SOIL-STRUCTURE INTERACTION
VOL. 2 INFLUENCE OF LIFT-OFF

C.A. Miller

DEPARTMENT OF NUCLEAR ENERGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, LONG ISLAND, NEW YORK 11973

THE CITY UNIVERSITY OF NEW YORK
UNDER CONTRACT TO THE
STRUCTURAL ANALYSIS DIVISION
CONTRACT NO. 586956-S

Date Published — April 1986

Prepared for
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
Under Contract No. DE-AC02-76CH00016
ABSTRACT

This study has been performed for the Nuclear Regulatory Commission (NRC) by the Structural Analysis Division of Brookhaven National Laboratory (BNL). The study was conducted during the fiscal year 1985 on the program entitled “Benchmarking of Structural Engineering Problems” sponsored by NRC. The program considered three separate but complementary problems, each associated with the soil-structure interaction (SSI) phase of the seismic response analysis of nuclear plant facilities. The reports are presented in three separate volumes. The general title for the reports is “Soil Structure Interaction” with the following subtitles:

Vol. 1 “Influence of Layering”,
   by A.J. Philippacopoulos

Vol. 2 “Influence of Lift-Off”,
   by C.A. Miller

Vol. 3 “Influence of Ground Water”,
   by C.J. Costantino

The two problems presented in Volumes 2 and 3 were conducted at the City University of New York (CUNY) under subcontract to BNL.

This report, Volume 2 of the report, presents a summary of the work performed defining the influence lift-off has on the seismic response of nuclear power plant structures. The standard lumped parameter analysis method was modified by representing the lumped soil/structure interaction horizontal and rocking dampers with distributed (over the foundation area) springs and dampers. The distributed springs and dampers are then modified so that they can only transmit compressive stresses. Additional interaction damping is included to account for the energy dissipated as a portion of the foundation which has separated comes back into contact with the soil.
The validity of the model is evaluated by comparing predictions made with it to data measured during the SIMQUAKE II experiment. The predictions were found to correlate quite well with the measured data except for some discrepancies at the higher frequencies (greater than 10 cps). This discrepancy was attributed to the relatively crude model used for impact effects.

Data is presented which identifies the peak acceleration required to cause liftoff. For parameters typical of nuclear power plant structures liftoff was found to occur when the peak accelerations are in the range of 0.3 to 0.6 G's. Studies were then performed to evaluate the consequences of neglecting liftoff when it occurs. Significant spectral differences were found for the rocking and vertical motions between the analyses performed considering and neglecting liftoff effects. It was found that peak accelerations 1.33 that required to cause liftoff (0.4 to 0.8 G's) result in unconservative response spectra when the liftoff effects are neglected in the SSI analysis.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>viii</td>
</tr>
<tr>
<td>EXECUTIVE SUMMARY</td>
<td>ix</td>
</tr>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.0 ANALYSIS OF LIFTOFF</td>
<td>3</td>
</tr>
<tr>
<td>2.1 Equations of Motion</td>
<td>3</td>
</tr>
<tr>
<td>2.2 Soil/Structure Interaction Forces</td>
<td>4</td>
</tr>
<tr>
<td>2.2.1 Base Interaction</td>
<td>4</td>
</tr>
<tr>
<td>2.2.2 Sidewall Interaction</td>
<td>7</td>
</tr>
<tr>
<td>2.2.3 Impact Effects</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Computer Simulation</td>
<td>9</td>
</tr>
<tr>
<td>3.0 COMPARISON OF LIFTOFF MODEL WITH DATA</td>
<td>15</td>
</tr>
<tr>
<td>3.1 Description of SIMQUAKE Test</td>
<td>15</td>
</tr>
<tr>
<td>3.2 Comparison of Predicted and Measured Responses</td>
<td>16</td>
</tr>
<tr>
<td>4.0 EFFECTS OF LIFTOFF</td>
<td>31</td>
</tr>
<tr>
<td>4.1 Non-Dimensional Parameters</td>
<td>31</td>
</tr>
<tr>
<td>4.2 Peak Acceleration Required to Cause Liftoff</td>
<td>32</td>
</tr>
<tr>
<td>4.3 Effect of Neglecting Liftoff</td>
<td>33</td>
</tr>
<tr>
<td>5.0 CONCLUSIONS</td>
<td>45</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>48</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

2.1 Geometry of Model ........................................................................................................... 11
2.2 Base Interaction Model ....................................................................................................... 12
2.3 Sidewall Interaction Model .............................................................................................. 13
2.4 Impact Model .................................................................................................................. 14
3.1 Plan of SIMQUAKE II Experiment .................................................................................. 20
3.2 Section Through Structure S 01 .................................................................................... 21
3.3 Effect of Impact Parameter on Horizontal Base Spectra (α=0) .................................... 22
3.4 Effect of Impact Parameter on Horizontal Top Spectra (α=0) ....................................... 23
3.5 Effect of Impact Parameter on Vertical Spectra (α=0) .................................................. 24
3.6 Effect of Impact Parameter on Horizontal Base Spectra (α=1) .................................... 25
3.7 Effect of Impact Parameter on Horizontal Top Spectra (α=1) ....................................... 26
3.8 Effect of Impact Parameter on Vertical Spectra (α=1) .................................................. 27
3.9 Effect of Neglecting Liftoff on Horizontal Base Spectra ............................................. 28
3.10 Effect of Neglecting Liftoff on Horizontal Top Spectra .............................................. 29
3.11 Effect of Neglecting Liftoff on Vertical Spectra ......................................................... 30
4.1 Peak Accel. Required to Cause Liftoff (ζ=0.5; ε=1.0; ψ=0.0) ..................................... 36
4.2 Peak Accel. Required to Cause Liftoff (ζ=0.5; ε=1.0; ψ=1.0) ..................................... 36
4.3 Peak Accel. Required to Cause Liftoff (ζ=0.5; ε=5.0; ψ=0.0) ..................................... 37
LIST OF FIGURES (Continued)

