Nucl. Sci. and Tech., Vol.7, No. 4 (2017), pp. 34-41

Nuclear Science and Technology

Journal homepage: https://jnst.vn/index.php/nst

Dynamic behaviour of nuclear island structure of AP1000 under El Centro and Dien Bien earthquakes

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Abstract: AP1000 is a nuclear power plant developed by Westinghouse based on an advanced passive safety feature, and it is one of selected technologies for Ninh Thuan 2 Nuclear Power Plant. The dynamic behavior of the plant under earthquakes is the most concerned in design and construction of the plant. This paper presents a seismic analysis of the AP1000 nuclear island structure by using the computational finite element software ANSYS. A 3D finite element model for the structure is developed and its dynamic response, including the time histories for displacements, velocities and accelerations, deformed configurations and von Mises stresses of the structure are obtained for America El Centro (6.9 Richter) and Vietnam Dien Bien (5.3 Richter) earthquakes. A comparison on the dynamic response of the structure under the two earthquakes is given, and the dynamic behavior of the structure under the earthquakes is discussed.

Keywords: *AP1000, nuclear island, seismic analysis, finite element modeling, ANSYS.*

I. INTRODUCTION

The safety of nuclear power plants under earthquakes is the most concern of researchers in designing a nuclear plant and evaluating the existing plants. Many investigations on the dynamic response of nuclear power plants to earthquakes have been reported in the literature, the contributions based on the finite element method are briefly discussed below.

Tunon-Sanjur et al. [1] developed stick and shell finite element models for dynamic analysis of the AP1000 nuclear island under seismic loading. The models take the effects of soil-structure interaction into account can be used for firm rock to soft-to-medium soil. Nakamura [2] presented method for evaluating the seismic behaviour of a nuclear power building deeply embedded into the soil. The finite element method was then used in combination with the Newmark method to compute the dynamic characteristics of the building. In [3], Nakamura and his co-workers used a nonlinear three-dimensional finite element model to study the ultimate seismic response and fragility assessment of a nuclear power building. The building was assumed to be under action of the increasing input acceleration up to 3500 Gal, until the ultimate condition. Perotti et al. [4] proposed a procedure for studying fragility of isolated nuclear buildings under earthquakes. The procedure makes the use of the response surface methodology to model the influence of the random variables on the

https://doi.org/10.53747/jnst.v7i4.95
Received 03 October 2017, accepted 29 December 2017

dynamic response. Zhao and Chen [5] investigated the dynamic behaviour of the nuclear power reinforced concrete containment under three-directional seismic loading by the finite element method. Using the software ANSYS, Chen et al. [6] investigated the effect of isolators on the dynamic response of nuclear island subjected to safe shutdown earthquakes. Politopouos et al. [7] modelled the soil domain under the nuclear power plant by the finite elements and Lysmer radiation boundaries for investigating the effect of foundation embedment on the floor response spectra of the plant. A 3D nonlinear finite element model was developed and incorporated into the software ABAQUS by Sener et al. [8] for studying the seismic behaviour of a pressurized water reactor containment internal structure. Xu et al. [9] considered the effect of water level in water tank into the dynamic response of the AP1000 shield building under actions of seismic loading.

The advanced passive safety system of the AP1000 plant has been chosen for the Ninh Thuan nuclear power plant of Vietnam. The investigation on dynamic behaviour of the plant due to earthquakes is very important for Vietnamese engineers and researchers from both design and research points of view. As a first effort, this paper presents an investigation on the dynamic response of the AP1000 nuclear island under three-directional ground motions by using the finite element package ANSYS [10]. A three-dimensional finite element model for the structure is created and used in the analyses. The dynamic characteristics, including the time histories for displacement, velocity, acceleration, and von Mises stress distribution of the structures are obtained for the well-known El Centro earthquake (6.9 Richter) and then for the Vietnam Dien Bien earthquake (5.3 Richter). A comparison on the dynamic response of the structure under the two earthquakes is given and the dynamic behaviour of the structure is discussed.

