Strong Seismic Response Analysis of 3D Nuclear SSI System Using the Explicit Finite Element Method in Time Domain

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SUMMARY:
Since nuclear power plants have three-dimensional size, the effect of soil and structure dynamic interaction can be rationally considered only when three-dimension analysis is performed. In this paper, a practical nuclear model with a slightly soft site condition is analyzed. Some recently strong seismic records are chosen as vertical input wave. The three dimension explicit finite element schemes with multi-transmitting boundary condition are employed and the corresponding three-dimension explicit finite element program 3DSSI is developed in the present analysis. To show the effect of strong earthquakes on nuclear SSI system, the seismic response characteristics are presented and compared with other two kinds of common models. The safety problems on nuclear power plant are discussed based on the analysis results of response spectrum.

Keywords: soil-structure interaction, explicit FEM, response spectrum

1. INTRODUCTION

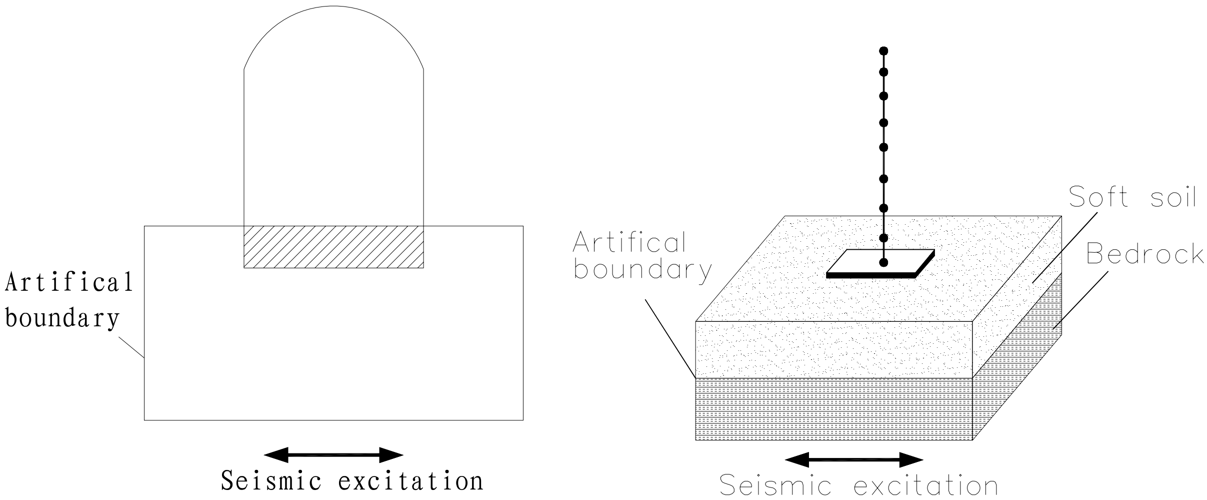
In order to estimate the behavior of nuclear power plant during strong earthquakes, the 3-D soil and structure dynamic interaction should be considered. For this calculation, it is important to construct more reasonable and complicated 3D FEM SSI system with a strong seismic input.

When the 3D simulation of complex SSI system met the computational difficult and non-economic numerical problem, the analysis models are often replaced by 2D or axisymmetric simplification (see, e.g., Rong et al., 2006, Li & Li, 2005). Obviously, this treatment will bring about certain error which may lead to the unreasonable analysis result.

Another consideration in seismic design for nuclear facilities focuses on response spectral shape. The current design spectra are mainly based on limited western United State earth strong motion records (see, e.g., Roabin et al., 1999). This kind of response spectra are being improved based on more strong seismic records. The updated design spectra are developing in many countries, including China. It is necessary to study the characteristics of response spectrum base on recently strong seismic record.

In this paper, a completely explicit FEM with a local transmitting boundary method and program 3DSSI in time domain is adopted to analyze the relatively complex 3D nuclear model. Compared with other similar methods (see, e.g., Nakamura et al., 2008, Zhang et al., 1999, Ryu et al., 2010) and specialized software such as CLASSI (1980) and SASSI (1981), the adopted method and software 3DSSI are advantageous in the following aspects: (1) unlike substructure, no computation of the impedance function and free-field response, (2) much more efficient since an explicit procedure. Based on this procedure, a more reasonable nuclear power plant model with a complex site condition is founded. Moreover, many strong seismic records chosen from Wenchuan (M = 8.0, 2008, China) and Fukushima (M = 9.0, 2009, Japan) earthquakes as seismic input. The characteristics of response spectrum and floor spectrum during strong earthquake condition are studied. The effect on seismic safety level of nuclear power plant is discussed under the site condition, earthquake magnitudes and distances.

