Prediction of low level vibration induced settlement

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ABSTRACT: A prediction model of vibration induced settlement was developed for small to intermediate vibration levels (0.25-1.78 cm/s). Seven factors affecting vibration induced settlement such as vibration amplitude, deviatoric stress, confining pressure, soil gradation, duration of vibration, relative density, and moisture content were considered. A special vibratory frame was designed to shake a soil sample within a triaxial cell. An experimental program was devised using a multi-factorial experimental design method, which allowed the investigation of many factors influencing settlement using a relatively small number of experiments. The settlements from the case histories matched the settlements calculated from the model. This demonstrated the potential usefulness of a mathematical model for the evaluation and prediction of the vibration induced, in-situ settlement of sands.

INTRODUCTION

Vibrations from cyclic and dynamic loadings are important primarily due to their potential to cause damage to structures. In the urban environment, most attention is focused on vibrational effect on underground utilities and multi-story buildings and the problems associated with low-level, man-made vibrations such as those caused by vehicular traffic (subways, heavy trucks, etc.), machine operations, and construction practices. Standard damage criteria were developed from damage caused by blasting vibrations transmitted directly to structures (Edwards and Northwood 1960; Nicholls et al. 1971). Alternatively, many buildings are damaged not directly from vibrations but by differential settlement, which is often caused by low level repetitive vibrations in granular soils. To date few have studied this subject. Several case histories in the New York metropolitan area (Lacy and Gould 1985) showed significant settlement and damage to adjacent buildings occurring at peak particle velocities as low as 0.23 cm/s (substantially less than the 5.1 cm/s criterion currently recommended). Moreover, case histories for underground utilities indicate that pipeline settlement and lateral movement, induced by construction and traffic vibrations, are the controlling factors for predicting damage (Linehan et al. 1992). 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.

In this study, 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. This approach allows for the simultaneous evaluating of multiple parameters with a minimal number of test runs. Finally, predicted settlements from the MED model were compared with actual settlements measured from case histories.

TESTING EQUIPMENT

The soil sample was placed inside a triaxial cell which was attached to a shake table with a specially designed vibratory frame (Fig. 1). 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 (1970) 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./s (0.25 to 1.78 cm /s)], the settlement was continuously monitored with a LVDT connected to a high precision data acquisition system.

VARIABLES IN MULTI-FACTORIAL EXPERIMENTAL DESIGN

An experimental program was developed using MED which included the following seven variables: vibration characteristics (vibration amplitude and duration), in-situ stress conditions (confining pressure and deviator stress); and soil factors (grain size distribution, moisture content, and relative density).

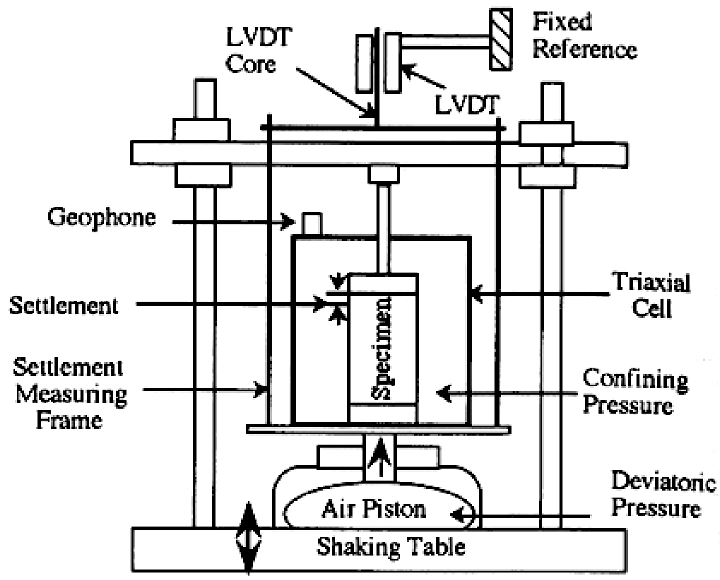


FIG. 1. Schematic Diagram of Testing Equipment

The vibration amplitude (factor 1) was defined as peak particle velocity. A maximum level was chosen at 0.7 in./s (1.78 cm/s), which corresponded to a vibration amplitude at a distance of 10 ft (3 m) or less from vibratory pile driving. Similarly, a minimum vibration level was chosen at 0.1 in./s (0.25 cm/s), which for steady-state, or non-transient vibrations, is at a distinctly perceptible level (Wiss 1981).

