Investigation of Low-Level Vibrations and Their Induced Settlement in Urban Environments

Dong-Soo Kim and Sergey Drabkin

Dept. of Civil Engrg. Polytechnic University
Six Metrotech Center, Brooklyn NY 11201, USA

This paper investigated the characteristics of low-level vibrations and evaluated the vibration induced settlements in urban environment. To rationally assess the current design practice, criteria for limiting vibrations regarding low-level vibrations and their impacts on the stability of adjacent structures are critically reviewed. The parameters affecting low-level vibration impacts such as types of vibration sources, attenuation characteristics, soil types and site conditions ,and long-term effects are discussed. The importance of vibration induced settlement for assessing the stability of adjacent structures was emphasized from the urban case histories. As a key aspect, vibration induced settlement was studied A special vibratory frame was designed and seven factors affecting vibration induced settlement were considered. A settlement prediction equation was developed using the Multifactorial Experimental Design (MED) method. Substantial settlement occurred in a vibration range which is about 10 times less than current vibration criteria of 2 in/sec. Loss of lateral support (frequently found during excavation in urban areas) adversely affected the vibration induced settlement. With increasing isotropic confining pressure, the settlement is substantially reduced at a given stress anisotrophy. Settlement was also affected by grain size distribution.

1.Introduction

Vibrations from cyclic and dynamic loadings are important primarily because of their potential to cause complaints of discomfort and/or damage to adjacent buildings and infrastructure systems. In the urban environment, most attention is focused on underground utilities and multi-story buildings and the problems associated with low-level, human-made vibrations such as those caused by vehicular traffic (rapid train, subway, heavy trucks etc.), machine vibrations, pile driving, and blasting. The volume and weight of heavy traffic is steadily increasing in urban areas. Consequently there is a critical engineering need to evaluate possible architectural and structural damages as well as human discomforts due to low-level vibrations. In addition to traffic induced problems, many case histories show damage to adjacent structures and underground utilities due to construction vibration. Moreover, as the level of tolerable vibrations in modern manufacturing is becoming more restrictive, control of low-level vibrations has become a major design criteria.

The vibration levels which cause discomfort to people, and damage to machineries and structures have been investigated by several researchers [1,2,3]. In current practice, however, recommended vibration criteria limits are applied without any consideration of important design variables such as vibration source, frequency and attenuation characteristics, soil type and site condition. Furthermore, the available vibration damage criteria have been developed by observing the structural damage induced by direct transmitted vibrations with little consideration taken to damage caused by settlement of foundation soils due to repetitive vibrations, particularly the cumulative effects of long-term repeated exposure.

This paper will address these critical engineering needs and evaluate vibration induced settlements in urban environments. The parameters affecting low-level vibration impacts are critically reviewed. Current criteria for limiting vibration from the literature are summarized. The importance of vibration induced settlement for assessing the stability of adjacent structures is emphasized from the urban case histories. To investigate vibration induced settlement, a special vibratory frame was designed and various factors which influence the vibration induced settlement were investigated, including vibration amplitude, soil gradation, deviatoric stress, confining pressure, and number of vibration cycles.

2. Parameters Affecting Low-Level Vibration Impact in Urban Environment

2.1 Type of Vibration Source

Vibrations produced in the urban environment can be classified by their natures: transient or pseudo steady-state vibrations distinguished by their periodicity, and surface or in-depth vibrations by their path of vibration. For example, traffic induced vibrations can be considered a surface, pseudo steady-state vibration while underground compressor induces an in-depth, pseudo steady-state vibration. Different types of vibrations have a varying response on the stability of adjacent structures. It is therefore important to investigate source dependent vibration effects under representative urban conditions.

It has long been known in earthquake engineering that ground motion is magnified by the building if the major frequency component of the ground vibration is coincident with the natural frequency of the building. In current practice, however, the frequency characteristics of the vibrations are seldom considered. The investigations of frequency response (power spectrum) of typical urban vibrations generated by various vibration sources must be performed, and a data base relating the major frequency ranges of typical urban vibration sources with observed structural damages needs to be constructed. Once this data base is compiled available, vibrations on adjacent buildings and infrastructure systems can be effectively controlled through the avoidance of frequency ranges which cause structural vibration amplification.

2.2 Attenuation Characteristics

Vibrations lose energy during the propagation through the ground. The decay of the amplitude of the vibrations with distance can be attributed to two components: geometrical damping and material damping [1]. Because the surface wave attenuates more slowly with distance (by geometrical damping) than body waves, surface wave is of primary concern for structures on or near the ground surface.

