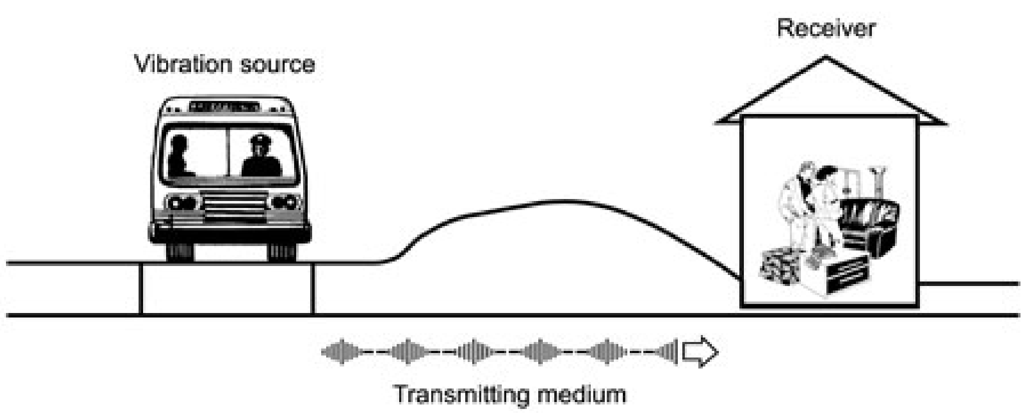

Figure 2.1: Traffic induced vibrations to the building structure

2.3 IMPORTANT PARAMETER OF VIBRATION

There are four important parameter used to analyze the effect of vibration to the structure building and environment. These four types of parameter are:

a) Displacement – Maximum distance of the wave particle from its initial point, normally it is measured in unit mm.

b) Velocity – Total movement distance of wave particle from its initial point in one second and its unit is mms^{-1}

c) Acceleration – rate of alteration of particle velocity, normally it is measured in unit mms^{-2} or g (gravity acceleration)

d) Frequency – Number of complete cycles of oscillation in one second and its unit is Hertz, abbreviated Hz.

From these four types of vibration parameters, particle velocity is the most important parameter because generally all vibration data analyzed from the site is in the form of velocity parameter. Others parameter can be achieved from the value of particle velocity by using method of differential, integration, and Fourier series transform.

2.4 FACTORS INFLUENCING VIBRATION LEVEL AND FREQUENCY

Generally, road traffic tends to produce vibrations with frequencies predominantly in the range from 5 to 25 Hz (oscillations per second). The amplitude of the vibrations ranges between 0.005 and 2 m/s^2 measured as acceleration, or 0.05 and 25 mm/s measured as velocity (Hunaidi, 2000). The predominant frequencies and amplitude of the vibration are dependent on many factors including (Ammann W., 1995):

a) Vehicle weight *m*

b) Speed and suspension system of the vehicle

c) Condition of the road

d) Soil type and stratification

e) Distance of the road from affected structures

f) Type of building

The effect of vehicle speed, for instance, depends on the roughness of the road. Generally, the rougher the road, the more speed affects the vibration amplitude. The effect of the suspension system type also depends on vehicle speed and road roughness. For low speed and smooth road conditions, the effect of the type of suspension system is not significant. But for high speeds and rough roads, the type of suspension system becomes important as showed in Figure 2.2. This interdependence can be seen in Table 2.1, which presents vibration levels recorded for a transit bus and a truck of the same weight category, traveling on a rough road. Vibration levels induced by the two vehicles were similar at 25 km/h. At 50 km/h, however, vibration levels induced by the bus were about twice those induced by the truck.

Table 2.1: Comparison of vibration levels (mm/sec2, rms) induced by a bus and a truck, to demonstrate the effect of different suspension systems at different speeds* (Huinaidi, 2000)

Location	25 km/h		50 km/h	
	Bus	Truck	Bus	Truck
Ground in front of house	20.5	19.9	64.5	33.2
External foundation wall	11.2	10.1	30.9	15.7
Mid-point of floor in 1st storey	20.3	20.8	62.9	30.1
Mid-point of floor in 2nd storey	35.0	37.3	96.2	46.7
*Bus had air-bag suspension system; truck had multi-leaf steel spring suspension system.				

