Proceedings of 30th Indian Engineering Congress, the 21st Century Engineering: The Make in India Pathway, *December 2015*, pp. 99-107

Effect of Ground Vibrations on Civil Engineering Construction

Bibha Das Saikia*

Civil Engineering Department, Royal School of Engineering and Technology, Guwahati, India

Abstract

The effect of ground vibrations has become a subject of current research interest amongst the civil construction engineers because of its serious environmental effects. Several sources of vibrations like pile driving dynamic compaction, blasting and operation of heavy equipment generate elastic waves in soil which may adversely affect the surrounding environment. It has been observed that dynamic effect of such vibration on the nearby structures depends on soil deposit at the construction site as well as the susceptibility rating of the structures. It is, therefore imperative to monitor the vibrations and assess their dynamic effects from the start of construction activities till the completion of construction. The paper attempts to focus the absence of criteria and guidelines relating to the effects of construction vibration in Indian building codes and to generate some awareness amongst the building constructors in India about the importance of the problem.

Keywords: Building Code, Construction, Dynamic, Vibration

1. Introduction

The effect of ground vibrations has become a subject of current research interest amongst the civil construction engineers because of its serious environmental effects. Several sources of vibrations like pile driving dynamic compaction, blasting and operation of heavy equipment generate elastic waves in soil which may adversely affect the surrounding environment. It has been observed that dynamic effect of such vibration on the nearby structures depends on soil deposit at the construction site as well as the susceptibility rating of the structures. In fact the vibrations induced in close proximity of driven piles may exceed tolerable limit and may cause foundations to yield or settle down if the soil is loose. It is, therefore imperative to monitor the vibrations and assess their dynamic effects from the start of construction activities till the completion of the entire process of construction.

Literature provides evidences of several researchers such as Barkan[3], Attewell and Farmer[1], Richart[12], Kramer[8], Svinkin, Henwood and Haramy[7], Masoumi et al[9] who have made significant contributions in this field through systematic investigations.

The present paper deals with an attempt to stress the importance of the effect of vibrations on civil constructions. Various influencing parameters vis a vis ground vibration like wave propagation, wave attenuation and damping, pile impedance, soil resistance, pile length effects have been taken into account. Assessments of the effects of vibration and measures to reduce the vibration intensity have been included in the study.

* *Author for correspondence*

2. Vibration and Wave Propagation

Various sources of vibration at the construction site are machineries with dynamic load used for soil excavation, blasting, compacting, pile driving. Ground vibrations induced by these sources are of two types- transient and steady-state vibrations. The first type includes single event or sequence of transient vibrations and each transient pulse of varying duration is dying away before the next impact occurs. Such vibrations are excited by air, diesel or steam impact pile drivers, by dynamic compaction of loose sand and granular fills, and also by highway and quarry blasts. The dominant frequency of propagating waves from impact sources ranges mostly between 3 Hz and 60 Hz. The second type contains continuous harmonic or some other periodic motion. These forced vibrations are caused by vibratory pile drivers, double acting impact hammers operating at relatively high speeds, and heavy machinery.

The vibration records of ground vibrations close to the pile driver are similar to those from forge and drop hammers. The vibration effects from impact hammers are identical to forge hammers because of their comparable energy release and the dominant frequency range. One wide spread dynamic source of vibration is vibratory pile driving equipment. The most important characteristic of this machine is frequency with the resultant relationships between dynamic force and eccentric moment. Low frequency machines have vibratory frequency between 5-10 Hz and used mainly for piles with big mass and toe resistance, such as concrete and large steel pipe piles. Medium frequency machines have the vibratory frequency range of 10-30 Hz and used with light weight piles, such as sheet piles and small pipe piles. High frequency machines operate at frequencies of more than 30 Hz. The major advantage of these machines is their reduced transmission of ground excitation to adjacent structures.

The vibration sources generate body (compression and shear) waves and surface waves of which Rayleigh waves are the primary type. These waves transmit vibrations through soil medium. Rayleigh waves have the largest practical interest for design engineers because building foundations are placed near the ground surface. In addition, surface waves contain more than 2/3 of the total vibration energy and their peak particle velocities are dominant on the velocity records.

