COMBINATION OF TORSIONAL, ROTATIONAL AND TRANSLATIONAL RESPONSES IN THE SEISMIC ANALYSIS OF A NUCLEAR POWER PLANT

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SUMMARY

A particular type of seismic analysis performed on the Nuclear Island Buildings (NIB) complex of a nuclear power plant and the methods developed to combine torsional, rotational and translational responses are described. The NIB complex analyzed consists of various buildings supported on a common foundation mat and tied together from the underground foundation to the roof levels. Three independent building mathematical models were used for the three components of the earthquake with a lumped-mass method utilizing direct integration of the coupled equations of motion. The input ground acceleration time histories were based on three 20 s long statistically independent records whose normalized response spectra enveloped those of Regulatory Guide 1.60. A linear stochastic model was used to generate these records which simulated strong motion earthquakes. Due to site characteristics, the soil material properties were calculated considering different ranges of soil moduli below and above the foundation.

For the response spectrum analysis of equipment supported on the building floors, seven response spectra (three translational, two torsional and two rotational) were developed at each node for each of the two earthquakes (OBE and SSE). These seven spectra were required to completely define the floor motion since each building node was given three degrees of freedom in the horizontal models (E-W and N-S) and one degree of freedom in the vertical model. The general formulation is given initially, whereby these seven response spectra are applied individually for the equipment analysis. However, since this general procedure is time-consuming, a more practical, simplified procedure which combines the seven spectra and reduces them to the conventional three response spectra (two horizontal and one vertical) has been developed. This procedure combines the translational spectra with the translational components produced by the torsional and rotational spectra at a particular location of the equipment away from the node point. The combination is made on the square root of the sum of the squares basis. Therefore, this simplified procedure requires that the resulting directional effects (stresses, deflections) be combined absolutely. The application of the simplified procedure is demonstrated to yield results equal to or greater than those with the general procedure. For uncoupled equipment, the simplified procedure gives the same results as the general procedure. For coupled equipment, the simplified procedure is always conservative with the amount depending on the degree of directional coupling of the particular equipment.

1.0 INTRODUCTION

The seismic analysis and design of floor-supported nuclear power plant components which may be treated uncoupled from the supporting building requires a definition of the seismic response motion at their supports. The response motion is derived from a complete analysis of the building and foundation system. The method of analysis and mathematical modeling employed affect the type of floor responses obtained which must be considered in the components analyses. This paper describes the type of seismic analysis performed for the Nuclear Island Buildings (NIB) complex of a nuclear power plant, whereby three independent lumped-mass mathematical models were used for the three components of the seismic motion. A discussion of the pertinent parameters used in the analysis, the analytical methods, and methods developed to combine torsional, rotational and translational responses are given.

The mathematical models of the NIB utilized node points located at the center of mass of the applicable floors modeled. For each of the two horizontal directions (E-W and N-S), each node was given three degrees of freedom consisting of translation and rotation in the direction of the motion, and torsion about the vertical axis. For the vertical analysis, each node was given only a translational degree of freedom in the vertical direction. Therefore, the floor responses produced by this type of building analysis consisted of translation, torsion and rotation for each of the two horizontal directions, and direct translation for the vertical direction. This definition of building floor response motion requires that seven spectra (three translational, two torsional and two rotational) be used for the response spectrum analysis of components for each of the two earthquakes (OBE and SSE).

The general application of the above seven spectra is discussed which results in converting the torsional and rotational spectra into equivalent translational spectra for the appropriate direction of input. Since seven response spectrum analyses would be required for each earthquake (when giving proper consideration to the combination of seismic effects for each earthquake direction), a more practical, simplified procedure has been developed. This simplified procedure is based on combining the individual spectra for each spectrum input direction by the square root of the sum of the squares. This results in three equivalent total translational spectra (two horizontal, one vertical) which are used in the response spectrum analysis for the appropriate direction. The similar seismic effects obtained for each of the three directions are then combined absolutely. It is shown that the application of the simplified procedure gives results equal to or greater than those of the general procedure depending on the degree of directional coupling of the component.

2.0 NUCLEAR ISLAND BUILDINGS ANALYSIS

The nuclear power plant analyzed is a sodium cooled, fast breeder reactor plant with three loops. The Nuclear Island Buildings complex consists of the following Seismic Category I buildings whose plan layout is shown on Fig. 1.

