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The effects of soil-structure interaction on the seismic response of structures due to torsional unbalance

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ABSTRACT : For many structures the severity of an earthquake may be lowered dramatically by considering the flexibility of the supporting subgrade medium. For a torsionally unbalanced structure, when a transverse mode is coupled to a rotational mode, dynamic amplification of the torsional component will dominate the seismic response because of structural asymmetry and low damping. A seismic Soil-Structure Interaction(SSI) of a typical nuclear power plant building with a moderate torsional unbalance will be analyzed to demonstrate that by taking into account the flexibility of soil underneath the structure, the response peak at floors due to the coupling of transverse mode and torsion mode will be flattened or even eliminated.

1. INTRODUCTION.

A structure is torsionally unbalanced when its center of stiffness is offset from its center of mass. Some structures show inherent torsional unbalance due to an asymmetric floor plan or an asymmetric layout of the structural members. Even with nominally balanced structures, accidental torsional unbalance can arise due to non-homogeneous material; distribution of live loads; rotational component of ground motion about the vertical axis or progressive failure of structural members. Building Codes(ICBO 1994, NBC 1993)[1,2] or Standard Review Plan[6], therefore, call for an "accidental eccentricity", typically 5% of the major dimension of the building, in the story under consideration perpendicular to the direction of the applied earthquake forces.

When a transverse mode is coupled to a rotational mode by moderate torsional unbalance, the dynamic amplifications of the torsional component of seismic responses increase dramatically. This phenomenon is more pronounced for a structure which has closely spaced modal frequencies, large torsional unbalance and sufficiently low modal damping. For nuclear power plant structures, SSI analysis shall be performed if the structures are not supported by rock or rock-like foundation media. According to USNRC SRP Section 3.7.2[6], a fixed-base support may be assumed in modeling plant structures for seismic response analysis when the site soil conditions have a shear wave velocity of 3500ft/sec(1100m/sec) or greater at shear strain of 0.001% or smaller when considering preloaded soil conditions due to the structure.

This paper presents the results of a study involving interaction effects on the seismic responses of a nuclear power plant structure which is torsionally unbalanced.

2. DESCRIPTION OF STRUCTURES & SITE CONDITION

The typical nuclear power plant fuel building is a reinforced concrete shear wall structure founded on grade. The building is composed of 4 levels including the roof. The slabs are connected by a system of reinforced concrete shear walls with various thickness. Figure 1 shows the typical elevation view of the Fuel Building with the unbalanced geometry along the X-axis (NS direction) which may cause torsion in the horizontal (X-Y) plane.

The soil profile underneath the foundation consists of a weak zone overlying hard rock. The weak zone includes approximately 30 ft of backfill, a 50 ft upper fractured zone, a 50 ft hydrothermally altered zone, and a 40 ft lower fractured zone. The shear wave velocity of the weak zone varies from 1650 ft/sec to 3300 ft/sec.

