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SOIL-STRUCTURE INTERACTION FOR SEISMIC ANALYSIS OF A NUCLEAR FACILITY

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ABSTRACT

The effects of soil-structure interaction (SSI) on the seismic responses of a nuclear facility are evaluated in accordance with the procedure of CSA N289.3. Load-deformation and damping characteristics of the foundation rocks are represented by foundation springs, which are derived based on the formulas recommended in FEMA-356 and ASCE-4 publications. Equivalent "effective linearized" models are used to represent the non-linear load-deformation characteristic of rock foundation and the seismic intensity. Six foundation springs are estimated for the three translational and three rotational axis of the structure, and both material and geometrical damping are considered in the SSI analysis. The adequacy of the models is verified by the ultimate foundation capacities and the structural design. The uncertainty in soil properties is defined by an upper and a lower bound estimates. Three-dimensional time history analyses are performed for the seismic SSI analysis of the nuclear facility. The two horizontal and one vertical synthetic time histories are first spectral-matched to the design response spectrum, and then used as inputs to the model. The results of analysis show the variations in peak structural response due to the effects of foundation stiffness. For design purpose, the envelope of the variations is used.

1. Introduction

The effects of soil-structure interaction (SSI) shall be considered in seismic design of nuclear facilities, if the foundation materials are not a rock or rock-like soil to support structures. Generally direct or impedance method is used for SSI seismic analysis. For direct method, the entire soil-foundation-structure system is modeled and analyzed in a single step based on the input of ground motions at the boundaries. However, impedance method uses multiple steps to combine two primary causes of SSI, i.e. the inability of the foundation to match the free-field deformation and the effect of the dynamic response of the structure-foundation system on the movement of the supporting soil.

Finite element and lumped spring models are normally used for soil modeling in dynamic

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analysis of SSI. The soil is discreted into finite elements to which the soil properties are specified using finite element model. The boundary of soil considered for SSI shall be large enough so that the seismic response at the points of interest is not significantly affected. Compared to more elaborate finite element model, lumped spring model is a simplified method for dynamic analysis of SSI. The stiffness and damping of foundation springs can be calculated based on the dynamic properties of soil. In general, finite element model can provide more accurate results in seismic response of structures.

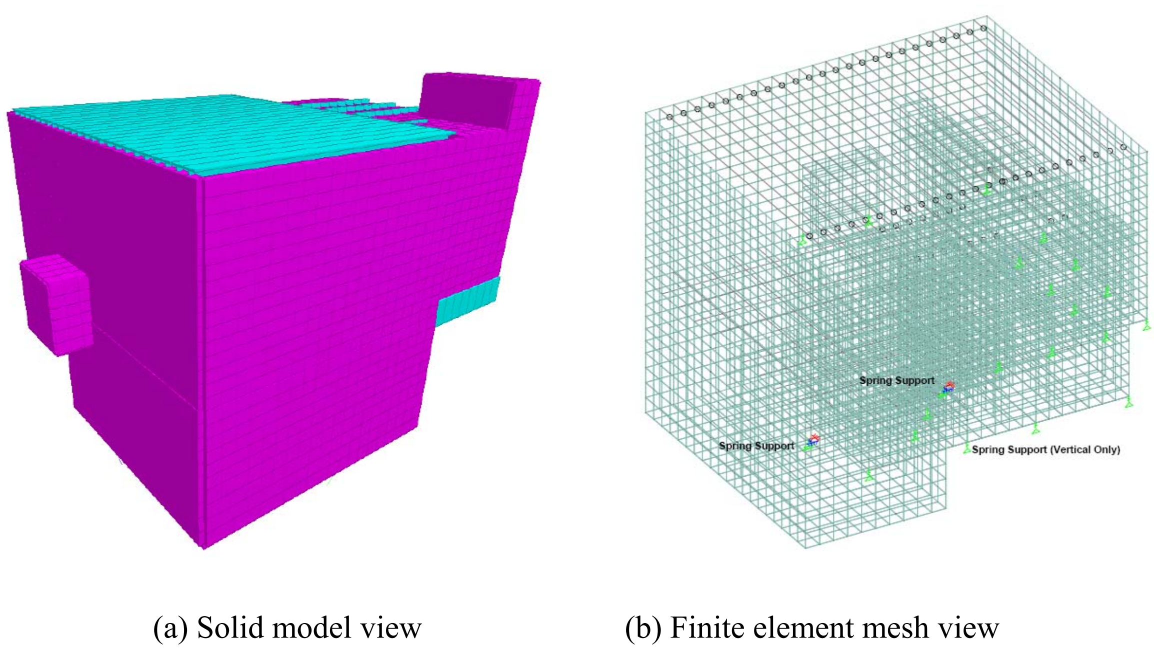
In this paper, a case study for dynamic analysis of a nuclear facility located in a high seismic hazard zone is presented. Direct method and lumped spring model are used in dynamic analysis of SSI. The seismic response of nuclear facility due to foundation springs is discussed. The significance of modeling of SSI in this study is to consider deep embedment of building into soil, irregular shape of base slab, and application of soil springs at different elevations.

