CRITICAL SEISMIC RESPONSE OF NUCLEAR REACTORS

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Summary

A new method is described for the assessment of structural earthquake resistance, and results are reported that are obtained by its application to three nuclear reactor installations. The method leads to assessments which are believed to be inherently more reliable than those derived by others currently in use or under consideration. This high level of confidence is admittedly purchased as a certain degree of conservatism, which may however be well justified in structures of the importance of nuclear reactors.

1. Introduction

It is generally conceded that the integrity of nuclear structures during a strong motion earthquake is of considerable social importance, and accordingly that assessments of it should be made on as high a level of confidence as possible. This paper describes a method by which such assessments can be made and it reports some results that were achieved with it.

The method relies on the concept of the "critical excitations" of a structure. These are synthetic excitations, constructed in such a way that they are realistic candidates for possible strong ground motions at the site of the structure, but which at the same time drive one of the design variables (e.g., a displacement or a moment or a shear force) to a largest response peak.

The high assurance level that can be attached to the results derives from the fact that the method avoids information, especially of a probabilistic nature, which is not known at present on the necessary level of confidence. That level of assurance is admittedly purchased at the expense of some conservatism which may however be well justified in structures such as nuclear reactors. Other applications have been described previously (see, e.g., [1]).

2. The Concept of a Critical Excitation

The central concept of the approach described in this paper is that of a critical excitation. One is led to it by the following line of reasoning.

The safety of an important structure is presumably to be assured for excitations that can realistically be expected at its location during a strong earthquake. It is thus necessary to start by defining the characteristics an excitation must have in order to be considered "realistic" (or "credible," to use another common term). Vanmarcke, in a recent review of this subject [2], observed that the present state of knowledge of seismology does not permit a very reliable distinction between realistic and unrealistic candidates for possible ground motions but that it frequently can be made on the basis of four characteristics, namely (1) intensity, (2) duration, (3) Fourier spectrum, and (4) time envelope of the vibrations. This is assuming that the focal distance, the site soil conditions, and macro as well as microzone of the location of the structure are known.

In this study, it was accordingly assumed that any ground motions already recorded at or near that location ought to be considered realistic, as well as any others recorded at locations with similar geological and seismological properties. These were called the basis excitations for the structure. In order to extrapolate to other, not yet recorded, excitations it was observed that the four characteristics listed above are shared by all linear combinations of basis excitations, provided that their intensities do not exceed the realistic maximum. Therefore all those combinations, and only those, were admitted as being realistic as well.

In this way, a set of excitations was defined all of which are "realistic" (or "credible"). In mathematical symbols, if x_i, $i = 1, 2, \ldots, n$, are the basis excitations the members of the set are of the form

$$x(t) = \sum_{i=1}^{n} a_i x_i(t), \qquad (1)$$

provided their intensity does not exceed the realistic maximum E. This constraint was interpreted as implying that

$$\left[\int_0^T x^2(t)dt\right]^{\frac{1}{2}} \leq E. \tag{2}$$

The response y of a variable of an elastic structure to an excitation in the set is then of the form

$$y(t) = \sum_{i=1}^{n} a_i y_i(t) \tag{3}$$

where y_i are the responses to the basis excitations.

The excitations that are of main interest or the ones that are realistic, i.e., lie in this set, and that drive a variable (such as a moment, or shear force, or displacement) to its largest response peak. These are called the "critical excitations" of the structure. Evidently, if a structure maintains its integrity under its critical excitations it will do so also under all other realistic ones. They therefore recommend themselves as test cases towards the assessment of its earthquake resistance.

3. Determination of Critical Excitations

A critical excitation has just been defined as a member of a set of excitations, and more particularly as one which drives one of the variables of a structure to its highest response peak. The set under consideration is characterized by (1) and (2), and the response y produced by any of its members x by (3). To be critical, therefore, an excitation must achieve

$$\max_t \max_{a_i} |y(t)| = \max_t \max_{a_i} \left| \sum_{i=1}^{n} a_i y_i(t) \right|,$$

subject to (2). Let x_c be one that does.

