Three Dimensional Uplift Response Analysis of a Nuclear Reactor Building

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Abstract

In this paper conventional methods of uplift analysis are reviewed and a new three dimensional method is proposed. And then conventional and new methods are compared using simplified 2-mass model and full model of PWR 3-Loop reactor building.

The vertical input motion is judged to have scarce effect on the uplift, however biaxial horizontal input motion increases the uplift ratio remarkably. Vertical response is induced by uplift even in the case of horizontal uniaxial input. The response contains the frequency components of even number times that of input motion. Also in the horizontal response odd number times frequency components are induced by uplift.

2. Introduction

Nuclear power plant structures designed for severe earthquake excitation are often subjected to very large overturning moment. As a consequence of this load condition the base slab of the reactor building may partially uplift from the ground. The uplift phenomena have influence not only on the design of reactor building structures but also on the design of important machines set on the structures.

Up to this time, most of the uplift response analyses have been done in plane. The effect of vertical input acceleration is considered mostly in the form of equivalent static force, and the effect of biaxial horizontal input motion is rarely considered. Recently some results of response analysis subjected to the vertical input motion and the orthogonal horizontal input are already reported. According to these reports, it is pointed out that vertical input motion has little influence on the uplift and torsion can be caused by orthogonal horizontal input on the occasion of uplift. But the phenomena are not necessarily grasped sufficiently by analytical study.

In this paper, a new three dimensional method is proposed to calculate the uplift more exactly. Conventional methods and the new one are compared using 2-mass model. And uplift phenomena due to triaxial input motion are discussed using the new method. Finally the method is applied to typical PWR 3-loop reactor building and the results are discussed.

2. Conventional Methods of Uplift Response Analysis

Three conventional methods of uplift response analysis used in the earthquake resistant design are reviewed and discussed.

The first one is called "Linear OTM Method", where overturning moment of linear response is applied to the nonlinear moment-rotation relationship of base to calculate the maximum base rotation. The second one is called "Energy Balance Method"/1/, where energy equilibrium of linear and nonlinear response is assumed considering strain energy. The third one is called "Nonlinear Rocking Method"/2/, where nonlinear response calculation is done considering the nonlinearity of rotational soil spring.

These three methods have following defects or approximations.

(1) The shift of resonance frequency due to the nonlinearity by uplift can not be taken into account by linear methods.

(2) Input motion is usually assumed as horizontally uniaxial. The effect of vertical input motion is represented by the approximate static force which is not equivalent strictly and leads to the overestimation of uplift. Orthogonally biaxial horizontal input motions are not considered simultaneously, which leads to the underestimation of uplift.

(3) Vertical response induced by uplift is not considered in these methods.

(4) Nonlinearity of translational soil spring due to the reduction of contact area by uplift is not considered in most cases, which leads to the erroneous estimation of response.

3. Proposed Three-dimensional Method

Three dimensional method is proposed to calculate the uplift response more exactly. In this method the following factors are considered:

(1) The geometrical nonlinearity of soil spring due to the decreasing of basement contact area

(2) Vertical movement of the center of gravity and the change of vertical load acting on base mat due to the vertical movement

(3) P-δ effect and vertical movement of the centroid of horizontal soil reaction

(4) Torsional vibration induced by uplift

Six degrees of freedom are considered at the base and every node; three translations and three rotation along and around X, Y and Z axes. Soil reactions are calculated at each time step of response based on the following assumption (as shown in Fig. 1):

(1) Vertical soil reaction is distributed linearly over the contact area at the base.

(2) Horizontal soil reaction is constant over the contact area.

(3) Coefficients of subsoil reactions are constant irrespective of the contact area.

(4) The border line between contact and decontact zone is linear.

Therefore in this method two horizontal and one vertical motions can be input simultaneously. Vertical response induced by uplift even in the case of horizontally uniaxial input can be estimated automatically.

4. Results of Fundamental Analysis

Uplift responses are calculated by conventional and new methods using simplified 2-mass model subjected to sinusoidal motion. In the case of conventional methods, uniaxial input is considered. The natural frequencies of the soil-structure model for the linear case without uplift are 2.0, 5.4 and 13.2 Hz.