2. Analysis Model

2. 1 Structural Model

A concrete nuclear facility is investigated in this study. The structure consists of underground rooms with a large open area above. There are a three-story structure at one side and a two-level structure at the opposite side. The total height of facility including underground rooms is 80 feet. The seismic force resisting system (SFRS) is concrete shear wall.

Fig. 1 shows a three-dimensional finite element model. STAAD.Pro is used for dynamic analysis of SSI in this study. The concrete shear wall is modeled using plate element. The concrete and steel beams and the precast double Tee slabs are modeled using beam element.



(a) Solid model view (b) Finite element mesh view

Figure 1. Structural model in STAAD.PRO

2. 2 Soil Spring Model

In this study for seismic analysis of SSI, foundation springs are used to represent load-deformation and damping characteristics of the foundation soil materials. The foundation springs are derived based on the formulas and procedures as outlined in Federal Emergency Management Agency 356 (FEMA-356, 2000) and American Society of Civil Engineers 4 (ASCE-4-98) publications. They are functions of:

- Building foundation stiffness relative to supporting rocks (rigid or flexible with respect to foundation rock),
- Engineering characteristics of supporting rocks (shear modulus and Poisson's ratio),
- Foundation dimensions (width and length), and
- Seismic load intensity.

Effective shear modulus of rock is used in the above formulas, consistent with the shear strain induced by earthquake. Maximum shear modulus is attained at small shear strain value, and it decreases as shear strain increases. Since earthquake-induced shear strain is a function of earthquake loads, correlation between shear modulus reduction ratio and earthquake Peak Ground Acceleration (PGA) is normally used for estimating the effective shear modulus. One set of foundation spring is developed for the Design Basis Earthquake (DBE) ground motion.

The building structure is supported by the fractured rock with overburden sandy and clayey soils. The foundation is socketed into the rock to resist the seismic lateral force. Two sides of building are supported by piles which are also socketed into the rock.

The base slabs are at two different elevations. One at the lower elevation is an irregular "L" shape on the fractured rock and another is rectangular shape on the lean concrete back fill. As a result, two types of soil spring representing the fractured rock and lean concrete are used in the structural model. The location of soil spring for base slab is at the rigidity center as shown in Fig. 1(b). Fig. 1(b) also shows the foundation springs for piles which only provide the vertical support to the structure.

The development of foundation springs (i.e., load-deformation characteristic and equivalent damping coefficient) is discussed in the following subsections.

2.2.1 Foundation Stiffness

Effective Shear Stiffness

While load-deformation characteristic of rocks is non-linear, it has been common practice to represent the non-linear behavior with an equivalent effective linearized load-deformation. Furthermore, for shallow foundation (including mat foundation) that is rigid with respect to the supporting rock, uncoupled spring models can be used to represent the foundation stiffness (FEMA 356, 2000).

Six uncoupled or independent foundation stiffness values are calculated for the mat foundation: 3 in translational directions (x, y and z directions) and 3 in rotational directions (xx, yy and zz directions), in accordance with the FEMA-356 guidelines. Note, the formulas consist of two parts: 1) formulas for stiffness values at the ground surface (i.e., without the foundation embedment effects) and 2) those used to correct the stiffness values for the effects of foundation embedment. It is worth noting that the embedment effects are functions of foundation dimensions (width and length), as well as the foundation embedment depth and thickness.

In this study, the effects of foundation embedment are included only in the vertical and rotational directions. The effects of lateral partial soil-structure interaction are conservatively ignored in the calculation of horizontal springs. Effective shear modulus of the foundation rock is obtained based on FEMA 356, which provides the G/G_{max} ratios as a function of earthquake PGA. G is the effective shear modulus (or shear modulus adjusted for seismic-induced shear strain) and G_{max} is the shear modulus at small shear strains (or maximum shear modulus).

