Computation of Co-Directional Seismic Responses for Large Scale Soil-Structure Interaction Systems

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ABSTRACT

Seismic responses generated for nuclear safety-related buildings by codes such as SASSI for the design of reinforced concrete and structural steel members require consideration of three components of the earthquake motion. To properly account for the responses of systems subjected to the three-directional excitation, a statistical combination is used to obtain the total response according to either the square-root-of-the-sum-of-the-squares (SRSS) criterion of Regulatory Guide 1.92 or the Load Factor method (100%, 40%, 40%) of ASCE 4. Either method, applied to the responses associated with the three components of ground motion, is used for determining the design forces for steel and reinforced concrete structures.

For seismic analysis, SASSI calculates time history responses (of a coupled 3-dimensional finite element dynamic model of the soil and building) due to time history input motion at the free field using the Fast Fourier Transform method. The input acceleration is applied in one direction only within each run while the response time histories (and stress time histories) are in all directions. For example, for input motion applied in the X-direction, the time history responses will be in the X, Y and Z directions. Co-directional responses are then combined outside of the SASSI computer program. The accelerations obtained from the SASSI time history analysis result in 9 response components from the 3 directions of seismic input. Combining these, using the 100%, 40%, 40% rule, and taking into account positive and negative phasing, results in 2^9 or 512 combinations for each direction of earthquake excitation or 1536 combinations for three directions at each response location. Evaluation of this large number of response combinations becomes prohibitive for large-scale soil-structure interaction models.

This investigation was initiated to determine the feasibility of using a reduced set of seismic response combinations due to three component earthquake input. Two buildings were analyzed rigorously to obtain the full suite of responses. Responses were then recalculated using reduced set of spatial combinations to confirm the proposed simplified methodology. It was shown that, for regular buildings, two reduced sets of combinations are adequate, based on conservative phasing assumptions. These reduced sets are 24 in number for above ground structures (slabs, walls and frames) and 96 for exterior walls below grade. Comparison of responses from the 1536 combinations with those from the reduced sets, for all locations in the two buildings, resulted in a maximum response exceedance of less than 5% in most cases.

1.0 INTRODUCTION

Seismic responses generated for nuclear safety-related buildings by codes such as SASSI (Ref. 1) for the design of reinforced concrete and structural steel members require consideration of three components of the earthquake motion. To properly account for the responses of systems subjected to the three-directional excitation, a statistical combination is used to obtain the total response according to either the square-root-of-the-sum-of-the-squares (SRSS) criterion of Regulatory Guide 1.92 (Ref. 2) or the Load Factor method (100%, 40%, 40%) of ASCE 4 (Ref. 3). Either method, applied to the responses associated with the three components of earthquake ground motion, is used for seismic stress computation for steel as well as for resultant seismic member force computations for reinforced concrete design.

For seismic analysis, SASSI calculates time history responses (of a coupled 3-dimensional finite element dynamic model of the soil and building) due to time history input motion at the free field using the Fast Fourier Transform method.

The input acceleration is applied in one direction only within each run while the response time histories (and stress time histories) are in all directions. For example, for input motion applied in the X-direction, the time history responses will be in the X, Y and Z directions. Co-directional responses are then combined outside of the SASSI computer program.

The accelerations obtained from the SASSI time history analysis results are:

X-directional excitation: X_x, Y_x, Z_x (Horizontal - EW)
Y-directional excitation: X_y, Y_y, Z_y (Vertical - Y)
Z-directional excitation: X_z, Y_z, Z_z (Horizontal - NS)

where X_y, for example, is defined as the acceleration in the X-direction due to excitation in the y direction. Combining acceleration responses for the above 9 components using the 100%, 40%, 40% rule, and taking into account positive and negative phasing, results in 2^9 or 512 combinations for each direction of earthquake excitation or 1536 combinations for three directions at each response location. Evaluation of this large number of response combinations becomes prohibitive for large-scale soil-structure interaction models and clearly, a more simplified but justifiable methodology, suitable for application to design, is needed. This investigation considers reduced sets of co-directional response combinations for determining the seismic design forces.