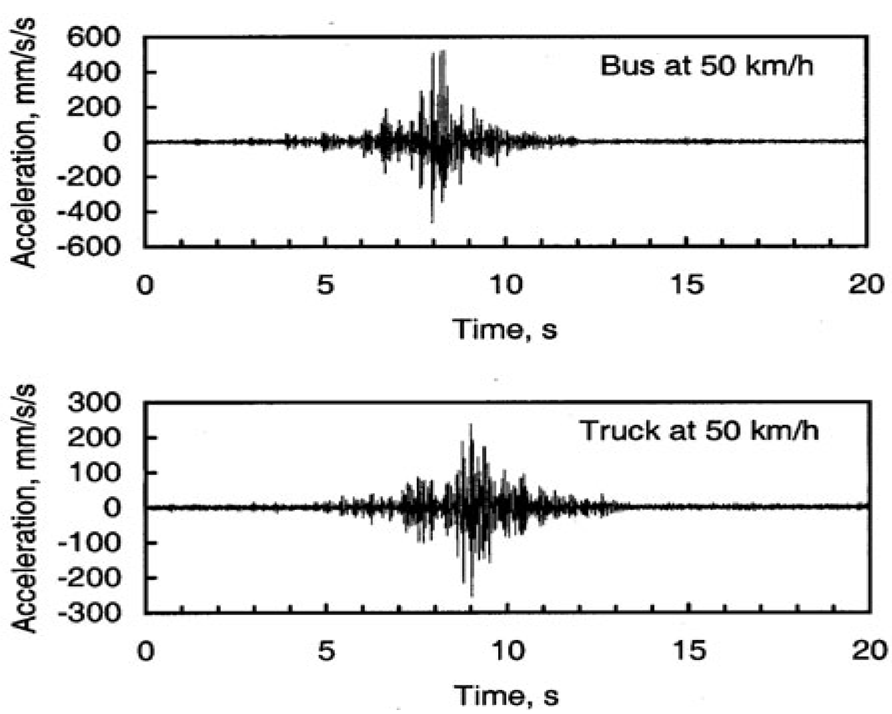

Figure 2.2: Comparison between vibration levels induced by a transit bus and a truck

Vibration amplitudes and the predominant frequencies are influenced significantly by the soil type and stratification. Vibration levels increase as stiffness and damping of the soil decrease. For soils, the natural frequencies depend on stiffness and stratification. Typically, traffic vibrations are worst in areas underlain by a soft clay soil layer between 7 meters and 15 meters deep (Hunaidi and Tremblay, 1997). In these areas, the natural frequencies of the soil can coincide with those of houses and their floors, leading to resonance or amplified vibration.

Vibration levels decrease with distance from the road as a result of "geometrical spreading" of the vibration energy and its dissipation by soil viscosity and/or friction. By way of example, geometrical spreading is the effect by which ripples induced by throwing a stone into a pond become flatter as they spread out. For homogeneous soil sites, vibration propagation patterns are simple, and general simple relationships can be found between vibration levels and distance. In general, however, soils are rarely homogeneous and are usually stratified. Propagation patterns are, therefore, very complex, and attenuation relationships are site-specific.

2.5 CLASSIFICATION OF VIBRATION

2.5.1 Introduction

Vibration can be classified in several ways. Some of the important classifications are as followed:

a) Free and Forced vibration

b) Deterministic (periodic) and random vibration

2.5.2 Free Vibration

When a system is displaced from its static equilibrium position and then released, it vibrates freely with a frequency that depends upon the mass and stiffness of the system is known as *free vibration.* Such vibration diminishes with time because of energy losses from the system, which are referred to damping losses. There is no external force acts on the system (James et al., 1989).

Free vibration of such a system is characterized by the homogenous equation of motion (Pretlove, 1995):

$$m\ddot{x} + c\dot{x} + kx = 0 \qquad (2.1)$$

Where x = displacement

m = mass

c = viscous damping coefficient

k = stiffness

The solution to this equation is a sinusoidal vibration the frequency of which is strongly dependent on k and m. The value of c affects the decay of the vibration but has a relatively weak influence on the frequency of vibration.

2.5.3 Forced Vibration

Forced vibration occurs when a system is subjected to some type of external excitation that adds energy to the system. Generally, the amplitude of such vibration depends upon the natural frequencies of the system and the damping inherent in it, as well as upon the frequency components present in the exciting force. The amplitude of a forced vibration can become very large when a frequency of the external exciting force coincides with one of the natural frequencies of the system. Such condition is known as resonance, and the attendant stresses and strains have the potential of causing failures in structures (James et al., 1989).

When a time-varying force F (t) is applied to the system the differential equation of motion of the system is now inhomogeneous (Pretlove, 1995) as shown below:

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{2.2}$$

2.5.4 Deterministic (Periodic) Vibration

If the value of the excitation (force or motion) acting on a vibratory system is known at any given time, the excitation is called deterministic. The resulting vibration is known as deterministic vibration. (Singiresu S. Rao, 2004). The simplest form of dynamic effect is the periodic loading which maybe caused by out-of-balance machinery, and this maybe represented by a sine wave. It is referred to as simple harmonic loading. The standard equations of harmonic motion maybe used to describe this type of phenomenon.