4.4 Peak Accel. Required to Cause Liftoff ($\zeta=0.5; \varepsilon=5.0; \psi=1.0$) .... 37
4.5 Peak Accel. Required to Cause Liftoff ($\zeta=0.5; \varepsilon=10.0; \psi=0.0$) .... 38
4.6 Peak Accel. Required to Cause Liftoff ($\zeta=0.5; \varepsilon=10.0; \psi=1.0$) .... 38
4.7 Peak Accel. Required to Cause Liftoff ($\zeta=1.0; \varepsilon=1.0; \psi=0.0$) .... 39
4.8 Peak Accel. Required to Cause Liftoff ($\zeta=1.0; \varepsilon=5.0; \psi=0.0$) .... 39
4.9 Peak Accel. Required to Cause Liftoff ($\zeta=1.0; \varepsilon=10.0; \psi=0.0$) .... 40
4.10 Peak Accel. Required to Cause Liftoff ($\zeta=1.0; \varepsilon=11.0; \psi=0.0$) .... 40
4.11 Peak Accel. Required to Cause Liftoff ($\zeta=1.5; \varepsilon=10.0; \psi=0.0$) .... 41
4.12 Ratio Horizontal Liftoff/No Liftoff Spectra ........................................ 42
4.13 Ratio Rotational Liftoff/No Liftoff Spectra ......................................... 43
4.14 Ratio Vertical Liftoff/No Liftoff Spectra ......................................... 44
ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Mr. Herman Graves for his advice and support during this program. Mr. Graves, of the Mechanical Structural Engineering Branch of the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, served as technical monitor of this study. In addition, the author wishes to thank Dr. James Costello of the same office for his interest in the project and for information provided during the course of the study.
EXECUTIVE SUMMARY

This study has been performed for the Nuclear Regulatory Commission (NRC) by the Structural Analysis Division of Brookhaven National Laboratory (BNL). The study was conducted during the fiscal year 1985 on the program entitled "Benchmarking of Structural Engineering Problems" sponsored by NRC. The program considered three separate but complementary problems, of interest to the soil-structure interaction (SSI) phase of the seismic response analysis of nuclear plant facilities. The reports are presented in three separate volumes. The general title for the reports is "Soil Structure Interaction" with the following subtitles:

Vol. 1  "Influence of Layering",
       by A.J. Philippacopoulos

Vol. 2  "Influence of Lift-Off",
       by C.A. Miller

Vol. 3  "Influence of Ground Water",
       by C.J. Costantino

The two studies presented in Volumes 2 and 3 were conducted at the City University of New York (CUNY) under subcontract to BNL.

In the first volume, "Layering Effects in Soil-Structure Interaction", approximate analytic formulations were developed to obtain frequency dependent interaction coefficients applicable to the case of a rigid circular disk at the surface of an elastic, layered halfspace. With these approximations, SSI calculations can be made in a direct manner, eliminating the need to perform complicated and expensive interaction calculations by means of finite element or CLASSI-type computer programs. Such simplifications are particularly important when performing preliminary designs of nuclear facilities or when attempting to check the adequacy of the output of computer codes. The method developed was applied to both rigid and flexible structural models of actual plant facilities. Both harmonic and transient responses were computed using the approximate and exact interaction coefficients. Both amplification functions and floor response spectra showed good correlation.

In the second volume, "Influence of Lift-Off on Soil-Structure Interaction", a study was performed to evaluate the extent to which foundation separation may be important in the SSI evaluation. The standard lumped
parameter analysis method was modified by representing the typical lumped
soil/structure interaction springs and dampers with equivalent models
distributed over the area of the structural foundation. These springs and
dampers were modified to allow for transmission of compressive stress only
into the soil foundation. In addition to the normal radiation damping associated
with the SSI problem, it was determined that a second damping factor had to be
introduced into the problem to account for the impact which occurs when a
portion of the foundation, which had previously separated, comes back into
contact with the soil. The validity of the model was evaluated by comparing
predictions with data measured during the SIMQUAKE II experiment. The
predictions were found to correlate well with the measured data except for
some discrepancies at the higher frequency range ( > 10 cps). This discrepancy
is attributed to the crude model used to simulate impact effects. Studies were
performed to evaluate the effects of liftoff on facility response. It was found
that response spectra including liftoff effects were significantly higher than
those neglecting liftoff when the ground input acceleration is large enough to
cause liftoff.

The third volume report, "Influence of Ground Water on Soil-Structure
Interaction", presents a summary of the first year's effort on the subject of
the influence of foundation ground water on the SSI phenomenon. A finite
element computer program was developed for the two-phased formulation of
the combined soil-water problem. This formulation is based on the Biot
dynamic equations of motion for both the solid and fluid phases of a typical
soil. Frequency dependent interaction coefficients were generated for the
two-dimensional plane problem of a rigid surface footing moving against a
saturated linear soil. The results indicate that interaction coefficients are
significantly modified as compared to the comparable values for a dry soil,
particularly for the rocking mode of response. Calculations were made to study
the impact of the modified interaction coefficients on the response of a typical
nuclear reactor building. The amplification factors for a stick model placed
atop a dry and saturated soil were computed. It was found that pore water
caued the rocking response to decrease and translational response to increase
over the frequency range of interest, as compared to the response on dry soil.
1.0 INTRODUCTION

This report summarizes the work performed at the City University of New York (CUNY), under subcontract to Brookhaven National Laboratory (BNL), dealing with the effect of foundation/soil separation on the seismic response of the structure. The work was sponsored by the Nuclear Regulatory Commission (NRC) on the "Benchmarking of Structural Engineering Problems" program. This work was performed during fiscal year 1985.

The previous work on this contract (Ref. 5) attempted to correlate predictions made using standard soil/structure interaction (SSI) methods with measured data. The SIMQUAKE II data was one of the sources used for the correlations. Significant liftoff (separation of foundation and soil) occurred during this experiment. Predictions made using the standard SSI methods did not correlate well with the measured motion of the SIMQUAKE structures. The lack of correlation was attributed to liftoff effects which are not included in the standard SSI methods. The objectives of the work discussed in this report are to modify the standard lumped parameter SSI method to include liftoff effects, and to use this model to assess the significance of liftoff effects in predicting the seismic response of nuclear power plant structures.