II. FINITE ELEMENT MODEL

Fig.1 shows a picture of the AP1000 nuclear island, which consists of the containment building (the steel containment vessel and the containment internal structure), the shield building and the auxiliary building. The safety of the this building under actions of disasters such as earthquakes, tsunamis, air crashes… is the most concerned in design and operation of the AP1000 plant. A typical geometric and material data for the nuclear island are given in Table I [6].

Fig.1. AP1000 nuclear island building [1]

Table I. Geometry and material data of AP1000 nuclear island.

Item	Concrete	Steel	Size
Density (kg/ m^3)	2300	7800	
Young's modulus (MPa)	3.35 x 10^4	2.06 x 10^5	
Poisson's ratio	0.2	0.3	
Length of nuclear island (m)			77.42
Width of nuclear island (m)			26.67
Height of nuclear island (m)			81.98
Radius of shield building (m)			22.1
Radius of containment vessel (m)			19.8
Wall thickness (m)			0.92
Thickness of containment vessel (m)			0.041
Height of auxiliary building (m)			39.42

Due to the complexities of the building, a numerical method must be employed to study the dynamic behaviour of the structures due to earthquakes. To this end, a three-dimensional finite element model (3D-FEM model) for the AP1000 nuclear island building is created with the help of the "Geometry" library in ANSYS [11]. Both the concrete structures and steel containment vessel are incorporated in the FEM model as shown in Fig.2.

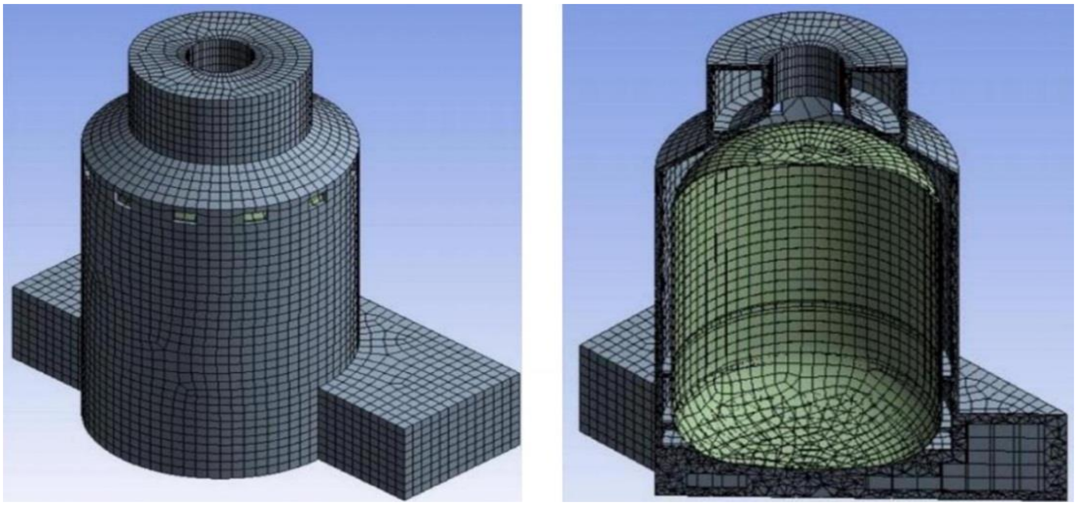

Fig.2. 3D-FEM model for AP1000 nuclear island building.

A 3D-FEM model in Fig.2 consists of shell and brick elements, in which the shell elements are used to model the steel containment vessel and the shield building, whereas the remaining parts are modelled by the brick elements. The interface between the upper part of the building and the base mat as well as between the walls of the building and the upper base mat are modelled by the share node option of ANSYS. The convergence of the mesh has been carried out in order to find out an acceptable mesh.

