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SYNOPSIS In urbanized areas, vibration induced settlement on granular soils depends on vibration characteristics including vibration path and source, in-situ stress conditions, and soil properties. Quantitative laboratory assessment of settlement was extrapolated using parametric study of in-situ settlement of sands. It is shown that vibration amplitude should be monitored within the volnerable soil layers or evaluated considering attenuation characteristics of soil. Combining the effects of influencing factors, the discussed model can be utilized to predict vibration induced settlement of structures on sand.

INTRODUCTION

Vibration induced damage to the built environment may be caused by the direct transmission of vibrations, or it may be caused by differential settlement due to vibration induced soil densification. In the United States, vibration related standards have been derived largely from the mining industry where blasting induced vibrations are transmitted directly to the structures in question (Edward and Northwood, 1960; Nicholls et al., 1971). In the urban environment, the moderate, pseudo steady-state, man-made vibrations such as those caused by vehicular traffic, machine operations, and construction practices are much more common than the transient, large scale blasts, associated with the mining industry. Several case histories have shown that even while operating within the allowable vibration levels of the codes, structures have been damaged (Lacy and Gould, 1985; Dowding, 1991; Linehan et al., 1992). In these cases, differential settlement, and not directly transmitted vibration, was determined to be the cause and controlling factor for the damage.

In the urbanized areas, vibration induced settlement on granular soils can be influenced by a variety of different mechanisms and parameters (Kim and Drabkin, 1993; Kim et al., 1994). These include vibration characteristics (type of vibration source, amplitude, frequency, and duration), attenuation characteristics (geometric and material damping), in-situ stress conditions (confining pressure and deviatoric stress), soil type (soil gradation, relative density, and moisture content). In order to evaluate a reliable vibration induced settlement, combined effects of various parameters should be studied.

In this paper, factors affecting vibration induced settlement in urbanized areas were critically reviewed. Using the settlement prediction model developed by multifactorial experimental design (Kim et al., 1994), effects of various individual factors and their combined effects on settlement were investigated. Parametric studies of settlements in typical urban environments were utilized to develop reliable vibration monitoring schemes.

FACTORS AFFECTING SETTLEMENT

Prediction of settlement induced by low level vibrations in urbanized area is too complex to use a mathematical equation which employs only one or two factors. The combinations of various factors must be considered.

1) Vibration Characteristics

Type of Vibration Source: Transient or pseudo steady-state sources of vibrations are distinguished by vibrations' periodicity. Surface or in-depth sources differ by the path of vibration. Various types of vibrations have different impacts on the stability of adjacent structures. Hence, it is important to investigate source dependent vibration effects under representative urban conditions.

Vibration Amplitude: This is the only criterion currently used as a limit. Low to medium vibrations with amplitudes of peak particle velocities ranging from 0.25 to 1.8 cm/sec are of special interest for settlement potential assessment. Case studies show that structures subjected to such vibration are damaged due to differential settlement as opposed to collapse caused by directly transmitted vibrations.

Vibration Frequency: The investigations of frequency response (power spectrum) of typical urban vibrations generated by various sources must be performed. A database relating the major frequency ranges of typical urban vibration sources with observed structural damage needs to be constructed. Once the database is compiled, dangerous vibration levels can be effectively controlled through the total avoidance of frequency ranges that cause structural vibration amplification.

The number of vibration cycles: This number depends on frequency and duration. In short-term analysis, low-level vibrations may not be significant enough to cause substantial settlement. If the same vibrations are analyzed for long-term impact, the accumulation of vibrations may be sufficient for considerable densification of sandy soil layers.

2) Attenuation Characteristics

Vibrations loose energy during their propagation through the ground. The decay of amplitude of vibrations with distance can be attributed to geometrical and material damping, which may be described by the equation (Wood and Jedele, 1985):

$$w_2 = w_1 (r_1 / r_2)^n e^{-\alpha (r_2 - r_1)} \quad (1)$$

where w_1 and w_2 are vibration amplitudes at distances r_1 and r_2 from a source of vibration; n is a coefficient depending on type of propagated wave (n=2 for body waves along the surface, n=1 for body waves in the ground, n=0.5 for Rayleigh waves); α is a coefficient of attenuation (units of 1/distance), which is affected by the material damping of soils and the vibration frequency. In urban areas, man-made construction materials and facilities including paved sidewalks, utilities, etc., may influence the attenuation and should be taken into account.