Examples of actual earthquakes during which liftoff occurred are cited in Ref. 6. Details of the liftoff effects which were measured during the SIMQUAKE experiments are discussed in Refs. 1-4 and 7. These works indicate that liftoff can occur during moderate magnitude earthquakes and that the effects of liftoff are significant when it occurs. Analysis of liftoff effects have been performed (Refs. 8, 9, and 11) using a moment interaction spring which softens as the foundation rotates and separation occurs. The moment interaction used in Ref. 10 is modeled with two vertical springs, one placed at each extremity of the foundation. The springs are allowed to separate from the foundation as liftoff occurs. The current study replaces the vertical and moment interaction coefficients with equivalent foundation moduli (i.e. a distributed spring-damper system linking the foundation to the soil). The distributed system is linear in compression but is not permitted to transmit tensile pressures between the foundation and soil. A mechanism for dissipating additional energy, resulting from impact of the foundation and soil when a separated portion of the foundation comes back into contact with the soil, is incorporated in the model.
The model used to include liftoff effects in the standard lumped parameter SSI formulation is discussed in Section 2 of the report. Results predicted with this model are correlated with the SIMQUAKE data in Section 3.0, and the effects of liftoff on typical nuclear power plant structures are discussed in Section 4.0. The report is summarized in Section 5.0.
2.0 ANALYSIS OF LIFTOFF

The fundamental equations describing the liftoff process are described in this section of the report. The equations of motion are developed for a rigid structural model. Parameters describing the soil/structure interaction process are developed as an extension of the standard parameters used for the lumped parameter SSI analysis. These parameters are put into a form such that liftoff effects may be included. Finally, the implementation of this analysis for a computer solution is discussed.

2.1 Equations of Motion

The equations of motion describing the seismic response of a rigid structure to both vertical and horizontal (in one direction) seismic input motions are developed in this section of the report. The soil/structure interface is modeled so that net tensile pressures at the interface are not allowed (i.e., liftoff can occur). The liftoff interaction model used for this study can be included in a lumped parameter analysis of flexible structures. The rigid body model is used for this study so that attention may be focused on the effects of liftoff. Liftoff will have a similar effect on the predicted response of flexible structures as it has on the rigid models considered in this study.

The equations of motion are developed for the structure shown on Figure 2.1. The structure has a mass (M) and a rotary mass moment of inertia about its center of gravity (J). The center of gravity is located a distance ($Z_0$) above the base. The deformation of the structure is measured in terms of the horizontal displacement of the base ($u$), the vertical displacement of the base ($w$), and the rotation of the structure ($\theta$). The positive sense of these deformations are shown on Figure 2.1. The base interaction forces ($H, V, T$) are the horizontal, vertical, and moment about the base respectively. These are discussed in Section 2.2. The equations of motion are found to be by sum of horizontal forces, sum of vertical forces, and sum of moments about the center of gravity:

$$M \ddot{u} + M Z_0 \ddot{\theta} + H = 0 \quad (1)$$
\[ M \ddot{w} - V + Mg = 0 \quad (2) \]
\[ J \dot{\theta} - HZ_0 + T = 0 \quad (3) \]
where, \( g \) = gravitational constant
\( (\cdot) = \) acceleration

This system of equations is subject to the initial conditions that all displacements and velocities are zero except that the vertical deformation is equal to the deformation due to the weight of the structure \( w(0) = -Mg / K_v \) where \( K_v \) is the vertical interaction coefficient.

2.2 Soil/Structure Interaction Forces

Equations representing the soil/structure interaction forces \( (H, V, \text{ and } T) \) shown on Figure 2.1 are developed in this section of the report. Consideration is given to: interaction on the base interface, interaction on the sidewall, and impact effects which may occur when the structure and soil come back into contact after separation has occurred.

2.2.1 Base Interaction

The interaction forces at the base are developed from the standard parameters used for lumped parameter analyses (Ref. 1). The standard analyses relate the forces to relative deformations and velocities between the structure and the free field as,

\[ H_b = K_h (u - \dot{X}) + C_h (\ddot{u} - \ddot{X}) \quad (4) \]
\[ V_b = K_v (Y - w) + C_v (\dot{Y} - \dot{w}) \quad (5) \]
\[ T_b = K_t \dot{\theta} + C_t \ddot{\theta} \quad (6) \]
Kh = 28.8 \frac{G R (1-\nu)}{(7-8\nu)} \quad (7)

K_v = 4 \frac{G R}{(1-\nu)} \quad (8)

K_t = 2.13 \frac{G R^3}{(1-\nu)} \quad (9)

C_h = 18.24 \frac{R^2 \rho_c (1-\nu) }{(7-8\nu)} \quad (10)

C_v = 3.4 \frac{R^2 \rho_c}{(1-\nu)} \quad (11)

C_t = 0.4 \frac{R^4 \rho_c}{(1-\nu)} \quad (12)

where,

X, Y = horizontal and vertical free field motion
R = radius of foundation
G = shear modulus of foundation material
\nu = poisson's ratio of foundation material
\rho_c = \sqrt{\frac{G}{Y}}
D = mass density of foundation material

The horizontal spring and damper may be used directly in the liftoff analysis. The vertical and rotational concentrated springs and dampers are converted to distributed springs and dampers so that liftoff effects may be included. The distributed spring and damper parameters are taken to be nonlinear. The constants for the distributed springs and dampers are taken to give values which are compatible with those shown above when the springs are in compression (i.e., no liftoff) but the constants are set equal to zero whenever a separation occurs. The model used to evaluate the distributed parameters is shown on Figure 2.2. The values of the foundation moduli may be derived from either the rotational parameters or from the vertical parameters. If the vertical parameters are used then,

\[ k_v = K_v / \pi R^2 \quad (13) \]

If the rotational parameters are used,

\[ k_t = 4 K_t / \pi R^4 \quad (14) \]
Eqs. (13) and (14) may be written with \( c \) and \( C \) replacing the \( k \) and \( K \).

Of course a single value of \( k \) and \( c \) must be used. If the above parameters are placed in Eqs. (13) and (14),

\[
k_V = \frac{4G}{\pi R (1-\nu)} \quad (15)
\]

\[
k_t = 8.52 \frac{G}{\pi R (1-\nu)} \quad (16)
\]

\[
c_V = 3.4 \frac{pc}{\pi (1-\nu)} \quad (17)
\]

\[
c_t = 1.6 \frac{pc}{\pi (1-\nu)} \quad (18)
\]

Since there is a difference between the distributed interaction parameters depending on whether the vertical or rotational constants are used, the parameters are selected as somewhere between. Therefore,

\[
k = k_V + \alpha (k_t - k_V) \quad (19)
\]

\[
c = c_V + \alpha (c_t - c_V) \quad (20)
\]

The value \( \alpha \) then is an input value to the solution.