III. SEISMIC ANALYSIS

Based on the material properties in Table I, the element stiffness and mass matrices are computed and then assembled into the structural stiffness and mass matrices to form the equations of motion which can be written in the form [11]:

$$\boldsymbol{M}\ddot{\boldsymbol{D}} + \boldsymbol{C}\dot{\boldsymbol{D}} + \boldsymbol{K}\boldsymbol{D} = -\boldsymbol{M}\boldsymbol{I}\ddot{\boldsymbol{D}}_{\boldsymbol{g}}(t) \quad (1)$$

where **M**, **C**, **K** are, respectively, the mass, damping and stiffness matrices of the structure;

D is the vector of relative nodal displacements,

$\dot{\mathbf{D}} = \partial\mathbf{D}/\partial t, \ddot{\mathbf{D}} = \partial^2\mathbf{D}/\partial t^2$ are the relative nodal velocities and accelerations;

$\ddot{\mathbf{D}}_g$ is the vector of ground motion which relates to the vectors of absolute and relative nodal accelerations by:

$$\ddot{\boldsymbol{D}}_{\boldsymbol{g}}(t) = \ddot{\boldsymbol{D}}_{\boldsymbol{a}} - \ddot{\boldsymbol{D}} \quad (2)$$

where $\ddot{\mathbf{D}}_a$ denotes the vector of absolute nodal accelerations.

In Eq. (1), **I** with size (*n*x3), is the influence coefficient vector, and it has the following form for the three-directional ground motions considered herein [12]:

$$\boldsymbol{I}^{\boldsymbol{T}} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & - & - & - & - \\ 0 & 1 & 0 & 0 & 1 & 0 & - & - & - & - \\ 0 & 0 & 1 & 0 & 0 & 1 & - & - & - & - \end{bmatrix} \quad (3)$$

In the above equation, 1 corresponds to the degrees of freedom in the direction of the applied ground motion and zero for the other degrees of freedom.

The proportional damping is adopted herein. In this regard, the damping matrix **C** is formed as a linear combination of the stiffness and mass matrices as

$$\boldsymbol{C} = \alpha\boldsymbol{K} + \beta\boldsymbol{M} \quad (4)$$

where α and β are, respectively, the stiffness and mass proportional damping coefficients. These damping coefficients can be calculated from the critical damping ratio and the structural natural frequencies as:

$$\alpha = 2\xi\frac{\omega_1\omega_2}{\omega_1+\omega_2}, \beta = \frac{2\xi}{\omega_1+\omega_2} \quad (5)$$

where ξ is the damping ratio, depending on the structural material, and in the present work ξ=5% is assumed for both the concrete and steel; ω_1 and ω_2 are natural frequencies of the structure, which are necessary to choose to bound the design spectrum. ω_1 is normally selected as the fundamental frequency (ω_1=3.6219 Hz obtained from modal analysis for the structure considered herein), and a value of 30 Hz is chosen for the ω_2 because the spectral contents of seismic design are insignificant above this frequency [12].

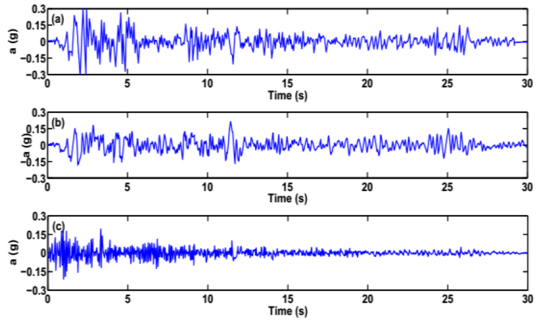

Fig.3. ATHs of El Centro earthquake: (a) NS component, (b) EW component, (c) UD component

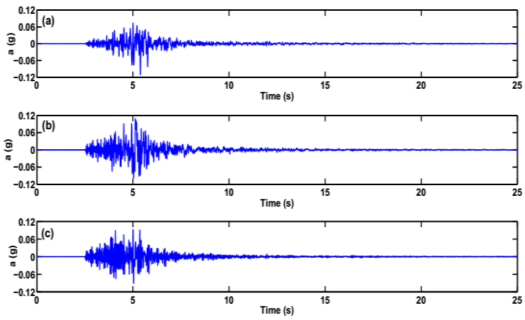

Fig.4. ATHs of Dien Bien earthquake: (a) NS component, (b) EW component, (c) UD component