3) In-Situ Stress Conditions

Deviatoric Stress was used to simulate anisotropic stress conditions caused by overburden pressure from the superstructure as well as by loss of lateral restraint during soil excavation.

Confining Pressure was employed to replicate subsoil stress conditions at various depths. With variable deviatoric stress, a range of earth pressure coefficients (the ratio of the horizontal stress to vertical stress) limited by static stability can be simulated. This can represent the state of stress from an isotropic confinement to maximum anisotropic conditions.

Relative Density: In-situ soil density may be the controlling factor for settlement potential. Soils with relative densities less than fifty-five percent are considered particularly sensitive.

Degree of Saturation and Drainage Conditions: In-situ moisture content, location of water table, and drainage conditions are very important characteristics. Vibration above a threshold level often increases the pore water pressure and reduces the effective stress for nearly saturated and saturated soils, thereby increasing settlement potential of granular soils.

DEVELOPMENT OF SETTLEMENT MODEL

A model of vibration induced settlement for small to intermediate vibration levels was developed using multi-factorial experimental design. Such factors affecting vibration induced settlement as vibration amplitude, deviatoric stress, confining pressure, soil gradation, number of vibration cycles, relative density, and moisture content were varied in the ranges shown in Table 1.

TABLE 1 Tested Ranges of Factors

#	Factors	Tested ranges
1	Vibration amplitude (cm/sec)	0.25-1.8
2	Deviatoric stress (kPa)	14-104
3	Confining pressure (kPa)	69-207
4	Sand mixture	Coarse to fine
5	Number of vibration cycles	60-500000
6	Moisture content	Dry,moist
7	Initial relative density	Loose,dense

Sand properties are shown in Table 2:

TABLE 2 Properties of tested sands

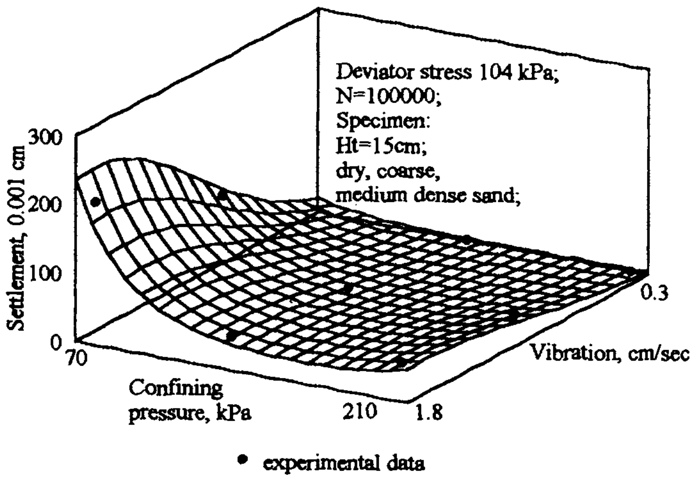
Sand	D50 mm	Maximum Dry Density kg/m^3	Minimum Dry Density kg/m^3
Fine	0.5	1704	1507
Mix	0.7	1702	1860
Coarse	1.7	1702	1577

A special vibratory frame was designed to shake a soil specimen with height of 15 cm within a triaxial cell. An experimental program was devised using a multi-factorial experimental design method. This allowed the investigation of many factors influencing settlement using a relatively small number of experiments (Kim and Drabkin, 1993 and Kim et al., 1994). The effects of various factors on vibration induced settlement will be discussed using the developed model in the following section.