2. THE GOVERNING EQUATIONS OF THE EXPLICIT FEM FOR 3-D DYNAMIC SSI ANALYSIS



(a) (b)

Figure 1. (a) A typical computational model for dynamic nuclear SSI analysis, (b) Models for nuclear SSI response history analysis

As shown in Fig. 1, the whole structure is divided into two parts: the artificial boundary domain *j* and the internal computational domain. Accordingly, as shown in Fig. 1, the nodes of the finite element mesh are also divided into the artificial boundary nodes and the internal nodes. Lumped-mass FEM are used in many fields because of its efficiency and accuracy (see, e.g., Symes & Terentyev, 2009). With the Rayleigh damping $C_{il} = \alpha M_{il}\dot{u}_l + \beta K_{il}\dot{u}_l$, the equation of motion to the internal nodes *i* can be expressed as:

$$\{u\}_i^{p+1} = 2\{u\}_i^p - \{u\}_i^{p-1} - \frac{\Delta t^2}{[M]_i}\{[\sum_i (1+\frac{\beta}{\Delta t})[K]_{il}\{u\}_l^p + \frac{\alpha}{\Delta t}[M]_i\{u\}_i^p]$$
$$-(\sum_l \frac{\beta}{\Delta t}[K]_{il}\{u\}_l^{p-1} + \frac{\alpha}{\Delta t}[M]_i\{u\}_i^{p-1})\} \qquad (2.1)$$

where $[M]_i$ denotes the diagonal lumped-mass matrix of the internal node *i*, $[K]_{il}$ is the stiffness coefficient matrix between the internal node *i* and node *l* adjoined with node *i*, u_i represents the displacement vector of node *i*, α and β denote the Rayleigh damping coefficient in proportion to the velocity. When the soil domain nodes are computed, the coefficient α often is ignored. The superscript *p* refers to the time step number and the relationship between time *t* and non-negative integer *p* is $t=p\triangle t$.

Assuming the time-history of the acceleration of the seismic wave is input from the bottom of the artificial boundary, the initial conditions are given as:

$$\{\ddot{u}\}_j^{\,0} = 0\text{；} \{\ddot{u}\}_j^{\,1} = 0\text{；} \{\ddot{u}\}_j^{\,2} = \{UINP\}^0\text{；} \{\ddot{u}\}_j^{\,p} = \{UINP\}^{p-2} \text{（}p=2, 3\cdots\cdots\text{）} \qquad (2.2)$$

The displacement of the artificial boundary nodes can not be computed by above Equation (2.1) because the motion of the nodes which connect the artificial boundary but outside the computational zone is unknown.

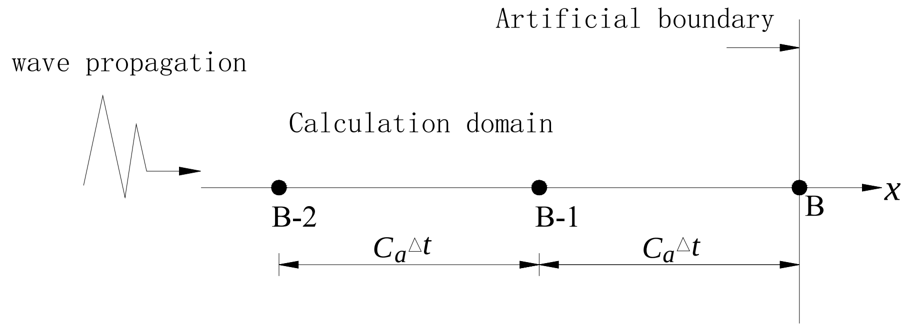


Figure 2. Spatial relationship of transmitting boundary

Instead the motion of the artificial boundary nodes can be obtained by the transmitting boundary presented by Liao, et al. (1984). The basic idea of the multi-transmitting method is to simulate outgoing waves travelling through the artificial boundary. The displacement of a certain time moment at artificial boundary node could be computed by those of neighbour interior nodes at previous time moments. Since the velocity and direction of outgoing wave in the boundary are unknown in advance, we assume the outgoing wave travels through boundary with an artificial velocity C_a. The formulation of transmitting boundary is:

$$\{u\}_B^{p+1} = \sum_{j=1}^{N} (-1)^{j+1} C_j^N \{u\}_{B-j}^{p+1-j} \tag{2.3}$$

where $\{u\}_B^{p+1}$ is the displacement vector of node B on the boundary at time level p+1, $\{u\}_{B-j}^{p+1-j}$ is the displacement vector of the interior node B-j at time level p+1-j and

$$C_j^N = \frac{N!}{(N-j)!\,j!}$$

is the binomial coefficient. As shown in fig.2, when two interior nodes are chosen, the displacement of boundary node can be derived approximately as:

$$\{u\}_B^{p+1} = 2\{u\}_{B-1}^{p} - \{u\}_{B-2}^{p-1} \tag{2.4}$$

However, the computing points involved the process does not generally coincide with the nodes of element, a proper interpolation is needed, the equation (2.3) can be rewritten as:

$$\{u\}_B^{p+1} = \sum_{j=1}^{N} (-1)^{j+1} C_j^N \mathbf{T}_j \mathbf{U}_j \tag{2.5}$$

where $\mathbf{T}_j = [T_1, T_2, \cdots\cdots T_{2j+1}]$ is the interpolation vector and

$$\mathbf{U}_j = [\{u\}_B^{p+1-j}, \{u\}_{C-1}^{p+1-j}, \cdots\cdots, \{u\}_{C-2j}^{p+1-j}]^T$$

is the displacement matrix including all the node displacement vectors on the boundary domain. and $\{u\}_{C-j}^{p+1-j}$ is the displacement vector of the interior FEM mesh node C-j at time level p+1-j.

3. THE INFORMATION OF NUCLEAR SSI STRUCTURE AND SEISMIC INPUT

Also as shown in Fig.1 (b), the actual nuclear SSI system is simplified to a 9 three-dimension beam element system with a rigid foundation on the surface of a semi-infinite soil medium. The parameters such as beam size, area, mass, rotary inertia and moment of inertia are given in Table 3.1. In addition, the parameters of elastic modulus, shear modulus are, respectively, E=3.0×10^{10} *Mpa* and G=1.2×10^{10} *Mpa*. The dimension of the rigid foundation is L×W×H=78m×77m×6.5m.

Table 3.1. Properties of the beams for the simplified structure

Number of beam	Length (m)	Area of across section (m^2)	Mass ($\times 10^3$kg)	Moment of inertia ($\times 10^3$kg·m^2)			Rotary inertia (m^4)		
				x-	*y*-	*z*-	*x*-	*y*-	*z*-
1	6.0	274.7	17040	12.11	12.11	10	167900	167900	10000
2	6.2	274.7	19930	14.17	14.17	10	167900	167900	10000
3	5.8	276.1	19740	13.8	13.8	10	164900	164900	10000
4	6.3	276.8	12040	8.24	8.24	10	154800	154800	10000
5	7.5	175.0	11670	4.05	4.05	10	162500	162500	10000
6	8.0	148.2	14700	4.46	4.46	10	139100	139100	10000
7	10.7	80.6	9300	2.83	2.83	10	76600	76600	10000
8	8.0	70.3	3850	1.94	1.94	10	39200	39200	10000
9	11.5	64.4	35.2	0.79	0.79	10	29600	29600	10000

Table 3.2. The information on chosen bedrock seismic record

Group	Region	Stations Code	Stations Position			Peak Acceleration (cm/s^2)	Magnitude
			Longitude	Latitude	Epicentral Distance (km)	NS	
1	C	51SPT	103.60	32.64	182.8	30.77	8.0
	J	IWTH23	141.83	39.27	169.2	347.19	9.0
2	C	51CNT	104.91	28.58	305.4	13.93	8.0
	J	TCGH17	139.70	36.98	305.1	28.00	9.0
3	C	53ZTT	103.71	27.32	409.0	2.71	8.0
	J	CHBH20	140.10	35.09	409.1	17.33	9.0
4	C	63LED	102.40	36.55	622.5	1.48	8.0
	J	FKIH01	136.36	36.09	618.5	1.28	9.0
5	C	64RJG	106.06	39.03	923.2	2.84	8.0
	J	OKYH07	133.32	35.05	918.0	0.48	9.0

C : Wenchuang , China. J: Fukushima Prefecture, Japan, NS: The North-South direction

The 10 records are chosen from the two presently earthquakes such as Wenchuan (M=8.0, 2008, China) and Fukushima (M=9.0, 2009, Japan) to be incident S wave. According to the Epicenter distance, the 10 records are divided into 5 groups. Epicenter distance range from about 100km ~1000km, belong to far field. Relevant information is shown in Table 3.2.

The soil domain is simplified as a two-layered model and the dimension of the soil domain in this case is L×W×H=312×308×50m for the soft soil layer and L×W×H=312×308×30m for the bedrock. The parameters of the soft soil and the bedrock are shown in Table 3.3. The bedrock shear velocity is chosen 700m/s based on the code for seismic design of nuclear power plant of China. The soil shear velocity is chosen 500m/s based on the traditional site condition. With the cutoff frequency f_s=25Hz and to meet the requirements of accuracy and stability of the explicit FEM, the 3-D mesh size is 9.75m×9.65m×2m and the time step $\Delta t = 1\times 10^{-4}$s.