- Reactor Containment (including the Steel Containment Vessel)
- Confinement
- Reactor Service
- Steam Generator, Intermediate and Auxiliary Bays, Control, and Diesel Generator

A The buildings are interconnected, reinforced concrete structures supported on a common foundation mat. The steel Containment Vessel is embedded in the concrete of the Reactor Containment Building below the level of the operating floor and is free-standing on its upper section. The material underlying the foundation consists of alternating layers of siltstone and limestone inclined at an angle of approximately 30° with the horizontal from West to East, as shown on Fig. 2. The Nuclear Island is located directly above the siltstone. The average shear wave velocity of the siltstone is 4000 ft/sec and that of the limestone is 6000 ft/sec.

The structural responses were investigated independently for the three directional components of the earthquake (E-W, N-S and Vertical). Artificial earthquake acceleration-time histories with a duration of 20 s and maximum acceleration of 0.25 g (for the SSE) were used in the analysis. To produce the input motions, a linear stochastic model was used to generate records of filtered non-stationary shot noise which simulated strong motion earthquakes. Three of the records were selected and modified to adjust to and envelop the design response spectra of Regulatory Guide 1.60 [1].

Three independent mathematical models of the buildings for each direction of the earthquake were used. Fig. 3 shows the model for the E-W direction. The buildings rest on a rigid plate which represents the common foundation mat, and are interconnected above the foundation with flexible ties. In the mathematical models for the two horizontal components of the earthquake (E-W and N-S), three dynamic degrees of freedom were allowed for each node. These were translation and rotation along the direction of the earthquake, and torsion about a vertical axis. In the model for the vertical direction, one dynamic degree of freedom (translation) was allowed per node.

The soil-structure interaction was represented in the mathematical models by equivalent massless foundation springs and dashpots. Each of the models for the horizontal directions has three foundation springs and dashpots. These consisted of a translational and a rotational spring and dashpot along the direction of motion, and a torsional spring and dashpot about the vertical axis through the mat centroid. Only one spring and dashpot were used for the vertical model. For the calculation of the foundation springs, a static finite element analysis was used since elastic half-space theory was not directly applicable to the inclined configuration of the soil strata. The damping coefficients for the foundation dampers were calculated based on the equations for geometric damping in an elastic half-space using equivalent half-space dynamic properties derived from the spring stiffnesses.

A lumped-mass method with direct integration of the coupled equations of motion was used in the analysis. The equations were solved using a computer program based on a formulation similar to that proposed by Tsai [2]. In this approach, the equations of motion are expressed in terms of the mode shapes, frequencies and damping values of the "fixed base" structure, and of stiffness and damping of the springs and dashpots that represent the soil effects on the structure. As a result of this formulation, the number of coupled equations to be integrated is reduced from N+S to M+S. N and M are the number of degrees of freedom and number of modes, respectively, of the "fixed base" structure, and S represents the number of degrees of freedom allowed in the foundation. For this large structure, M was much less than N. The analyses were made for lower and upper bounds of soil properties considering variation ranges of ±25% and ±50% below and above the foundation, respectively. The responses used for design were the envelope of those obtained with the above lower and upper bounds.

3.0 COMBINATION OF RESPONSE SPECTRA

For the particular building analysis and nodal degrees of freedom described above, seven response spectra are developed at each node. These are:

- horizontal translation in each of the E-W and N-S directions
- torsion due to each of the E-W and N-S earthquakes
- rotation due to each of the E-W and N-S earthquakes
- vertical translation

The torsional response produces a component of horizontal response for equipment located away from the node point on the same floor. Similarly, the rotational response produces a component of vertical response. In accordance with the criterion of combining similar effects (stresses, deflections) obtained for each of the three earthquake directions by the square root of the sum of the squares (SRSS) given in [3], the spectra are resolved for each input direction and applied individually as shown by the following equations:

Spectra Input in x-Direction

$$A_x^x = a_x + Y\theta_x;\ A_x^y = Y\theta_y \tag{1}$$

Spectra Input in y-Direction

$$A_y^y = a_y + X\theta_y;\ A_y^x = X\theta_x \tag{2}$$

Spectra Input in z-Direction

$$A_z^z = a_z;\ A_z^x = X\phi_x;\ A_z^y = Y\phi_y \tag{3}$$

where,

X, Y = absolute value of distance from node point to equipment location in x and y directions, respectively