Rayleigh waves induce vertical and radial horizontal soil vibrations. In horizontal layering soil medium, a large transverse component of motion could be caused by a second type of surface waves called Love waves. Waves propagate outward from the source in all directions. Spectra of the radial and transverse components of horizontal soil vibrations may have a few maxima and the one corresponding to the frequency of the source is not always the largest. Table 1 provides an indication of the approximate vibration levels that may be expected from various vibration source.[1]

3. Vibration Attenuation and Damping

In general, stress waves attenuate with distance. The attenuation is caused either due to the geometry of wave propagation (geometric damping) or materials through which the waves travel (material damping). Geometric damping reduces the amplitude of vibration as distance from the source increases as the same energy is spread over an increasingly larger surface or volume. Based on the theory of energy conservation,

Table 1. Vibration measurements (after Northern Expressway Environmental Report)[III]

Activity	Typical levels of ground vibration
Vibratory rollers	Upto 1`.5 mm/s at distance 25 m Higher levels could occur at closer distance, however, no damage would be expected for any building at distance greater than approximately 12m (for a medium heavy roller)
Hydraulic rock breakers (levels typical of a large rock breaker operating in hard sandstone)	4.50 mm/s at 5m 1.30 mm/s at 10m, 0.4 mm/s at 20m, 0'100 m/s at 50 m
Compactor	20 mm/s at distance of approximately 5 m, 2 mm/s at distance of 15 m,. At distance greater than 30m, vibration is usually below 0.3mm/s.
Pile driving/ removal	1 to 3 mm/s distance of 25m to 50m depending on soil condition and the energy of pile driving hammer. These levels are well below the threshold of any possibility of damage to structure in the vicinity of these works. At closer distance to the pilling operation, some compaction of loose fill would occur due to vibratory effects.
Bulldozers	1 to 2 mm/s at distance of approximately 5m, and. At distance greater than 20m, vibration is usually below 0.2mm/s.
Air track drill	4 to 5mm/s at distance of approximately 5m, and 1.5mm/s at 10m. At distance greater than 25m vibration is usually below 0.6 mm/ s and at 50m or more, vibration is usually below 0.1 mm/s
Truck traffic (over normal smooth road surface)	0.01 to 0.2 mm/s at the footing of building located 10 to 20m from a roadway.
Truck traffic (over irregular surface)	0.1 to 2.0 mm/s at the footing of buildings located 10m to 2om from a roadway.

the wave attenuation due to geometric damping can be described with the following expression given by Woods in 1997 (in Svinkin et al)[14] -

$$A_2 = A_1(r_1/r_2)^n \qquad (1)$$

where A_2 = amplitude of motion at distance r_2 from the source (m) ; A_1 = amplitude of motion at distance r_1 from the source (m) ; n= 1 for body waves ; n= 2 for body waves at the surface.

Since surface waves propagate as expanding rings, the energy per unit area of the wave decays inversely proportional to the distance from the source and surface waves experience a lower geometric damping than body waves[8].

4. Material Damping

Material damping occurs due to internal energy dissipation in the material as soil particles are moved by the propagating wave. Several researchers have reported that wave energy is dissipated as heat, and the amplitude of the wave decreases. The big difference between material damping and geometric damping is that in material damping, elastic energy is actually dissipated by viscous, hysteretic, or other mechanisms[8].

Dowding[6] suggested the following equation to describe material damping

$$A_2 = A_1 e^{-\alpha(r_2 - r_1)} \qquad (2)$$

Table 2. Attenuation Coefficient according to classification of rock and soil

Class	Attenuation Co-efficient, α(m-1)			
	5 Hz	40 Hz	50Hz	Description of Materials
I	0.033	0.08 - 0.26	0.1 – 0.3	Weak or soft soil
II	0.0033 – 0.01	0.026 -0.08	0.03 – 0.1	Competent soil
III	0.00033 – 0.03	0.0026 – 0.026	0.003 – 0.03	Hard soil
IV	<0.00033	< 0.0026	< 0.003	Hard competent soil

where A_2 = amplitude of motion at distance r_2 from the source (m) ; A_1 = amplitude of motion at distance r_1 from the source (m) ; α = absorption coefficient (m^{-1}).

The absorption coefficient, α, can be estimated using Eq-3[10]

$$\alpha = 2\pi Df/c \qquad (3)$$

where D = material damping $(Hz\ s)^{-1}$; f = vibration frequency (Hz) ; c = wave propagation velocity (m/s).

Attenuation coefficient according to classification of rock and soil materials are shown in Table 2[6].