2.0 CO-DIRECTIONAL RESPONSE COMBINATIONS – ABOVE GRADE WALLS AND SLABS

As discussed above, for locations within arbitrary buildings subject to general three-directional seismic input, applied one direction at a time, 9 separate seismic acceleration responses apply:

Horizontal X-Excitation: X_x , Y_x , Z_x
Vertical Y-Excitation: X_y , Y_y , Z_y
Horizontal Z-Excitation: X_z , Y_z , Z_z

When these acceleration responses are combined by the Load Factor method, with +/- phasing taken into account, the result is 3 x 2^9 = 1536 total combinations for displacement or stress responses, R_x, R_y, and R_z:

$$R_x = (\pm X_x \pm Y_x \pm Z_x) + 0.4\,(\pm X_y \pm Y_y \pm Z_y) + 0.4\,(\pm X_z \pm Y_z \pm Z_z) \quad \text{(512 Comb.)}$$

$$R_y = 0.4\,(\pm X_x \pm Y_x \pm Z_x) + (\pm X_y \pm Y_y \pm Z_y) + 0.4\,(\pm X_z \pm Y_z \pm Z_z) \quad \text{(512 Comb.)}$$

$$R_z = 0.4\,(\pm X_x \pm Y_x \pm Z_x) + 0.4\,(\pm X_y \pm Y_y \pm Z_y) + (\pm X_z \pm Y_z \pm Z_z) \quad \text{(512 Comb.)}$$

or, re-arranging,

$$R_x = (\pm X_x \pm 0.4X_y \pm 0.4X_z) + (\pm Y_x \pm 0.4Y_y \pm 0.4Y_z) + (\pm Z_x \pm 0.4Z_y \pm 0.4Z_z) \tag{1}$$

$$R_y = (\pm 0.4X_x \pm X_y \pm 0.4X_z) + (\pm 0.4Y_x \pm Y_y \pm 0.4Y_z) + (\pm 0.4Z_x \pm Z_y \pm 0.4Z_z) \tag{2}$$

$$R_z = (\pm 0.4X_x \pm 0.4X_y \pm X_z) + (\pm 0.4Y_x \pm 0.4Y_y \pm Y_z) + (\pm 0.4Z_x \pm 0.4Z_y \pm Z_z) \tag{3}$$

These 1536 combinations constitute the rigorous method for combining co-directional seismic responses.

The critical seismic response occurs when co-directional accelerations act in the same direction. As such, the 1536 load combinations of the rigorous method can be reduced to the following 24 critical load combinations:

$$R_x = \pm\,(X_x + 0.4X_y + 0.4X_z) \pm (Y_x + 0.4Y_y + 0.4Y_z) \pm (Z_x + 0.4Z_y + 0.4Z_z) \tag{4}$$

$$R_y = \pm\,(0.4X_x + X_y + 0.4X_z) \pm (0.4Y_x + Y_y + 0.4Y_z) \pm (0.4Z_x + Z_y + 0.4Z_z) \tag{5}$$

$$R_z = \pm\,(0.4X_x + 0.4X_y + X_z) \pm (0.4Y_x + 0.4Y_y + Y_z) \pm (0.4Z_x + 0.4Z_y + Z_z) \tag{6}$$

where, each of equations 4 to 6 consists of 8 combinations, thus resulting in a reduced number of 24 combinations to account for maximum seismic loads.