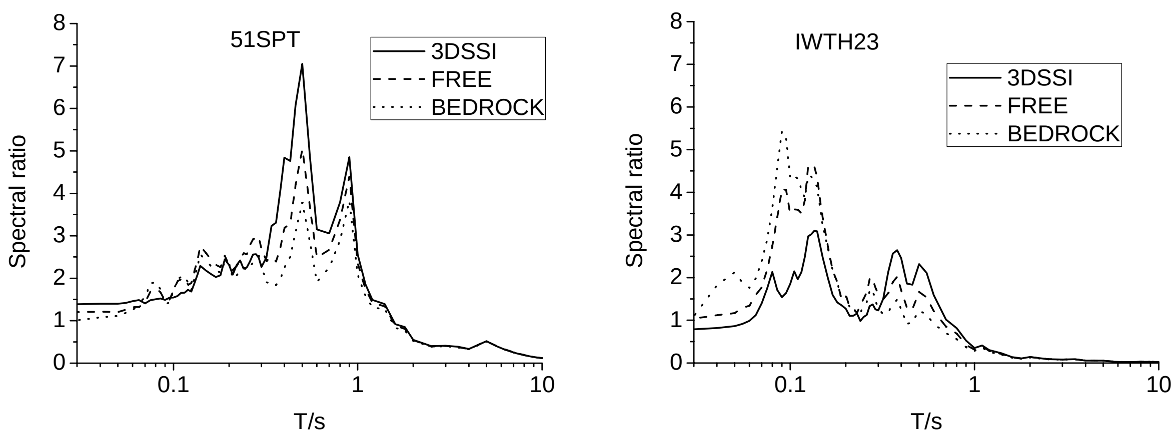
Table 3.3. Physical parameters of soil medium and bedrock

Kind of soil medium	Shear wave velocity *Vs* (m/s)	Densities（T/m^3）	Poisson ration ν	The damping ratio ξ
Soft soil	500	1.7	0.42	0.07
Bed rock	700	1.8	0.41	0.05

4. RESULTS AND DISCUSSIONS

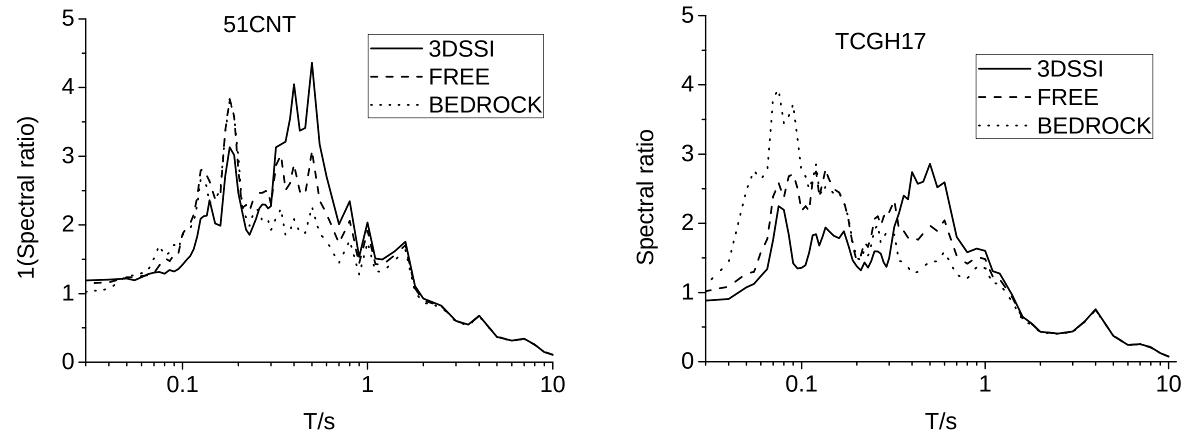
Based on the methodology presented in the section 2, software 3DSSI has been programmed for the analysis of 3-D elastic dynamic SSI problems in engineering applications. The verification of methodology and software 3DSSI has been done by Yang et al. (2011).To compare the differences of the dynamic response of a structure generated by other popular methods for dynamic response analysis and our method, the three seismic inputs are described as follows with the cutoff frequency f_s=25Hz:

Case one: the direct bed rock input of a seismic record referred as BEDROCK in all the figures,
Case two: the input computed by the free field response without the foundation and the upper structure, referred as FREE in all the figures,
Case three: the input computed by our method for a dynamic SSI system referred as 3DSSI in all the figures.