The deviatoric stress (factor 2) was varied from 2 to 15 psi (13.8 to 103.4 kPa) in order to simulate anisotropic stress conditions caused by overburden pressure from the superstructure and those caused by adjacent excavation, as well as from inherent anisotropy. The confining pressure (factor 3) was set from 10 to 30 psi (69 to 206.8 kPa) to simulate subsoil stress conditions at various depths. With the combination of deviatoric stress and confining pressure, a range of earth pressure coefficients was obtained from 0.4 to 0.94, representing the state of stress from an isotropic confinement to the maximum anisotropic condition limited by static stability (care was taken to ensure that the specimen was stable under a static load, prior to the vibration test).

The influence of grain size distribution was studied using three different sand configurations: fine, coarse and 1:1 mixture. The ratio of fine to coarse sand by weight was characterized by factor 4. Grain size distributions are shown in Fig. 2.

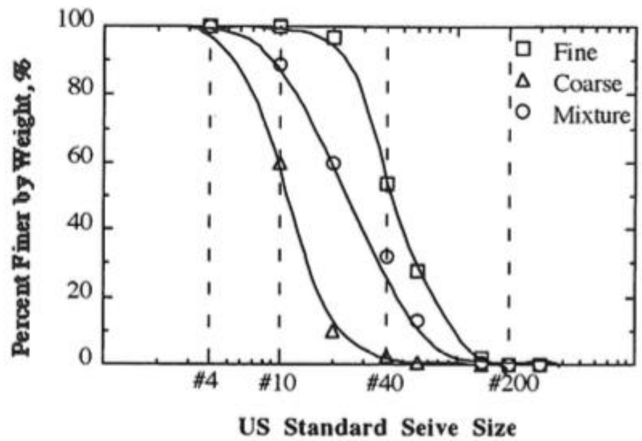


FIG. 2. Grain Size Distributions of Tested Sands

The number of vibration cycles depended on frequency and duration. Preliminary tests demonstrated that after about 500,000 cycles at 60 Hz, settlement ceased. To investigate long-term, as well as short-term behavior, the duration of the test (factor 5) was varied from 1 to 9000 seconds.

The influence of water content was evaluated using dry or moist sand (factor 6). The moist specimen had an initial degree of saturation of about 90%. Tests were performed under drained conditions.

The initial relative density of the specimen (factor 7) varied depending upon grain size distribution, moisture content, and specimen preparation technique. To prepare a loose sand specimen, a funnel was used to pour the sand into the mold. When sand was pluviated through a #10 sieve, a medium-dense specimen was obtained. The values of initial relative densities for different sand specimens are shown in Table 1.

TABLE 1. Initial Relative Density of Test Specimens

Soil Gradation	Moisture Condition	Relative Densities (%) Prepared by Funnel	Relative Densities (%) Prepared by Sieve
Coarse Sand	Dry	37	67
	Moist	34	62
Fine Sand	Dry	61	84
	Moist	47	65
1:1 Mixture	Dry	45	70
	Moist	48	62

In MED, variables are classified either as quantitative factors (from 1 to 5) or as qualitative factors (6 and 7). Each quantitative factor had to be controlled within a 5% maximum deviation. All factors had to be independent from each other, and every combination of factors had to be stable prior to testing.

The seven factors used in this study and their natural and coded values are shown in Table 2. The factor identification, F_i, was denoted by 0, 1, and 2 for quantitative factors and by 0 and 1 for qualitative factors depending on natural level of each factor. These were employed for the upcoming experimental design matrix (Table 3). The coded value was also denoted in the same manner by -1, 0, and 1 for quantitative factors and by -1 and 2 for qualitative factors.