3.0 CO-DIRECTIONAL RESPONSE COMBINATIONS – BELOW GRADE WALLS

Below grade walls may be subject locally to large lateral dynamic soil pressures. Since lateral dynamic soil pressure always resists the primary seismic inertia load (i.e. acts in the opposite direction), the min/max combined response of below grade walls may not occur when all co-directional terms act in the same direction (i.e., for the critical seismic 24 load combinations). In addition, the dynamic lateral pressure due to +X (or +Y) excitation applies to different wall locations for excitation in –X (or –Y) direction. Therefore, four separate load cases are required for horizontal excitations:

$H_x^+ =$ Dynamic lateral soil pressure applied in –X direction due to excitation in +X-direction
$H_x^- =$ Dynamic lateral soil pressure applied in +X direction due to excitation in -X-direction
$H_z^+ =$ Dynamic lateral soil pressure applied in –Z direction due to excitation in +Z-direction
$H_z^- =$ Dynamic lateral soil pressure applied in +Z direction due to excitation in –Z-direction

Let

$$+X_x^H = + X_x + H_x^+ \tag{7}$$

$$-X_x^H = - X_x + H_x^- \tag{8}$$

$$+Z_z^H = + Z_z + H_z^+ \tag{9}$$

$$-Z_z^H = - Z_z + H_z^- \tag{10}$$

In general, the primary seismic lateral inertia forces are greater than the dynamic soil pressure. The critical load combinations for considering dynamic soil pressure effect can be obtained by substituting Eq. 3 into Eq. 2 as follows:

$$R_x = \pm (X_x^H + 0.4X_y + 0.4X_z) \pm (Y_x + 0.4Y_y + 0.4Y_z) \pm (Z_x + 0.4Z_y + 0.4Z_z^H) \tag{11}$$

$$R_y = \pm (0.4X_x^H + X_y + 0.4X_z) \pm (0.4Y_x + Y_y + 0.4Y_z) \pm (0.4Z_x + Z_y + 0.4Z_z^H) \tag{12}$$

$$R_z = \pm (0.4X_x^H + 0.4X_y + X_z) \pm (0.4Y_x + 0.4Y_y + Y_z) \pm (0.4Z_x + 0.4Z_y + Z_z^H) \tag{13}$$

Since lateral dynamic soil pressure always resists the primary seismic inertia load (i.e. acts in the opposite direction), the min/max combined response of below grade walls may not occur when all co-directional terms act in the same direction (i.e. critical seismic 24 load combinations). For this case, the following provision applies:

When the absolute value of the section force (or moment) due to dynamic lateral soil pressure (H_x^+, H_x^-, H_z^+, or H_z^-) is greater than the force due to the primary lateral inertia load (X_x or Z_z), dynamic soil pressure dominates and the number of critical load combinations become 96 as follows:

$$R_x = \pm X_x^H \pm (0.4X_y + 0.4X_z) \pm (Y_x + 0.4Y_y + 0.4Y_z) \pm (Z_x + 0.4Z_y) \pm (0.4Z_z^H) \tag{14}$$

$$R_y = \pm (0.4X_x^H) \pm (X_y + 0.4X_z) \pm (0.4Y_x + Y_y + 0.4Y_z) \pm (0.4Z_x + Z_y) \pm (0.4Z_z^H) \tag{15}$$

$$R_z = \pm (0.4X_x^H) \pm (0.4X_y + X_z) \pm (0.4Y_x + 0.4Y_y + Y_z) \pm (0.4Z_x + 0.4Z_y) \pm Z_z^H \tag{16}$$

Equations 14 through 16 each represent 2^5=32 combinations, thus resulting in a total of 96 combinations when lateral soil pressure is present. This is a local effect only and does not apply to global response. Overall structural response is governed by the critical 24 load combinations in Equations 4 to 6 or Equations 11 to 13.

4.0 VALIDATION OF THE PROPOSED METHODOLOGY FOR CO-DIRECTIONAL RESPONSE COMBINATIONS

SASSI analyses for two buildings, Building A and Building B, were used to validate the proposed methodology. Both buildings are comprised of a concrete structure with steel superstructure as shown in figures 1 and 2. The dimension of building A is about 250ft wide by 560ft long, 120ft tall above grade and 45ft below grade. The building B is about 270ft wide by 450ft long, 125ft tall above grade and 20ft below grade.