A = total translational spectral acceleration for input to the response spectrum analysis

a = translational spectral acceleration from the translational response spectrum

Superscript = direction of the earthquake (E-W = x; N-S = y; Vertical = z)

Subscript = direction of spectrum input (x, y, z)

θ_x, θ_y = torsional spectral acceleration from the torsional response spectrum due to the E-W and N-S earthquakes, respectively

ϕ_x, ϕ_y = rotational spectral acceleration from the rotational response spectrum due to the E-W and N-S earthquakes, respectively

In eq. (1) the term $Y\theta_x$ is the equivalent translation in the x-direction produced by the torsional acceleration due to the E-W earthquake for equipment located at a distance Y (in the N-S direction) from the node point. The SRSS combination is performed on the similar effects which result from the individual application of the above spectra and as a last step after the modal combination for each earthquake direction. For example, if U, V, Z represent the combined modal displacements in the x, y and z-directions, respectively; and with the same superscript and subscript notation given above, then the combined displacements UC, VC and ZC for the three earthquake directions are given by

$$UC = [(U_x^x + U_y^x + U_z^x)^2 + (U_x^y + U_y^y + U_z^y)^2 + (U_z^z)^2]^{1/2} \tag{4}$$

$$VC = [(V_x^x + V_y^x + V_z^x)^2 + (V_x^y + V_y^y + V_z^y)^2 + (V_z^z)^2]^{1/2} \quad (5)$$

$$ZC = [(Z_x^x + Z_y^x + Z_z^x)^2 + (Z_x^y + Z_y^y + Z_z^y)^2 + (Z_z^z)^2]^{1/2} \quad (6)$$

The above procedure is a general formulation applicable to all systems and involves seven response spectrum analyses to identify the effects of each earthquake for each spectrum input direction.

Since the general procedure is time-consuming, a more practical, simplified procedure which combines the spectra and reduces them to the conventional three response spectra (two horizontal and one vertical) has been developed and is given by

$$A_x = [(a_x + Y\theta_x)^2 + (Y\theta_y)^2]^{1/2} \quad (7)$$

$$A_y = [(a_y + X\theta_y)^2 + (X\theta_x)^2]^{1/2} \quad (8)$$

$$A_z = [(a_z)^2 + (X\phi_x)^2 + (Y\phi_y)^2]^{1/2} \quad (9)$$

where A_x, A_y, A_z are the total horizontal and vertical spectral accelerations input individually in the x, y and z-directions, respectively, and the other terms are as defined for eqs. (1), (2) and (3). However, when using this simplified procedure, the similar effects obtained for each of the three spectral input directions must be combined absolutely and not by the SRSS. That is,

$$UC = |U_x| + |U_y| + |U_z| \quad (10)$$

$$VC = |V_x| + |V_y| + |V_z| \quad (11)$$

$$ZC = |Z_x| + |Z_y| + |Z_z| \quad (12)$$

where the subscripts x, y, z refer to the application of A_x, A_y, A_z, respectively. The absolute summation is required for this simplified procedure since the SRSS has already been included in the equations for each spectral input direction.

For comparison with eqs. (4), (5) and (6) of the general procedure, when the displacements corresponding to eqs. (7), (8) and (9) are substituted into eqs. (10), (11) and (12), the following equations (summed absolutely) result

$$UC = [(U_x^x)^2 + (U_x^y)^2]^{1/2} + [(U_y^y)^2 + (U_y^x)^2]^{1/2} + [(U_z^z)^2 + (U_z^y)^2 + (U_z^x)^2]^{1/2} \quad (13)$$

$$VC = [(V_x^x)^2 + (V_x^y)^2]^{1/2} + [(V_y^y)^2 + (V_y^x)^2]^{1/2} + [(V_z^z)^2 + (V_z^y)^2 + (V_z^x)^2]^{1/2} \quad (14)$$

$$ZC = [(Z_x^x)^2 + (Z_x^y)^2]^{1/2} + [(Z_y^y)^2 + (Z_y^x)^2]^{1/2} + [(Z_z^z)^2 + (Z_z^y)^2 + (Z_z^x)^2]^{1/2} \quad (15)$$

The adequacy of this procedure to yield results equal to or greater than those with the general procedure will be demonstrated in the subsequent section. The simplified procedure gives the same results as the general procedure for equipment whose effects in the directions normal to the direction of the spectral input are negligible, that is, directional uncoupled equipment. For coupled equipment, the simplified procedure is always conservative and the amount of conservatism obtained depends on the degree of directional coupling of the particular equipment.

