OVERTURNING BEHAVIOR OF NUCLEAR POWER PLANT STRUCTURES DURING EARTHQUAKES

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SYNOPSIS

Nuclear power plant structures are designed to withstand severe postulated seismic forces. Structures subjected to such forces may be found to "overturn", if the factor of safety is computed in the traditional way, treating these forces as static. This study considers the transient nature of the problem and draws distinction between rocking, tipping and overturning. Responses of typical nuclear power plant structures to earthquake motions are used to assess their overturning potential more realistically. Structures founded on both rock and soil are considered. It is demonstrated that the traditional factor of safety, when smaller than unity, indicates only minimal base rotations and not necessarily overturning.

INTRODUCTION

To adequately protect public safety against accidental release of radiation, nuclear power plant structures are designed for quite severe postulated seismic forces. An important consideration in the design is overturning potential of structures due to such seismic forces in conjunction with hydrostatic forces and earth pressure, if present. Normal practice is to compute the so-called factor of safety, defined as the ratio of righting moment to the maximum transient overturning moment and restrict it above a specified number greater than unity. An example is provided in the present U.S. Nuclear Regulatory Commission guidelines, where acceptable factors of safety against overturning are specified as 1.1 and 1.5 for the Safe Shutdown and the Operating Basis earthquakes, respectively (Ref. 1).

The main purpose of this paper is to demonstrate that because earthquake forces are highly transient, factors of safety even smaller than unity indicate only minimal base rotations, considerably smaller than those necessary for structures to overturn. Thus, computation of such a factor of safety may not be meaningful. The overturning phenomenon is discussed first to facilitate the subsequent presentation of seismic responses of two containment structures, one founded on soil and the other on rock, subjected to a synthetic and a historic earthquake ground motions.

OVERTURNING PHENOMENON

Structures subjected to lateral forces are potentially susceptible to overturning. Important examples are dams acted upon by hydrostatic forces, retaining walls subjected to earth pressures, and structures subjected to seismic forces.

The overturning phenomenon is illustrated in Figure 1. Because the interface between the structure foundation and the supporting medium cannot transmit tensile forces, it is important to consider different modes of motion. Rocking is rotation of the structure as a whole when at least a partial interface contact is maintained. As shown in Figure 1(c) when the contact is partial, the axis of rotation shifts. Tipping implies the rotation about one of the foundation edges and a full separation at the interface. Overturning can occur only when the structure rotation is sufficiently large to displace the center of gravity outside of the foundation dimensions.

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For steadily applied static lateral forces, the structure begins tipping, when overturning moment of the lateral forces about the structure base exceeds the resisting moment generated by the effective downward force on the structure about an edge of the foundation. The overturning moment acts with the same magnitude and direction during the tipping whereas the resisting moment progressively diminishes as base rotations become larger. Finally, the structure overturns, as the center of gravity is displaced outside the foundation dimensions. Thus, tipping is indicative of overturning and consequently, overturing potential can be expressed by a factor of safety which is the ratio of the resisting moment to the overturning moment. As discussed above, the structure overturns when this factor of safety is smaller than unity. For structures subjected to static lateral forces, the traditionally required factor of safety is greater than 1.5.

Seismic forces are transient and fluctuate considerably with time. During the transient structural response, the overturning moment may exceed the resisting moment instantaneously, several times, but would not persist with the same direction or magnitude. Thus, the factor of safety can instantaneously be smaller than unity indicating only tipping and not necessarily overturning. As demonstrated herein, this distinction is quite important in evaluating overturning potential of a structure.

SEISMIC RESPONSE ANALYSIS

The basic equations of motion for a multi-degree-of-freedom system shown in Figure 2 are briefly discussed below. The structure is modeled by a cantilever beam(s) with appropriately lumped inertia properties. The soil is modeled by compliance functions or springs and dashpots. This system is selected for two reasons: one, a structure founded on rock is a special case of this general system, and two, the soil-spring approach is more easily adaptable to the foundation separation phenomenon than the finite element approach. Equations of motion for the N masses above the base of the structures are given by

$$\underline{M}\ \ddot{\underline{U}} + \underline{C}\,\dot{\underline{u}} + \underline{K}\ \underline{u} = \underline{0} \tag{1}$$