DEVELOPMENT OF SETTLEMENT PREDICTION MODEL

When choosing the design of the experiment, we assumed that the vibration induced settlement could be approximated by a second order regression polynomial. To minimize the number of tests required for regression analysis, an orthogonal experimental design developed by Brodskii et. al. (1974) was employed. The design required only 27 different combinations of factors (test runs) to obtain the effects of five quantitative factors (1 to 5) and two qualitative factors (6 and 7) upon settlement, Y. The model was in the form of the following polynomial:

$$Y = b_o + \sum(b_i x_i + b_{ii} z_i) + b_6 x_6 + b_7 x_7 \qquad (1)$$

where b_o is a constant; b_i, and b_1, are the regression coefficients; x_i are coded value of factors; and $z_i = (3x_1^2-2)$. The second term in Eq. (1) shows the effect of the quantitative factors.

TABLE 2. Natural and Coded Values of Factors

#	Factor[1]	Factor levels		
		Natural value	ID[3] value F_i	Coded[4] value x_i
1	Vibration amplitude (in./s)	0.7 0.4 0.1	0 1 2	1 0 -1
2	Deviatoric stress (psi)	15 8.5 2	0 1 2	1 0 -1
3	Confining pressure (psi)	30 20 10	0 1 2	1 0 -1
4	Sand mixture	Fine sand 1:1 mixture Coarse sand	0 1 2	1 0 -1
5	Duration	9000 4500 1	0 1 2	1 0 -1
6	Moisture content	Dry Moist	0 1	-1 2
7	Initial relative density[2]	Loose Medium dense	0 1	-1 2

1. Factors #1, 2, 3, 4, and 5 are quantitative, factors #6 and 7 are qualitative.

2. Initial relative density varies with conditions in Table 1.

3. ID (identification) values, F_i, are used in experimental design matrix in Table 3.

4. Coded values x_i are used in polynomial equation.

TABLE 3. Experimental Design Matrix

Test No.	Test[1] Run No.	Experimental Design Matrix							Settlement	
		F1	F2	F3	F4	F5	F6	F7	Observed from Test	Calculated by Model
1	24	0	0	0	0	0	0	0	2.944	2.720
2	14	1	0	0	1	1	1	1	0.000	1.981
3	2	2	0	0	2	2	0	0	0.000	0.349
4	12	0	1	0	0	2	1	0	2.944	1.829
5	18	1	1	0	1	0	0	0	2.773	3.344
6	25	2	1	0	2	1	0	1	0.693	0.445
7	13	0	2	0	0	1	0	1	3.434	2.588
8	21	1	2	0	1	2	0	0	0.000	0.349
9	19	2	2	0	2	0	1	0	0.000	-0.822
10	9	0	0	1	0	0	1	1	0.000	1.861
11	8	1	0	1	1	1	0	0	4.094	2.271
12	22	2	0	1	2	2	0	0	0.000	0.064
13	10	0	1	1	0	2	0	0	1.609	2.119
14	17	1	1	1	1	0	0	1	3.829	3.059
15	7	2	1	1	2	1	1	0	0.000	-0.414
16	15	0	2	1	0	1	0	0	0.693	2.304
17	1	1	2	1	1	2	1	0	0.000	-0.510
18	6	2	2	1	2	0	0	1	0.000	-0.532
19	11	0	0	2	0	0	0	0	5.961	4.322
20	27	1	0	2	1	1	0	0	4.317	4.158
21	16	2	0	2	2	2	1	1	1.792	1.377
22	5	0	1	2	0	2	0	1	3.401	4.006
23	23	1	1	2	1	0	1	0	4.174	4.371
24	26	2	1	2	2	1	0	0	1.386	2.047
25	3	0	2	2	0	1	1	0	4.382	3.616
26	20	1	2	2	1	2	0	1	1.792	1.951
27	4	2	2	2	2	0	0	0	0.000	1.354

1. Randomized order of test runs.
2. Settlement measures in mils is presented in natural logarithmic scale (1 mil = 2.54×10^{-3} cm).
3. Average value of two runs for a given factor combinations.