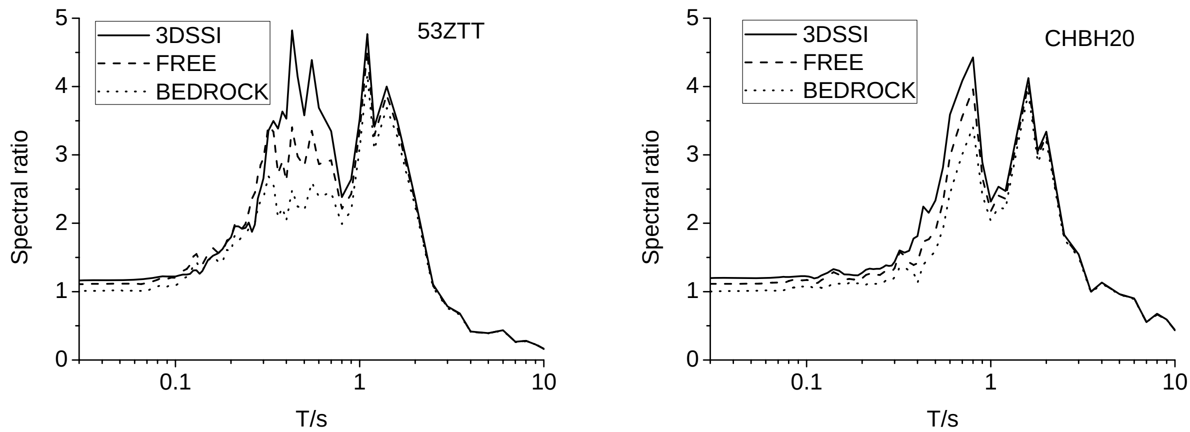
(a) (b)

Group1 (a M=8.0, ED=182.8; b. M=9.0, ED=169.2)



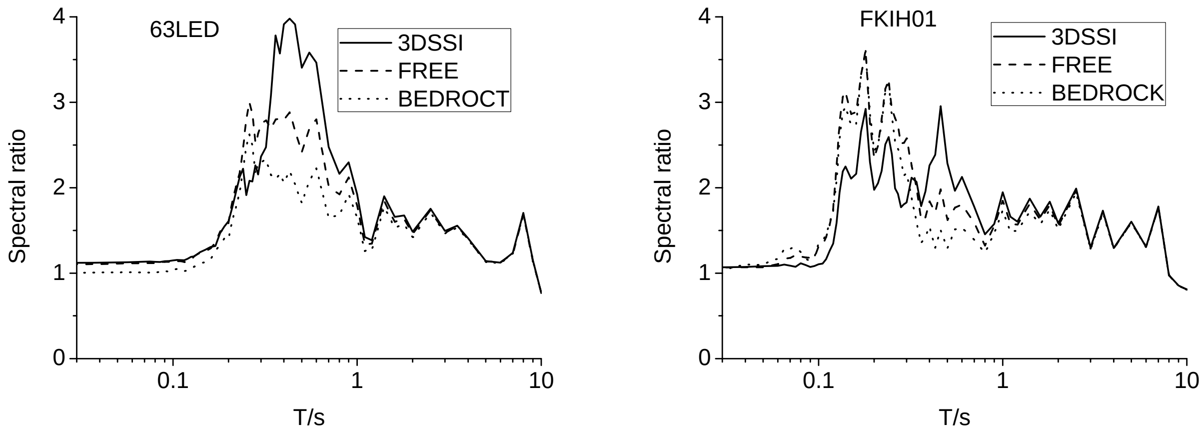
(c) (d)

Group2 (c. M=8.0, ED=305.4; d M=9.0, ED=305.1)



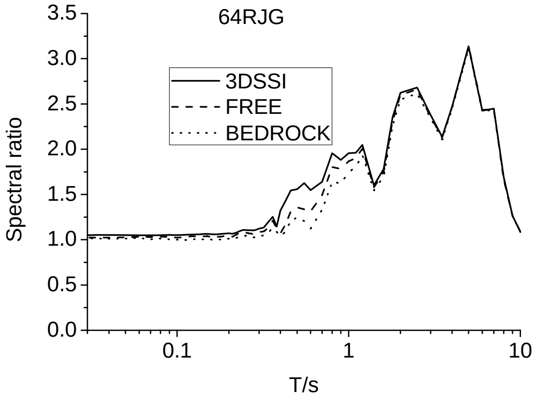
(e) (f)

Group3 (e. M=8.0, ED=409.0; f. M=9.0, ED=409.1)

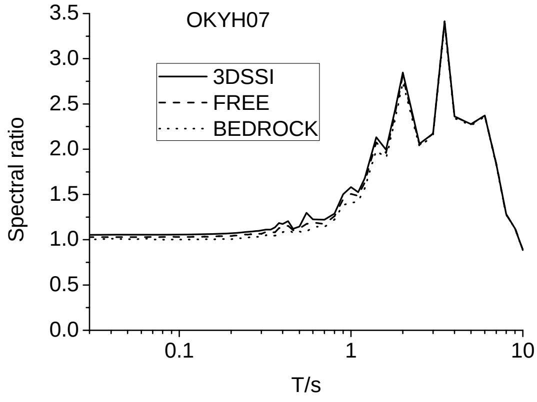


(g) (h)