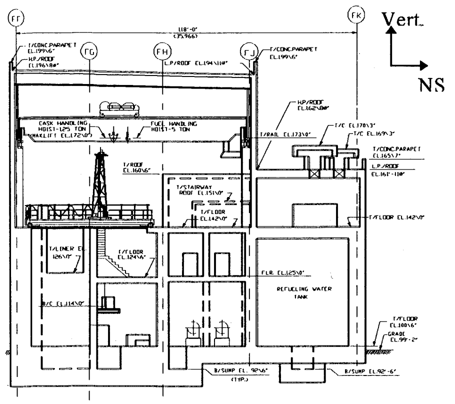


Figure 1. Typical elevation view of fuel building

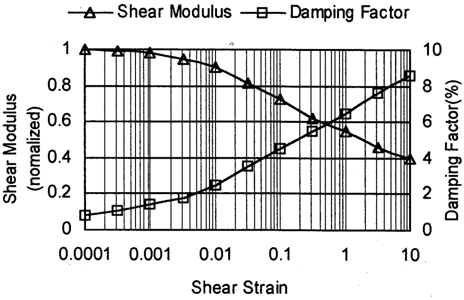
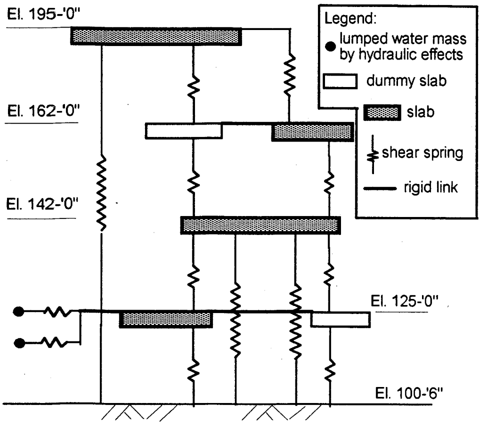


Figure 2. Strain dependent shear modulus and damping curve

3. SOIL MODELS FOR SSI

The primary nonlinear effect in the free-field has been accounted for by using an iterative scheme referred to as the "Equivalent Linear Method". The equivalent linear procedure was originally proposed by Seed and Idriss[5]. The equivalent linear procedure is based upon representing the hysteresis stress-strain loop by its equivalent secant modulus plotted as a function of the maximum shear strain reached in that hysteresis loop. The actual soil properties used are then iteratively adjusted to be compatible with the strains induced in each soil layer during the postulated earthquake ground motions. In the free-field analysis, the backfill below the building to achieve proper elevation is assumed to have properties of lean concrete. The strain dependent shear modulus and damping curve representing the 3 layered soil profiles are assumed as shown in Figure 2.

To take into account the variation of soil properties, the SSI analyses have been performed by using three sets of values. These three analyses have been performed by using average (best estimate) value, average value divided by 1.5 (ASCE standard 4-86) corresponding to a low shear strain modulus(G_{max} defined at 0.0001% peak shear strain), and value corresponding to a shear wave velocity of 3500 ft/sec. These three sets of soil properties are defined as mean value, lower bound and upper bound, respectively.



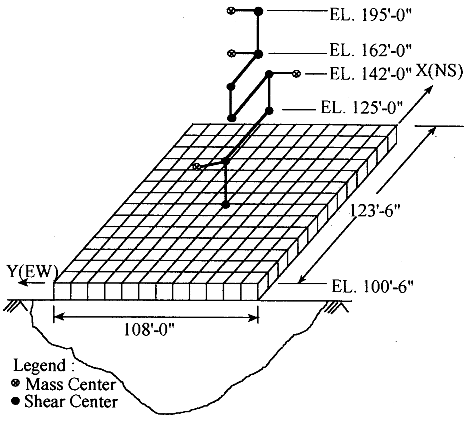


Figure 3. Lumped Mass Shear-Spring Model

Figure 4. Schematic Model for SSI Analysis

4. STRUCTURAL MODELS FOR ANALYSIS

In order to evaluate the effects of torsional unbalance on the structural response, seismic models for rigidly supported (fixed-base) condition and elastically supported (SSI) system have been developed.

4.1 *Fixed-base Model*

1) Structural Model : The floor slab-shear wall configuration of the Fuel Building is modeled as a slab-spring system in which the structure mass is lumped at each floors centeroid. The slabs are treated as infinitely rigid in their own plane and are interconnected by weightless linear elastic springs that simulate the stiffness of shear walls. Each slab in the model has two translational degrees of freedom in the horizontal direction and one rotational degree-of-freedom about the vertical axis of the structure.

To represent the torsional effect of the asymmetric mass-stiffness distribution of the building, weightless springs interconnecting each slab are used to model the shear walls. The hydrodynamic effects of the pool water in the spent fuel pool and the refueling water tanks are modeled by equivalent oscillators using the method suggested by G. W. Housner[3]. The lumped mass shear-spring model of the building structure is shown in Figure 3.