Fig. 2 and Fig. 3 show the horizontal and vertical resonance curve of upper point obtained by the new method in the case of the horizontal uniaxial input. The value of the vertical axis is the ratio of horizontal and vertical response to the input motion. In the linear case (50 Gal input), the fundamental horizontal resonance frequency is about 2.0 Hz and the amplification ratio is about 6. The resonance frequency and amplification ratio are reduced by uplift. The rate of decrements corresponds to the increments of input accelerations (i.e. increment of uplift). The vertical response is induced at the state of uplift even in the case of uniaxial horizontal input, though the vertical response is not caused without uplift.

Fig. 4 and Fig. 5 show the horizontal and vertical Fourier Spectra of the acceleration of the upper point of the 2-mass model in the case of 400 Gal input. These figures indicate the relationship between Fourier Spectra and input frequency. The horizontal response in the state of uplift contains the frequency components of odd number times that of the input motion. The vertical response induced by uplift consists of the frequency components of even number times that of the input motion.

Fig. 6 shows the uplift ratio obtained by the conventional and new methods in the case of 200 Gal input. The uplift ratio can be calculated easily by Linear OTM Method. This method mostly overestimates the ratio. But when the dominant frequency components of input motion is in the lower frequency range than the natural frequency of structure, there is possibility of underestimation of the ratio. By Energy Balance Method the uplift ratio can also be calculated easily. The results agree with that of the proposed method in most cases. But Energy Balance Method underestimates the uplift in the particular case such as mentioned above. Nonlinear Rocking Method shows good coincidence with the proposed exact solution.

Fig. 7 shows the horizontal resonance curve obtained by the new method subjected to the uniaxial, biaxial and triaxial input (maximum input acceleration is 200 Gal in each axis). The results are divided into two groups. One is the group of uniaxial input and biaxial (X + Z) input. The other one is the group of biaxial (X + Y) input and triaxial input. The resonance frequencies and amplification ratios of the latter are smaller than that of the former. According to the results, it is pointed out that the vertical input motion has slight influence on the uplift, however biaxial horizontal input motion increases the uplift remarkably.

5. Application to the Typical PWR 3-Loop Reactor Building

A typical PWR 3-Loop Reactor Building is modeled by three vertical beams with lumped masses and square rigid base mat (56 m by 56 m). O.S.W, I.C and S.C.V are expressed individually. The coefficients of soil reaction (vertical: 4.8×10^{-3} ton/cm^3, horizontal: 1.8×10^{-3} ton/cm^3) are calculated on the assumption of a rigid base mat resting on an elastic half-space. The horizontal natural frequencies of the 3 lowest modes for the linear case without uplift are 2.0, 4.1 and 5.4 Hz. Input motions used for this analysis are El Centro 1940 and Taft 1952. Input maximum accelerations are 300 Gal (S_1) and 450 Gal

(S_2) in X (NS) direction. The ratios of maximum accelerations in another directions to X direction are coordinated to actual ratios.

Table I shows the uplift ratios calculated by the new method. The uplift ratios subjected to horizontal uniaxial input increase in proportion to the input acceleration. In the case of biaxial (X + Z) input the uplift ratios hardly increase or decrease as compared with the results of uniaxial input. The uplift ratios subjected to biaxial (X + Y) input increase in comparison with the ratios for uniaxial input. In the case of triaxial input the uplift ratios can be understood by combining the result of the biaxial (X + Y) input to the result of biaxial (X + Z) input.

6. Conclusion

From uplift response analysis based on the proposed method and three conventional methods, the following conclusions can be obtained:

(1) In the case of sinusoidal excitation, base mat uplift results in significant shift in the magnitude and frequency of structural response.

(2) Vertical response is induced by uplift even in the case of horizontal uniaxial input. The response contains the frequency components of even number times that of the input motion.

(3) In the case of uniaxial sinusoidal excitation, the horizontal frequency components of odd number times that of the input motion are induced by uplift.

(4) Vertical input motion scarcely increases uplift or rather decreases it in some cases, however orthogonal horizontal input motion increases the uplift remarkably.

(5) Comparing conventional and new methods, Linear OTM Method overestimates the uplift and Energy Balance Method underestimates the uplift. Nonlinear Rocking Method shows good coincidence with the proposed method.