As dynamic loads on the ground induce elastic waves in the soil medium in all directions, the spectra of soil vibrations excited by impacts show a few maxima with the dominant frequency of the surface wave. Actually, these frequencies are the natural frequencies of the soil layers and the values obtained do not practically depend on conditions at the contact area where impacts are made directly on the soil. In general, soil profiles are nonlinear systems and the dominant frequency of soil profiles depends on the applied impact. Nevertheless, over a certain range, the system behavior may be linear and if the system is restricted to this range it is possible to safely use the linear approach. However if sizes of falling weights are considerably different, such impacts on the same contact area might generate surface waves with different dominant frequencies[13,14].

5. Blasting

Blasting energies are much larger than energies of other sources of construction vibrations. Blast design depends on large number of factors and is aimed to enhance blasting productivity and diminish generated ground vibrations without increasing the cost. The different blasting factors that affect ground vibrations are described below[6].

Explosive type and weight, delay-timing variations, size and number of holes, distance between holes and rows, method and direction of blast initiation, geology and overburden are the most important causes which affect ground vibrations. The explosive types affect ground motion through detonation velocities of explosives and square root of the charge weight. Microsecond-delayed blasts are used for reduction of PPV(peak particle velocity) of ground vibrations which are connected with the maximum charge weight detonated per delay. A choice of the proper delay is not a simple problem. Wave propagation might differ with direction if there is geologic complexity. The influence of overburden manifests itself in attenuation of high-frequency components of ground motion.

6. Effects of Ground vibration

The effects of ground vibrations are classified into three categories:

- Disturbance of the occupants of buildings – vibrations which cause inconvenience or possible disturbance (human exposure) to the occupants or users.
- Disturbance of the contents of buildings – vibrations that affect the building contents (i.e. rattling, shaking or movements)
- Effect on structural integrity of the building – vibration that affect the integrity of the building or its structure.

In general, vibration criteria for human disturbance are more stringent than the criteria for vibration effects on building contents and building structural damage. Hence, compliance with the more stringent limits set for human exposure would automatically ensure compliance achieved for other two categories.

7. Human Exposure

Table 3. Vibration level & human perception(After Northern Expressway Environmental Report)[11]

Vibration level (mm/s)	Degree of perception
0.01	Not felt
0.15	Threshold of perception
0.35	Barely noticeable
1.0	Noticeable
2.2	Easily noticeable
6.0	Strongly Noticeable

The Table 3 gives an indication of typical human perception of vibration

8. Vibration Effects on Building Contents

Typical ground vibration from road and bridge construction activities occurs in the frequency range of approximately 8 Hz to 100 Hz. Within this frequency range, building contents such as blinds and pictures would commence visible movement at 0.5 mm/s. At vibration levels higher than 0.9 mm/s, rattling of windows, crockery or loose objects would be audible and annoying. Given the proximity of residential buildings adjacent to the proposed Northern Expressway alignment, this vibration symptom is not likely to occur for the majority of residents. Henwood and Haramy[7] have suggested safe level of blasting vibration frequencies for houses using a combination of velocity and displacement.

9. Structural Damage to Buildings

The British Standard 7385: Part 2[4] that deals with 'Evaluation and measurement for vibration in buildings' can be used as a guide to assess the likelihood of building damage from ground vibration. BS7385 suggests levels at which 'cosmetic', 'minor' and 'major' categories of damages might occur. Further, the German Standard DIN 4150 – Part 3 dealing with 'Structural vibration in buildings – effects on Structures', also recommends maximum levels of vibration to reduce the likelihood of building damage caused by vibration. So far no recommendations related to this exist in Indian code[5].

10. Vibration Assessment

The effects of vibration can vary according to a number of factors including the magnitude of the vibration source, the particular ground conditions existing between the source and receiver, the foundation-to-footing interaction and the large range of structures that exist in terms of design (e.g. dimensions, materials, type and quality of construction, and footing conditions). The intensity, duration, frequency and number of occurrences of a vibration all play an important role in both the annoyance levels caused and the strains induced in structures due to (pile drivers, bulldozers (ripping), hydraulic rock breakers and vibratory rollers during road construction and bridge work). Vibration generated from construction activities is characteristically greater in magnitude than that generated from operational road traffic post-construction of the road. This is particularly the case with a road surface in good condition where there are no potholes or significant irregularities in the road surface.

Empirical equations employed for assessment of expected soil vibrations from construction and industrial sources usually only allow calculation of a vertical peak amplitude of vibrations though not always with sufficient accuracy. These equations cannot incorporate specific differences of soil conditions at each site because heterogeneity and spatial variation of soil properties strongly affect characteristics of propagated waves in soil from construction and industrial vibration sources.