Because of the uncertainties in determining soil and rock properties, an upper and a lower bound estimates of spring stiffness are taken as 1.5 and 0.5 times the best estimate, in accordance with CAN3-N289.3.

It is worth noting that the irregular "L" shape for the base at the lower elevation is simplified using an equivalent rectangular shape. Because the base slab at the higher elevation is relatively small as compared to the one at the lower elevation, the interaction of soil springs between the two levels is ignored.

Ultimate Foundation Capacity

In the seismic analysis model, the anchored point of the foundation spring at the fractured rock level is assumed to be fixed. The ultimate rock capacities are checked against the applied loads in the foundation design to verify the fixed boundary condition. The estimates of the foundation rock capacities are described below.

Similar to the effective shear stiffness, the lateral restraints provided by the surrounding soils and rocks above the mat foundation elevation are ignored in estimating the two translation foundation capacities (capacities in the x and y directions). In these two horizontal directions, the ultimate foundation capacities are defined by the frictional resistance along the foundation's base and/or the bearing capacities of the foundation against the rock at the sockets.

In the vertical direction (z direction), the ultimate foundation capacity is calculated by multiplying the foundation's base area to the unfactored Ultimate Limit States (ULS) bearing pressure on the rock. The resistance factor is 0.5 used in deriving ULS resistance.

The ultimate foundation rocking capacities are defined by the overturning and torsional capacities of the foundation base slabs. The overturning and torsional capacities are taken about the axis of the base slab using the unfactored ULS bearing pressure. For the torsional capacity only bearing over the slab thickness is considered. No contributions from the overburden soils and rocks are included.

2.2.2 Equivalent Damping Coefficients

Two types of damping are typically considered for foundation rocks: material damping and geometrical (radiation) damping. Material damping represents the internal energy loss within soil/rock mass, while geometrical damping is the energy loss through wave propagation away from the foundation.

In this study, the combined damping for the three translational soil springs is considered. The equivalent geometrical damping coefficient is in accordance with ASCE 4-98. For material damping of the foundation rock, a 2% to 3% of critical damping value is used in accordance with CAN3-N289.3. Since the values of geometrical damping calculated based on ASCE 4-98 exceed 30% for horizontal and vertical base motion and 20% for the rocking motion, the combined damping values used in this study are the maximum values allowed by CAS N289.3.

3 Seismic Analysis

3.1 Dynamic Analysis Procedure

The linear dynamic analysis procedure is applied in this study. The stiffness and mass distribution of building structure is considered through 3-D finite element model. The model response spectrum method is used to calculate the dynamic response of building structure. The time-history analysis method is used to generate floor response spectra (FRS) for equipment and components design. The complete quadratic combination (CQC) method is used for the modal combination in order to consider the closely spaced modes. The missing mass correction is considered in the response spectrum analysis.

3.2 Input Ground Motion

The DBE peak horizontal acceleration PGA is 0.257g at bedrock or equivalent firm strata with a peak horizontal velocity of 136 mm/s. The ratio of the vertical to horizontal components of ground motion is 2/3 which is used to calculate the vertical ground response spectra.

In this study, the synthetic time histories of ground motion are developed for time history analysis. The software RSPMATCH (Abrahamson, 1993) is used to develop the time histories which can match the ground response spectra (GRS) in accordance with CAN3-N289.3. The two horizontal and one vertical synthetic time histories are used and acting simultaneously as input of ground motions at the anchored points of foundation springs for dynamic analysis.

3.3 Results of Seismic Analysis

The fundamental natural frequencies of building structure for different rock spring conditions are summarized in Table 1. For the lower bound condition, the fundamental natural frequency drops about 5%, as compared to that of normal condition. It is only about 1.1% increase for the upper bound condition as compared to that of normal condition. This is due to that the rock is very stiff in this study. The increase of stiffness in soil spring has no significant effect on the dynamic response of building structure when the stiffness of soil springs changes from the normal to the upper bound condition.

The fundamental natural frequency based on a fixed base condition is calculated and is found to be similar to that of the upper bound condition as shown in Table 1. The comparison shows that the soil springs for the upper bound is very stiff as expected.