The interaction forces due to the base interaction is therefore,

\[
H_b = K_h (u-X) + C_h (u-X) \quad (21)
\]

\[
V_b = \int \left( k \delta + c \delta \right) dA \quad (22)
\]

\[
T_b = \int \left( k \delta + c \delta \right) x dA \quad (23)
\]

where,
\[ A^* = \text{area of foundation in contact with soil} \]
\[ \delta = Y - w + \theta x \]

2.2.2 Sidewall Interaction

Sidewall interaction forces are developed from the standard lumped parameter analysis used in Ref. 1. A typical horizontal slice taken through the cylindrical wall is shown on Figure 2.3. The sidewall interaction forces are computed from interaction pressures (\( \sigma \)) acting normal to the wall with the pressures given as,

\[ \sigma = k \Delta w + s \Delta w \quad (24) \]

where, \( k = \frac{E_c}{2R} \)

\( s = \rho c \)

\( w = \text{relative normal displacement structure to free field} \)

\( E_c = \text{confined modulus of soil} \)

\( \rho = \text{mass density of soil} \)

\( c = \text{dilatational wave speed} \)

The relative normal displacement (\( w \)) may be written in terms of the displacements defined in Figure 2.1 as,

\[ w = u + q \theta - X \quad (25) \]

Note that one half of the cylindrical wall will be separated from the free field while the other half will be in contact. The horizontal (\( H_s \)) and moment (\( T_s \)) interaction forces may be evaluated by integrating Eq. (25) over one half of the surface. The resulting forces are,

\[ H_s = \pi R/2 \left( k(uq_0 + \theta q_0^2/2 - Xq_0) + s(uq_0 + \theta q_0^2/2 - Xq_0) \right) \quad (26) \]

\[ T_s = \pi R/2 \left( k(uq_0^2/2 + \theta q_0^3/3 - Xq_0^2/2) + \right) \]
2.2.3 Impact Effects

The implementation of the above interaction model will reduce the forces since they are based on the area of the foundation which is in contact with the soil. Details of this are discussed in the next section of the report. The net effect of this approach is to reduce the stiffness of the foundation, and therefore the frequency of the combined soil/structure system. This is consistent with the observed phenomena. The damping of the system decreases, however, since it is proportional to a given coefficient times the foundation area in contact with the soil. One would expect to observe larger damping effects when liftoff occurs because of the energy dissipation which must occur when the foundation comes back into contact with the soil after it has separated. A simple model is considered so that the significance of this effect may be evaluated.

Consider the problem shown in Figure 2.4. A mass (M) travelling at a velocity \( V_0 \) impacts a one dimensional elastic rod of length \( r \). The problem considered is to evaluate the velocity of the mass after impact. This may be compared with a section of the foundation impacting on the soil after it has separated. The velocity change of the mass during impact reflects a loss in kinetic energy which may be related to a damping phenomena.

The classical one dimensional wave solution is used together with standard boundary conditions. The initial conditions are taken so that the rod displacements are zero and momentum is conserved so that,

\[
M V_0 = M u(0,0) + \int_0^r \rho u(x,0) \, dx 
\]

(28)

The velocity of the mass after impact \( u(0,0) \) is found to be,

\[
u(0,0) = V_0 \cos \left( \frac{\omega r}{c} \right)
\]

(29)
where \( \omega \) is obtained as the solution of,

\[
\tan \left( \frac{\omega r}{c} \right) = \frac{\rho c}{M \omega}
\] (30)

This effect is implemented in the solution by applying a force \( F_1 \) to the foundation of one integration time step \( \Delta t \) so that the impulse of the force equals the momentum change,

\[
F_1 = \Delta t M V_0 \left( 1 - \cos \left( \frac{\omega r}{c} \right) \right)
\] (31)

Of course this approach does not account for the combined rocking-translational motion of the foundation. At best it may be used to give some indication of the significance of the effect. If it proves to be significant, then a more detailed analysis should be considered.

2.3 Computer Solution

The above analysis is programmed for computer solution by modifying the SIM Code (Ref.1). This computer code is available at BNL and is based on the standard lumped parameter SSI analysis with no consideration given to liftoff effects. SIM Code treats flexible structures so that the modified code is restricted to consider only rigid structures. The equations of motion are integrated in time using a fourth order Runge-Kutta scheme.

The base interaction forces are calculated from Eqs. (21) through (23). The integrals in Eqs. (22) and (23) are evaluated by dividing the base area into strips and including the area if the foundation and soil are in contact. The total bearing pressure (interaction plus dead weight) is first calculated and the segment said to be in contact if this pressure is compressive. The impact model, discussed above, is implemented for those segments which were in contact for the last time step but are not now in contact. The impact forces are added to the interaction forces for the next time step. The mass of the segment (needed to evaluate the impact force) is taken to be that part of the total mass in proportion to the relative area of the segment. Sidewall interaction forces are calculated directly from Eqs. (26) and (27).
Output from the code consists of time histories and response spectra. The spectra routines are modified so that spectra for the three deformations (horizontal base, vertical, and rotation) are computed.
Fig. 2.1 GEOMETRY OF MODEL
Fig. 2.2 BASE INTERACTION MODEL
Fig. 2.3 SIDEWALL INTERACTION MODEL
Fig 2.4 IMPACT MODEL
3.0 COMPARISON OF LIFTOFF MODEL WITH DATA

An extensive series of tests were performed on model reactor containment structures during the SIMQUAKE experiments (Refs. 2-4). The magnitude of the seismic input was of sufficient magnitude so that liftoff occurred. The experiments are first described followed by a discussion of the results of a study comparing predictions made using the liftoff model described in the previous section with the measured data.

3.1 Description of SIMQUAKE TEST

The SIMQUAKE II experiment was conducted on June 2, 1977 at the University of New Mexico's McCormick Ranch test site south of Alberquerque, New Mexico. The test was conducted by the Civil Engineering Research Facility of the University for the Electric Power Research Institute (EPRI). A summary report of the experiment is given in Ref. 2, while a more complete description is contained in the eight volume report of Ref. 4. The data used in this study is taken from Ref. 4 and from a magnetic tape containing all of the recorded free field and in-structure measurements. This tape was obtained from EPRI through Applied Research Associates (Alberquerque, New Mexico).