3.1 Comparison of Simplified and General Procedures

To demonstrate the adequacy of the simplified procedure of combining response spectra, it will be proved that eq. (13) of the simplified procedure will always yield results as great or greater than those of eq. (4) of the general procedure. The following notation will be used to facilitate the writing

$U_x^x = A$; $U_y^y = B$; $U_x^y = C$; $U_y^x = D$; $U_z^z = E$; $U_z^y = F$; $U_z^x = G$

$UC = U_g$ for the general procedure and U_s for the simplified procedure

Eqs. (4) and (13) then become

$$U_g = [(A + D + G)^2 + (C + B + F)^2 + E^2]^{1/2} \tag{16}$$

$$U_s = (A^2 + C^2)^{1/2} + (B^2 + D^2)^{1/2} + (E^2 + F^2 + G^2)^{1/2} \tag{17}$$

by squaring both equations and elminating the common terms,

$$U_g = AD + AG + DG + CB + CF + BF \tag{18}$$

$$U_s = [(AB)^2+(CB)^2+(AD)^2+(CD)^2]^{1/2} + [(AE)^2+(AF)^2+(AG)^2+(CE)^2+(CF)^2+(CG)^2]^{1/2} + [(BE)^2+(BF)^2+(BG)^2+(DE)^2+(DF)^2(DG)^2]^{1/2} \tag{19}$$

the proof will consists of three parts in determining that

$$[(AB)^2 + (CB)^2 + (AD)^2 + (CD)^2]^{1/2} \geq AD + CB \tag{20}$$

$$[(AE)^2 + (AF)^2 + (AG)^2 + (CE)^2 + (CF)^2 + (CG)^2]^{1/2} \geq AG + CF \tag{21}$$

$$[(BE)^2 + (BF)^2 + (BG)^2 + (DE)^2 + (DF)^2 + (DG)^2]^{1/2} \geq DG + BF \tag{22}$$

Using eq. (20), after squaring both sides yields

$$AB/2CD + CD/2AB \geq 1 \tag{23}$$

The minimum value of this function is determined in accordance with standard methods to be 1.0. Therefore, eq. (23) is always $\geq$ 1.0 for any positive value of AB/CD.

Eqs. (21) and (22) are treated similarly by squaring both sides and obtaining, respectively

$$AE^2/2CGF + AF/2CG + CE^2/2AFG + CG/2AF \geq 1 \tag{24}$$

$$BE^2/2DFG + BG/2DF + DE^2/2BGF + DF/2BG \geq 1 \tag{25}$$

If only the second and fourth terms of each equation are used, that is, AF/2CG + CG/2AF, for eq. (24), and BG/2DF + DF/2BG, for eq. (25), the proof is the same as for eq. (20).

Other variations of the simplified procedure were investigated such as removing the SRSS from eqs. (7), (8), (9) and combining eqs. (10), (11), (12) by the SRSS. However, for this case (and others) the results would not be always as great as those of the general procedure.

4.0 CONCLUSIONS

A particular type of seismic dynamic analysis performed on the building complex of a nuclear power plant has been described. Descriptions were given of the mathematical models, foundation characteristics, input accelerograms and analytical methods employed. Due to independent mathematical models for each direction of the earthquake and the specific degrees of freedom assigned to the node points, seven floor response spectra were derived at each node (for each earthquake) to completely define the floor motion. These spectra consisted of two torsional and two rotational spectra in addition to the three translational spectra. Accordingly, for analysis of floor-supported components located away from the building models node points, seven response spectrum analyses were required for each earthquake.

The general formulation on the individual application of these spectra has been given.

The torsional and rotational spectra were converted to equivalent translational spectra by multiplying them by the distance from the node point to the location of the component on the same floor. The importance of the torsional and rotational spectra is obvious when the above distances are large.