The experimental design matrix (Table 3) was developed with the following procedure (Brodskii et al. 1974). When the identification values are replaced by their coded values, the experimental design matrix becomes an orthogonal matrix. The order of test runs was randomized to exclude occasional bias in testing procedures.

Since the design matrix is an orthogonal matrix of independent variables, the regression coefficients in the Eq. (1) were derived from the formulas:

$$b_o = \frac{\sum_{u=1}^{n} y_u}{n};\; b_i = \frac{\sum_{u=1}^{n}(x_{ui} y_u)}{\sum_{u=1}^{n} x_{ui}^2};\; b_{ii} = \frac{\sum_{u=1}^{n}(z_{ui} y_u)}{\sum_{u=1}^{n} z_{ui}^2} \qquad (2)$$

in which y_u is the observed settlement, x_{ui} and z_{ui} are values of x_i and z_i in the corresponding rows of an experimental matrix. Then, prediction model of settlement is:

$$Y = 2.27 + 1.19 \times x_1 - 0.71 \times x_1^2 + 0.49 \times x_2 - 0.68 \times x_2^2 - 0.80 \times x_3 + 1.09 \times x_3^2$$

$$-0.46 \times x_4 + 0.06 \times x_4^2 + 0.45 \times x_5 - 0.38 \times x_5^2 - 0.19 \times x_6 - 0.10 \times x_7 \qquad (3)$$

The statistical adequacy of the developed model was evaluated with both the Fisher (F), and Pearson Chi-Square (x^2) criteria. For statistical considerations, each experimental combination was tested twice. The Fisher criterion (Box et al. 1978) showed an adequacy with a significance level of 99%. The Pearson x^2 criterion was determined using Brandt and Snedecor's formula (Bailey 1959) and resulted in an adequacy with a significance level of 95%. The predicted settlements using Eq. (3) were tabulated in Table 3 together with observed settlements for all experimental runs.

EFFECTS OF VARIABLES ON SETTLEMENTS

Vibration induced settlements are predicted by the proposed model [Eq. (3)] 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./s (5.1 cm/s). For example, at a vibration amplitude of 0.4 in./s (1.0 cm/s) and 300,000 cycles, vibration induced settlement of 37 mils occurred in the laboratory with the 5.6 inch (14.2 cm) height specimen. If direct extrapolation to the in-situ condition is to be feasible, approximately 4 inch of settlement would occur in the 50 ft (15.2 m) of soil column thus causing a substantial damages to the adjacent structures which encountered in case studies (Lacy and Gould 1985).

Adjacent construction, typical in urban areas, can produce static settlement. This is due to the reduction of lateral support by temporary retaining structures during excavation and does not require vibration to induce the phenomena. 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 anisotropy is shown in Fig. 4. Vibration induced settlement is adversely affected by the stress anisotropy (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 anisotropy should be taken into consideration in the estimation of vibration induced settlement.

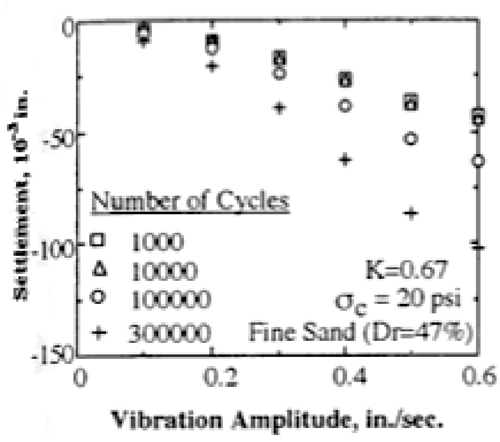


FIG. 3. Variation in Vibration Induced Settlement with Vibration Amplitude at Various Number of Cycles