Figure 3.1 shows a plan of the test site. As may be seen the loading was induced with two plane, high explosive arrays each covering a vertical plane about 200 feet wide and 75 feet deep. The top of the arrays were located about 25 feet below the surface, and were separated from each other by 100 feet. The back array was detonated first with the front array detonated about 1.2 seconds later. The resulting free field motion consisted of two principal acceleration peaks with the first peak having a magnitude of 4 to 5 G's in the vicinity of the test structures.

The top 26 feet of the soil at the test site consists of alternating layers of fine silts, clay, and caliche. Dry cohesionless sand extends from this depth to an unknown depth. The ground water table is below 300 feet. Wave speed characteristics were determined from refraction surveys and uphole-crosshole measurements and indicate shear wave velocities of 804 fps for 0-6 feet depth; 951 fps for 6-25 feet depth; and 1100 fps for depths greater than 25 feet.
The structures were scale models of reactor containment buildings. Structure S 01 was used for this study and its dimensions are shown on Figure 3.2. It is a 1/8 scale model and was located at 200 feet from the front array. At this range the peak free field acceleration was 5 g's. A detailed analysis of the dynamic characteristics of S 01 is given in Ref. 5. The structure may be shown to be rigid so that the only significant flexibilities are associated with the SSI process. It has a weight of 253.31 kips and the following interaction properties:

- Horizontal Frequency = 25.5 cps
- Rocking Frequency = 10.6 cps
- Vertical Frequency = 20.9 cps
- Horizontal Damping = 37.5 %
- Rocking Damping = 6.8 %
- Vertical Damping = 44.1 %

There were extensive free field and in-structure measurements taken during the experiments. Vertical and horizontal free field accelerograms were obtained immediately below the level of the structure. These are used as input to the liftoff model. It should be noted that there was relatively little variation of the free field pulse as one moves away from the structure. Horizontal structural acceleration measurements were obtained at the top and bottom of the structure. These are used to evaluate the rigid body horizontal and rotational components of the structures response. Vertical basement measured accelerations are used to obtain the vertical response of the structure.

3.2 Comparison of Predicted and Measured Responses

The motivation for this study came from the results presented in Ref. 5. The standard lumped parameter SSI model was applied to the SIMQUAKE II data, and was found to give poor results. The predicted rocking motion of the test structures was found to contain much higher frequency content and more total energy than the measured rocking motion. The calculated vertical motion was also found to have a higher frequency content than the measured spectra. However, the calculated motion was found to have significantly less energy at all frequencies than the measured vertical motion. The predicted horizontal motion was found to be in reasonable agreement with the measured motion.
except for somewhat higher energy content of the calculated motion at the higher frequencies.

Comparisons are made using the liftoff model described in Section 2 to evaluate the extent to which the inclusion of liftoff effects may improve these correlations. All of the comparisons are done in terms of three response spectra: horizontal base motion; top of structure horizontal motion (which includes the rocking effect); and vertical motion. Two percent of critical equipment damping is used for all response spectra. The measured vertical and horizontal motions near the foundation are used as input to the model. A preliminary analysis indicates that the SIMQUAKE structure S01 would undergo liftoff for peak free field accelerations of about 0.4 G's. The actual input to the structure is about 12 times this value indicating that liftoff effects should have been severe. This is in agreement with the observed large permanent rocking deformations of the structures. It should also be noted that such extreme liftoff effects would not be expected in real nuclear power plant structures.

The liftoff model described in Section 2 contains two parameters that are not directly related to physical properties of the problem. The first parameter (\( \alpha \); see Eqs. 19-20) determines whether the foundation modulus is determined from the standard vertical or rotational interaction coefficients. The second parameter is related to the amount of energy dissipation that is associated with impact effects as portions of the foundation which have been separated come back into contact with the soil. This effect is represented as the fraction of the relative velocity between the foundation and soil that is dissipated at impact (see Eq. 31). The effect of this second parameter is studied by obtaining solutions for no dissipation of the relative velocity and for 90% dissipation of the relative velocity. The results of these analyses are shown on the floor response spectra of Figures 3.3 through 3.5. The curves marked with circled points represent no energy dissipation resulting from impact while the triangle marked curves represent the 90% dissipation results. The crossed marked curves represent spectra derived from the measured in-structure motions. The parameter (\( \alpha \)) is taken as zero for these analysis indicating that the foundation modulus is derived from the vertical interaction coefficients.

There is little difference for the horizontal base spectra (Figure 3.3) between the two solutions. Liftoff has little effect on the horizontal
component of the motion so the details of the liftoff model do not change the predicted values. As may be seen the predicted spectra are higher than the measured spectra. The comparisons for the top horizontal spectra are shown on Figure 3.4. The 90 % impact dissipation gives significantly better results than the 0 % model at the high frequency end of the spectra. Once again the liftoff predictions are fairly good except at the higher frequencies where the predictions are too high. The inclusion of impact energy dissipation improves the prediction. Perhaps a more realistic impact model should be developed. It should be noted that the peaks in the measured top horizontal spectra are in the range of 10 G's while the base horizontal spectra has peaks of about 4 G's. This indicates that rocking motion is significant for the SIMQUAKE experiment. The comparison of the vertical motion spectra is shown on Figure 3.5. The 90 % impact model is in reasonable agreement with the spectra of the measured data. There is a large improvement between the 0 % and 90 % impact models again demonstrating the importance of the energy dissipated during impact.

The same solutions are obtained for the case where the foundation modulus is evaluated from the rocking interaction coefficients (α=1). The spectra obtained from these solutions are shown on Figures 3.6 through 3.8. As may be seen the impact model has the same influence on these results as it did on the case when the foundation modulus is derived from the vertical interaction coefficients. A comparison of the two sets of results indicate better correlation of the calculated and measured spectra when the (α=0) results are used. The top horizontal motion spectra show a larger overshoot relative to the measured spectra at the high frequency end when the (α=1) solution is used (see Figures 3.4 and 3.7). The comparison between the vertical spectra (Figures 3.5 and 3.8) show a very significant difference between the two solutions with the solution based on (α=0) being far better than the other solution. All of the subsequent work is based on the 90% impact factor and the (α=0) parameter.