A simplified method of combining the seven spectra and reducing them to only three equivalent total translational spectra has also been given. This method reduces computation time and yields conservative results. The adequacy of the simplified method has been shown by comparison with the general, seven spectra method. It was shown that the simplified method gives responses equal to those of the general method for uncoupled components, and greater for coupled components.

REFERENCES

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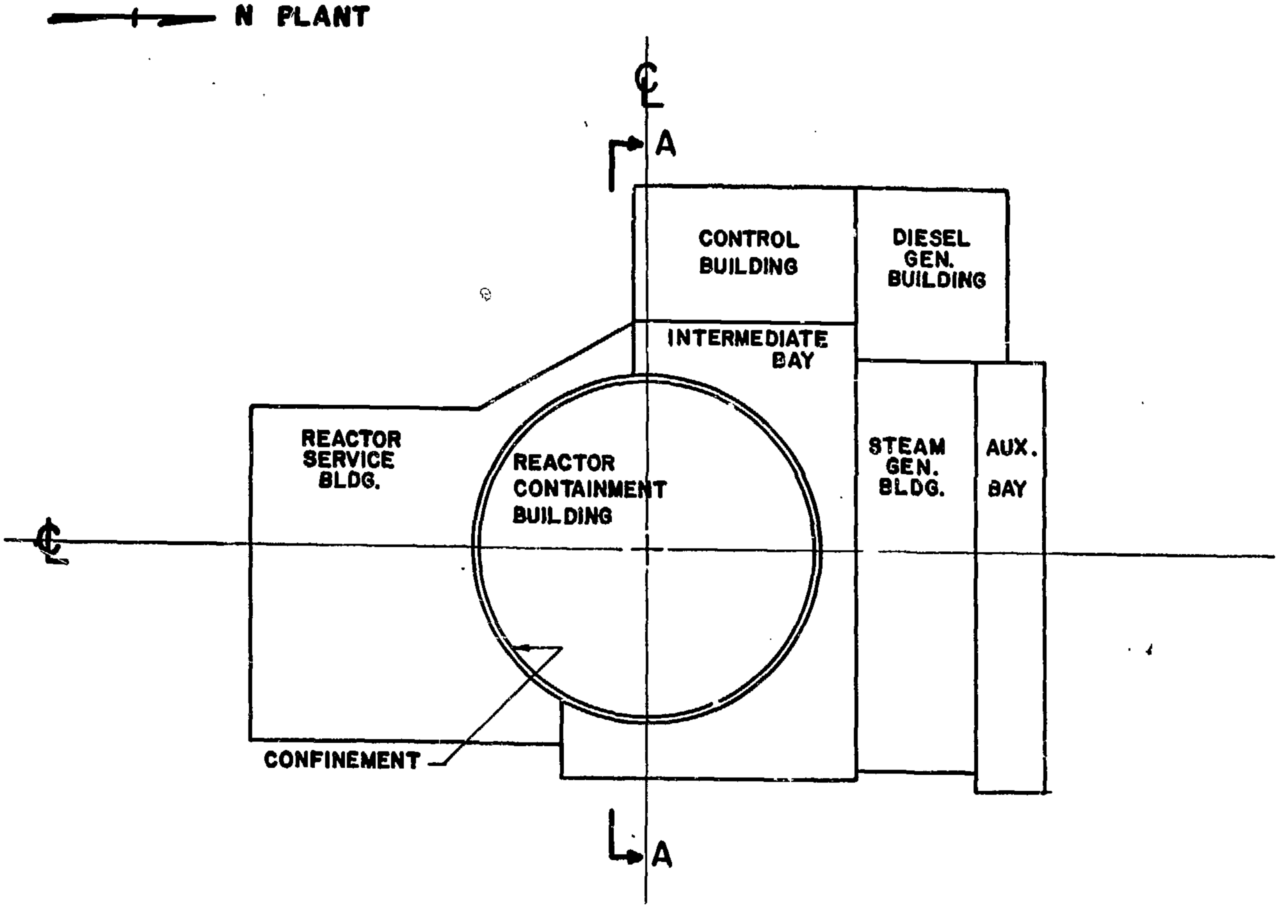
N PLANT
℄
A
A
CONTROL BUILDING
DIESEL GEN. BUILDING
INTERMEDIATE BAY
REACTOR SERVICE BLDG.
REACTOR CONTAINMENT BUILDING
STEAM GEN. BLDG.
AUX. BAY
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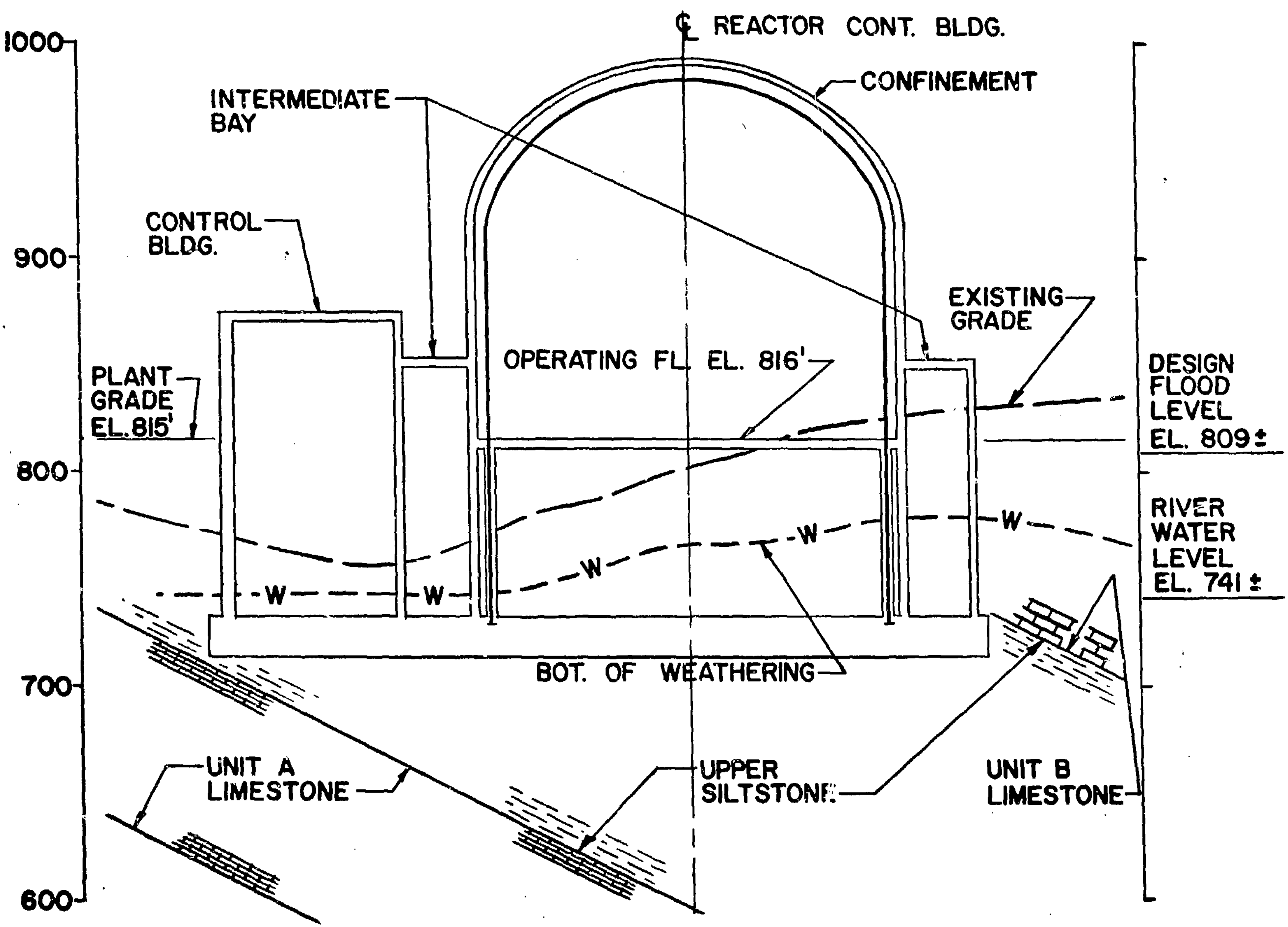