Group4 (g. M=8.0, ED=622.5; h. M=9.0, ED=618.5)



(i)



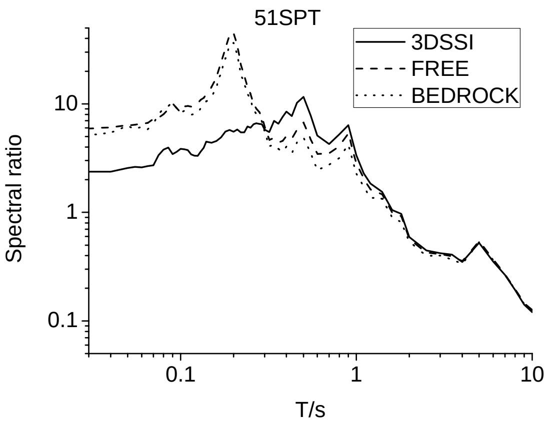
(j)

Group5 (i. M=8.0, ED=937.9; j M=9.0, ED=918.0)

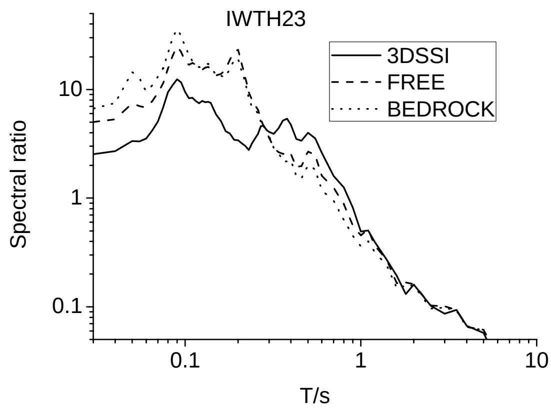
Figure 3. The acceleration response spectra at the ground surface

In Fig.3, significant differences of response spectra at ground surface in the three cases are shown, the largest response spectrum presents in some cases considering SSI such as Fig. 3 (a), (c), (e), (f), (g), indicating that not considering the dynamic soil-structure interaction may be unsafe in some cases. Some characteristics on ground motion can be derived from the work presented in these results as follows:

(1) There are two peaks in every figure keeping the similar position. This indicates the natural frequencies of SSI system and site fields not depending on the earthquake.
(2) The longer the response spectrum level, the further the epicentral distance in the three cases.
(3) The effect of SSI is relative to the earthquake, but it do not show the stronger magnitude bring about the stronger SSI effect.
(4) The SSI presents a notable influence on response spectrum in near field long period component. The influence will be ignored in far fields.

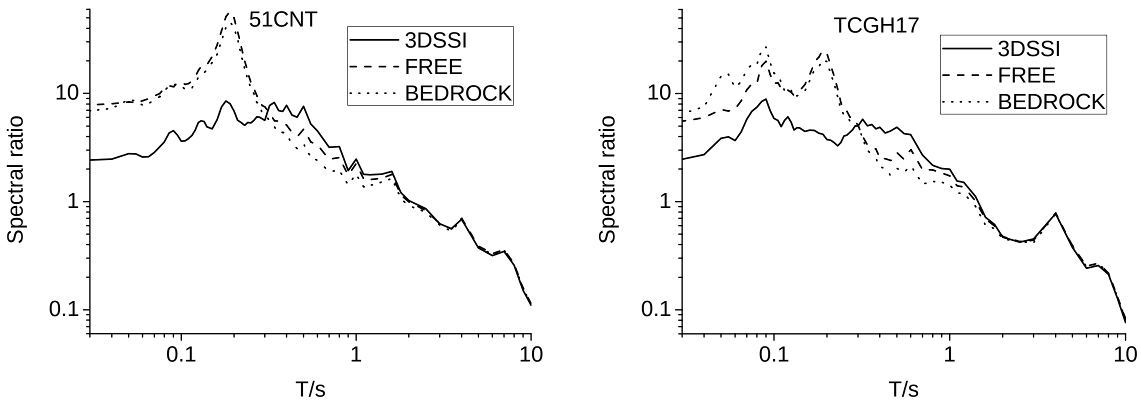


(a)