Equations of motion of the structure as a whole are expressed as

$$\sum_{j=1}^{N} m_j \ddot{U}_j + m_o\,(\ddot{u}_g + \ddot{u}_o) + c_u \dot{u}_o + k_u u_o = 0 \tag{2}$$

$$\sum_{j=1}^{N} m_j \ddot{U}_j h_j + I\ \ddot{\theta} + c_\theta \dot{\theta} + k_\theta \theta = 0 \tag{3}$$

$$U_j = u_g + u_o + h_j \theta + u_j \tag{4}$$

where I = rotary inertia of the whole system about the axis of base rotation. $\underline{M}$, $\underline{C}$, $\underline{K}$ = mass, damping, and stiffness matrices for the structure respectively. For a structure firmly founded on rock, Eqs. 2 and 3 are not applicable because θ and u_o are absent. The above equations represent systems assumed to be in full contact with the foundation medium throughout the duration of seismic motion.

For soil foundations, when base mat is in partial contact with foundation medium, Eq. 2 is of the same form, however, soil spring and dashpot are nonlinear and depend on contact area. Eq. 3 is modified as follows to also account for the shift of axis of rotation which coincides with the neutral axis of the contact area.

$$\sum_{j=1}^{N} m_j h_j \ddot{U}_j + I'\ \ddot{\theta} + c_\theta \dot{\theta} + k_\theta \theta = \pm \overline{W}\ r \tag{3a}$$

I' = rotary inertia of the system about the new axis of rotation.

The sign of the righthand side term is determined by the nature of rotation.

When base mat starts tipping, Eq. 2 vanishes and Eq. 3 takes the following form:

$$\sum_{j=1}^{N} m_j h_j \ddot{U}_j + I'\ddot{\theta} = \pm \overline{W}R \qquad (3b)$$

The above is applicable to both rock and soil foundations. In rock supported structures, tipping and subsequent impact of the base produces impulsive forces. Vertical impulsive forces can be computed using the impulse-momentum principle as

$$Imp = (\sum_{j=0}^{N} m_j)\ R\ (\dot{\theta}_1 - \dot{\theta}_2) \qquad (5)$$

where $\dot{\theta}_1$ and $\dot{\theta}_2$ are velocities before and after impact respectively.

It is noted that in the above equations, the term, $\sum_{j=1}^{N} m_j h_j \ddot{U}_j$ represents the base moment. Ideally, all these equations should be solved simultaneously to determine the system response. The solution should also appropriately consider vertical seismic response and other relevent forces, such as, hydrostatic and earth pressures. In this paper, however, the following assumptions are made to simplify the response computations:

1. The base moments computed from the original equations are used. This assumption is conservative (Ref. 2).
2. The effective net weight is computed by subtracting the buoyancy force and the maximum vertical seismic force from the total structure weight. This is a conservative assumption because the vertical seismic force fluctuates in time.
3. Base rotations are small. Thus, the shift in the line of action of the net weight need not be considered. This assumption is quite valid as demonstrated by the results.
4. Effects of foundation embedment are not included in the analysis.

With these assumptions, Eqs. 1, 2 and 3 for both soil and rock founded structures are solved for two different seismic motions and a number of different conditions as listed in Tables 1 and 2.

RESULTS AND DISCUSSION

Horizontal seismic ground motions considered herein are shown in Fig. 2. Typical overturning moment time histories obtained from seismic analysis of multi-degree-of-freedom system models due to these excitations are shown in Fig. 4. The models represent the containment and internal structures supported on the base mat. Significant portions of time histories of base rotation and factor of safety are shown in Fig. 5 for containment on rock foundation. The factor of safety values are computed as instantaneous ratios of righting moment to overturning moment. Base rotations of the Containment on soil foundation are shown in Fig. 6. Response shown in Fig. 6(a) is based on the conventional soil spring approach to represent the foundation. Base rotation shown in Fig. 6(b) is obtained by considering partial contact and the shifted axis of rotation when the structure rocks. Significant response values are summarized in Table 2.

Base rotations are quite small for all conditions considered despite the fact that the factor of safety values are smaller than unity at several instants during the seismic event. For example, the maximum base rotation of 0.07° is computed for the containment on rock foundation with the minimum factor of safety of only 0.75. Base rotations necessary for overturning of typical containment structures are generally in excess of 45°. The presence of uplift forces, such as buoyancy force, tends to produce greater base rotations due to the reduced righting moment. For rock supported structures, significant impulsive forces may be induced under "high" seismic conditions.