Attenuation due to material damping is affected by the soil type and the frequency of vibration. Wood and Jedele [4] classified site soils into four classes ranging from sound, hard rock to very soft clay and loose sand. Their correlation between soil type and the attenuation coefficient indicates that soft soil has a higher attenuation rate than stiff soil. The material damping of the soil increases as the strain level (e.g. vibration amplitude) increases. Consequently, the coefficient of attenuation will vary depending on the magnitude of energy released from vibration source. Moreover, in urban areas, the man-made construction materials and facilities including the paved sidewalks, utilities, etc. may dominate the attenuation. Effects of the built-environment must be considered.

2.3 Soil Type and Site Condition

The volume of a cohesionless soil is reduced by vibration related densification and result in foundation settlement. The case histories discussed by Lacy and Gould [5], indicated that the soils most vulnerable to densification are medium to loose (relative density less than 55%), narrow-banded, clean sands. The gradation of vulnerable sands falls within the same bounds which define soils that are liquefiable.

For cohesive soils, stiffness degrades by cyclic loading (or vibration) when the amplitude exceeds a certain threshold. The degradation rate increases as the vibration level and/or the sensitivity of cohesive soil increases.

The vibrational impact on structures and foundation soils depends on the site conditions. Settlement of a structure on excavated slopes is potentially more severe because of loss of lateral support than those on level ground. The age and condition of the structure in question also needs to be considered in the analysis.

2.4 Long-Term Effect

Structures adjacent to the urban highways are subjected to accumulated repetitive vibrations caused by the heavy traffic. Even though the level of vibration is not large enough to cause damage by a single occurrence, the accumulation of repetitive vibrations may cause long-term settlement through the densification of loose sands, as well as the fatigue degradation of sensitive clay. In urban areas, the long-term cumulative effects of low-amplitude vibrations on the adjacent structures should be a major design concern. However, the long-term cumulative effects of low-level vibrations on foundation soils have not yet been studied.

3. Criteria for Limiting Vibrations

Vibrations generated in urban areas can cause stresses thus triggering architectural and structural damage. Peak particle velocity is commonly accepted as a standard for measuring potential damage to structures. Table 1 provides insight into the level of vibration considered safe for buildings. Vibration restrictions around old buildings are three to five times more stringent than around new construction. The criteria for steady-state vibrations are about five to ten times more stringent than those for the transient vibrations. However, the ranges of criteria for limiting vibrations are very broad and differ depending on the agencies. Most importantly, these limiting criteria have been empirically derived from the observation of structural damages caused directly by transmitted vibrations and very few studies have considered the criteria for damage caused by the settlement of the foundation soils due to low-level vibrations.

Regardless of damage criteria for structures, complaints and claims by residents are usually filed before the damage criteria is reached. Fig. 1 shows human sensitivity to vibrations. It is apparent that the vibration intensities which are classified as "perceptible" or "disturbing" are well below the intensities that cause damage. Therefore, the vibration limit for residential type structures in urban area should take human responses into consideration.

Table 1 Summary of Recommended Maximum Allowable Peak Particle Velocity (in / sec) [From Ref.(2)]

Vibration Type	Investigator	Structure Quality*			
		I	II	III	IV
Transient	U.S.B.M	2.0	2.0	2.0	2.0
	Chae	2.0	2.0	1.0	0.5
	Medearis	1.3-2.5	1.3-2.5	1.3-2.5	1.3-2.5
	Swiss	0.7-1.0	0.7-1.0	0.5-0.7	0.3-0.5
	M.R.C.E.	2.0	2.0	1.0	0.5
Steady-State	Swiss	0.3-0.5	0.3-0.5	0.2-0.3	0.1-0.2
	AASHTO	0.2-0.3	0.2-0.3	0.2-0.3	0.1
	BRRL	0.4	0.4	0.2	0.08
	M.R.C.E	1.0	0.8	0.5	0.2

* I: structure of substantial condition
II: relatively new and sound condition
III: relatively old and poor condition
IV: old and poor condition