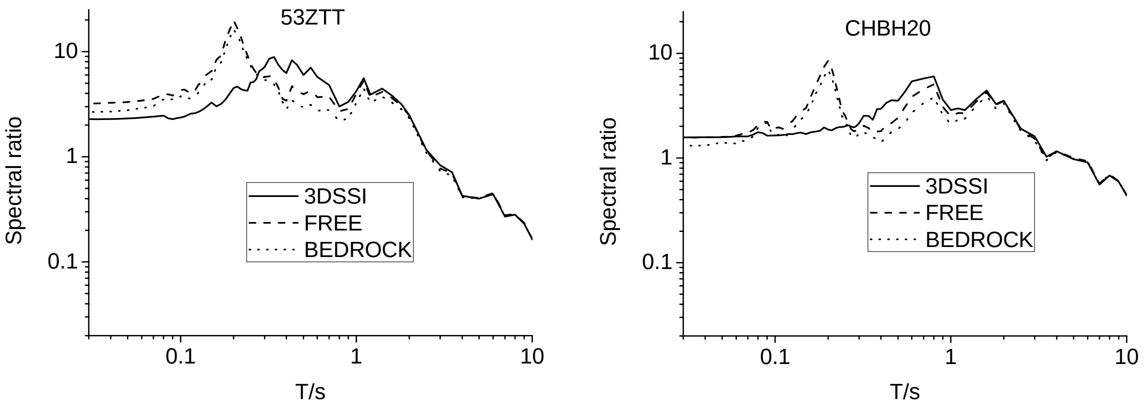
(b)

Group1 (a. M=8.0, ED=182.8; b. M=9.0, ED=169.2)



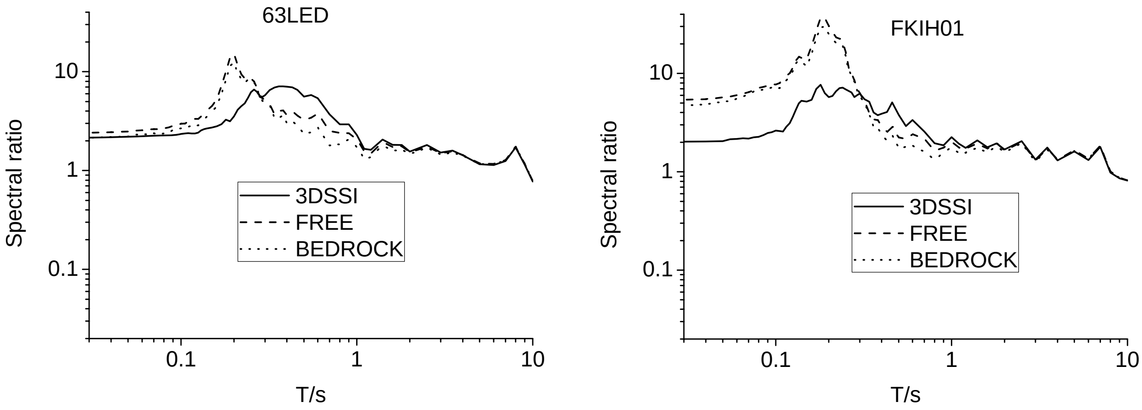
(c) (d)

Group2 (c. M=8.0, ED=305.4; d .M=9.0, ED=305.1)



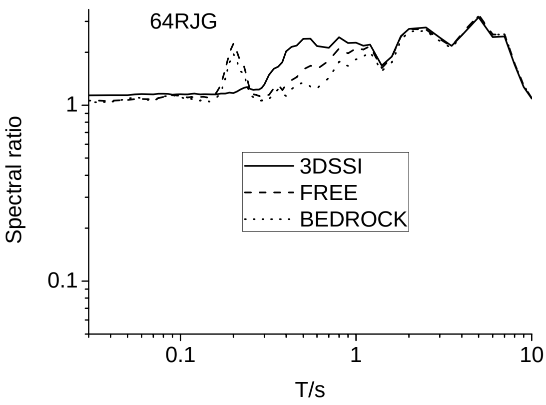
(e) (f)

Group3 (e. M=8.0, ED=409.0; f. M=9.0, ED=409.1)

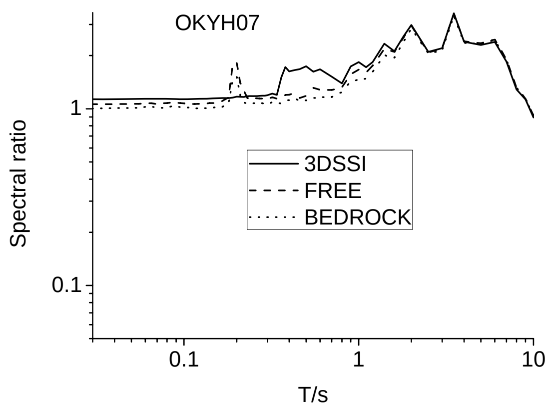


(g) (h)

Group4 (g. M=8.0, ED=622.5; h. M=9.0, ED=618.5)



(i)



(j)

Group5 (i. M=8.0, ED=937.9; j. M=9.0, ED=918.0)

Figure 4. The acceleration floor response spectra at the top of the structure

In Fig. 4, the smallest response spectrum value presents nearly in all the case considering SSI, but the width of the spectrum level become long, indicating the characteristics of the dynamic response may be changed under the dynamic soil-structure interaction case. Moreover, from the results shown in Fig.3., some significant differences among the three seismic input can be discussed in detail.