A new Impulse Response Function Prediction method (IRFP) has been conceived by Svinkin[13,14] for determining complete time domain records on existing soils, structures and equipment prior to installation of construction and industrial vibration sources. The IRFP method has significant advantages in comparison with empirical equations and analytical procedures.

A number of attempts have been made to correlate vibration parameters (displacement, velocity and acceleration) with observed human annoying disturbances of sensitive devices, and structural damage. It was found that structural damage could be well correlated with the peak particle velocity (PPV) of structural vibrations. The same criterion for structural damage of residential buildings was set at 50 mm/s peak particle velocity in the frequency range of 3-100 Hz. For commercial and engineering structures, Wiss[15] suggested a conservative limit of 100 mm/s.

Building damage occurs due to the combined influence of displacement, velocity, acceleration and frequency occurring due to vibration. A set of criteria was developed for the frequency range of 1-100 Hz, involving both displacement and velocity.

11. Vibration Measurement and Instrumentations

Vibration instruments are required to monitor, measure and record ground motion. Accelerometers and geophones can be used for vibration measurement. If acceleration limits are available for sensitive devices or foundation settlements, acceleration must be measured in parallel to velocity measurements. It should be noted that the devices must be used with proper calibration curves. Otherwise it is possible to receive misleading results.

Seismographs typically measure particle velocity, but there are displacement and acceleration seismographs. Some velocity seismographs can be equipped to produce either a displacement or acceleration record. A typical seismograph produces a visual record of three wave traces, one for each direction of motion. An additional acoustic wave trace may be produced if the seismograph is equipped with a microphone.

12. Measures to Minimize Effects during Construction

12.1 Vibration Management Plan

First a detailed vibration management plan need to be chalked out prior to starting construction activities. This plan should clearly outline the vibration mitigation measures to be implemented. Mitigation measures should include the following actions:

- Vibration monitoring at selected residences less than 25 m from construction activities.
- Regular community (or affected residents') updates advising when and where construction activities may generate perceptible levels of vibration.
- Minimization of piling energy (i.e. reduced hammer drop distance) as necessary depending upon receptor distance.
- Establishing a complaint hotline and implementing a procedure to effectively deal with any issues raised by the community which require urgent attention.

12.2 Building Condition Inspection

The vibration resulting from some construction activities may cause damage to nearby public utilities, structures, buildings and their contents. If these are located in the vicinity of the construction activity as specified in Table 4, a building condition inspection may be undertaken before construction activities begin.

Table 4. Distance from construction activity for building condition inspection (after Northern Expressway environmental Report)

Activity	Distance
Pile driving	100 m
Vibration compaction	>7 t plant – 50 m
Vibration compaction	<7 t plant – 25 m
Demolition of structures	50 m

13. Criteria and Guidelines

Various state and federal agencies have adopted empirical vibration limits, based on blasting research, to serve as a blanket guideline for all construction induced vibrations. As with most generalized guidelines, they must be used with extreme caution and careful consideration.

Most available guidelines are based on frequency-velocity control bounds. Studies have shown that velocity seems to correlate closely with observed damage. Frequency plays a large role in vibration related structural damage. Common structures have a low natural frequency, typically less than 30 Hz. Structural vibration is exponentially increased if the vibration frequency falls within the bounds of the natural frequency of the structure. This phenomenon is commonly known as resonance. Thus, low frequency vibrations are potentially more of a concern than their high frequency counterparts. Structural resonance caused by low frequency vibrations, initiating increased movements, proved to be a significant finding during a traffic induced vibration study carried out by Henwood and Haramy[7]. Prior to this study, the commonly used vibration criteria were independent of frequency. Table 5 and 6 present values of peak particle velocity with respect to frequency for different structures and vibrations produced by various machines.