2) Mass and Stiffness Properties : Each slab has three degrees of freedom, two horizontal translations and one rotation about the vertical axis. Mass properties are the weights associated with the two horizontal translations and the weight polar moment of inertia of the slab. The stiffness of each spring representing a shear wall is calculated by inverting the deflection from the combination of flexure and shear as

$$K = 1/\Delta \quad , \quad \Delta = \frac{h^3}{12EI} + \frac{12h}{GA} \tag{1}$$

where, h and A represent height and cross section area of the shear wall respectively; G and E are respectively shear and elastic modulus of concrete; I is moment of inertia of the shear wall for bending about a centroidal axis perpendicular to the length of the wall.

4.2 *SSI Model*

The fixed-base seismic model is a horizontal lumped mass shear-spring model simulating slabs and shear walls. A rigid space frame is used to simulate the dynamic behavior of a system of horizontal slabs connected with shear walls. The superstructure of the SSI model is converted from the fixed-base model. The model consists of mass points joined together by weightless members. The mass points represent the slabs and are placed at the slab centroids of mass. The weight components given at mass points are those of the actual structure. The model considers vertical columns as pure-shear members. There are no masses at column ends. The masses presented are only lumped at the slab centroids. The basemat is modeled by 168 eight-node solid brick elements which are connected to the underlying soil at 195 nodes(see Figure 4).

5. ANALYSIS PROCEDURE

5.1 *Fixed-base Model*

The time history analysis method is used to calculate the acceleration response of the structure. Newmark's β-method for numerical integration combined with the modal superposition method has been used for solving the governing differential equation for linear systems with time dependent input base motion. The computer program DYNAS[1] is used to perform the analysis. Subsequently, the RSG program[2] is used to generate acceleration response spectra at different wall and slab locations. In the analysis, the earthquake excitations in the North-South and East-West directions are applied simultaneously because it has been shown that the input time histories are statistically independent.

5.2 *SSI Model*

There are two different approaches to assess the effects of soil-structure interaction. The first involves modifying the free-field design ground motion and evaluating the response of the structure to the modified motion. The second involves modifying the dynamic properties of the structural system and then evaluating the response of the modified structural system to the prescribed free-field ground motion[7]. When properly implemented, both approaches lead to equivalent results. However, the second approach, involving the use of the free-field ground motion, is more convenient for design purposes and is adopted for this evaluation. The computer program SASSI[4] was used to perform the SSI seismic analysis. The half-space solution technique has been used and the analysis is comprised of the following steps:

a) Solve the site response to determine the free-field motions within the embedded portion of the structure: The site is assumed to consist of horizontal soil layers overlying a uniform halfspace. All material properties are assumed to be viscoelastic. The mode shapes and wave numbers corresponding to control motions at any layer interface for SV wave and P wave are determined.

b) Solve the impedance problem: This step involves determining the impedance matrix which is a complex stiffness matrix corresponding to interacting nodes in free-field soil medium of the substructure. The calculation of the impedance matrix is achieved by inverting the dynamic flexibility (compliance) matrix for each frequency of the analysis.

c) Structural analysis: The structure which consists of the superstructure and the basemat is modeled by finite elements. The material damping ratio defined at the element level is used to compute the complex stiffness of the element, thus allowing for variation of damping from element to element. The acceleration amplitudes are obtained by forward reduction and back-substitution of the load vector using the reduced coefficient matrix.

The acceleration response spectra at different wall and slab locations are generated by the computer program RSG.

5.3 *RESULTS*

Modal frequencies and modal participation of fixed-base model are presented in Table 1. The first 4 modes are due to hydrodynamic effects of pool water in the spent fuel pool and refueling water tanks. For the rigidly supported system, the first mode undamped natural period of the structure is 0.095 sec in both horizontal directions. The second structural mode is 0.05 sec. in X(NS) direction and 0.06 sec. in Y(EW) direction.