CONCLUSIONS AND RECOMMENDATIONS

1. Factor of safety computed using the maximum transient overturning moment is not a realistic measure of the overturning potential. At best, the factor of safety is indicative of tipping only.
2. Even with factors of safety much smaller than unity, very small base rotations occur. Structures cannot "overturn" with such rotations. Thus, the factor of safety may be computed more realistically by comparing the induced base rotations with those allowable from functional and other structural considerations.
3. In the case of structures supported on rock, impact forces should be appropriately considered in design when tipping is permitted.
4. Although it is demonstrated that small base rotations are not detrimental from the overturning viewpoint, tipping could produce high bearing pressures in the foundation medium and affect the base mat. Such considerations should also be included in design.

ACKNOWLEDGEMENTS

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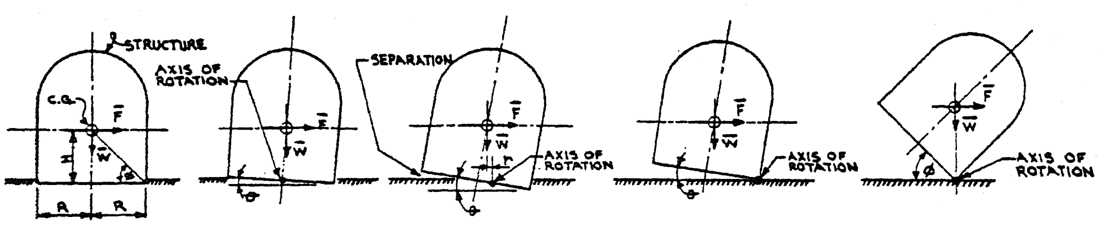


(a) No Rocking (b) Rocking (No Separation) (c) Rocking (Partial Separation) (d) Tipping (e) Incipient Overturning

NOTES: 1. Figs. 1(b) and 1(c) are applicable for soil foundation only
2. Notations: $\bar{W}$ = net weight = total structural weight - uplift forces
$\bar{F}$ = equivalent lateral force = base moment/H
θ = base rotation and ϕ = base rotation for incipient overturning

FIGURE 1 STRUCTURE ROCKING, TIPPING AND INCIPIENT OVERTURNING

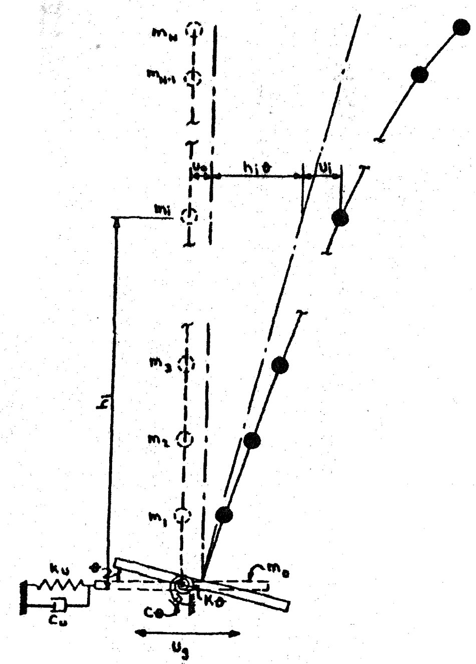
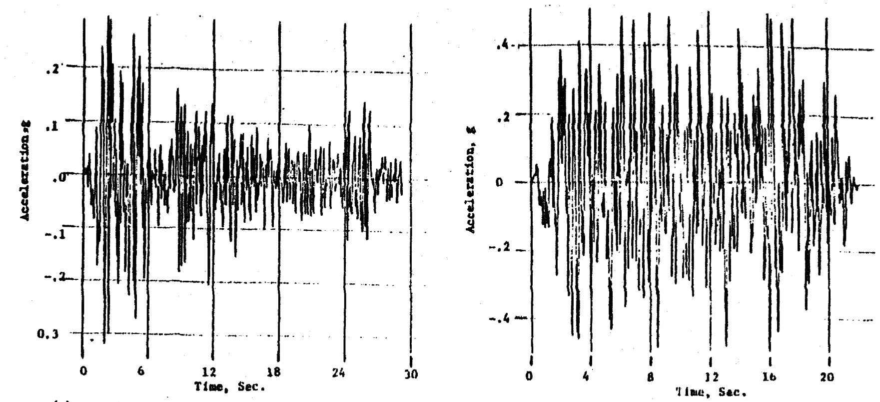