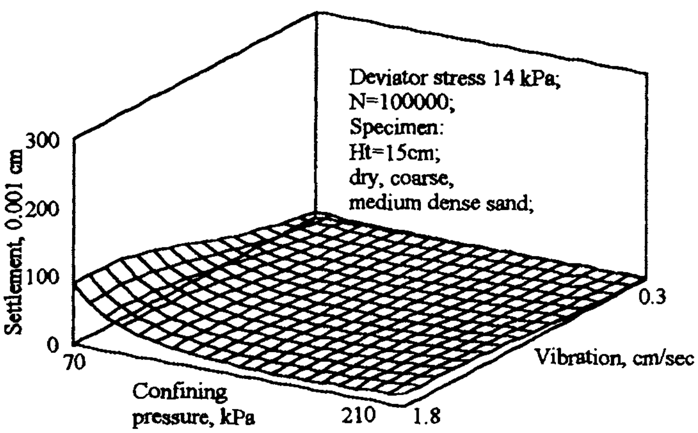
EFFECTS OF FACTORS ON VIBRATION INDUCED SETTLEMENT

The variations in settlement with vibration amplitude and confining pressure at two different devatoric stresses are shown using three dimensional surface plots in Fig.1a. Settlement is significantly affected by both vibration amplitude and confining pressure. With increasing vibration amplitude and decreasing confining pressure, settlement generally increases. At a given vibration amplitude, the settlement is substantially reduced with increasing confining pressure. Therefore, in the thick soil layer, the upper part at a shallow depth is more susceptible to settlement than a part at larger depth, where the confinement is bigger.

Vibration induced settlement is adversely affected by the stress anisotropy. Settlement under high deviatoric stress (Fig.1a) is significantly larger than that under low deviatoric stress (Fig. 1b). If the response surfaces in Fig. 1 are sliced off at various settlement levels and then the outlines of the slices are projected on the same plane, settlement contours are obtained as shown in Fig.2. The region of settlement less than 0.01 cm was defined as a negligible settlement zone. At high deviatoric stress when stress anisotropy is large, this zone is small. At low deviatoric stress this zone becomes large. In other words, a threshold vibration amplitude above which the vibration induced settlement occurs, decreases at a given confining pressure with an increase of stress anisotropy.



a) Maximum deviatoric stress



b) Minimum deviatoric stress

Fig. 1. Response Surface of Vibration Induced Settlement at Different Deviatoric Stresses

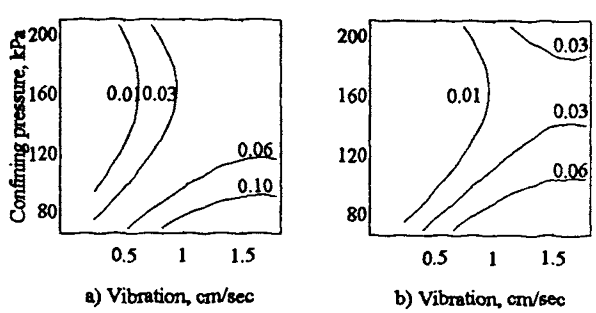


Fig. 2. Settlement Contour Graphs at: a) Maximum b) Minimum Deviatoric Stresses

In order to investigate the effect of stress anisotropy, the vibration induced settlement was calculated for increasing deviatoric stresses at a given confining pressure. The earth pressure coefficient, varied approximately in the range between 0.4 and 0.9. The variation in settlement with earth pressure coefficient is shown in Fig.3.

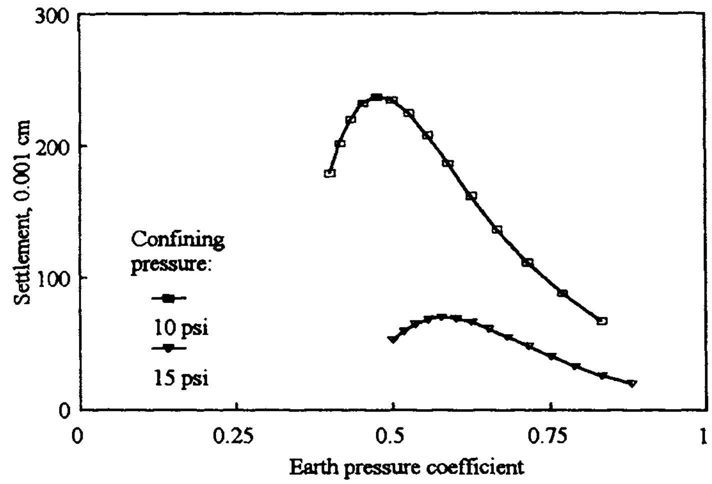


Fig. 3. Settlement for Different Earth Pressure Coefficients (All Quantitative Factors Except Stresses are on Medium Levels)

It can be clearly seen that vibration induced settlement increased significantly with increasing stress anisotropy (decreasing earth pressure coefficient).

The increase of number of vibration cycles caused at first substantial settlement especially for large vibration amplitudes (Fig.4).