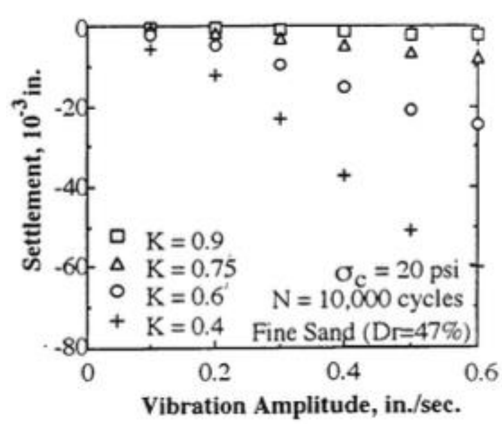


FIG. 4. Variation in Vibration Induced Settlement with Stress Anisotrophy

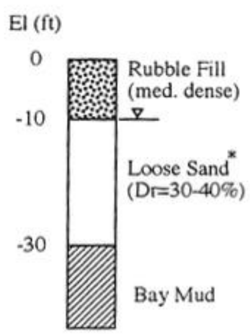
With increasing confining pressure, the settlement is substantially reduced at a given vibration amplitude. Settlement is more susceptible at a shallow depth, where the confinement is smaller than at a greater depth. As relative density decreases, the settlement increases. Because relative density was used as a qualitative factor in this study, it is difficult to quantify the effect.

EVALUATION OF PROPOSED MODEL FROM CASE HISTORIES

In order to evaluate the proposed model, the predicted and measured settlements are compared from two case histories. It should be noted that some factors were not directly available from the case histories. The extrapolation scheme to in-situ condition, although preliminary, showed strong indications of adequate correlation, and will provide a solid basis for future refinements.

Embarcadero Area

The Embarcadero area is located in the northeast San Francisco waterfront. Site E2 between Greenwich and Filbert Streets was chosen from the case history by Clough and Chameau (1980). A simplified boring log of this site is shown in Fig. 5. Sheetpiles were driven for culvert construction by an ICE Model 812 vibratory hammer operated at a fixed frequency of 1,100 rpm. The peak acceleration and vibration induced settlement versus distance from the sheetpile line was provided.



Vib. Amp. (in/sec)	Dist. from Pile (ft)	Meas. Sett. (in)	Cal. Sett. (in)
0.5	10	2.0	2.3
0.2	20	0.7	0.6
0.1	30	0.3	0.3

Factor	Natural Value	Coded Value
1	0.5 in/sec	0.33
2#	4 psi	-0.3
3**	10 psi	-1
4	Mix.	0
5	9000 sec	1
6	Moist	2
7	Loose	-1

* vulnerable layer for settlement
in-situ stress condition was estimated at the center of layer.

** As a factor #3 (confining pressure), a mean effective stress ($\bar{\sigma}_m$) was estimated by assuming Ko = 0.5. $\bar{\sigma}_m = (1+2*Ko)/3 * \bar{\sigma}_v$

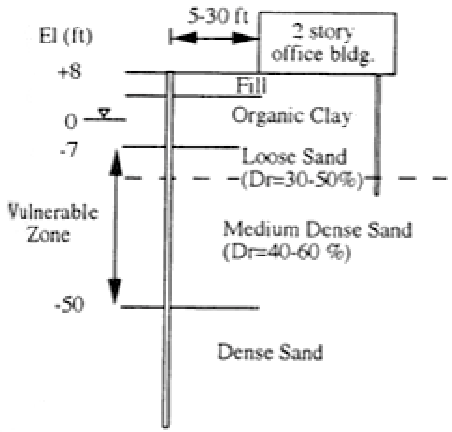
\# Deviatoric stress (factor #2) = $\bar{\sigma}_v - \bar{\sigma}_m$

FIG. 5. Case History at Embarecadero Area (E2 Site) (after Clough and Chameau 1980)