The determination of x_c is a double maximization. The one with respect to the a_i is a fairly standard calculus problem. Its solution is best written in matrix form, namely

$$a = \left[y^T X^{-1} y\right]$$

where a and y are column vectors with the components a_i and $y_i(t)$, respectively, and X is a matrix with the elements

$$X_{ij} = \int_0^T x_i(t) x_j(t) dt;$$

$\lambda = \lambda(t)$ is a scalar multiplier, namely

$$\lambda = E(y^T X^{-1} y)^{-\frac{1}{2}}.$$

The second maximization with respect to t can apparently be achieved only numerically. Both can be carried out quite efficiently. A typical computation time is 2 min, on an IBM 360/65 computer.

4. Analysis of Nuclear Reactor Structures

The critical excitation approach, as has been mentioned above seems particularly appropriate to the assessment of the seismic safety of structures of sufficient importance to warrant the conservatism of the method. Nuclear reactor structures seem highly suitable candidates. Accordingly three analyses are presented below.

Reactor structure I consists of a containment structure and an auxiliary building. The model is due to Hamilton and Hadjian [3]. It is a two-dimensional two-sticks model shown in Fig. 1, with seven lumped masses on one and four on the other. The soil-structure interaction is represented by two springs attached to the foundation, one horizontal and one rotational.

The installation is assumed to be located in California, on a stiff-soil site. Accordingly, 12 recorded ground motions on stiff-soils were selected as basis excitations. An intensity $E = 2.37 m/sec^{3/2}$ was used for the basis excitations as well as the critical one. This was the intensity of the ground motion recorded at El Centro, USA on 18 May, 1940.

A typical critical excitation for this structure is shown in Fig. 2. An inspection of it suggests that the critical excitation is indeed credible as a strong ground motion. Some of the critical response peaks are listed in Table 1 along with those generated by previously recorded ground motions. Also shown is the response "envelope," i.e., the highest among the peaks generated by the basis excitations.

Reactor structure II is an installation to be constructed on a stiff-soil site in India. It consists of outer and inner containments, as well as an internal equipment supporting structure. This installation was modeled by Arya et al. [4] by three-sticks, with 26, 22, and 2 lumped masses, respectively, shown in Fig. 1. Soil-structure interaction is represented by nine springs acting on the embedment portion, eight translational and one rotational.

In the analysis employed in this report, the basis excitations, and the intensity E were the same as those used for reactor structure I. The results are shown in Table 2.

Reactor structure III is an installation intended for a rock site in the USA. The design is by an engineering consulting firm and is represented by the three-dimensional stick model also shown in Fig. 1. It includes soil-structure interaction springs in three translational and rotational directions. The set of basis excitations is different from those used for the preceding two structures. They are past ground motions recorded at rock sites. The intensity $E = 5.37 m/sec^{3/2}$ was that of one of the members of the basis excitations, namely the ground motion recorded at the Pacoima Dam, USA, on 9 February 1971. Table 3 contains a list of response peaks calculated for the critical excitation as well as for some recorded motions.

The conclusion reached from this study is that there are realistic excitations, among them the critical, which produce higher responses than any of those produced by past ground motions recorded at locations with similar geological and seismological properties. Hence to improve the safety of important structures, it appears that design engineers need to consider critical excitation in their assessment process.

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Table I. Response Peaks of Reactor Structure I

Structural Variable	Excitation: Critical	El Centro^{+}	Envelope
Top displ't (cm)			
Containment	3.01	1.33	2.08*
Auxiliary Bldg.	0.12	0.07	0.09**
Bottom moment (10^6 ton-m)			
Containment	1.480	0.627	1.043*
Auxiliary Bldg.	.207	0.113	0.155**
Bottom shear (10^4 ton)			
Containment	2.89	1.45	2.08*
Auxiliary Bldg.	1.71	0.93	1.30**

+) Peaks due to ground motion at El Centro, USA, 18 May 1940

*) Peaks due to ground motion at Alexander Building, San Francisco, USA, 22 March 1957

**) Peaks due to ground motion at Sixth Street, Los Angeles, USA, 9 February 1971

Table II. Response Peaks of Reactor Structure II

Structural Variable	Excitation: Critical	El Centro+	Envelope
Top Displacement (cm)			
Node 1	22.7	16.9	16.9+
Node 2	14.0	10.3	10.3+
Bottom Moment (10^6ton-m)			
Member 25	.711	.546	.546+
Member 47	.471	.357	.357+
Bottom Shear (10^4tons)			
Member 25	1.093	.841	.841+
Member 27	1.398	1.075	1.075+