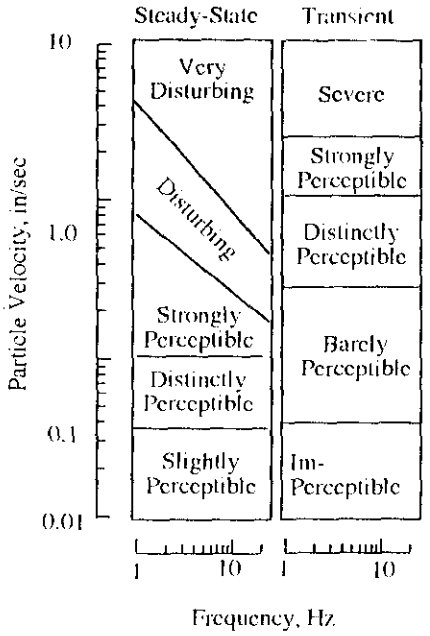

Fig. 1 Comparison of Human Response to Steady-State and Transient Vibrations (Alter Wiss 1981)

4. Importance of Vibration Induced Settlement

Damage to structures caused by vibration induced settlement can be more significant than structural damage due to directly transmitted vibrations, particularly in granular soils. Case history in the New York Metropolitan area [4] shows that pile driving close to existing structures can result in unacceptable settlement due to the densification or lateral movement of foundation soils. It is of specific interest to note that significant settlement and damage to adjacent buildings and infrastructure system occurred with measured peak particle velocities ranging between 0.09 and 0.4 in/sec figures substantially less than criteria recommended in practice (2 in/sec).

Underground utilities in urban environments for water, electricity, and gas supplies are very important parts of the infrastructure system for public life. The concerns for potential damage to these buried pipelines due to vibrations induced by traffic and construction activities are consequently growing in urban areas. Differential movement causes an additional bending stress to the pipeline and loses the serviceability. Case studies [6, 7] indicated that pipeline settlement and/or lateral movement has induced by construction and traffic vibrations, and controlling factor for the damage of pipelines was the differential movement induced by densification not directly transmitted vibrations.

5. Experimental Study on Vibration Induced Settlement

5.1 Testing Equipment and Test Variables

The soil sample was placed inside a triaxial cell which was attached to a shake table with a specially designed vibratory frame (Fig.2). Vibration was applied by the shaking table with a frequency of 60 Hz, and the vibration amplitude was monitored with a geophone. Test results by Youd [8] showed that settlement of granular soils was not affected by the loading frequency of vibration. Consequently a frequency was selected which best suited the capabilities of the equipment. In order to simulate an anisotropic, in-situ stress condition, vibration tests were performed under anisotropic confinement, as well as under the isotropic confinement. Isotropic confinement was applied by the cell pressure and deviatoric stress was applied by a low friction air piston. Both were regulated by an air pressure panel. At what is considered low to medium vibration amplitudes (0.1 to 0.7 in./sec), the settlement was continuously monitored with a LVDT connected to a high precision data acquisition system.

Currently most vibration criteria are tied exclusively to peak particle velocity. Prediction of vibration induced settlement in urban environments is too complex to use a mathematical equation solely based on one factor. Various factors including vibration amplitude, deviatoric stress (or stress anisotropy), confining pressure, soil gradation, duration of vibration, relative density, and moisture content should be considered when estimating settlement. The experimental program was designed using a multifactorial experiment design (MED) which gives the possibility to substantially reduce the number of tests needed. Regression analysis was performed using a second order polynominal model. The detailed explanation of multifactorial analysis will be discussed elsewhere [9]. The settlement prediction equation was developed through MED. The parameters affecting vibration induced settlement will be discussed in the following section.

5.2 Discussion of Test Results

Vibration induced settlements are predicted by the MED equation at a wide range of vibration amplitudes and number of cycles (Fig. 3). Settlement generally increases with the vibration amplitude and the number of cycles. It is interesting to note that substantial settlement occurred in the vibration range that is about 10 times less than the current vibration criteria of 2 in/sec. For example, at a vibration amplitude of 0.4 in/sec and 300,000 cycles, vibration induced settlement of 37 mils occurred in the laboratory