At distances of 10, 20, and 30 feet from the sheetpile, peak particle velocities and measured settlements were obtained from the case history. In order to predict a settlement using a proposed model, the natural values and coded values were determined (Fig. 5). Because vibration induced settlement is affected by various factors a vulnerable layer should be divided into several sublayers considering each factor's contribution for a rigorous analysis. Sensitivity analysis is being performed to investigate the controlling factors in typical circumstances. For this study, however, a simple extrapolation scheme to in-situ conditions was adopted using a single soil layer. The in-situ stress conditions (factors 2 and 3) were estimated at the center of the settlement's most vulnerable layer (loose sand). A deviatoric stress (factor 2) was determined by subtracting σ_m from a vertical effective stress. A mean effective stress (σ_m)was determined as factor 3 (confining pressure) by assuming an earth pressure coefficient at rest (K_o) as 0.5. The sand was considered to be a loose twist sand (factors 6 & 7) with a grain size distribution of 1:1 mixture (factor 4). The number of cycles was presumed to be exceeding 540,000 cycles (factor 5). The calculated settlement at a vibration amplitude of 0.5 in./s (1.27 cm/s) was 0.058 inches (0.15 cm) for a 6 inch (15.2 cm) high laboratory specimen. If direct extrapolation to the in-situ condition is assumed to be feasible, approximately 2.3 in. (5.8 cm) of settlement would occur in the 20 foot (6.1 m) layer of loose sand. The recorded settlement was 2 in. (5.1 cm). The calculated settlements were also compared with measured settlements at vibration amplitudes of 0.1 and 0.2 in. /s (0.25 and 0.51 cm/s). The calculated settlements matched closely with the measured settlements (Fig. 5).

West Brooklyn Area

H-piles were driven by a Vulcan 08 hammer for a roadway ramp construction at West Brooklyn, New York City (Case C in Lacy and Gould, 1985). After driving about 40 piles, an adjacent building experienced 2.4 inches (6.1 cm) of accumulated settlement. The building was founded on wooden piles penetrating through organic soils, loose, fine sands and a short distance into a medium dense sand (Fig. 6).



Vib. Amp. (in/sec)	Meas. Sett. (in)	Cal. Sett. (in)
0.1[a]	2.4	0.2
0.6[b]	2.4	2.2

Factor	Natural Value	Coded Value
1	0.1 in/sec	-1
2[#]	6 psi	-0.38
3[**]	12 psi	-0.8
4	Fine.	1
5	9000 sec	1
6	Moist	2
7	Loose	-1

and ** same as Fig. 3
(a) measured inside the adjacent building.
(b) assumed in the vulnerable zone considering 20 ft distance from pile tip.

FIG. 6. Case History at West Brooklyn (Case C) (after Lacy and Gould 1985)

The natural and coded values of each factor were determined in the same manner as the previous case history and are tabulated in Fig. 6. In-situ stress conditions were calculated at the center of a 45 ft (13.7 m) deep, loose to medium-dense sand layer. With a vibration amplitude of 0.1 in/s monitored on the building, the calculated settlement was 0.2 inch (0.51 cm) which is 10 times less than the measured settlement. However, vibrations from pile driving are propagated from the pile tip in the ground, directly through the vulnerable soil. Even though the monitored vibration amplitude on the building is small, the amplitude inside the vulnerable layer is substantially higher. With the vibration amplitude of 0.6 in./s (1.52 cm/s) roughly estimated from the Vulcan 08 impact hammer at a distance of 15 ft (4.6 m), the calculated settlement is 2.2 inches (5.6 cm) which is close to the one measured. This means that vibration amplitude should be monitored not only at the ground surface but also within the ground. This takes into consideration the vibration path, thus allowing for proper settlement assessment.

SUMMARY

The current literature, provides many examples where conventional limits on vibrations failed to adequately protect structures and utilities in the vicinity of man-made vibrations. It is believed that damage was not caused by direct transmission of vibration, but rather through subsequent settlement caused by soil densification. Given these cases, it was proposed that the current criteria, based solely on peak particle velocity was inadequate to predict settlement in granular soils. In order to establish a more reliable model to predict vibration induced settlement at low to medium levels [0.1-0.7 in./s (0.25-1.78 cm/s)], a battery of tests was run using seven settlement inducing parameters. These included vibration amplitude, deviatoric stress, confining pressure, soil gradation, duration of vibration, relative density, and moisture content. A special vibratory frame was designed to shake a soil sample within a triaxial cell. A multi-factorial experimental design method was used to establish the testing program. This statistical approach allowed the testing of numerous variables using relatively few experiments. The calculated settlements from the model closely matched those measured from case histories. This study demonstrates the potential usefulness of this mathematical model for the evaluation and prediction of the vibration induced, in-situ settlement of sands.

APPENDIX - REFERENCES

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