Other types of periodic loading which might be encountered are more complex even though they are repeated in consecutive time periods. Such excitations maybe represented by a Fourier series which consists of a sum of sine waves. Both the simple and complex forms of periodic loading maybe treated in a similar manner. (Boswell et al., 1993)

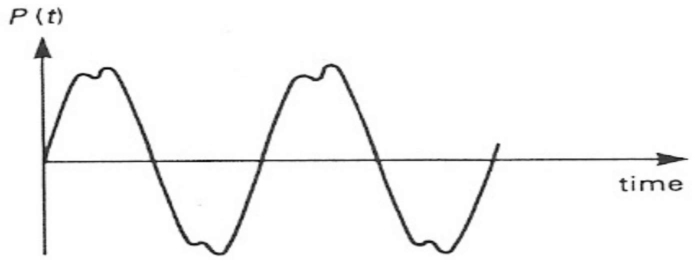

Figure 2.3: Deterministic (periodic) excitation

2.5.5 Random (Non-periodic) Vibration

In some cases, the excitation is nondeterministic or random, the value of the excitation at a given time cannot be predicted. In these cases, a large collection of records of the excitation may exhibit some statistical regularity. If the excitation is random, the resulting vibration is called random vibration. (Singiresu S. Rao, 2004)

Impulsive or short-duration excitation is characteristic of piling, shock and blasting operations and may have a non-zero value for a maximum time of only a few seconds. Other types of non-periodic loading may have a longer duration than shock or impulsive loads. The ground motion caused by seismic disturbance for example is extremely complex and random. Further sources of non-periodic dynamic loading which may be of concern to the engineer are caused by road traffic and railway vibration. (Boswell et al., 1993)

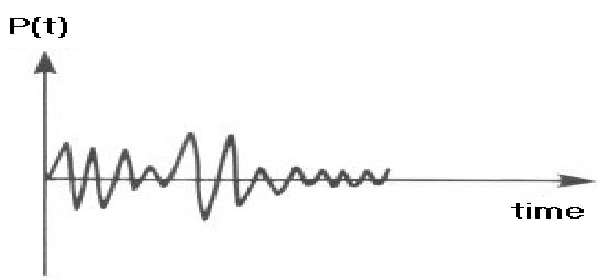

Figure 2.4: Random excitation

2.6 VIBRATION WAVES

2.6.1 Introduction

Generally, there are 4 major types of wave which are :

a) Compressive wave, *P-wave*

b) Shear wave, *S-wave*

c) Rayleigh wave, *R-wave*

d) Love wave, *L-wave*

Vibration waves generated from sources e.g. traffic will be reflex and refract at one covered surface layer inside the soil medium. Waves can be measured in 3 directions which are radial (parallel with the direction of wave propagation), vertical and transverse (perpendicular with the direction of wave propagation).

These 4 types of waves can be categorized into two main groups:

a) Body waves – waves is transmitting through rock and soil medium under the earth's surface in a sphere shape from the sources. Body waves will reflex and refract on the ground surface or rock layer under the ground. Body waves can be divided into 2 types of waves which are compressive wave and shear wave

b) Surface waves – waves is transmitting on the rock and earth's surface from the source to all direction. Surface waves are generated by the constructive interference of incident compressive and shear waves arriving at the free surface and propagating parallel to the surface. The 2 main waves of surface waves are Rayleigh waves and Love wave.

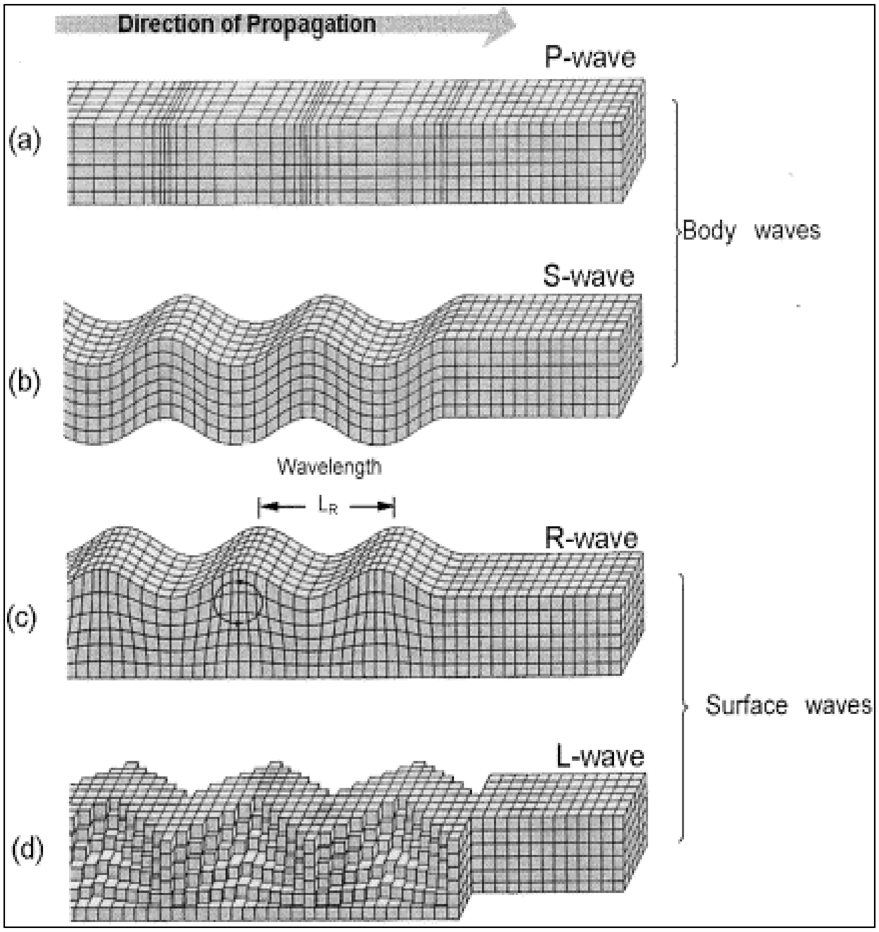

Figure 2.5: Types of waves propagating in the ground: (a) compressional–dilatational waves; (b) shear waves; (c) Rayleigh waves; and (d) Love waves