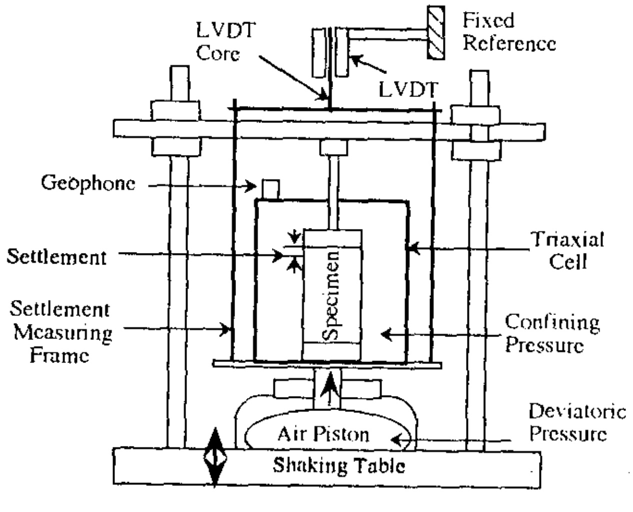

Fig. 2 Schematic Diagram of Testing Equipment

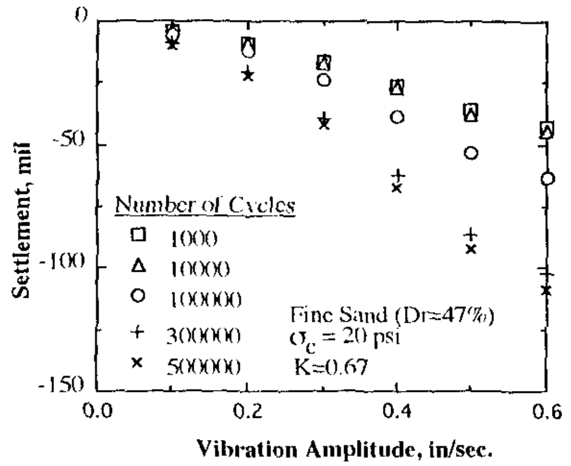

Fig. 3 Variation in Vibration Induced Settlement with Vibration Amplitude at Various Number of Cycles

with the 5.6 inch height specimen. An axial strain of 0.66% was also produced. If direct extrapolation to the in-situ condition is assumed to be feasible, approximately 4 in of settlement would occur in the 50 ft of soil column thus causing a substantial damages to the adjacent structures.

Adjacent construction, which is typical in urban area, produces the static settlement. This is due to the reduction of lateral support by temporary retaining structures during excavation. In addition, loss of lateral support will produce site conditions more vulnerable to vibration induced settlement than level ground. A typical variation in vibration induced settlement with stress anisotrophy is shown in Fig. 4. At a given vertical earth pressure of 20 psi, the horizontal earth pressure was reduced up to 8 psi where the earth pressure coefficient (K) is 0.4. Vibration induced settlement is adversely affected by the stress anisoprphy (the more loss of lateral support, the larger the settlement). Even for the at-rest stress condition where no lateral deformation is expected, earth pressure coefficient of sands is in the range of 0.5. Therefore, stress anisotrophy should be taken into consideration in the estimation of vibration induced settlement.

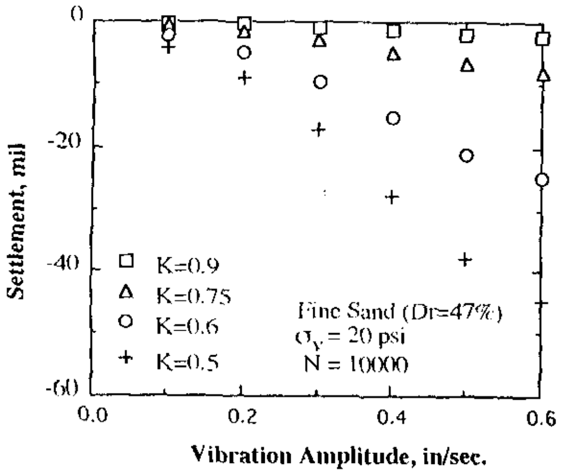

Fig. 4 Variation in Vibration Induced Settlement with Stress Anisotrophy

Typical variation in vibration induced settlement with confining pressure at a given stress anisotrophy (K=0.67) is shown in Fig. 5. With increasing confining pressure, the settlement is substantially reduced at a given vibration amplitude. In the deep soil layer, therefore, the settlement is more susceptible at a shallow depth, where the confinement is small, than at a greater depth. For in-depth vibration such as pile driving, however, vibration amplitude should be considered in the settlement estimation because vibrations are propagated from the pile tip to a shallow depth and are attenuated during the path.