In order to evaluate the dynamic response of the nuclear island due to earthquakes, the Acceleration Time Histories (ATH) of the earthquakes are applied at the base of the building. The ATHs of El Centro earthquake and Dien Bien earthquake, which are plotted from the seismic data of these earthquakes, are shown in Fig.3 and Fig.4, respectively. The ATHs in the figures represent the time histories of the ground motion in three directions, namely North-South (NS), East-West (EW) and Up-Down (UD) directions. These ATHs are used to compute the vector of external loads in the right-hand side of equation (1) for evaluating the dynamic response by using the integration Newmark method. By examining Fig. 3 and Fig. 4 in more detail one can see that the ground acceleration due to the El Centro earthquake is more than twice higher than that due to the Dien Bien earthquake.

IV. RESULTS AND DISCUSSION

The time histories for relative displacement, velocity and absolute acceleration at the top point of the nuclear island under the El Centro earthquake are illustrated in Fig. 5-Fig. 7, respectively. The corresponding time histories at the point of the building under the Dien Bien earthquake are depicted in Figs. 8-10. A time step Δt=0.02s for Newmak method has been used all computations herein. The following remarks on the dynamic behaviour of the nuclear island under the earthquakes can be drawn from these figures.

- The dynamic response of the nuclear island due to the El Centro earthquake is much stronger than that of the building under the Dien Bien earthquake, and the displacement at the top point of the building due to the El Centro earthquake is almost 10 times higher than that due to the Dien Bien earthquake. Noting that the peak ground acceleration (PGA) of the El Centro earthquake is just twice times higher than that of Dien Bien earthquake, and thus, there is no correlation between the ground acceleration and the displacement response.
- The dynamic behaviour of the nuclear island under the El Centro earthquake is very different from that of the structure under Dien Bien earthquake. Under the Dien Bien earthquake, the structure oscillates significantly during the first 5 seconds, and it then rapidly decays. The situation is different when the structure is under action of the El Centro earthquake. The building, as seen from Figs. 5-7, vibrates greatly in most of the ground motion time, 30 seconds. This difference is resulted from the difference between the time histories for ground motion of the two earthquakes. The main contribution of the Dien Bien ground motion, as seen from Fig.4, is mainly in the first 5 seconds for all three components, while the ground accelerations in NS and EW directions of El Centro earthquake are considerably high in all the shaking time period.

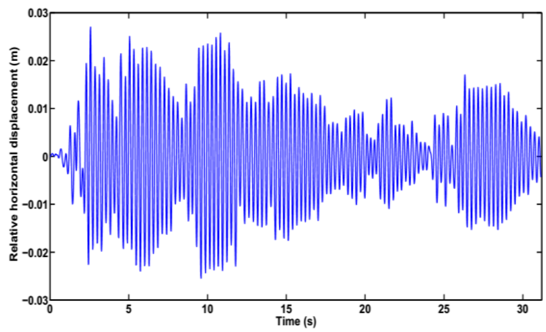

Fig.5. Time history for relative displacement in x-direction at top point of nuclear island under El Centro earthquake

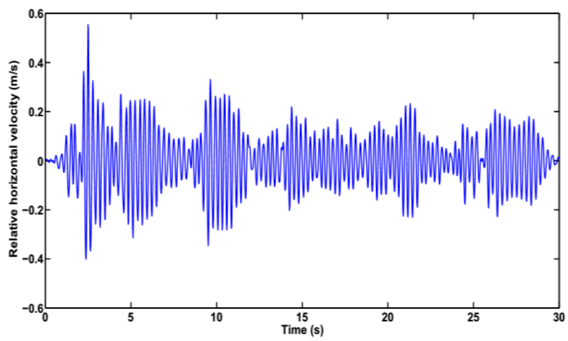

Fig.6. Time history for relative velocity in x-direction at top point of nuclear island under El Centro earthquake