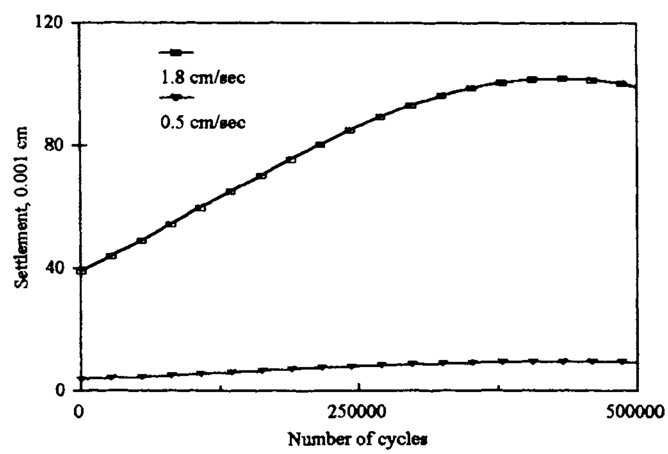
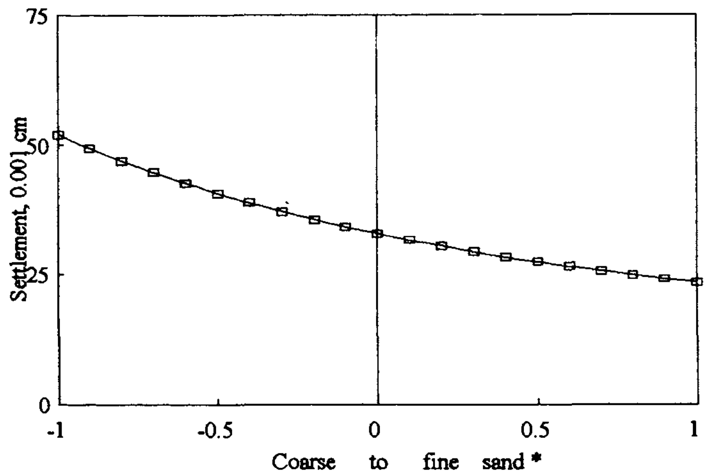


Fig. 4. Settlement at Different Number of Cycles for Different Vibration Amplitudes(Other Quantitative Factors are on Medium Levels)

Then, the settlement ceased and the system came to the state of equilibrium.

Coarse sand specimens with small content of fines were more susceptible to vibration than fine sand specimens (Fig.5), which can be explained by small differences in initial densities.



* -1=Coarse sand; 0=1:1Mixture of coarse and fine sand; 1= Fine sand

Fig. 5. Settlement of Different Sands (All Quantitative Factors are on Medium Levels)

PARAMETRIC ASSESSMENT OF SETTLEMENT FOR TYPICAL URBAN SITES

In order to develop reliable vibration monitoring and control schemes, parametric assessment of vibration induced settlement was performed for representative urban conditions. Three typical vibration environments were considered as shown in Fig.6: surface traffic vibration (highway); in-depth traffic vibration (subway); and in-depth construction vibration (pile driving).

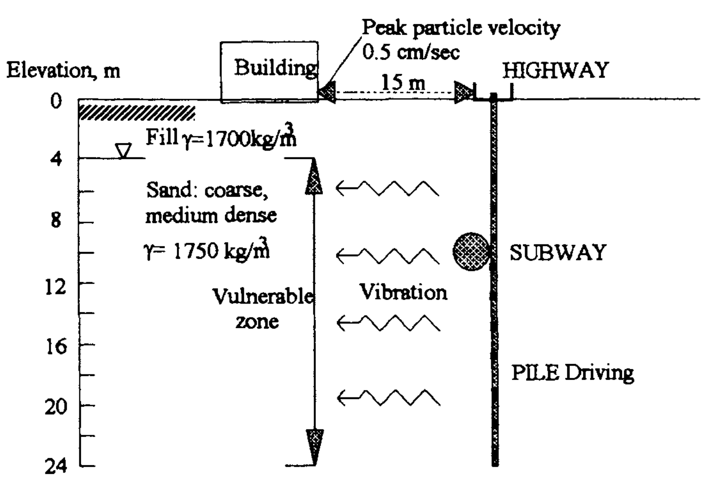
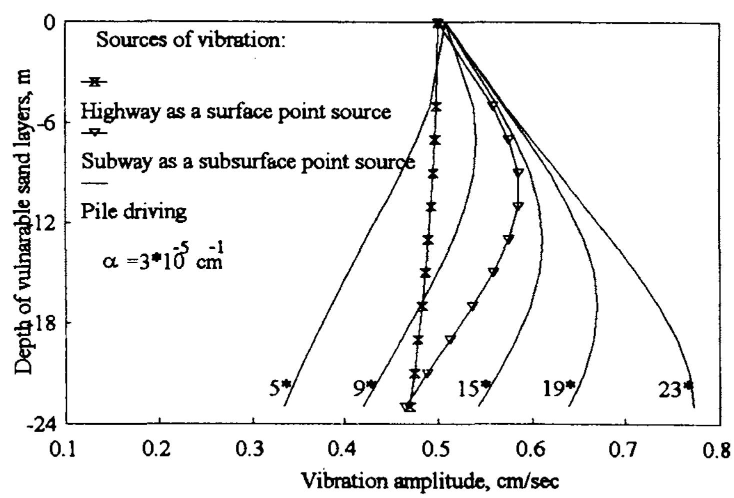