To investigate the effects of grain size distribution on vibration induced settlement, tests were performed on three different soil types: i) fine sand (soil #1), ii) mixed sand (soil #2) and iii) coarse sand (soil #3). As shown in Fig. 6, tested sands are clean and uniform. The vibration induced settlement is affected by grain size distribution as shown in Fig. 7: at a given vibration amplitude, soil #1 provides the least settlement while soil #3 provides the biggest settlement. Even if the model predicts that coarse sand provides bigger settlement than fine sand in this study,

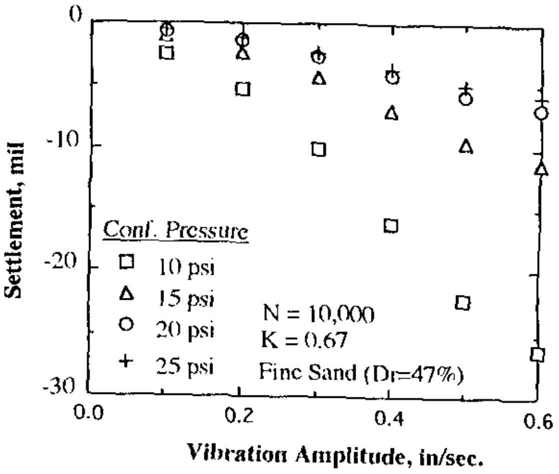

Fig. 5 Variation in Vibration Induced Settlement with Confining Pressure

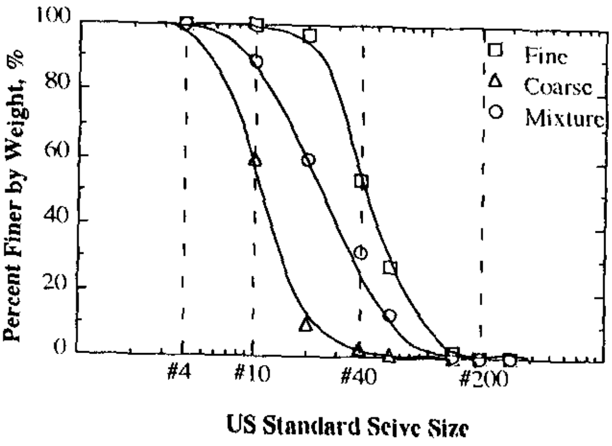

Fig. 6 Grain Size Distributions of Tested Sands

it is not conclusive for all cases because at high level vibrations (above 0.7 in/sec) fine sand provides a substantially bigger settlement and grain size distributions of tested sands are not representative for all natural soil types. Therefore, more study is recommended with various soil types which provide a wider variations of grain size distribution and also mix of fine soil particles.

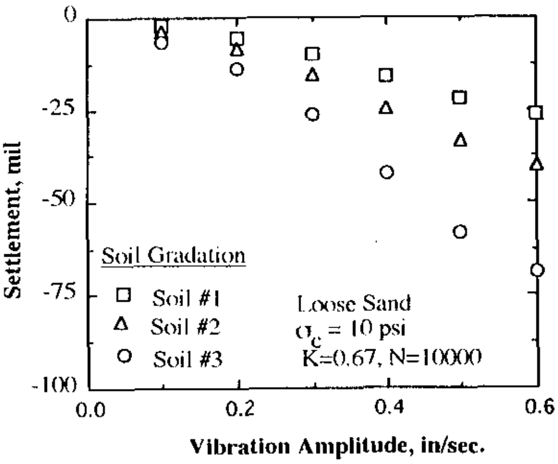

Fig. 7 Variation in Vibration Induced Settlement with Soil Gradation

6. Conclusion

In this paper, characteristics of man-made, low-level vibrations and their induced settlements in urban environments were investigated. We believe that various parameters such as type of vibration source, attenuation characteristic, soil type, site condition, and long-term effect, influence the stability of adjacent structures and should be considered when assessing urban vibration problems. From several case histories, vibration induced differential settlement (in contrast to a direct transmitted vibration) was found to be a controlling factor for damages of adjacent buildings and underground utilites.

A special vibratory frame was designed to shake the triaxial cell with the soil sample in it. Using a multifactorial experimental design, various parameters affecting vibration induced settlement were investigated Substantial settlement occurred in a vibration range which is about 10 times less than current vibration criteria of 2 in/sec. Loss of lateral support (frequently found during excavation in urban areas) adversely affected the vibration induced settlement. With increasing isotropic confining pressure, the settlement is substantially reduced at a given stress anisotrophy. Settlement was also affected by grain size distribution.

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