2.6.2 Types of Wave

2.6.2.1 Compressive Wave, *P-wave*

Compressive wave (or P-wave, primary wave, longitudinal wave) is the particles of the ground which vibrate parallel to the direction of wave propagation. Since compressional and dilational forces are active in these waves, they are also called pressure waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compressive waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements. Its propagation velocity (Klein, 1995) is shown as below:

$$V_p = \sqrt{\frac{(\lambda + 2\mu)}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{2.3}$$

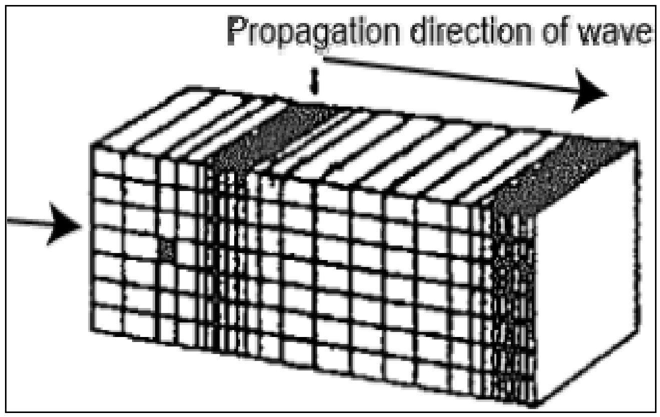

Figure 2.6: Propagation direction of compressive wave (*P-wave*)

2.6.2.2 Shear Wave, *S-wave*

Shear wave (or S-wave, torsional wave, secondary wave, transverse wave) is the particles which vibrate perpendicular to the direction of wave propagation. Shear waves require an acoustically solid material for effective propagation and, therefore, are not effectively propagated in materials such as liquids or gasses. Shear wave travel slower than P-wave in a solid and, therefore, arrive after the P-wave. Shear waves are relatively weak when compared to compressive waves. In fact, shear waves are usually generated in materials using some of the energy from compressive waves. Its propagation velocity (Klein, 1995) is:

$$V_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \tag{2.4}$$

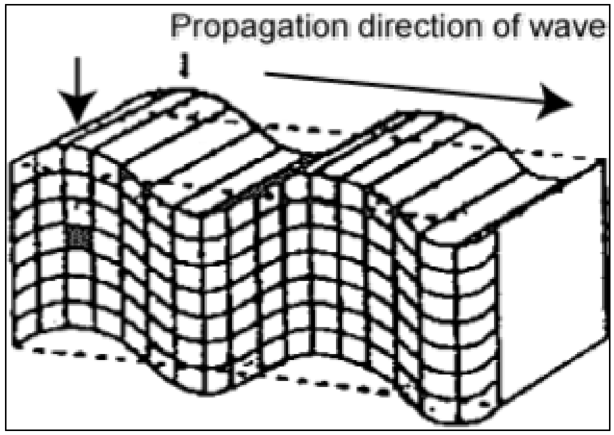

Figure 2.7: Propagation direction of shear wave (*S-wave*)

2.6.2.3 Rayleigh Wave, *R-wave*

Rayleigh waves, which are the main carrier of traffic vibrations, are confined to a region near the surface of the ground that is roughly one wavelength deep. The particle movement has an elliptical orbit as shown in the figure below. The ground motion induced by these waves has both horizontal and vertical components, which diminish with depth. Rayleigh waves that are induced by a point-like source on the ground surface e.g. a vehicle striking a pothole, have cylindrical wave-fronts and are therefore attenuated much more slowly than shear and compression waves, which have hemispherical wave-fronts. Rayleigh waves are useful because they are very sensitive to surface defects and since they will follow the surface around, curves can also be used to inspect areas that other waves might have difficulty reaching. Rayleigh waves are dispersive and the amplitudes generally decrease with depth in the Earth. Its propagation velocity v_R (Klein, 1995) can be obtained from figure 2.9 and as an approximation:

$$v_R \approx \frac{v_s(0.86+1.14\nu)}{1+\nu} \tag{2.5}$$

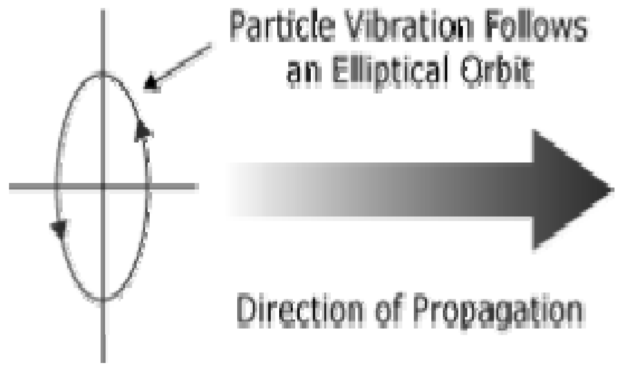

Figure 2.8: Direction of propagation of Rayleigh wave (*R-wave*)