Comparisons of the solutions including liftoff and not including liftoff effects are shown on Figures 3.9 through 3.11. The spectra marked with the circled points are developed from the motions calculated with the liftoff model using 90 % impact dissipation and (α=0). The spectra marked with the triangles are developed from motion calculated when liftoff effects are neglected, while the spectra marked with crosses are developed from the measured motions. As is expected there is little difference in the base
horizontal spectra (Figure 3.9) between that calculated with liftoff or that calculated without consideration of liftoff. Both agree reasonably well with the measured spectra except for the higher predicted accelerations at the higher frequencies. The comparison for the top horizontal spectra is shown on Figure 3.10. The liftoff model gives reasonable agreement with spectra from the measured data at the low frequency end of the spectra and predicts larger than measured accelerations at the high frequency end. Except at the high frequency end the liftoff model gives better results than does the no liftoff model. It is also important to note that the no liftoff model predicts lower than measured spectral accelerations in the low frequency end of the spectra. This occurs at a range that would be particularly important to the design of equipment and piping systems located in nuclear power plant structures. Figure 3.11 shows the comparisons for the vertical motion spectra. The no liftoff results generally underpredicts the spectral accelerations except at the high frequency end where there is a significant overprediction. The liftoff model does better in all ranges of the spectra and generally gives reasonably good results.

In summary, comparisons of predictions made using the liftoff model agree reasonably well with measured data of the SIMQUAKE experiment. There is a range at the high frequency end where the top horizontal motion predictions are too high. This is probably attributable to the impact model. There is some indication that a more refined impact model should be developed. It is also generally true that predictions made using the liftoff model are significantly better than those made neglecting the effects of liftoff. It is important to observe that liftoff was a very important effect in the SIMQUAKE experiments. It is unlikely that liftoff could have as significant an effect in any real nuclear power plant structure.
Fig. 3.1 PLAN OF SIMQUAKE II EXPERIMENT
Fig. 3.2 SECTION THROUGH STRUCTURE S 01
Fig. 3.3 - Effect of Impact Parameter on Horizontal Base Spectra ($\alpha=0$)
Fig. 3.4 - Effect of Impact Parameter on Horizontal Top Spectra ($\alpha=0$)
Fig. 3.5 - Effect of Impact Parameter on Vertical Spectra ($\alpha=0$)
Fig. 3.6 - Effect of Impact Parameter on Horizontal Base Spectra (α=1)
Fig. 3.7 - Effect of Impact Parameter on Horizontal Top Spectra (α=1)
Fig. 3.8 - Effect of Impact Parameter on Vertical Spectra (α=1)
Fig. 3.9 - Effect of Neglecting Liftoff on Horizontal Base Spectra
Fig. 3.10 - Effect of Neglecting Liftoff on Horizontal Top Spectra
Fig. 3.11 - Effect of Neglecting Liftoff on Vertical Spectra
4.0 EFFECTS OF LIFTOFF

The effects of liftoff on the response of nuclear power plant structures are discussed in this section of the report. The effects are interpreted in terms of floor response spectra with two percent equipment damping used for all cases in calculating the floor response spectra. The El Centro N-S and vertical time histories are used as input to the liftoff models. Non-dimensional parameters are first defined so that the results may be presented in a concise manner. The peak free field accelerations required to cause liftoff to occur are then calculated, and finally the effect, on floor response spectra, of neglecting liftoff effects when they are present is calculated.

4.1 Non-Dimensional Parameters

The equations of motion, developed in Section 2, are made non-dimensional for all dimensions except time. The following parameters are used to define the physical system:

\[ \gamma = \frac{G R}{M} \]
\[ \delta = \frac{G R^3}{J} \]
\[ \varepsilon = \sqrt{\gamma G R^2 / M} \]
\[ \zeta = \frac{Z_0}{R} \]
\[ \psi = \frac{q_0}{Z_0} \]

All of the variables are as defined in Section 2 of this report. The interaction frequencies are related to these parameters as follows:

\[ f_V = \left( \frac{4 \gamma}{1 - \nu} \right)^{1/2} / 2 \pi \]
\[ f_R = \frac{K_R}{2 \pi} \]
\[ f_H = \frac{K_H}{2 \pi} \]
where, \( f_V, f_R, f_H \) = vertical, rocking, horizontal frequencies

\[
K_R = [2.13 \delta / (1-\nu) + K \pi \delta \zeta^3 \psi^2 (\psi / 12 - 1/8)]^{1/2}
\]

\[
K_H = [28.8 \psi (1-\nu) / (7-8\nu) + K \pi \psi \zeta / 4]^{1/2}
\]

\[
K = 2 (1-\nu) / (1-2\nu)
\]

The corresponding interaction damping values (expressed as a ratio of critical) are:

\[
C_V = 3.4 \epsilon / (4 \pi f_V)
\]

\[
C_R = (0.4 \epsilon \delta / \gamma + \sqrt{K \pi \epsilon \delta \zeta^3 \psi^2}) (\psi / 6\gamma - 1/4\gamma) / 2 K_R
\]

\[
C_H = (18.24 \epsilon (1-\nu) / (7-8\nu) + \sqrt{K \pi \epsilon \psi \zeta / 2}) / 2 K_H
\]

4.2 Peak Acceleration Required to Cause Liftoff

The peak accelerations required to cause liftoff to occur are calculated in this section of the report. The El Centro horizontal and vertical pulses are used as input with the acceleration values scaled so that liftoff occurs. Results are obtained for realistic variations in the non-dimensional parameters defined in the previous section.

The results are presented in Figures 4.1 through 4.11. The results follow a similar trend for all cases. There is only a slight dependence of the liftoff acceleration on the rocking frequency except when the rocking frequency is less than 3 cps. There is a significant increase in the required accelerogram magnitude for the low rocking frequencies. The liftoff acceleration increases slightly with increasing rocking frequencies for rocking frequencies above 3 cps. The acceleration required to cause liftoff increases as the vertical interaction frequency decreases. Therefore the tendency for liftoff to occur increases with stiffer horizontal interaction frequencies and with softer
vertical interaction frequencies.

The variation in liftoff acceleration with the remaining three parameters $(c, C, q)$ is as would be expected. The acceleration required to cause liftoff decreases as the height of the structure’s center of gravity above the base $(\zeta)$ increases; increases as the interaction damping $(\epsilon)$ increases; and increases as the depth of burial $(\psi)$ increases. These variations are illustrated in Table 4.1.