The mathematical model of building A consists of about 7000 joints, 8000 plate elements for walls and slabs, and 5000 beam/column element for the steel superstructure. The building B consists of about 6000 joints, 5000 plate elements for walls and slabs, and 3000 beam/column element for steel superstructure.

These two structures were first analyzed for soil-structure interaction with SASSI, using a coarser finite element model. The maximum nodal accelerations were obtained considering the responses from all three directions of input motion. Due to the layout of the two buildings, the eccentricity between the center of mass and center of rigidity at each floor levels is large. Consequently, the acceleration response components in the directions perpendicular to the excitation direction are significant. The nodal accelerations at each floor were reviewed and accelerations to be used in subsequent equivalent static analyses were determined. These accelerations are applied all in the same direction, thus maximizing the total lateral load applied to the structure.

Typical acceleration profiles from SASSI analysis which are used as input into the static equivalent analysis are shown in tables 1 and 2, buildings A and B, respectively. As can be seen from Table 1, different accelerations were used in segments of some floor levels in Building A. In the case of Building B, constant floor accelerations were used.

Table 1: Building A - Seismic Inertia Loads - Design Accelerations (g)

Elevation	X(E-W)-Excitation			Y(Vertical)-Excitation		Z(N-S)-Excitation		
(ft)	X_x	Y_x	Z_x	$Y_y^{(1)}$	$Y_y^{(2)}$	X_z	Y_z	Z_z
120	1.3/0.9(3)	0.2	0.25	0.5	1.0/1.9/1.75	0.45	0.25	1.8/1.0
98	0.8/0.5	0.2	0.3	0.5	1.2/0.75/0.95	0.15	0.2	0.9/0.6
77	0.45	0.2	0.05	0.35	0.75	0.1	0.15	0.5
56	0.4	0.1	0	0.3	0.5	0.1	0.1	0.42
28	0.35	0.05	0	0.3	0.6/0.4/0.4	0	0.1	0.37
0	0.3	0.05	0	0.25	0.25	0	0.05	0.3
-21	0.3	0	0	0.2	0.2	0	0	0.3
-45	0.3	0	0	0.2	0.2	0	0	0.3

NOTES: (1) Y_y values applicable at column and wall locations.
(2) Y_y values applicable at floor and roof locations.
(3) Different acceleration values applied to different areas at same elevation.

Table 2: Building B - Seismic Inertia Loads - Design Accelerations (g)

Elevation	X(E-W)-Excitation			Y(Vertical)-Excitation		Z(N-S)-Excitation		
(ft)	X_x	Y_x	Z_x	$Y_y^{(1)}$	$Y_y^{(2)}$	X_z	Y_z	Z_z
86	1.2	0.3	0.36	0.48	0.8	0.18	0.12	1.08
70.5	0.72	0.3	0.36	0.48	---	0.18	0.12	0.72
57	0.48	0.3	0.24	0.48	0.96	0.18	0.12	0.48
36	0.84	0.12	0.18	0.24	---	0.18	0.12	0.42
13&23	0.72	0.12	0.12	0.24	---	0.18	0	0.42
0	0.3	0.1	0	0.2	---	0	0	0.3
-21	0.3	0	0	0.2	---	0	0	0.3
-31	0.3	0	0	0.2	---	0	0	0.3

NOTES: (1) Y_y values applicable at column and wall locations.
(2) Y_y values applicable at floor and roof locations.

From the acceleration values tabulated in Tables 1 and 2 for the two buildings, it is noted that there is no response contribution to the horizontal components from the excitation in Y-vertical direction.. Therefore, the general 9 components are reduced to 7 components, i.e. X_x, Y_x, Z_x, Y_y, Z_x, Z_y, Z_z. The full set of 1536 load combinations is reduced to 384 ($3x2^7$) load combinations. The critical sets of 24 and 96 load cases remain the same. In the process of validation, structural analyses of the two buildings are first performed for the seven components of seismic inertia loads and the four lateral dynamic soil pressures. Member forces and element stress resultants are then transferred to spread sheets. Excel is used to perform load combinations for full 384 load cases. The envelope force components of the full load cases are checked against the set of 24 load cases. If a maximum/minimum force component is not within the 24 load cases, then it is checked against the 96 load cases for dynamic lateral pressure effects.