FIGURE 3 - MULTI-DEGREE-OF-FREEDOM STRUCTURE MODEL

TABLE 1 SYSTEM PROPERTIES

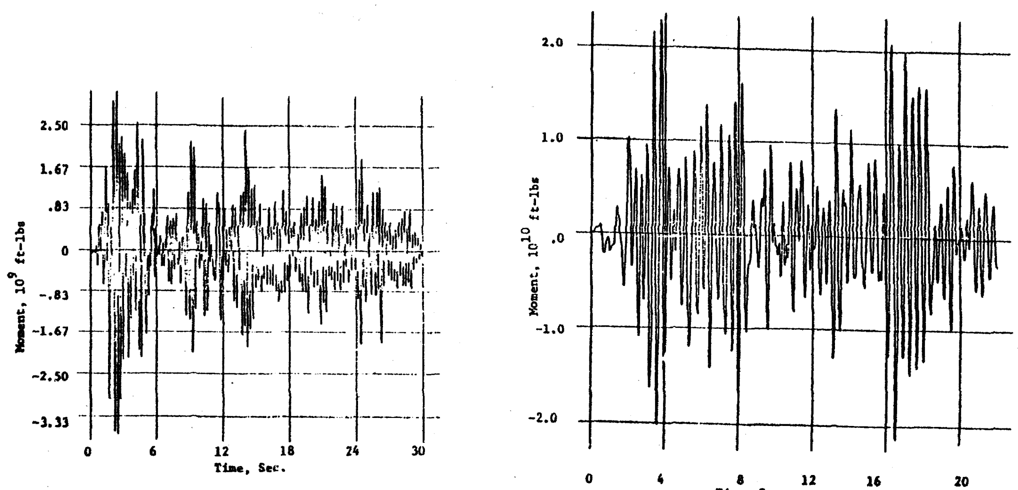
Structure			Foundation	Buoyancy Force
H(ft)	W(10^8 lbs)	I (10^{11} lbs-ft^2)		(10^7 lbs)
75.5	1.154	9.0	Rock	7.20
100.0	3.167	33.0	Soil: $k_\theta = 2.78 \times 10^{13}$ lb-ft/rad. 8.5% damping	11.76



(a) Acceleration Time History - 1940 El Centro, N-S Horizontal Component

(b) Acceleration Time History - Synthetic Motion Enveloping USNRC Reg. Guide 1.60 Horizontal Spectra - Peak Accl. = 0.5g

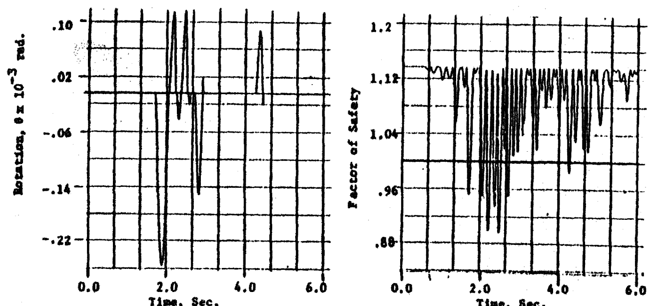
FIGURE 2 SEISMIC GROUND MOTIONS CONSIDERED IN THE STUDY



(a) Rock Foundation, El. Centro Motion Scaled to Peak Accl. = .25g

(b) Soil Foundation, Synthetic Motion

FIGURE 4 - Base Moment Time Histories from Linear Analyses of Multi Degree of Freedom Models