2.6.2.4 Love Wave, *L-wave*

Love wave is the particles which vibrate transverse horizontal motion, perpendicular to the direction of propagation and generally parallel to the Earth's surface. In general, the Love waves travel slightly faster than the Rayleigh waves. They are largest at the surface and decrease in amplitude with depth. Love waves are also dispersive, means that wave velocity is dependent on frequency, generally with low frequencies propagating at higher velocity. Depth of penetration of the Love waves is also dependent on frequency, with lower frequencies penetrating to greater depth.

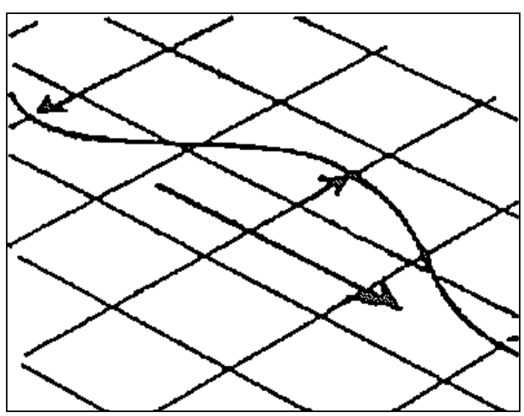

Figure 2.19: Direction of propagation of Love wave (*L-wave*)

2.6.3 Mathematical Description of Waves

So far we have looked at waves graphically, like this:

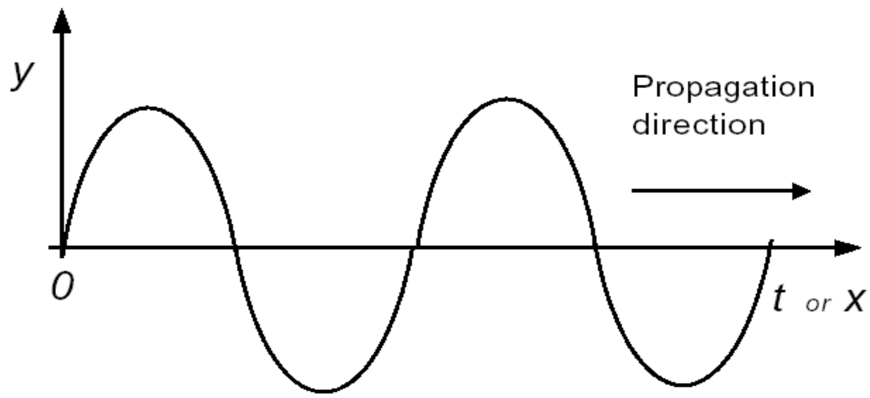

Figure 2.10: Form of waves using a graph

This looks exactly like a sine function. (If we shifted the zero along to the right by ¼ λ (or 1/ 4T) it could equally well be a cosine)