Table 5. Peak Particle velocity with respect to frequency for different structures[5]

PPV Guide Values (mm/s)			
Structure Type	Frequency		
	< 10 Hz	< 10 – 50 Hz	< 50 – 100 Hz
Office and industrial premises	20	20 -40	40 – 50
Domestic and similar construction	5	5 – 15	15 – 20
Other building sensitive to vibration	3	3 – 8	8 – 10

Table 6. Values of frequency and peak particle velocity with respect to vibration source. (Swiss Standard for vibration in building in Henwood & Haramy[7])

Building Class (1)	Vibration source (2)	Range frequency, In Hz (3)	Peak particle velocity, In mm/s (4)	Peak particle velocity, in inches/s (5)
I [a]	Machines, Traffic	10 – 30	12	(0.5)
		30 – 60	12 – 18	(0.5 – 0.7)
	Blasting	10 – 60	30	(1.2)
		60 – 90	30 – 40	(1.2-1.6)
II [b]	Machines, Traffic	10 – 30	8	(0.3)
		30 – 60	8 – 12	(0.3-0.5)
	Blasting	10 – 60	18	(0.7)
		60 – 90	18 – 25	(0.7-1.0)
III [c]	Machines, Traffic	10 – 30	5	(0.2)
		30 – 60	5 – 8	(0.2-0.3)
	Blasting	10 – 60	12	(0.5)
		60 – 90	12 – 18	(0.5-0.7)
IV [d]	Machines, Traffic	10 – 30	3	(0.12)
		30 – 60	3 – 5	(0.12-0.2)
	Blasting	10 – 60	8	(0.3)
		60 – 90	8 - 12	(0.3-0.5)

14. Conclusion

Advance technology has produced revolutionary changes in building construction process. As a result new heavy machineries and equipment are used for construction of modern building structures. These equipment produce ground vibrations which not only cause damage to adjacent building structures but also generate discomfort and annoyance to the inhabitants and pedestrians. Although enough awareness about this problem has been generated abroad, we, in India, are yet to realize the importance of the problem. A review of several important systematic investigations conducted abroad has been discussed in this paper. To start with, the nature and level of wave generation as a result of vibrations caused by different machines and equipment and their effects on human beings and building structures have been discussed. This is followed by discussion on various measuring techniques used to assess the effects of the vibration. Subsequently the steps needed to mitigate the effect of vibrations have been dealt with and necessary criteria and guidelines specified

The paper also stresses the fact that although criteria and guidelines to contain the effects of construction vibration exist in building codes of foreign countries, such guidelines are absent in indian building code. Hopefully this paper will generate some awareness amongst the building constructors in India about the importance of the problem.

15. References

1. Attewell PB, Farmer IW. Attenuation of ground vibrations from piles. Ground Engineering. 1973; 6(4):26–9.
2. Athanasopoulos GA, Pelekis PC. Effect of soil stiffness in the attenuation of Rayleigh-wave motions from field. Soil Dynamics and Earthquake Engineering. 2000; 19(4):277–88.
3. Barkan DD. Dynamics of bases and foundations. New York: McGraw Hill Co; 1962.
4. British Standard 7385: Part2. Evaluation and measurement for vibration in building. Part3: Structural vibration in building. 1993.
5. Din 4150. Vibration in building construction. German Standard 1970
6. Doeding CH. Construction Vibrations. USA; Prentice- Hall; 1996.
7. Henwood JT, Haramy YK. Federal Highway Administration, Denver, CO 80225. Vibration induced by construction traffic: A historic case study.
8. Kramer SL. Geotechnical Earthquake Engineering. Pearson Education 2003.
9. Masoumi HR, Degrande G, Lombeart G. Prediction of free field vibration due to pile driving using a dynamic soil–structure interaction formulation. J of soil dynamics and earthquake engineering. 2007; 27.
10. Massassch KR, Fellenius BH. Ground Vibrations Induced by Impact Pile Driving. Proceedings of the 6th International Conference on Case Histories in Geotechnical Engineering; 2008 Aug 11-16; Arlington.
11. Govt of South Australia. Department of Transport &Energy & Infrastructure. Northern Expressway Environmental Report 2007.
12. Richart FE, Hall JR, Woods RD. Vibrations of soils and foundations. New Jersey: Prentice-Hall Inc.; 1970. p. 414.
13. Svinkin MR et al. Available from www.vulcanhammer.net 12. Svinkin MR. Discussion of 'Impact of weight falling onto the ground. Journal of Geotechnical Engineering ASCE. 1996; 122(5):414–5.
14. Svinkin MR. Overcoming soil uncertainty in prediction of construction and industrial vibrations. ASCE Proceedings of Uncertainty in the Geologic Environment: from theory to practice, Geotechnical Special Publications No. 58. C.D. Shackelford, P. Nelson, and M.J.S. Roth, editors, 1996; 2:1178–94.
15. Wiss JF. Construction vibrations: state- of- the –Art. Journal of Geotechnical Engineering Division. 1981; 107(GT 2).