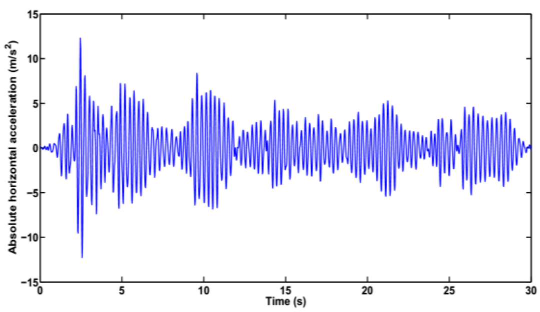

Fig.7. Time history for absolute acceleration in x-direction at top point of nuclear island under El Centro earthquake

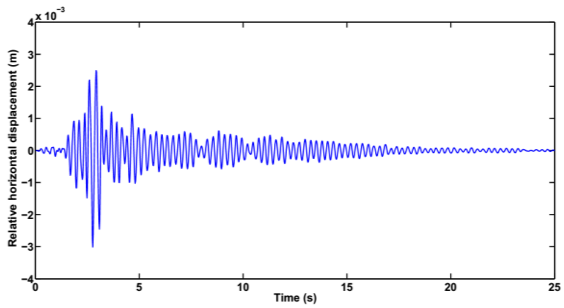

Fig.8. Time history for relative displacement in *x*-direction at top point of nuclear island under Dien Bien earthquake

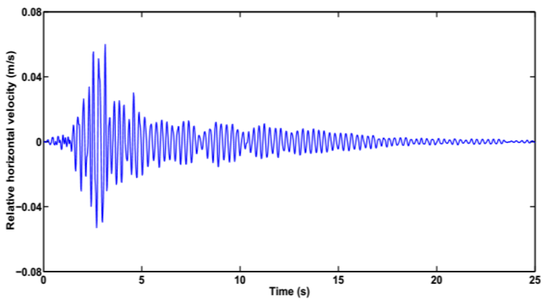

Fig.9. Time history for relative velocity in x-direction at top point of nuclear island under Dien Bien earthquake

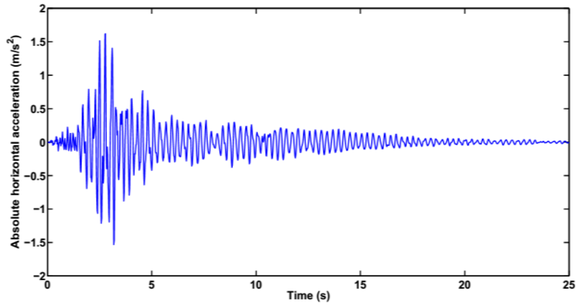

Fig.10. Time history for absolute acceleration in x-direction at top point of nuclear island under Dien Bien earthquake

In Table II, the maximum response at the top point of the AP1000 nuclear island to the El Centro and Dien Bien earthquakes is given. As can be seen from the table that the relative displacement and velocity at the point of the structure under the El Centro earthquake is almost ten times higher than that of the point when the structure is subjected to the Dien Bien earthquake. The difference in the absolute acceleration response is slightly smaller, just more than seven time higher in the El Centro earthquake compares to that in Dien Bien earthquake. From the safety point of view, the safety of the nuclear island under the El Centro earthquake is much more concerned than under the Dien Bien earthquake.

In order to investigate the dynamic behaviour of the nuclear island under seismic loading, Fig.11 and Fig.12 show the deformed configuration and the distribution of the von Mises stress of the structure under the El Centro earthquake at the time when the displacement at the top attains the maximum value. The corresponding figures for the structure under the Dien Bien earthquake are depicted in Fig.13 and Fig.14. The von Mises is defined as follows:

$$\sigma_{vM} = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]}$$

where σ_1, σ_2 and σ_3 are, respectively, the first, the second and the third principle stresses.