Table 4.1

"AVERAGE" LIFTOFF ACCELERATIONS

<table>
<thead>
<tr>
<th>CG LOC. (\zeta)</th>
<th>DAMPING (\epsilon)</th>
<th>DEPTH OF BURIAL (\psi)</th>
<th>VERTICAL INTERACTION FREQ</th>
<th>5 CPS</th>
<th>10 CPS</th>
<th>20 CPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
<td>0.24</td>
<td>0.16</td>
<td>0.11</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
<td>0.30</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>0.5</td>
<td>5.0</td>
<td>0.0</td>
<td></td>
<td>0.40</td>
<td>0.28</td>
<td>0.17</td>
</tr>
<tr>
<td>0.5</td>
<td>5.0</td>
<td>1.0</td>
<td></td>
<td>0.57</td>
<td>0.41</td>
<td>0.26</td>
</tr>
<tr>
<td>0.5</td>
<td>10.0</td>
<td>0.0</td>
<td></td>
<td>0.34</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>10.0</td>
<td>1.0</td>
<td></td>
<td>0.51</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>1.0</td>
<td>5.0</td>
<td>0.0</td>
<td></td>
<td>0.13</td>
<td>0.13</td>
<td>0.09</td>
</tr>
<tr>
<td>1.0</td>
<td>10.0</td>
<td>0.0</td>
<td></td>
<td>0.16</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>10.0</td>
<td>1.0</td>
<td></td>
<td>0.49</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>10.0</td>
<td>0.0</td>
<td></td>
<td>0.12</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

* Rocking frequency is taken as 10 cps

As may be seen from the results in Figures 4.1 through 4.11 and this table, liftoff begins to occur when the peak accelerations are rather low (0.1–0.4 G’s).

4.3 Effect of Neglecting Liftoff

Floor response spectra are calculated for a structure subjected to an
accelerogram with peak accelerations greater than that required to cause liftoff. Solutions are found when liftoff is modelled as described in Section 2 and when liftoff effects are neglected (i.e., tensile pressures are allowed to develop at the foundation/soil interface. A comparison of the two response spectra (including and neglecting liftoff) indicate the potential significance of liftoff effects.

The structure which is used has the following properties:

- Rocking frequency = 5 cps ($\delta = 318.88$)
- Vertical frequency = 20 cps ($\gamma = 2770.08$)
- Horizontal frequency = 17.3 cps
- Rocking damping = 1.0 % ($\epsilon = 10.0$)
- Vertical damping = 19.3 %
- Horizontal damping = 12.8 %
- Depth of burial = 0.5 x radius ($\psi = 1.0$)
- Height of CG = 0.5 x radius ($\zeta = 0.5$)

The results on Figure 3.6 indicate that liftoff will occur at a peak acceleration of 0.275 G's. Solutions are obtained for peak accelerations of 1.33 (0.366 G's), 1.67 (0.459 G's), and 2.00 (0.55 G's) times this liftoff acceleration. As indicated above, two solutions are obtained for each input, one including liftoff and one neglecting liftoff. Two percent equipment damping spectra are obtained for the horizontal, rocking, and vertical motions. The spectra obtained including liftoff are divided by the spectra obtained by neglecting liftoff. The results are shown on Figures 4.12 through 4.14. The spectra marked with circles are for the input at 1.33 times the liftoff acceleration; those marked with triangles are for the input at 1.67 times the liftoff acceleration; and those marked with crosses are for input at 2.00 times the liftoff acceleration. There is no difference between the liftoff and no liftoff spectra when the spectral value is unity.

As may be seen on Figure 4.12, liftoff has no effect on the horizontal spectra. This is as expected since the horizontal interaction parameters are not effected by base uplift. The effect of liftoff on the rotational spectra has a significant effect when the input acceleration is larger than 1.33 times the liftoff acceleration. The spectral peaks when liftoff is considered exceed the no liftoff spectra by factors of 1.5 and 3.2 for the inputs of 1.67 and 2.00.
times the liftoff acceleration. The liftoff model results in higher spectral peaks than does the no liftoff model. It should also be noted that the liftoff spectra exceeds the no liftoff spectra over a wide frequency range. This frequency range (1-4 cps) is important for the seismic design of equipment and piping systems. It can therefore be concluded that it is important to consider liftoff for those problems where rocking motion is significant.

The effect of liftoff on the vertical motion is shown on Figure 4.14. It can be seen that liftoff has a significant effect for frequencies higher than 10 cps. It is likely that this effect is due in large part to impact effects as discussed in Section 3. As shown on Figure 3.5 the liftoff model overpredicts the vertical response of the SIMQUAKE tests in this same frequency range. It is likely that these large overshoots in the vertical spectra at the high frequency range is not realistic.
Fig. 4.1 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 0.5$; $\epsilon = 1.0$; $\psi = 0.0$)

Fig. 4.2 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 0.5$; $\epsilon = 1.0$; $\psi = 10$)
Fig. 4.3 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF \( (\zeta = 0.5 \; ; \; \epsilon = 5.0 \; ; \; \psi = 0.0) \)

Fig. 4.4 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF \( (\zeta = 0.5 \; ; \; \epsilon = 5.0 \; ; \; \psi = 1.0) \)
Fig. 4.5 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 0.5$ ; $\varepsilon = 10.0$ ; $\psi = 0.0$)

Fig. 4.6 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 0.5$ ; $\varepsilon = 10.0$ ; $\psi = 1.0$)
Fig. 4.7 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 1.0$; $\epsilon = 1.0$; $\psi = 0.0$)

Fig. 4.8 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 1.0$; $\epsilon = 5.0$; $\psi = 0.0$)
Fig. 4.9 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 1.0$; $\epsilon = 10.0$; $\psi = 0.0$)

Fig. 4.10 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 1.0$; $\epsilon = 10.0$; $\psi = 1.0$)
Fig. 4.11 PEAK ACCEL. REQUIRED TO CAUSE LIFTOFF ($\zeta = 1.5$; $\epsilon = 10.0$; $\psi = 0.0$)
Fig. 4.12 - Ratio Horizontal Liftoff/No Liftoff Spectra
Fig. 4.13 - Ratio Rotational Liftoff/No Liftoff Spectra
Fig. 4.14 - Ratio Vertical Liftoff/No Liftoff Spectra
5.0 CONCLUSIONS

The effects of liftoff on the soil/structure interaction process are discussed in this report. A liftoff model is developed as a direct extension of the lumped parameter soil/structure interaction analysis. The standard vertical and moment interaction springs are used to determine an equivalent foundation modulus acting over the entire foundation area. There are two conditions that may be used to evaluate the foundation modulus, the moment spring and the vertical spring. The liftoff model contains a parameter that determines whether the foundation modulus is determined from the moment spring, vertical springing, or some average of the two. Distributed dampers are also placed at the foundation/soil interface representing the moment and vertical interaction dampers. The same parameter used for the foundation modulus is used to specify whether the distributed dampers are evaluated from the moment or vertical damper. During the response calculation, the pressure acting in the distributed spring/damper system is restricted to compression and set equal to the dead weight bearing pressure when the foundation separates from the soil. The foundation area is divided into strips with the force evaluated in each strip. In essence this approach scales the interaction parameters in proportion to the area of the foundation that is in contact with the soil.