+Peaks due to ground motion at El Centro, USA, 18 May 1940

Table III.Peak Responses of Reactor Structure III

Structural Variable	Excitation: Critical	Pacoima+	Envelope
Top Displacement (cm)			
Node 16	10.63	5.97	10.05
Node 21	8,15	4.49	7.77
Moment (10^6ton-m)			
Member 2, Node 1	9.51	5.30	8.48**
Member 6, Node 2	5.58	3.11	5.23*
Member 17, Node 1	2.25	1.15	1.96**
Shear force (10^4tons)			
Member 2, Node 1	.259	.143	.231**
Member 6, Node 2	.110	.054	.105*
Member 17, Node 1	.090	.045	.077**

+) Peaks due to ground motion at Pacoima Dam, USA, 9 February 1971

*) Peaks due to ground motion at Golden Gate Bridge, San Francisco, USA, 22 March 1957

**) Peaks due to ground motion at Santa Anita Dam, USA 9 February 1971

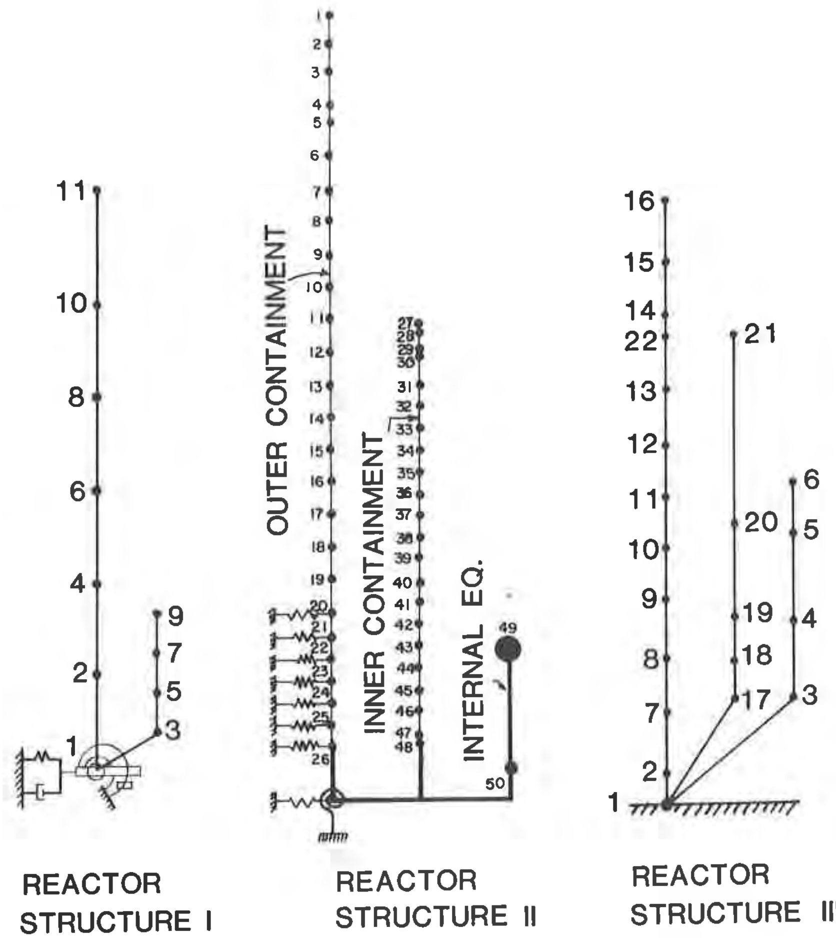

Figure 1 (top): Stick Models of Reactor Structures

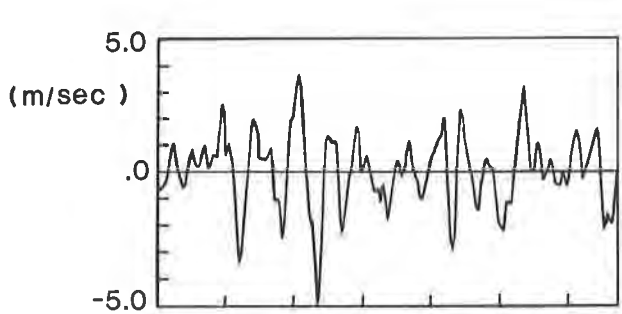

Figure 2 (bottom): Critical Excitation of Reactor Structure I (Bottom Moment, Containment Building)