Tables 3 to 6 show the comparisons of force components between full 384 load cases and the set of 24 critical load combinations. In building A, all force components of the steel structure and concrete walls are basically enveloped by 24 load cases as shown in Tables 3 and 4. Table 3 provides a comparison of the steel forces and Table 4 for reinforced concrete sections. The maximum difference is 7% in in-plane shear force due to relatively large dynamic lateral soil pressure. However, all force components not within the LC 24 are enveloped by the set of LC 96.

Tables 5 and 6 are summaries of comparison for concrete walls of building B, both for concrete walls. Table 5 considers only the seismic loads with dynamic lateral soil pressure. In general, all maximum/minimum force components are within LC24. Some force components with small values have larger differences in ratios such as maximum shear Vz in item 7. However, all force components are basically within the LC 24 when the seismic loads combined with static loads as shown in Table 6.

Table 3: Building A - Summary of Load Combinations for Steel Members

				MAX VALUE			MIN VALUE		
ITEM NO.	MEMBER NO.	JOINT NO.	FORCE COMP[2]	LC 384 kips/kip-ft	LC 24 kips/kip-ft	RATIO[1]	LC 384 kips/kip-ft	LC 24 kips/kip-ft	RATIO
1	7670	7704	MY	22.5	22.5	1.00	3.6	3.6	1.00
2	7670	5704	FX	209.3	209.3	1.00	-235.7	-235.7	1.00
3	7575	4331	FX	1539.8	1539.8	1.00	365.0	365.0	1.00
4	11375	5702	FX	82.9	82.9	1.00	9.5	9.5	1.00
5	11186	4203	FX	11.4	11.4	1.00	-15.4	-15.4	1.00
6	7670	7704	FZ	1.4	1.4	1.00	0.2	0.2	1.00
7	7670	7704	FX	241.5	241.5	1.00	-203.5	-203.5	1.00
8	7575	6331	FX	-359.2	-359.2	1.00	-1534.0	-1534.0	1.00
9	11186	6204	FX	16.0	16.0	1.00	-10.9	-10.9	1.00
10	12424	7656	FX	48.9	48.9	1.00	-26.9	-26.9	1.00
11	11375	7703	FX	-9.0	-9.0	1.00	-82.3	-82.3	1.00
12	9110	15731	FX	164.0	164.0	1.00	4.4	4.4	1.00
13	9110	17731	FX	1.0	1.0	1.00	-158.6	-158.6	1.00
14	16947	19245	FX	208.6	208.6	1.00	-220.5	-220.5	1.00
15	9678	18255	FX	199.2	199.2	1.00	-200.6	-200.6	1.00
16	9678	18255	MZ	12.2	12.2	1.00	12.2	12.2	1.00
17	9724	16256	FX	22.2	22.2	1.00	0.9	0.9	1.00
18	9724	16256	MY	-0.3	-0.3	1.00	-1.7	-1.7	1.00
19	9724	16256	MZ	25.8	25.8	1.00	-33.0	-33.0	1.00
20	9512	16235	FX	63.2	63.2	1.00	3.1	3.1	1.00
21	9512	16235	FY	28.3	28.3	1.00	-32.2	-32.2	1.00
22	9512	16235	FZ	5.64	5.61	1.01	-4.5	-4.48	1.00
23	9512	16235	MY	97.1	96.4	1.01	-121.2	-120.4	1.01
24	9512	16235	MZ	606.4	606.4	1.00	702.9	702.9	1.00

NOTES: (1) RATIO = LC384 / LC24.
(2) FX=axial force, FY and FZ=shears, MX, MY and MZ =moments.

