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Rocking response of arbitrarily shaped rigid bases allowed to uplift

K. Imamura
Metropolitan Expressway Public Corporation, Japan

H. Kawakami
Saitama University, Japan

ABSTRACT: In the earthquake-resistant design of structures such as nuclear power plants and above-ground tanks, consideration is given to the effect of base uplift on the response of these structures. This paper presents an iterative procedure for analyzing the rocking response of a rigid base allowed to uplift. The base is placed on an elastic half-space and is subjected to a gravitational force and an overturning moment. The proposed method is applied to a rectangular base under dynamic loading conditions.

1 INTRODUCTION

The phenomenon of partial separation (lift-off) of the base of a structure from its foundation during strong ground shaking has been observed in many earthquakes (Psycharis and Jennings 1983). For example, during the Arvin-Tehachapi, California, earthquake of July 1952, a number of towers stretched their anchor bolts and rocked back and forth on their foundations (Housner 1956). After the Alaska earthquake of March 1964, ice was found under some oil tanks, evidence that lift-off occurred during the earthquake (Hanson 1973).

In the earthquake-resistant design of structures such as nuclear power plants and above-ground tanks, consideration is given herein to the effect of base uplift on the response of these structures. Several methods for analyzing soil-structure interaction with partial uplift have been proposed (Kobori et al. 1984; Psycharis and Jennings 1983; Toki et al. 1981). In one of these methods, the interaction forces, represented by springs and dashpots, are assumed not to take tension (Psycharis and Jennings 1983). It is difficult to accurately determine the spring and damping constants used in this method. In another method (Toki et al. 1981), the soil is subdivided into a number of elements with joint elements placed at the interface between the soil and the base of the structure. Then, using the finite element method, the structure's dynamic response is analyzed. However, it is difficult to deal with the three-dimensional problem because of the computation costs. Wolf and Obernhuber (1984) have proposed another method based on the continuum elasticity theory. However, since the problem is formulated only in the time domain, this method is not suitable for dealing with the problem of steady-state vibration.

2 OUTLINE OF METHOD OF ANALYSIS

In this paper, a static gravitational force and a dynamic overturning moment are applied to a rigid base on an elastic half-space. Then, an iterative procedure is used to analyze the rocking response of the base with partial uplift. It consists of two steps:

1. The relationship between soil surface displacements and the surface tractions that the rigid base exerts on the soil (the interaction forces) is derived from a boundary element analysis in the frequency domain.
2. Displacements and tractions are modified in the time domain so that the boundary conditions are satisfied at the interface between the base and the soil.

The results from each step are connected by the fast Fourier transformation.

3. ANALYSIS TECHNIQUES

In this study, a static vertical force W_z, representing the dead weight of the structure, and a harmonic moment around the horizontal y-axis M_y, are applied to a rigid base on an elastic half-space (Figure 1). Under these loads, not only lift-off, but also slipping, can occur and be quite significant. However, for simplicity, the analysis is based on the assumption that no slipping is permitted between the base and the foundation. A periodic response with the

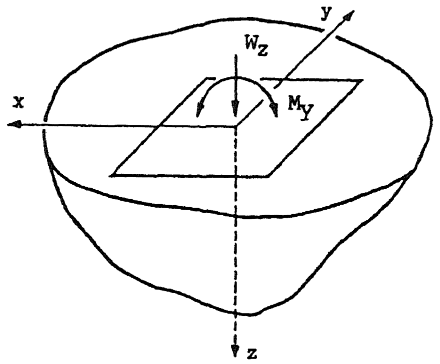
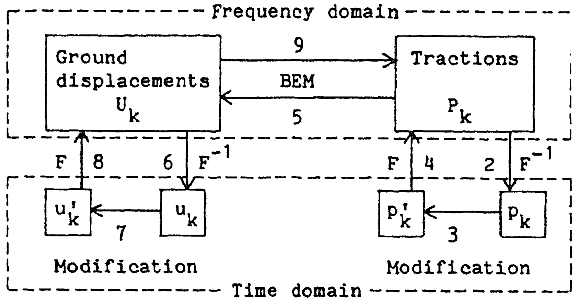


Figure 1. Coordinate system and applied loads.