Table 1 : Modal frequencies and participation factors

Mode	Period (sec)	Frequency (cycle/sec)	Participation	
			X-excitation(N-S)	Y-excitation(E-W)
1	6.897	0.1450	0.0	-11.409
2	3.676	0.2720	0.0	-4.064
3	3.493	0.2863	7.127	0.0
4	3.362	0.2974	3.665	0.0
5	0.096	10.3623	-17.366	-15.057
6	0.095	10.5320	-20.387	13.024
7	0.064	15.5330	0.773	17.116
8	0.057	17.5421	-0.586	21.021
9	0.051	19.6717	22.071	0.007
10	0.040	25.1784	0.210	8.181
11	0.028	35.2280	-0.701	-0.974
12	0.026	38.2632	-4.082	-0.941
13	0.025	39.8689	0.621	-4.227
14	0.021	48.3568	-0.190	-0.599

The floor response spectra are generated over a range of frequencies from 0.5 Hz to 50 Hz and at damping ratio of 2%. The response spectra comparisons between rigidly and elastically supported systems subjected to a strong earthquake in the horizontal direction are plotted on the same grid. Figure 5 and Figure 6 show the typical response spectra for the well-balanced structure(NS direction) and for the torsionally unbalanced structure(EW direction) at the third floors(EL. 162'-0"), respectively. Figure 6 shows that although the predominant response of the unbalanced structure occurs at the second or higher modes which are not major structural frequencies under the fixed base analysis, the responses for the SSI analysis are dominated by the first-mode(about 10 Hz) which is the major structural frequency. Additionally, the first-mode response increases and the ratio of higher-mode to first-mode response decreases due to SSI effects.

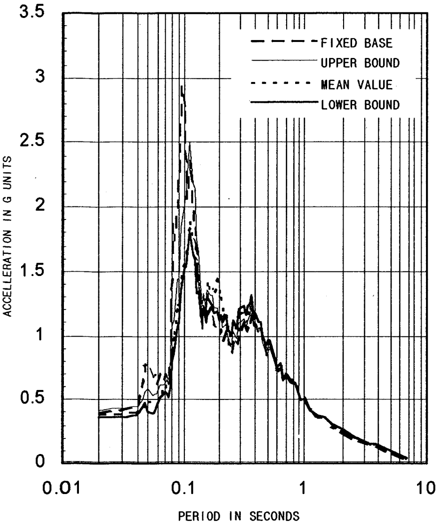


Figure 5. Response Spectra (N-S direction)

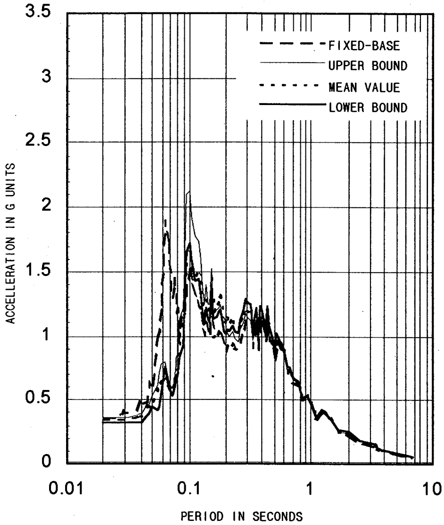


Figure 6. Response Spectra (E-W direction)

6. CONCLUSIONS

The interaction effects usually result in a frequency shift to the lower frequency range and tend to flatten sharp peaks or even eliminate the fixed-base response peaks. The horizontal slab accelerations in the torsionally balanced direction(Y-dir.) are controlled primarily by the period and damping of the first vibration mode. Under the SSI analyses, the elastically supported system acts like a seismic isolator to reduce torsional unbalance due to the effect of soil springs and half-space radiational damping. With the range of soil properties, the behavior of the SSI responses are: Higher responses in the high frequency range are observed for stiff medium; Higher responses at low frequency ranges are observed for weak medium; Frequency shifts are very insignificant, and the variation in acceleration responses are within 20%.

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