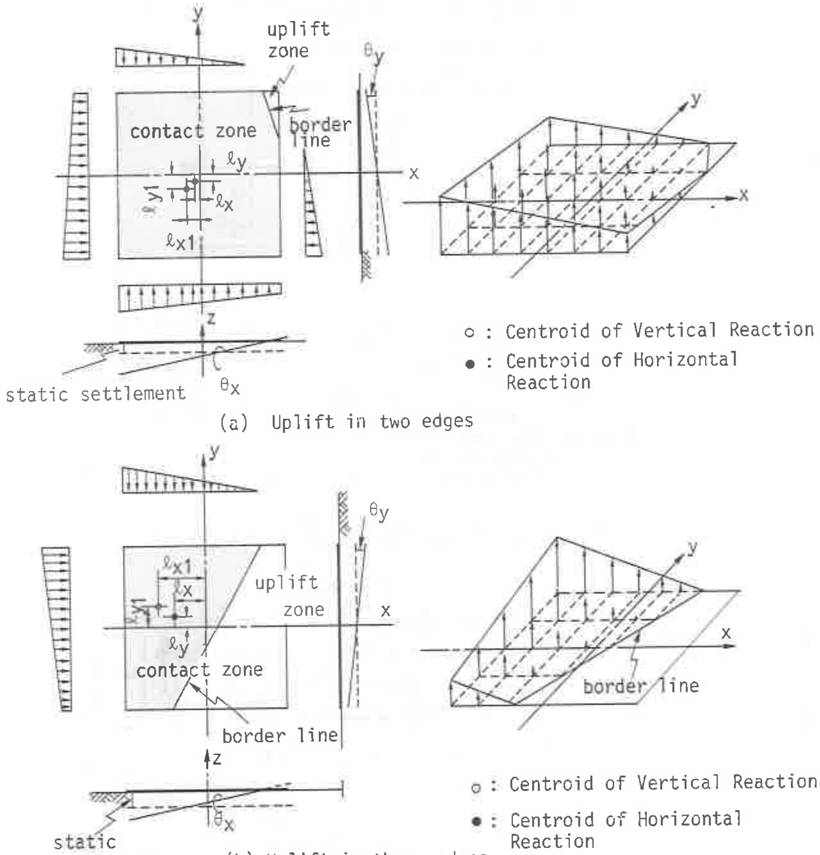
Reference

/ 1 / W.S. TSENG, D.D. LIOU "Simplified Method for Predicting Seismic Basemat Uplift of Nuclear Power Plant Structures", Proceedings 6th Intl. Conf. on Structural Mechanics in Reactor Technology, August 1981, Paper K3/6

/ 2 / T. TAKEMORI, K. SOTOMURA, M. YAMADA, "Nonlinear Dynamic Response of Reactor Containment" Nucl. Eng. Design 36,463-474 (1976)

Table I Uplift Ratio of Full Model Subjected to Earthquake Excitation

Input Motion / Input Axes	EL CENTRO		TAFT	
	S_1	S_2	S_1	S_2
Uniaxial (X)	24.0	38.2	22.6	38.4
Biaxial (X+Z)	26.3	38.9	15.2	35.7
Biaxial (X+Y)	29.3	48.1	29.0	45.0
Triaxial	31.7	47.9	25.1	44.2