Fig. 6. Typical Urban Environments Considered in the Parametric Study

To calculate the vibration induced settlement using the prediction model, the seven influencing factors need to be evaluated. In the current practice, vibration amplitude is monitored on the ground surface next to the adjacent structure of concern. For the fixed vibration amplitude (0.5 cm/sec) next to the building, variations in vibration amplitude (factor 1) with depth along the vulnerable zone was determined considering attenuation characteristics (Equation 1). This zone was considered consisting of 10 layers with the thickness of 2 m. For each layer, the vibration amplitude and the state of stresses was computed separately. The total number of vibration cycles from each source was 500,000. The pile driving was approximated by a set of discrete vibration sources located at each sublayer. The number of vibration cycles from each such source increased proportionally to the increase of confining pressure. It is interesting to note that the vibration amplitude varied substantially with depth (Fig.7) depending on the vibration source even though the monitored amplitude on the ground surface was assumed to be the same.



* Vibration amplitude at a pile penetration depth of 5-23 m

Fig. 7. Variations in Vibration Amplitudes with Depth for Different Vibration Sources

The variations in vibration induced settlement with depth (Fig. 8) is source dependent; pile driving can result in settlement that is twice as large as one from surface traffic vibration. The input of individual upper layers in settlement can be bigger than that of lower layers even though vibration amplitude registered in upper layers may be smaller than in deeper layers.

Therefore, for proper settlement assessment in urban environments, vibration amplitude should be monitored not only at the ground surface but also within the ground. Otherwise, vibration amplitude should be evaluated considering attenuation characteristics of soil as well as vibration paths.

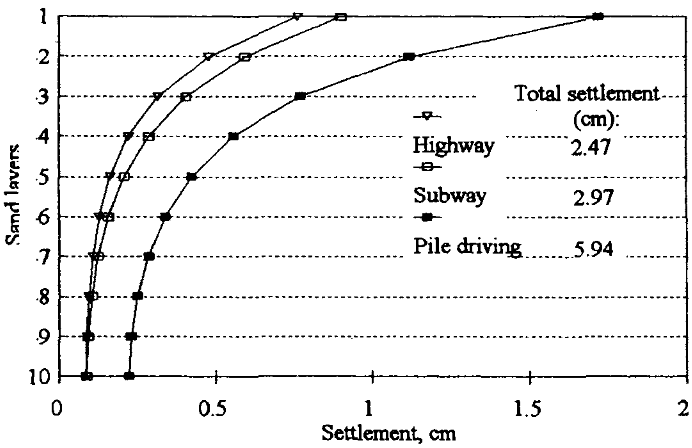


Fig. 8. Variations in Vibration Induced Settlement with Depth (Layers) for Different Vibration Sources

SUMMARY

Vibration induced settlement on granular soils, especially in urbanized areas, is affected by combination of various factors such as vibration characteristics, attenuation characteristics of soils, in-situ stress conditions, and soil type. With increasing confinement, the settlement is substantially reduced. An increase of stress anisotropy causes increase of settlement. For proper settlement assessment, vibration amplitude should be either monitored within the vulnerable soil layers or evaluated considering soil characteristics. Parametric study demonstrated the potential usefulness of the discussed model for prediction of vibration induced in-situ settlement of sands.

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