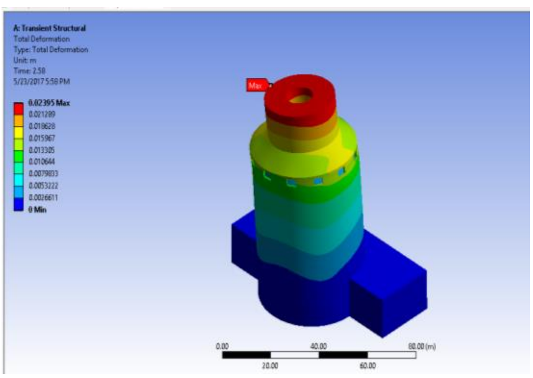

Fig.11. Deformed configuration corresponding to maximum displacement at top point of nuclear island under El Centro earthquake

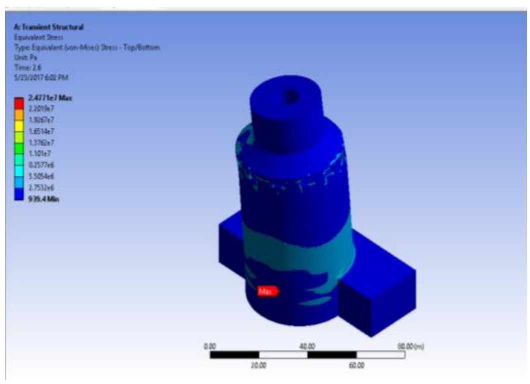

Fig.12. Distribution of equivalent Von Mises corresponding at the time of maximum displacement at top point of nuclear island under El Centro earthquake

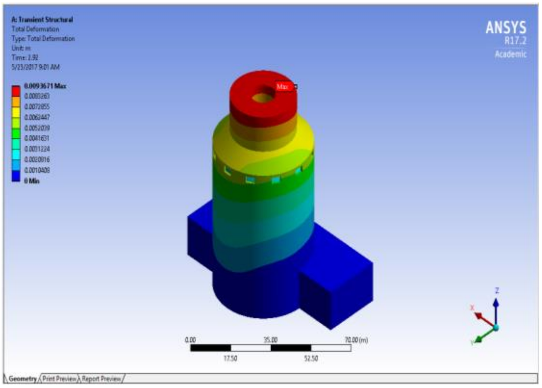

Fig.13. Deformed configuration corresponding to maximum displacement at top point of nuclear island under Dien Bien earthquake

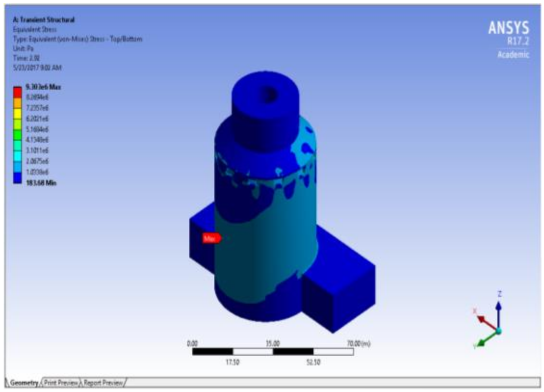

Fig.14. Distribution of equivalent Von Mises corresponding at the time of maximum displacement at top point of nuclear island under Dien Bien earthquake

The difference in the dynamic response of the nuclear island under the action of the two earthquakes can also be seen from Fig.11-14. The building deforms much more strongly under El Centro earthquake than it does under Dien Bien one. The displacement at the top of the building is much higher than at the base for both the earthquake. The situation is different for the von Mises stress, and the stress tends to be larger at the areas of the shield building which are located at the lower part of the nuclear island. It should be noted that the von Mises stress at some areas of the building under El Centro earthquake is of order of 107 Pa, which is quite large and it may exceed the yield stress. In this case, a nonlinear analysis is necessary to perform, but it is beyond the scope of this paper. The larger amplitude in dynamic deformation and von Mises stress of the building under the El Centro earthquake compares to that of the structure under Dien Bien earthquake can be also observable from the figures, and the concern on the safety of the structure under the El Centro earthquake is again noted.