(1) When the epicentral distance is short, the response spectrum level value of case one is higher than the other two cases in the high frequency, but the value of case two becomes the biggest one among the three cases at 0.2s and the value of case three becomes the biggest one among the three cases at 0.4s.This phenomenon is mainly caused by the resonance.
(2) Compared with the response spectrum level of ground motion, the floor spectrum values are often bigger. This is mainly caused by the amplification of the upper structure.
(3) The floor spectrum values of case one are nearly the same to case two among the five group figures. They show a different from case three which is SSI model. Near the 0.2s, one peak value often shown in the case one and case two, but the peak value often occurred in the case three near 0.5s. This phenomenon indicated the dangerous position will be difference depend on the different models even if the practical system is the same.

Obviously, the effects of different soil parameters and structural parameters with inputs of various earthquake records on the strong seismic response of a dynamic SSI system and the characteristics of the response spectrum should be focus on.

5. CONCLUSIONS

An explicit finite element method with transmitting boundary condition is adopted to complete the 3D nuclear SSI system analysis of seismic response. The recently seismic records are used to the input waves. Another two common models are considered for comparison. Some key points we derived from the work presented in this paper are as follows.

(1) With S wave input, if the soil medium is relatively soft, the SSI system produces a response with not only a horizontal component, but also a swing component at the foundation. Using the SSI system to calculate the dynamic response of the structure can generate results with significant difference from those using direct input or using free-field seismic response.

(2) The peaks corresponding to the natural frequency of the foundation and soil bring about key influence on the response spectrum. This characteristic can be shown either in Figure 3 or Figure 4.

Without considering the SSI influence, the seismic response may be overestimation or underestimation.

(3) This article focuses on one slightly soft sit effects of soil parameters on 3-D dynamic SSI analysis. The effects of soil nonlinearity, sophisticated site conditions, sophisticated systems of the upper structure and the foundation depth etc. will be considered in our future study.

ACKNOWLEDGEMENT

The financial support of the National Natural Science Foundation of China (Project Number: 51178123) is gratefully acknowledged

REFERENCES

Li Z.C. and Li Z.X. (2005) Analysis and evaluation of seismic response of reactor building for Daya Bay nuclear power plant. *Nuclear Power Eng* 26: 614-617.

Liao Z.P., Wong H.L., Yang B.P., Yuan Y.F. (1984). A transmitting boundary for transient wave analyses. *Science in China(Series A)*. **XXVII**: 1063-1076.

Lysmer, J., Symes, B., TabataBaie-Raissi, M, Tajirian, F., Vahdani, S. and Ostandan, F. (1981). Analysis of soil-structure Problems (SASSI)[R]. University of California., Berkeley.

Nakamura N., Yabushita N., Suzuki T, Yamada J., Tsunashima N., Nakano T. (2008). Analyses of reactor building by 3D nonlinear FEM models considering basemat uplift for simultaneous horizontal and vertical ground motions *Nuclear Engineering and Design* **238**: 3551–3560.

Roabin,K.,Walter,J.and Roger,K.(1999). Hazard-and risk-consistent spectra. *Nuclear Engineering and Design* **192**:137-145.

Rong F., Wang J.C., He S.Y. and Dong Z.F. (2006) Analysis of soil-structure interaction and floor response spectrum of reactor building for china advanced research reactor. *Nuclear Power Eng* **27**: 19-23.

Ryu J.S., Seo C.G., Kim J.M. and Yun,C.B. (2010).Seismic response analysis of soil-structure interactive system using a coupled three-dimensional FE-IE method. *Nuclear Engineering and Design* **240**:1949-1966.

Symes, B.and I. Terentyev.(2009).Subgrid modeling via mass lumping in constant density acoustics. *SEG Houston 2009 International Exposition and Annual Meeting*, 2572-2576.

Wong H.L. and Luco J. E. (1980).Soil structure interaction: a linear continuum mechanics approach (CLASSI) [R]. LOS Angeles, California: CE, Department of Civil Engineering, University of California,U.S.C.

Yang X.M.,Guo D.W. and Yang B.P., (2011).A two-step explicit finite element method in time domain for 3D dynamic SSI analysis. *Journal of Earthquake Engineering and Engineering Vibration* **31**:4, 9-17.

Zhang X., Wegner J.L., Haddow J.B. (1999). Three dimensional soil-structure-wave interaction analysis in time domain. *Earthq. Eng Struct Dynam* **36**: 1501-1524.