Table 4: Building A - Summary of Load Combinations for Concrete Walls

				MAX VALUE			MIN VALUE		
ITEM NO.	ELEM NO.	JOINT NO.	FORCE COMP(1)	LC384 kips/kip-ft	LC24 kips/kip-ft	RATIO	LC384 kips/kip-ft	LC24 kips/kip-ft	RATIO
1	7329	30927	Fx	1424	1424	1.00	-621	-621	1.00
2	7329	30927	Fy	406	406	1.00	-90	-90	1.00
3	7329	30927	Fz	-123	-126	0.98	-245	-244	1.00
4	7329	30927	Mx	1273	1273	1.00	182	182	1.00
5	7329	30927	My	-113	-113	1.00	-1339	-1339	1.00
6	14:J-N6	cut results	P	-403	-403	1.00	-12420	-12420	1.00
7	14:J-N6	cut results	V(2)	9425	9135	1.03	3877	4167	0.93
8	14:J-N6	cut results	V(3)	1979	1979	1.00	-1979	-1979	1.00
9	14:J-N6	cut results	V(4)	2910	2910	1.00	-2638	-2638	1.00
10	14:J-N6	cut results	V(5)	8494	8494	1.00	4536	4536	1.00
11	14:J-N6	cut results	Vz	-398	-407	0.98	-8740	-8732	1.00
12	14:J-N6	cut results	Mb	55272	55272	1.00	-13556	-13556	1.00
13	14:J-N6	cut results	Mt	2771	2771	1.00	-22894	-22894	1.00
14	14:J-N6	cut results	Mz	198222	198222	1.00	104968	104968	1.00

NOTES:

1. Fx, Fy and Fz= element nodal forces, Mx and My = element nod moments, P = Force normal section, V= In-plane shear force, Mz= In-plane rotational moment, Vz= Transverse shear force, Mb=Bending moment, Mt=Twisting moment.
2. Combination of static loads and seismic load with dynamic lateral soil pressure.
3. Seismic inertial load without dynamic lateral pressure.
4. Seismic inertial load with dynamic lateral pressure.
5. Combination of static loads and seismic load without dynamic lateral soil pressure.

Table 5: Building B - Summary of Load Combinations for Concrete Walls (Seismic Loads Only)

ITEM	FORCE[1]	Cut A			Cut B			Cut C		
NO.	kip/kip-ft	LC1536	LC24	RATIO	LC1536	LC24	RATIO	LC1536	LC24	RATIO
1	V_max	9221	9217	1.00	1906	1906	1.00	1847	1847	1.00
2	V_min	-9187	-9183	1.00	-1889	-1889	1.00	-1805	-1805	1.00
3	P_max	1809	1772	1.02	781	781	1.00	2262	2262	1.00
4	P_min	-1714	-1676	1.02	-757	-757	1.00	-2252	-2252	1.00
5	Mz_max	174555	174555	1.00	7856	7856	1.00	4334	4325	1.00
6	Mz_min	-173593	-173593	1.00	-7916	-7916	1.00	-4582	-4573	1.00
7	Vz_max	304	280	1.09	84	70	1.21	30	30	1.01
8	Vz_min	-1044	-1006	1.04	-322	-304	1.06	-31	-31	1.01
9	Mb_max	3796	3662	1.04	1888	1806	1.05	289	264	1.10
10	Mb_min	-7513	-7380	1.02	-2906	-2823	1.03	-314	-288	1.09

NOTES: (1) See note 1 in Table 4.