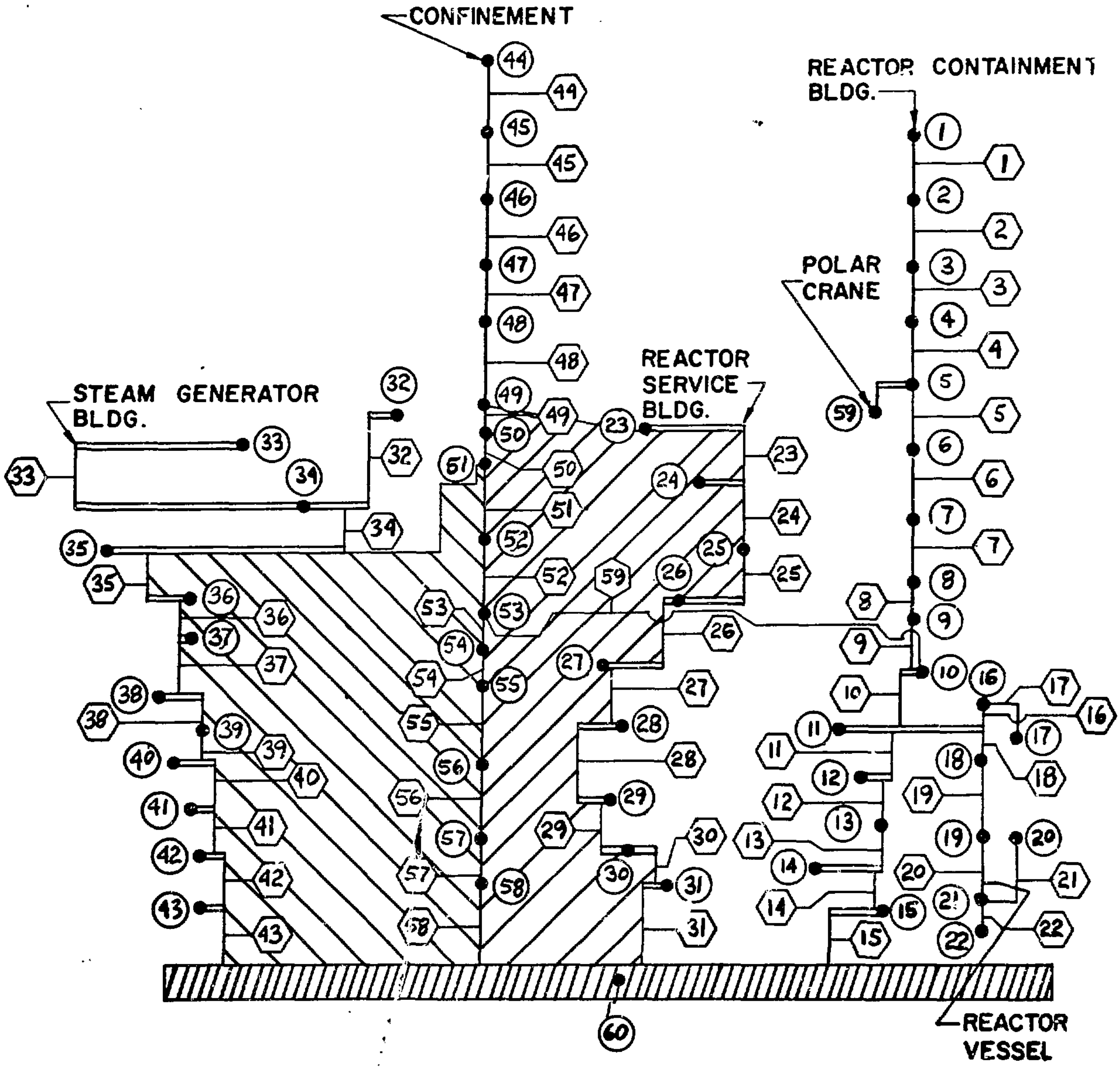
CONFINEMENT



℄ REACTOR CONT. BLDG.
CONFINEMENT
INTERMEDIATE BAY
CONTROL BLDG.
EXISTING GRADE
OPERATING FL. EL. 816'
PLANT GRADE EL. 815'
DESIGN FLOOD LEVEL EL. 809 ±
RIVER WATER LEVEL EL. 741 ±
W
BOT. OF WEATHERING
UNIT A LIMESTONE
UPPER SILTSTONE
UNIT B LIMESTONE
1000
900
800
700
600



○ MASS POINTS

⬡ BEAM ELEMENTS

▨ INTERCONNECTING ELEMENTS

* FOUNDATION SPRINGS NOT SHOWN