Table 1. Fundamental natural frequencies of building structure

Soil Conditions	Lower Bound	Normal	Upper Bound	Fixed
Fundamental natural frequency (Hz)	6.96	7.27	7.32	7.33

Fig. 2 shows the response spectra at the nodes with the foundation springs attached. It can be seen that the difference between the response spectra based on the normal, upper and lower bound conditions and the DBE ground response spectra (GRS) is not significant. This also means the effects of rock foundation on amplification of dynamic response of structural are not significant in this study.

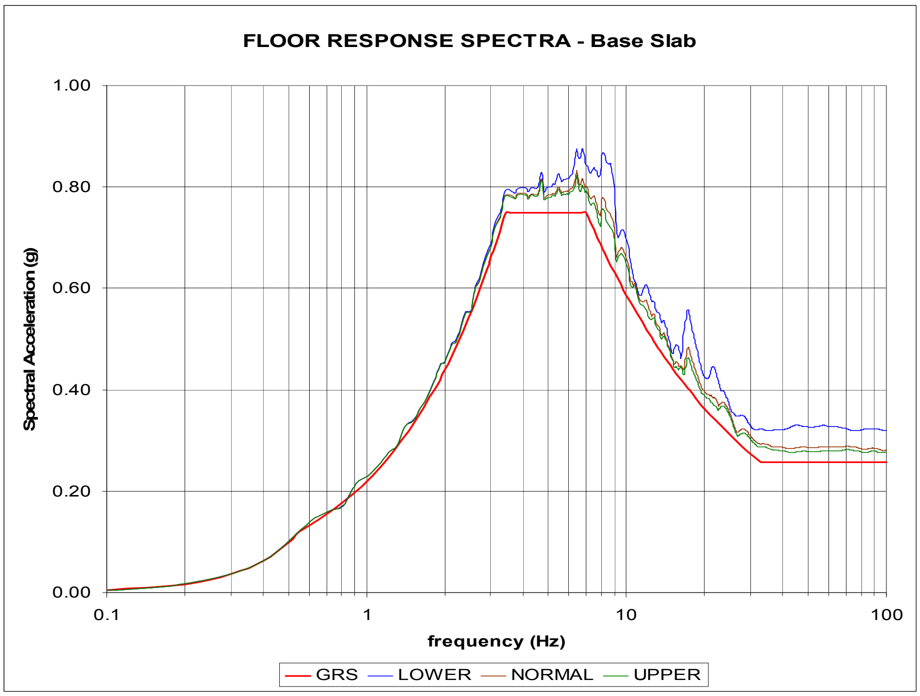


Figure 2. Floor response spectra at the base slab level for 5% damping

Figs. 3 and 4 show the FRS at the grade floor elevation above the base slab. The affixture T, E and S are used to represent the different control points at which the process systems are supported. Fig. 3 shows the enveloped response spectra at the nodes of interest based on the normal soil condition in the horizontal direction. It can be seen that the response at the nodes of interest is similar because of stiff shear wall used as the lateral force resist system in this study.

Fig. 3 shows that the peak acceleration occurs around the fundamental natural frequency of building structure. The peak value is about 3.8 times of the peak spectral acceleration at the base slab.

Fig. 4 shows the comparison of enveloped FRS at the grade floor elevation for lower, normal and upper bound soil conditions. It can be seen that the peak values for the different soil conditions are similar because the variations of the fundamental natural frequencies are insignificant as shown in Table 1. The maximum peak value is obtained based on the normal soil condition.