Table 6: Building B - Summary of Load Combinations for Concrete Walls (Static and Seismic Loads Combinations)

ITEM NO.	FORCE$^{(1)}$ kip/kip-ft	Cut D			Cut E			Cut F		
		LC1536	LC24	RATIO	LC1536	LC24	RATIO	LC1536	LC24	RATIO
1	V_max	6158	6157	1.00	3453	3453	1.00	1321	1320	1.00
2	V_min	-6146	-6145	1.00	-3493	-3493	1.00	-1404	-1404	1.00
3	P_max	6522	6522	1.00	4766	4766	1.00	126	124	1.02
4	P_min	-6576	-6576	1.00	-4785	-4785	1.00	-33	-32	1.02
5	Mz_max	68818	68818	1.00	29275	29275	1.00	6457	6455	1.00
6	Mz_min	-66978	-66978	1.00	-28735	-28735	1.00	-6277	-6276	1.00
7	Vz_max	1977	1976	1.00	546	543	1.01	45	45	1.01
8	Vz_min	-1906	-1906	1.00	-541	-539	1.01	-181	-179	1.01
9	Mb_max	14731	14665	1.00	4903	4889	1.00	1494	1492	1.00
10	Mb_min	-14610	-14545	1.00	-4886	-4872	1.00	-349	-345	1.01

NOTES: (1) See note 1 in Table 4.

5.0 CONCLUSIONS

Seismic analysis and design of massive nuclear safety-related structures require consideration of soil-structure interaction and three components of earthquake motion. In general, soil-structure interaction analyses are carried out separately for seismic input in each orthogonal direction, using a code such as SASSI. This process results in nine response parameters at each node and for each element. These response parameters are maximum values considering the entire time-history output. Since occurrence of maximum responses simultaneously is unlikely, algorithms such as the component factor method (ASCE 4) are routinely used to obtain the design values. Using the component factor method, rigorous treatment of these responses to determine the design values requires 1536 seismic response combinations. This paper examined the feasibility of reducing the number of combinations using the factor method.

Two structures were analyzed using SASSI with independent earthquake inputs applied in three orthogonal directions. Seismic responses were combined by the rigorous approach as well as by a proposed method consisting of a reduced number of seismic response combinations. Results show that, for above ground structures, the 1536 response combinations can be reduced to 24 that will envelop the results from the rigorous analysis. Comparison of results in terms of design forces is given for the two structures- as well as response accelerations over the height of the structures.

For the parts of the structures below ground, the response combination equations can be reduced to 96 to envelop the responses by the rigorous analyses. These 96 combinations would be needed in some cases where the lateral incremental dynamic soil pressure results in greater design forces than those due to wall inertial loads. Even in this case, use of the basic 24 combinations resulted in design forces that are within 5% of the values obtained from the rigorous analysis for most cases. A procedure based on these reduced combinations has been incorporated into a design software package for production engineering use.

It is recommended that the basic 24 response combinations be incorporated into the analysis process or into a design software that interfaces with the analyses code output. In addition, for parts of the structure subject to dynamic soil pressure, the adequacy of the basic 24 response combinations should be evaluated and, if necessary, the 96 response calculations should be carried out to determine the design forces. This approach will optimize the effort needed to complete the analysis and design process for such massive structures."

6.0 REFERENCES

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2. Regulatory Guide 1.92, *Combining Modal Responses and Spatial Components in Seismic Response Analysis,* July, 2006
3. ASCE 4, *Seismic Analysis of Safety-Related Nuclear Structures and Commentary*