F : Fast Fourier transformation

F^{-1}: Inverse fast Fourier transformation

Figure 2. Iterative procedure.

period of the excitation is also assumed, and the Fourier transform is applied to the duration of a cycle. The methodology is shown in Figure 2. This is an iterative procedure consisting of the following operations (Kawakami 1990):

1. The base is subdivided into a number NN of smaller square subregions. Using a boundary element analysis in the frequency domain, the response behavior of the rigid massless base and the contact tractions between the base and the half-space are evaluated under fully bonded contact conditions (Wong and Luco 1976, 1978).
2. The contact tractions obtained from the preceding frequency-domain analysis are transformed into the time domain by the inverse fast Fourier transform algorithm.
3. From the sign of the normal traction within the subregion, each of the NN subregions is determined to be either a contact or uplift subregion for each time step. The distribution of contact tractions is corrected so that tension does not occur in the uplift region and the equations of motion for the base are still satisfied.
4. The tractions obtained from the time-domain analysis described are transformed into the frequency domain.
5. Because the surface tractions were changed in step 3, the corresponding vertical displacement of the soil surface must also be changed. Therefore, displacements of the soil surface are corrected to new values by using the boundary element method. In this calculation, the horizontal components of surface tractions are all set to zero, so that the relaxed boundary conditions at the soil surface may be satisfied.
6. The surface displacements obtained from the preceding frequency-domain analysis are transformed into the time domain.
7. Because the displacements of the soil surface were changed in step 5, the soil surface and the base may not be on the same plane even in the contact region. Therefore, the vertical displacement of the base and the corresponding displacement of the soil surface are corrected to be the same for each of the subregions that have been determined to be in contact in step 3. For the uplift subregions, if the base and the soil overlap each other, such a subregion is changed from an uplift subregion to a contact subregion.
8. The surface displacements obtained from a time-domain analysis of step 7 are transformed into the frequency domain.
9. Using the boundary element method, the surface tractions are obtained from the surface displacements that were calculated in step 8.

Steps 2-9 are repeated until the displacements of the soil surface and the base, the surface tractions, and the uplift area converge.

4. STATIC ANALYSIS

As a simple example, a mathematical model of a rectangular base is shown in Figure 3. A perfectly elastic half-space with a P velocity of 800m/s, an S velocity of 400m/s, a unit weight of $1.6t/m^3$, and a Poisson ratio of 1/3 is assumed.

The relationship between the static moment M_y and the rotational displacement ϕ_y is examined for the different values of the gravitational force W_z. There is a linear relationship between M_y and ϕ_y for small M_y-values. However, when uplift occurs, the relationship becomes nonlinear. The rotational compliance C_{MM}, defined as ϕ_y/M_y, becomes larger as M_y increases.

The results are compared with those from use of the Winkler foundation. The interrelationships of the dimensionless overturning moment, $M_y/(W_z \cdot L)$, the ratio of no-uplift C_{MM}" to C_{MM} (uplift), and the ratio of the area contacting the soil to the total

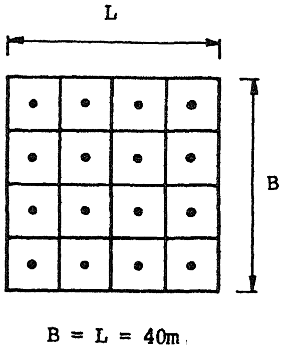


Figure 3. Analytical model.

area of the base are shown in Figures 4. The results of the proposed analysis method are in reasonable agreement with those of the Winkler foundation. The amount of lift-off dramatically affects the response of the base. When lift-off is allowed, the compliance and the contact ratio decrease as the overturning moment increases.