(a) Uplift in two edges

(b) Uplift in three edges

Fig. 1 Distribution of Vertical Soil Reaction

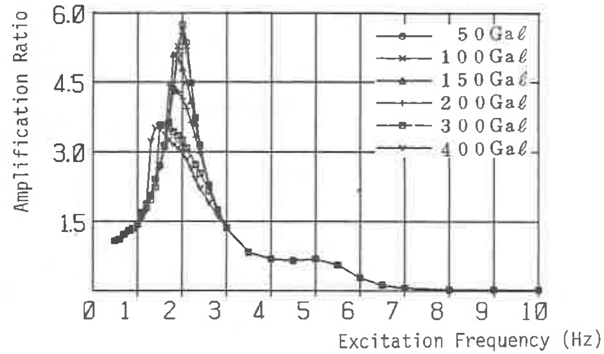


Fig. 2 Horizontal Resonance Curve of Upper Point

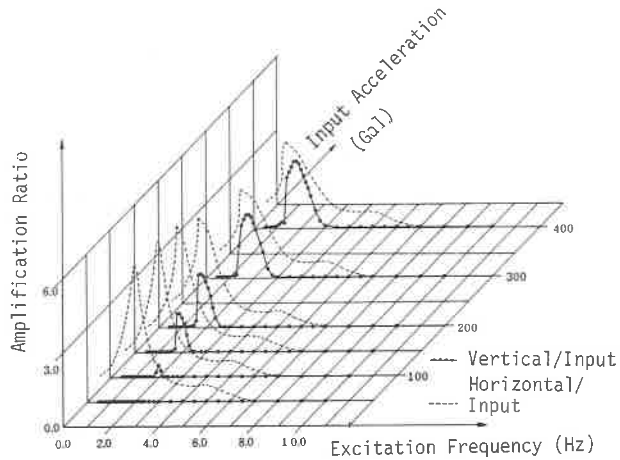


Fig. 3 Vertical Resonance Curve of Upper Point (Vertical/Horizontal)

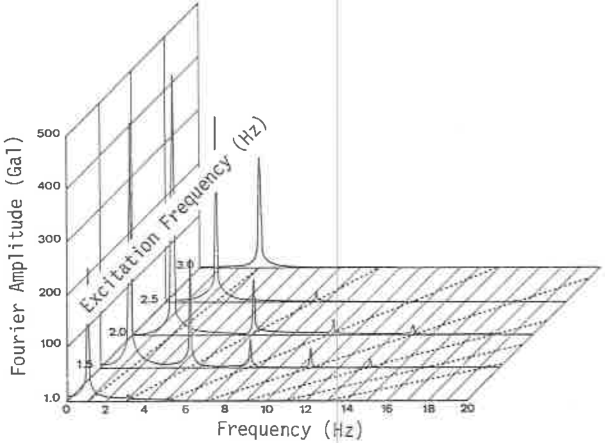


Fig. 4 Horizontal Fourier Spectra of Upper Point (400 Gal)

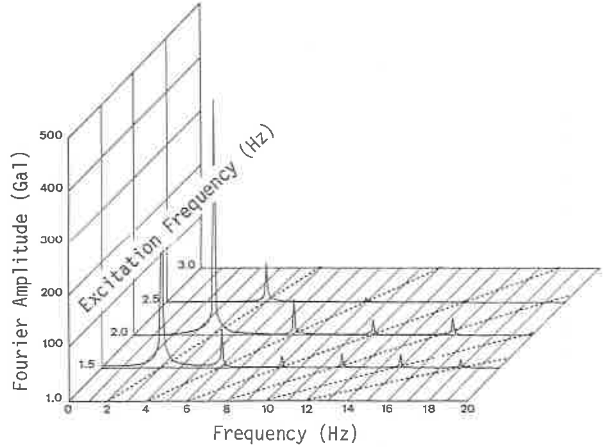


Fig. 5 Vertical Fourier Spectra of Upper Point (400 Gal)

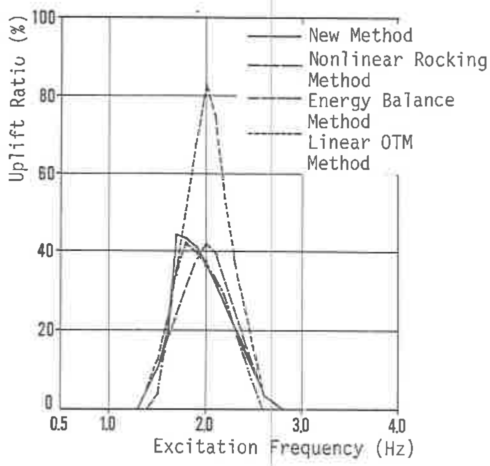


Fig. 6 Uplift Ratios of 2-mass Model Subjected to 200 Gal Sinusoidal Acceleration

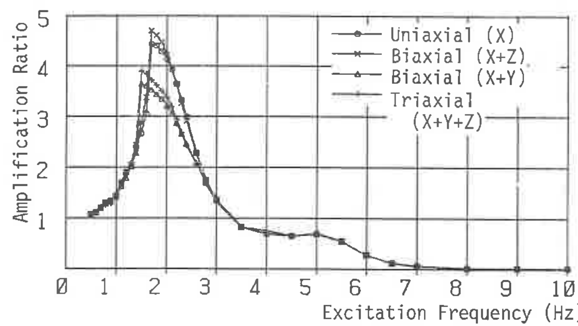


Fig. 7 Horizontal Resonance Curve Subjected to Input Axes