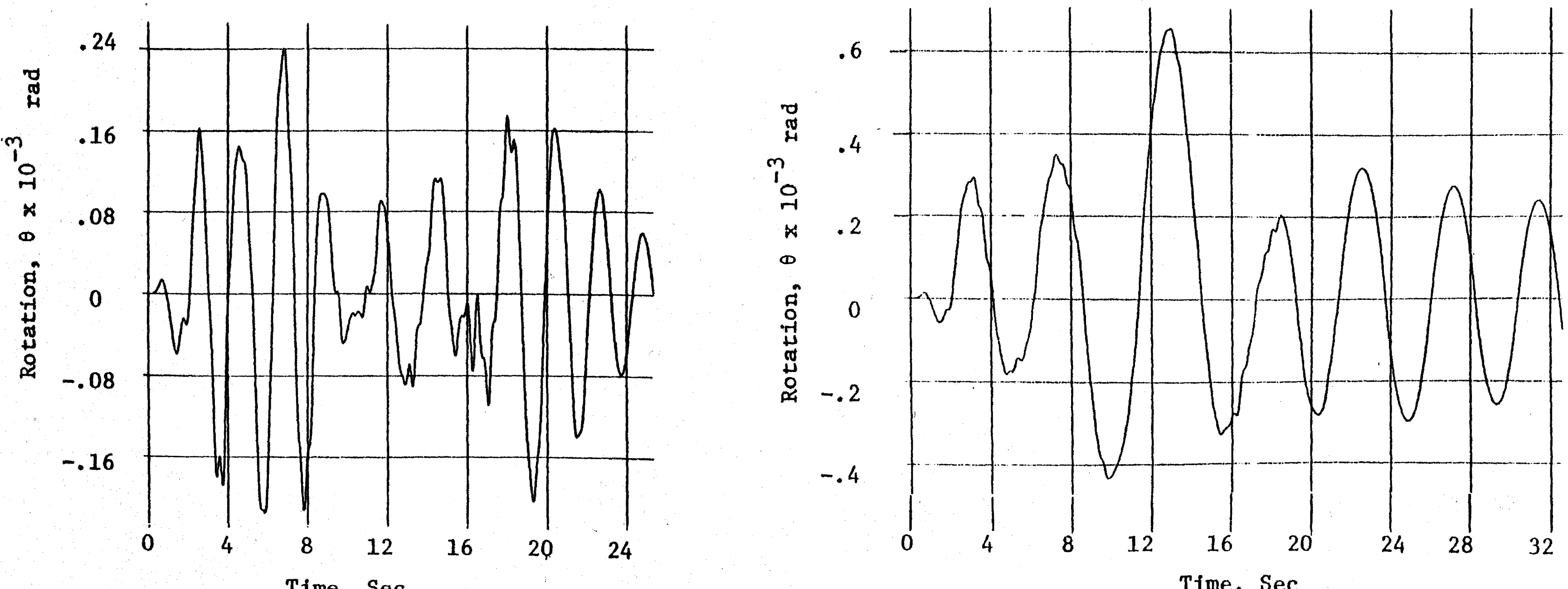


(a) Base Rotation (b) Factor of Safety

FIGURE 5 BASE ROTATION AND FACTOR OF SAFETY TIME HISTORIES OF CONTAINMENT ON ROCK FOUNDATION, EL CENTRO EARTHQUAKE, PEAK ACCELERATION SCLAED TO 0.25g.

TABLE 2 SUMMARY OF RESPONSE RESULTS

Earthquake Motion	Peak Accl.,g	Buoyancy	Containment Structure Response				
			Soil Foundation		Rock Foundation		
			Minimum Factor of Safety	Maximum Base Rotation (Degree)	Minimum Factor of Safety	Maximum Base Rotation (Degree)	Maximum Impulse (10^6 lb-sec)
Synthetic Motion - Envelope USNRC Spectra	.25	yes	1.07	0.009	0.75	0.07	1.63
	.25	no	1.62	0.007	1.42	0.00	0.00
	.50	no	0.81	0.038	0.71	0.03	3.96
El Centro 1940 N-S Component	.25	yes	1.32	0.003	0.90	0.02	1.21
	.25	no	2.60	0.003	2.03	0.00	0.00
	.50	no	1.30	0.007	1.02	0.00	0.00



(a) Base Rotation, Linear Analysis

(b) Base Rotation, Non-Linear Analysis

FIGURE 6 BASE ROTATION RESPONSE OF CONTAINMENT ON SOIL, SYNTHETIC MOTION (PEAK ACCL. = .5g), NO BUOYANCY FORCE

DISCUSSION

B. Sarkar (U.S.A.)

How do the authors propose to reconcile with the N.R.C. criteria for overturning ? Have they already approached and discussed the suggested alternative criterion with the N.R.C. and if they have, what is the out come ?

Author's Closure

With regard to the question of Mr. Sarkar, we wish to state that the criteria of the United States Nuclear Regulatory Commission for overturning due to seismic forces are based on the traditional approach of considering seismic forces static. Thus, it is required that the factor of safety computed on this basis be restricted to be greater than a specified number greater than unity. Our paper treats the seismic forces as dynamic and demonstrates that even when factors of safety are smaller than unity, the base rotations are extremely small and thus no overturning is indicated. Therefore, we maintain that the traditional approach is not realistic, especially for structures designed for high seismic forces. We recommend that more realistic criteria should be developed on the basis of base rotation calculations.

We have not approached the NRC on the above recommendations, but hope that the forum of this conference will expose them to it.