5. DYNAMIC ANALYSIS

Consider the case of a rigid rectangular base excited by a sinusoidally varying moment

$$M_y(t) = M_{ymax} \cos(\omega t) \qquad (1)$$

The vertical tractions, vertical displacements, and uplift regions distributed in the base are shown in Figures 5 (a), (b) and (c), respectively, for each time over one-half the period of the excitation. Conditions are W_z=1.6x10^{10}N, M_{ymax}=2x10^{11}N·m, and $\omega = 2\pi$ rad/s. Inspection of Figure 5 shows that the uplift area is much larger than the tension area in the case where lift-off is not allowed, and that the concentration of the tractions at two corners of the base becomes more prominent from the effect of lift-off. As for the displacements, the results shown in Figure 5(b) indicate, for instance, that the rotational displacement becomes larger as a result of the base uplift.

A comparison of Figures 5(a) and (b) indicates that in the uplift region the surface tractions are all zero. In the contact region, however, the vertical displacements of the base are equal to those of the corresponding soil surface and compressive surface tractions are produced.

It should also be noted that when lift-off is allowed, vertical vibration of the base is also excited, though in this case only a static gravitational force and a sinusoidal

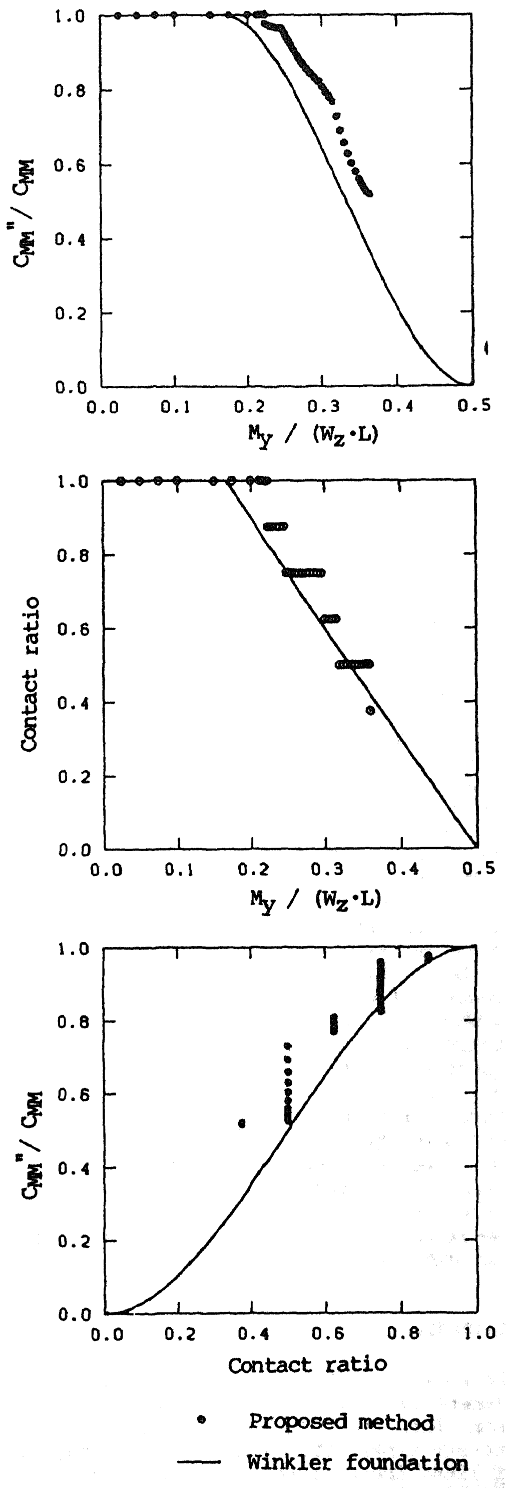


Figure 4. Interrelationships of rocking compliance, overturning moment and contact ratio.