This neglects an important source of damping which occurs when a segment of the foundation which has separated from the soil comes back into contact with the soil. There will be a considerable dissipation of energy during this impact process because of the velocity differential between the soil and foundation. A simple model of this impact process is included in the liftoff model used for the study.

The validity of the model is evaluated by comparing predictions made with it to data measured during the SIMQUAKE II experiment. It should be noted that the acceleration levels during the SIMQUAKE experiment were extremely high and about 12 times that required to cause liftoff. Structures at nuclear power plants would not usually be exposed to peak accelerations more than 2-3 times that required to cause liftoff. Additional experimental data should be obtained where a wider range in the peak accelerations are used. One would expect much better agreement between the model and the experiment if the structures had been exposed to lower accelerations. The following conclusions may be drawn
from these comparisons:

1. There is a significant improvement when the liftoff model is used to calculate the SIMQUAKE II results as compared with predictions made with the standard lumped parameter models. The standard models generally underestimate the vertical response and predict too high a frequency content for the rocking motion. Both of these deficiencies are corrected when liftoff effects are included in the computations.

2. Better results are obtained when the distributed foundation springs and dampers are calculated based on the standard vertical interaction spring and damper rather than the moment values.

3. The additional damping, which occurs during impact when a separated portion of the foundation comes back into contact with the soil, is important. The inclusion of this source of energy dissipation improves the correlation between the measured and calculated data. The impact model is rather crude and additional work should be performed to improve it.

4. There is a reasonably good correlation between the predicted and measured response spectra when the liftoff model is used. There is poorer correlation at the higher frequencies for the rocking and vertical spectra, and this is attributed to the impact phenomena.

Solutions are then found evaluating the magnitude of the peak acceleration required to initiate liftoff. The El Centro horizontal and vertical pulses are used as input and the accelerations in the input pulses scaled until liftoff occurs. The following conclusions are drawn from the results of these data:

1. Peak horizontal accelerations in the range of 0.2 to 0.6 G's are usually required to cause liftoff to occur. The specific value depends, of course, on the parameters defining the structure and the free field properties. It can be seen that liftoff can be expected to occur in many nuclear power plant structures, especially so in those located in high seismic regions.

2. The liftoff acceleration tends to increase with increasing rocking
interaction frequency (when it is greater than 3 cps) and to decrease with increasing vertical interaction frequency.

3. The liftoff acceleration: decreases as the height of the structure's center of gravity above the base increases; increases as the interaction damping increases; and increases as the depth of burial increases.

An example is then considered where a structure is subjected to accelerograms having peak accelerations 1.33, 1.67, and 2 times that required to cause liftoff. Response spectra for the horizontal, rocking, and vertical motions are then calculated using the liftoff model and the standard lumped parameter model neglecting liftoff effects. A comparison of the two solutions leads to the following conclusions:

1. There is very little difference in the horizontal spectra between those calculated including liftoff effects and those calculated neglecting liftoff effects. This is as expected since the liftoff process does not effect the horizontal interaction spring or damper.

2. There is a significant difference between the rocking liftoff and no liftoff spectra when the input motion is greater than 1.33 times that required to cause liftoff. The difference occurs at frequency ranges (1-4 cps) of interest in the seismic design of equipment and piping systems. When liftoff is neglected the predicted accelerations are too low (unconservative) by factors of up to 3.

3. The vertical liftoff and no liftoff spectra are similar up to a frequency of 10 cps. Above this frequency the spectra calculated by neglecting liftoff effects are again too low by factors up to 6. This frequency range is not of too much importance. It is also likely that much of this difference occurs because of the relatively crude impact model.
REFERENCES


**BIBLIOGRAPHIC DATA SHEET**

**TITLE AND SUBTITLE**

Soil Structure Interaction
Vol. 2 Influence of Lift-Off

---

**AUTHOR**

C. A. Miller

---

**PERIOD COVERED**

January 1986

---

**DATE REPORT ISSUED**

April 1986

---

**SPONSORING ORGANIZATION NAME AND MAILING ADDRESS**

U.S. Nuclear Regulatory Commission
5650 Nicholson Lane
Rockville, MD 20852

---

**TYPE OF REPORT**

Formal

---

**ABSTRACT**

This study has been performed for the Nuclear Regulatory Commission (NRC) by the Structural Analysis Division of Brookhaven National Laboratory (BNL). The study was conducted during the fiscal year 1985 on the program entitled "Benchmarking of Structural Engineering Problems" sponsored by NRC. The program considered three separate but complementary problems, each associated with the soil-structure interaction (SSI) phase of the seismic response analysis of nuclear plant facilities.

This report presents a summary of the work performed defining the influence lift-off has on the seismic response of nuclear power plant structures. The standard lumped parameter analysis method was modified by incorporating into the lumped soil/structure interaction model nonlinear foundation stiffness. Additional interaction damping is included to account for the energy dissipated as a portion of the foundation which has separated comes back into contact with the soil.

Data is presented which identifies the peak acceleration required to cause lift-off. For parameters typical of nuclear power plant structures lift-off was found to occur when the peak accelerations are in the range of 0.3 to 0.6 G's. Studies were then performed to evaluate the consequences of neglecting lift-off when it occurs. Significant spectral differences were found for the rocking and vertical motions between the analyses performed considering and neglecting lift-off effects. It was found that peak accelerations 1.33 that required to cause lift-off (0.4 to 0.8 G's) result in unconservative response spectra when the lift-off effects are neglected in the SSI analysis.

---

**DOCUMENT ANALYSIS - KEYWORDS/DESCRIPTIONS**

Unlimited

---

**SECURITY CLASSIFICATION**

Unclassified

---

**NUMBER OF PAGES**

Not specified

---

**PRICE**

Not specified