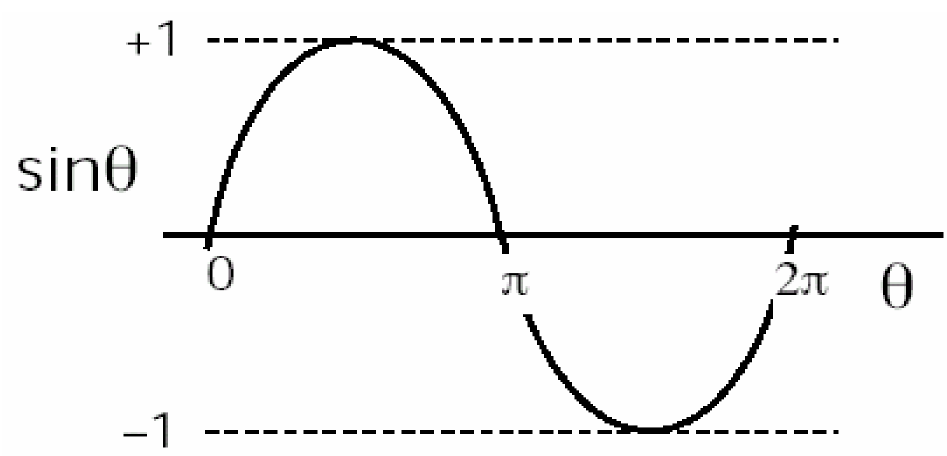

Figure 2.11: Sine function

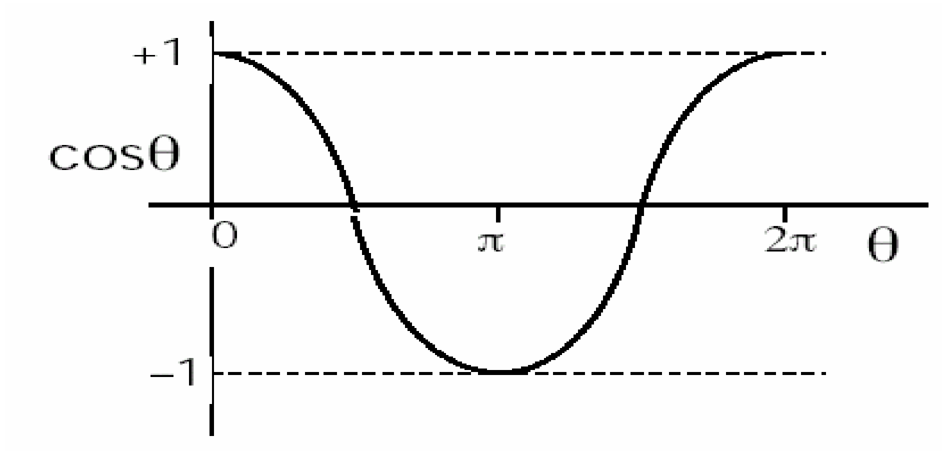

Figure 2.12: Cosine Function

θ is in radians. 2π radians = 360º

s = circular arc length

r = circle radius

θ = s/r radians

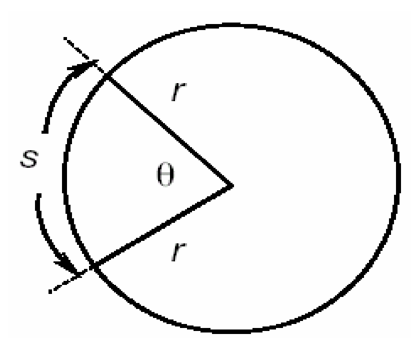

Figure 2.13: Important parameters of a circular

Above, we gave frequency in hertz (Hz) as the number of complete oscillations per second. Comparing now the wave directly with the sine function,

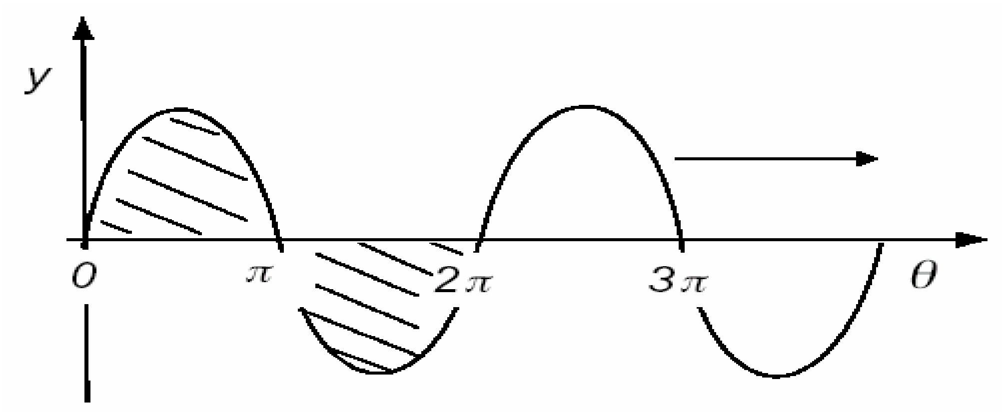

Figure 2.14: Complete cycle of oscillation as shown hatched

The first complete cycle of oscillation is shown hatched. One cycle is completed in a time *T*.

Along the horizontal axis, the angular measure θ is the phase of the wave. One complete cycle of the wave corresponds to a change in phase of 2π radians. We can write the wave mathematically as

$$y = A \sin \theta \qquad (2.6)$$

Where *A* is the amplitude of the wave (in meter)

We make the connection with frequency and time by noting that (we will say exactly why this is shortly)

$$\theta = \omega t \qquad (2.7)$$

Where ω is called the angular frequency, related to the frequency in hertz by

$$\omega = 2\pi f \quad \text{(angular frequency)} \qquad (2.8)$$

The angular frequency is measured in radians per second, abbreviated rad.s-1. So that,

$y = A\ \sin\omega t$ (mathematical description of a harmonic wave) (2.9)

The equation $y = A\ \sin\omega t$ will give a sensible description of a wave as shown in the figure 2.14 below:

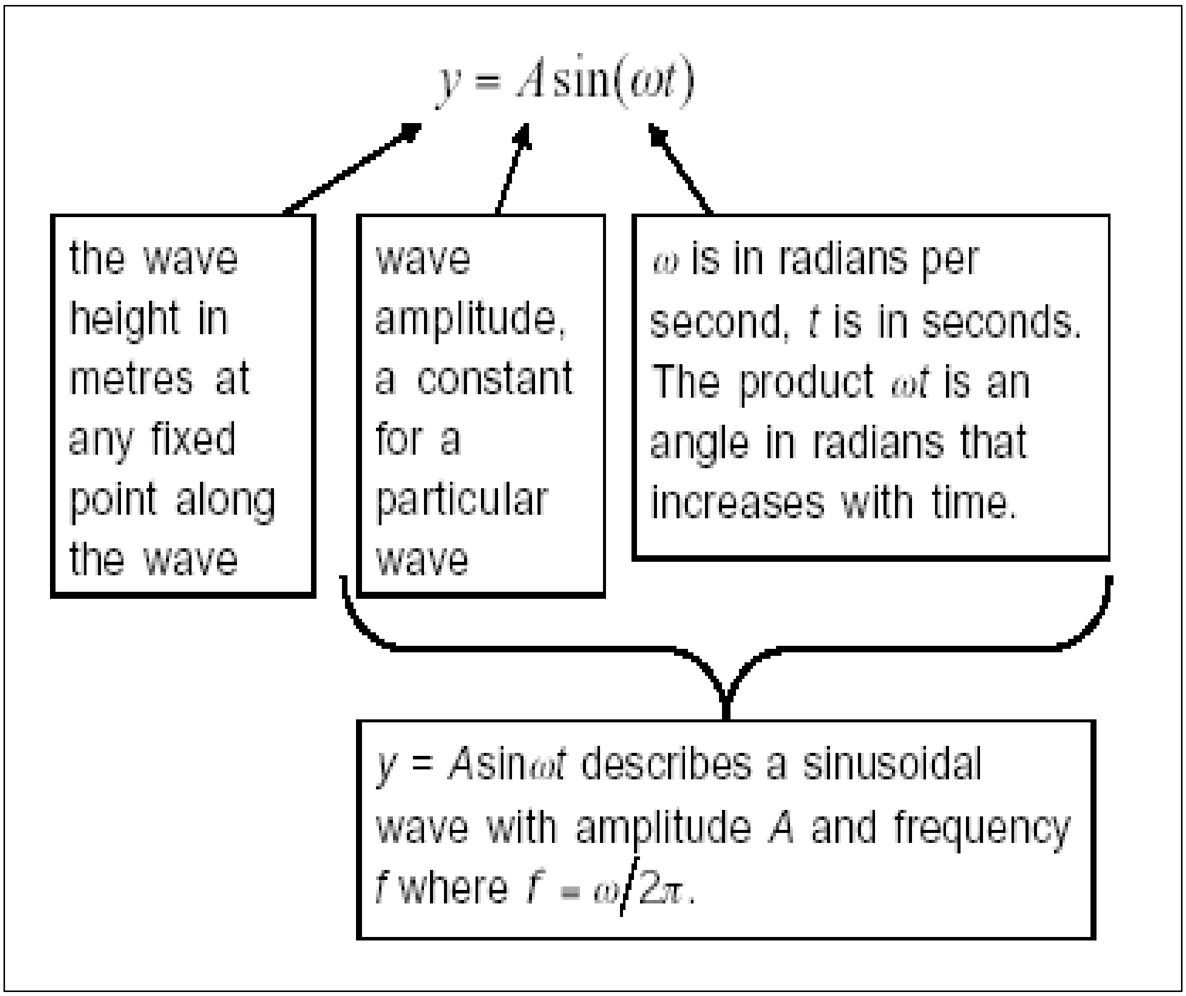

Figure 2.15: Description of a wave equation

2.6.4 Wavelength, Frequency and Velocity

Among the properties of waves propagating are wavelength, frequency, and velocity. The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave.

Consider a wave propagating along the horizontal direction, starting at position 1 and moving to position 2 in a time *T* wave period as shown in figure.