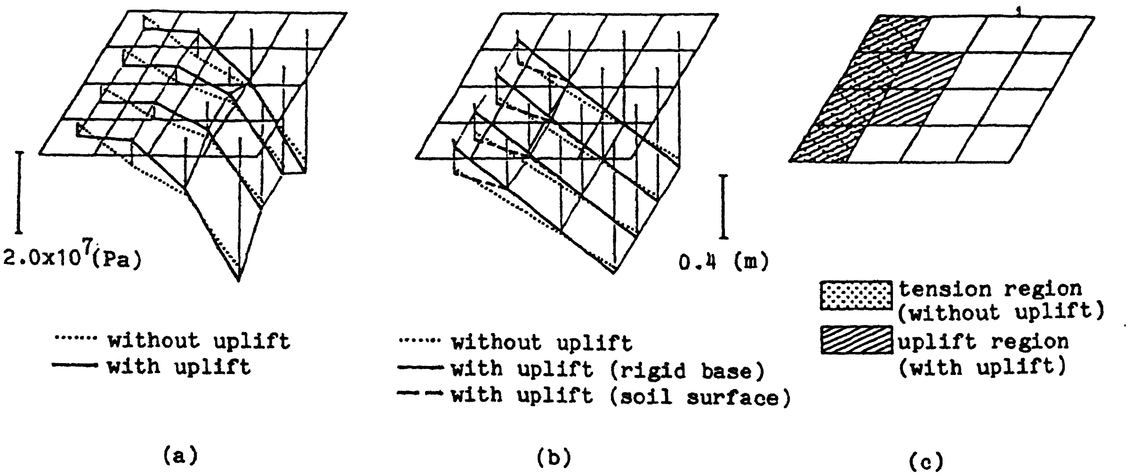


Figure 5. Distributions of: (a) vertical tractions; (b) vertical displacements; (c) uplift region.

overturning moment are applied to the base. A vertical component with one-half the period of the excitation is dominant.

6. SUMMARY AND CONCLUSIONS

The principal results and conclusions are as follows:

1. In general, uplift leads to a softer vibrating system that behaves nonlinearly, i.e., rocking compliance increases with increasing values of the rotational moment.
2. The uplift area under the base in the lift-off case is much larger than the tension area in the case in which lift-off is not allowed. Moreover, along the edge of the rigid base, compressive tractions are more concentrated when lift-off is allowed.
3. When lift-off is allowed, the vertical vibration of the base and the higher frequencies of vibration are also excited, even in the case where only the static vertical force and the sinusoidal rotational moment are applied.

This analysis method is a way to economically compute the main effects of seismic uplifting on rigid base structures. These results can be utilized in design of structures able to survive seismic waves.

REFERENCES

Brebbia, C.A. 1984. Topics in boundary element research. Springer-Verlag.

Hanson, R.D. 1973. Behavior of liquid-storage tanks. The Great Alaska Earthquake of 1964, Engineering, National Academy of Sciences, Washington, D.C.

Housner, G.W. 1956. Limit design of structures to resist earthquakes. Proc. 1st World Conf. Earthquake Eng.

Kawakami, H. 1990. Rocking compliance functions for rigid bases allowed to uplift. ASCE, GT 116: 725-739.

Kobori, T., T. Hisatoku & T. Nagase 1984. Nonlinear uplift behavior of soil-structure system with frequency-dependent characteristics. Proc. 8th World Conf. Earthquake Eng. 3: 897-904.

Lysmer, J., T. Udaka, H.B. Seed & R. Hwang 1974. LUSH, a computer program for complex response analysis of soil-structure systems. EERC 74-4, Earthquake Engineering Research Center, University of California, Berkeley, CA.

Psycharis, I.N. & P.C. Jennings 1983. Rocking of slender rigid bodies allowed to uplift. Earthquake Eng. Struct. Dyn. 11: 57-76.

Titchmarsh, E.C. 1937. Introduction to the theory of Fourier integrals. Oxford University Press.

Toki, K., T. Sato & F. Miura 1981. Separation and sliding between soil and structure during strong ground motion. Earthquake Eng. Struct. Dyn. 9: 263-277.

Wolf, J.P. & P. Obernhuber 1984. Nonlinear soil-structure interaction analysis using dynamic flexibility of soil for impulse forces. Proc. 8th World Conf. Earthquake Eng. 3: 969-976.

Wong, H.L. & J.E. Luco 1976. Dynamic response of rigid foundations of arbitrary shape. Earthquake Eng. Struct. Dyn. 4: 579-587.

Wong, H.L. & J.E. Luco 1978. Dynamic response of rectangular foundations to obliquely incident seismic waves. Earthquake Eng. Struct. Dyn. 6: 3-16.