V. CONCLUSIONS

The dynamic behaviour of the AP1000 nuclear island subjected to seismic loading of El Centro and Dien Bien earthquakes has been investigated. With the aid of the soft ware ANSYS, a three-dimensional finite element model for the building has been created and employed to compute the dynamic response. The dynamic characteristics of the building in the two earthquakes have been computed. The numerical result reveals that the dynamic response of the structure under the two earthquakes is quite different, and the safety of the building due to the America earthquake is much more concerned that in the Vietnam earthquake. The displacement, velocity and stress of the structure under El Centro earthquake are much larger than that under Dien Bien earthquake. It should be mentioned that the present work is just the first attempt in the seismic analysis of the AP1000 structures, and many factors such as the nonlinear behaviour of the building materials, the interaction between the structure and soil foundation has not been considered. More efforts should be made to understand the dynamic behaviour of the nuclear structures under seismic loading.

ACKNOWLEDGEMENT

This research was carried out under grand number ĐTCB 12/16/VP supported by

Ministry of Science and Technology. The authors would like to thank Dr. Tran Chi Thanh – the President of Vietnam Atomic Energy Institute for his invaluable supports in forming the first team working on the field of structural analysis of nuclear power plant.

REFERENCES

[1] L. Tunon-Sanjur, R.S. Orr, S. Tinic, D.P. Ruiz, Finite element modeling of the AP1000 nuclear island for seismic analyses at generic soil and rock sites, *Nuclear Engineering and Design*, vol. 237**,** pp. 1474-1485, 2007.

[2] N. Nakamura, Seismic response analysis of deeply embedded nuclear reactor buildings considering frequency-dependent soil impedance in time domain, *Nuclear Engineering and Design*, vol. 238, pp. 1845-1854, 2008.

[3] N. Nakamura, S. Akitab, T. Suzuki, M. Kobab, S. Nakamura, T. Nakano, Study of ultimate seismic response and fragility evaluation of nuclear power building using nonlinear three-dimensional finite element model, *Nuclear Engineering and Design*, vol. 240, pp. 166-180, 2010.

[4] F. Perotti, M. Domaneschi, S. De Grandis, The numerical computation of seismic fragility of base-isolated Nuclear Power Plants buildings, *Nuclear Engineering and Design*, vol. 262, pp. 189-200, 2013.

[5] C. Zhao, J. Chen, Numerical simulation and investigation of the base isolated NPPC building under three-directional seismic loading, *Nuclear Engineering and Design*, vol. 265, pp. 484-496, 2013.

[6] I. Chen, C. Zhao, Q. Xu, and C. Yuan, Seismic analysis and evaluation of the base isolation system in AP1000 NI under SSE loading, *Nuclear Engineering and Design*, vol. 278, pp. 117-133, 2014.

[7] I . Politopouos, I. Sergis, F. Wang, Floor response spectra of a partially embedded seismically isolated nuclear plant, *Soil Dynamics and Earthquake Engineering*, vol. 78, pp. 213-217, 2015.

[8] K.C. Senera, A.H. Varma, P.N. Bootha, R. Fujimoto, Seismic behavior of a containment internal structure consisting of composite SC walls, *Nuclear Engineering and Design*, vol. 295, pp. 804-816, 2015.

[9] Q. Xu, J. Chen, C. Zhang, J. Li, C. Zhao, Dynamic analysis of AP1000 shield building considering fluid and structure interaction effects, *Nuclear Engineering and Technology*, vol. 48, pp. 246-258, 2016.

[10] Inc. A., ANSYS Release 15.0 (Canonsburg, PA, USA, 2013).

[11] A.K. Chopra, *Dynamics of structures, theory and applications to earthquake engineering*, 4th edition, Prentice Hall, Boston, 2014.

[12] R.D. Cook, D.S. Malkus, M.E. Plesha, *Concepts and applications of finite element analysis*, 3rd edition, John Wiley & Sons, New York , 1989.