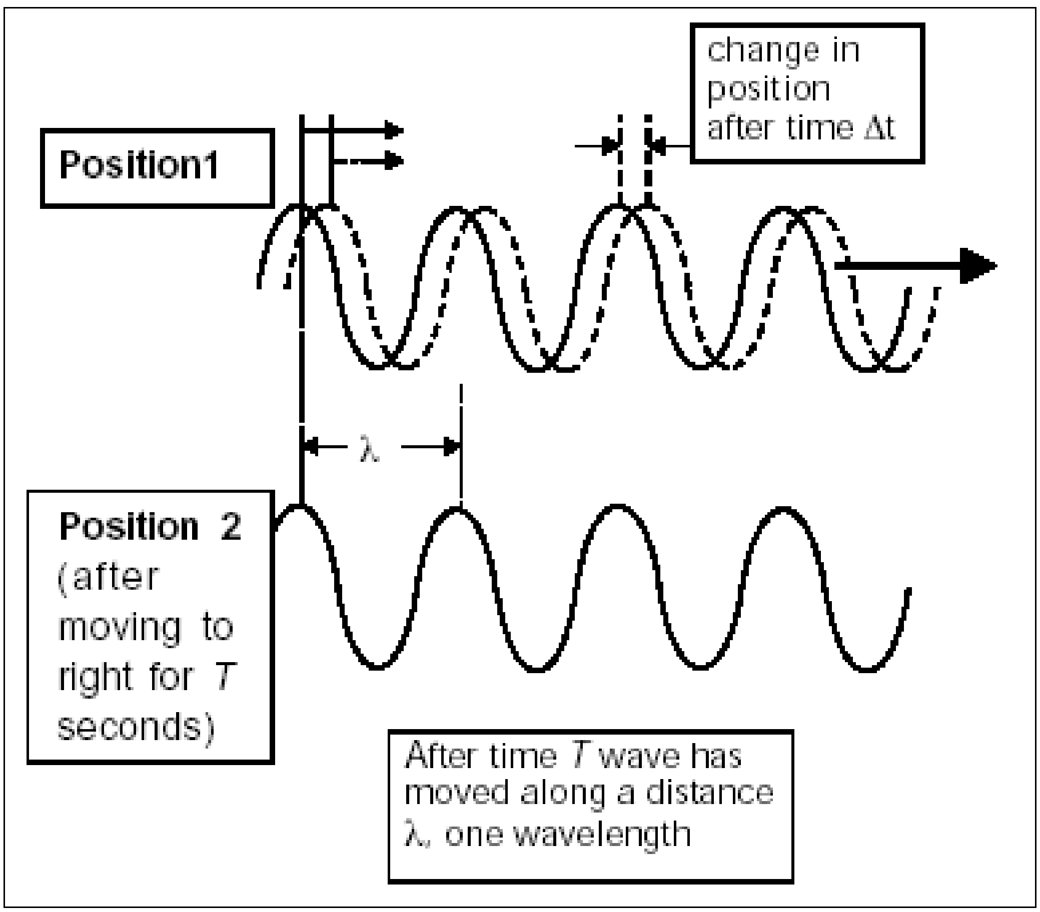

Figure 2.16: Moving of waves in interval time T to show the relationship between velocity, frequency and wavelength

As we know,

$$Velocity, v = \frac{DisTance\,moved, \lambda}{Time\,taken, T} \tag{2.10}$$

But, since we already know that frequency is the same as inverse period (f = 1/T), therefore we can write the equation as

$$Velocity, v = Frequency,\ f \times wavelength, \lambda \tag{2.11}$$

2.7 PEAK PARTICLE VELOCITY ESTIMATION

2.7.1 Introduction

The propagation of vibration in the ground is characterized by a decrease in vibration amplitudes with distance from the sources. It is caused by the reduction of energy when vibration waves transmitting through a distance. Particle velocity is generally used as the appropriate measurement quantity. The attenuation depends on the type of the vibration source as well as the type of wave generated. The intensity of particle velocity is reduced on account of geometric dispersion and material damping of the soil.

2.7.2 Attenuation Laws

Formula used for attenuation of particle velocity (Klein et. al., 1995) is showed as below:

$$\frac{V}{V_i} = \left(\frac{R_i}{R}\right)^n .D \tag{2.12}$$

Where V = vibration amplitude at distance R

V_i = vibration amplitude at reference distance R_i

D = factor taking account of the transmitting medium

n = exponent of the amplitude reduction law

D = exp ([-α (R-Ri)]), with the attenuation coefficient $\alpha \approx 2\pi\zeta / \lambda$ where λ is the wave length , ζ is the damping ration of the transmitting medium. Value of α is depended on soil condition or surrounding rock, normally α value for soil is bigger than α value for rock. Table 2.2 below shows the differential α value for different type of soil and at the specific frequency range.

Table 2.2: Attenuation coefficient, α for differential transmitting medium

Class	Attenuation coefficient, α (1/ft)		Transmitting medium
	5 Hz	50 Hz	
I	0.003 – 0.01	0.03 – 0.10	Soft and weak soils
II	0.001 – 0.003	0.01 – 0.03	Competent soils
III	0.0001 – 0.001	0.001 – 0.010	Hard soils
IV	< 0.0001	< 0.001	Hard and competent rock

The exponent n for amplitude reduction is depends on:

- the geometry of the vibration source (point source or line source)
- the type of excitation (stationary or impulsive)
- the predominant type of wave (Rayleigh waves on the surface , body waves at some depth)

Table 2.3: Value n for Point source (e.g. machine foundation)

Type of excitation	Predominant type of wave	
	Surfaces waves	Body waves
Stationary	0.5	1.0
impulsive	1.0	1.5

Table 2.4: Value n for line source (e.g. traffic)

Type of excitation	Predominant type of wave	
	Surfaces waves	Body waves
Stationary	0.0	0.5
impulsive	0.5	1.0

2.8 EQUATION OF MOTION

Consider a single degree-of-freedom system as shown in figure below, since the system has a single-degree-of-freedom, the displacement of the mass, spring and damper components will be the same (Irvine, 2000).

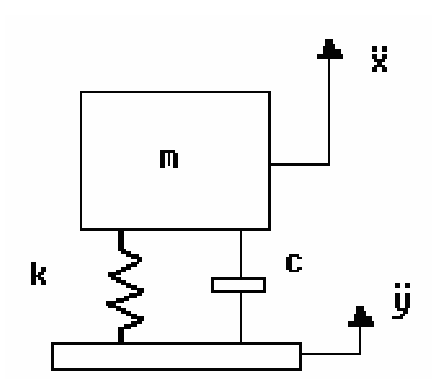

Figure 2.17: Single-degree-of-freedom (SDF) system