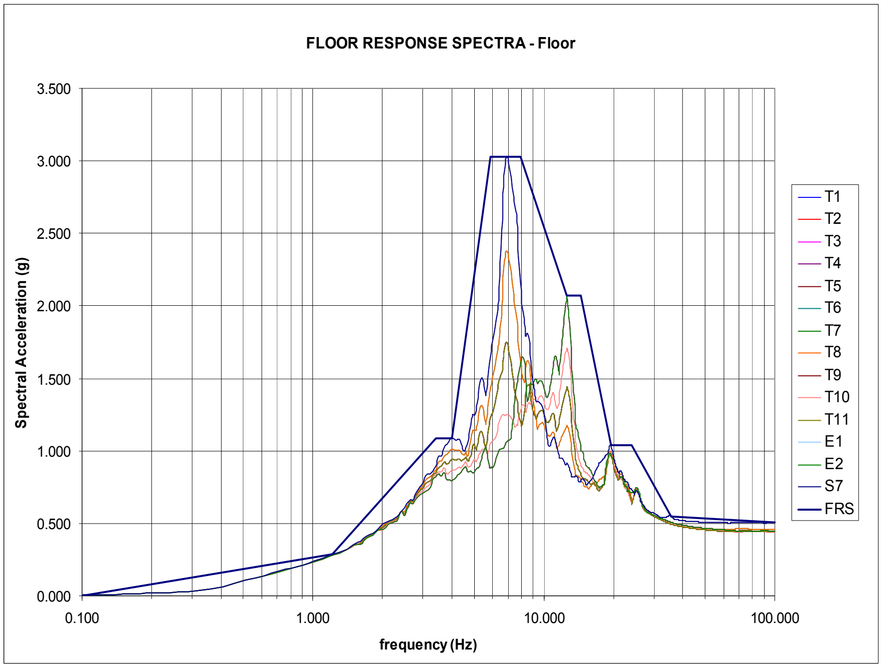


Figure 3. Floor response spectra at the grade floor level for 5% damping

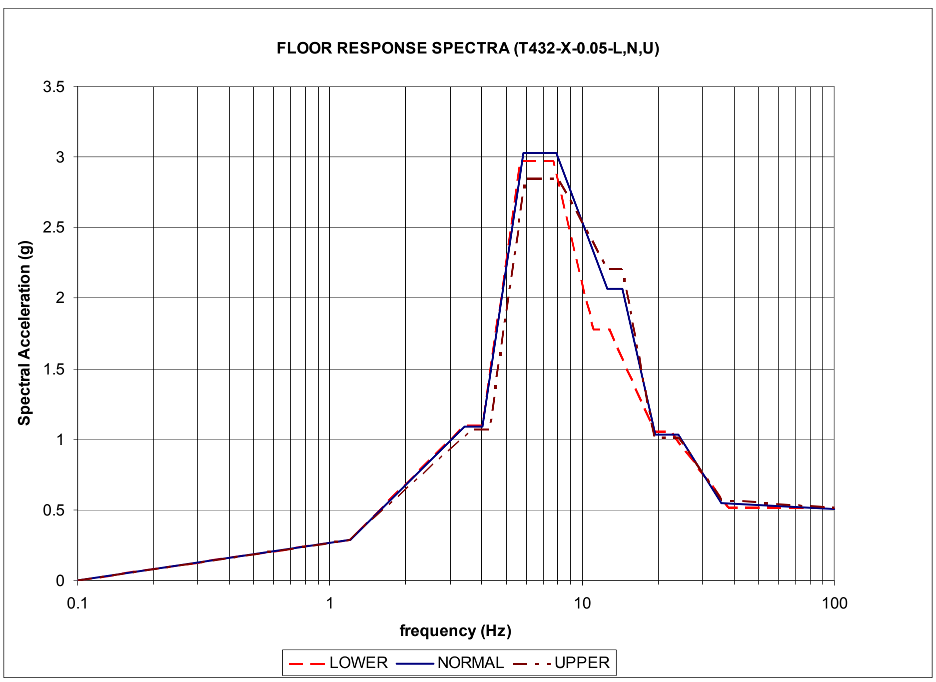


Figure 4. Comparison of FRS due to variation of soil properties

4 Conclusions

The effects of soil-structure interaction (SSI) on the seismic responses of a nuclear facility are evaluated using direct method and lumped spring model. Load-deformation and damping characteristics of the foundation rocks are represented by foundation springs, which are derived based on the formulas recommended in the Federal Emergency Management Agency 356 (FEMA-356, 2000) and American Society of Civil Engineers 4 (ASCE-4, 1998) publications. Equivalent effective linear models are used to represent the non-linear load-deformation characteristic of rocks foundation. Six foundation springs are estimated for the three translational and three rotational axis of the structure, and both material and geometrical dampings are considered in the SSI analysis. The adequacy of the assumptions for the seismic model is verified later by results of the seismic loads which are used in the structure design and checking against the foundation rock capacities. The uncertainty in soil properties is defined by an upper and a lower bound estimates and the envelope is used for design.

Three-dimensional time history analyses are performed for the seismic SSI analysis of the nuclear facility. The two horizontal and one vertical synthetic time histories are first spectral-matched to the design response spectrum, and then used as inputs to the model. The results of analysis show slight variations in peak structural response due to effects of foundation stiffness.

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