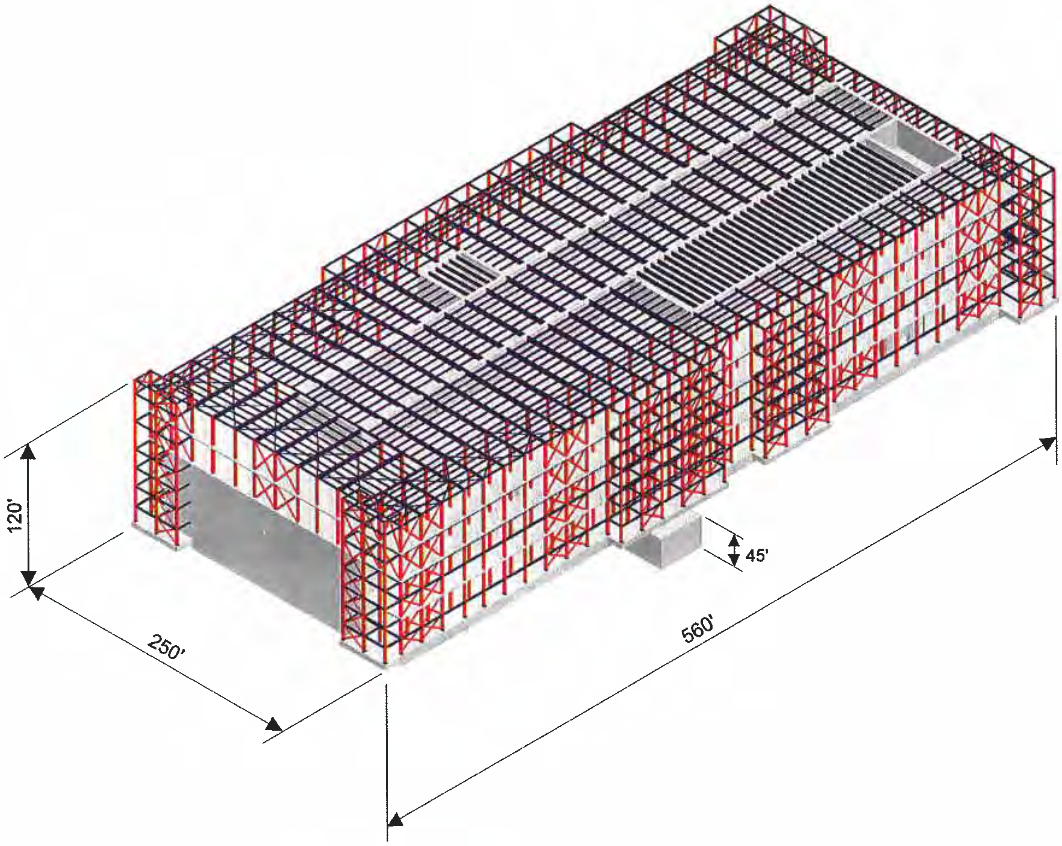

Figure 1: Building A

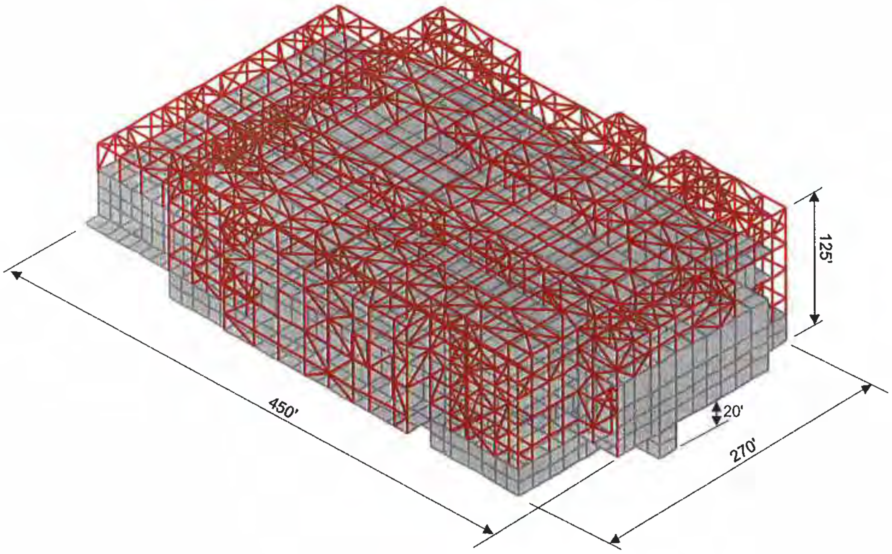

Figure 2: Building B