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Seismic Analysis of the Main Steam Pipelines in Seismically Isolated Nuclear Power Plants

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1. Introduction

Base isolation is used as a seismic protective system in the design of next generation nuclear power plants. Nuclear structures, secondary systems and components must remain undamaged in the event of safe shutdown earthquake (SSE) shaking. Earthquake shaking associated with the SSE will result in high seismic response demands in the stiff nuclear power plant (NPP) structural systems and extremely high demands on the safety-related secondary systems like pipelines. Seismic isolation of nuclear structures or primary systems can substantially mitigate these high demands on primary structural components and main piping systems, by reducing the natural frequency of the NPP. Lot of studies have been conducted on base isolation as a seismic protective measure to structures. There are four applications of base isolation to NPPs in France and another two in South Africa [1,2]. All the previous studies showed significant reductions in the seismic response of secondary systems through the use of properly designed seismic isolation systems [1,2]. This paper presents the results of coupled and decoupled analysis of piping systems connected between a base isolated nuclear reactor and an auxiliary building which shares a common base mat, with a conventionally constructed turbine building. The coupled and decoupled models are analyzed for safe shutdown earthquakes. Seismic responses of main steam pipelines connected between a seismically isolated reactor building and conventional turbine building are established.

Peak Ground Acceleration (PGA) is a parameter which indicates the peak value of the strong ground motion and used as a measure of the intensity of the seismic wave. Usually, seismic waves consist of other characteristics and can have different effects on structure. Therefore, it is undesirable to evaluate the effects of seismic wave on structure using only PGA. Therefore an alternate index which can reflect both seismic and structural characteristics is required. In this study, PGA, Peak Ground Velocity (PGV), spectrum intensity (SI) scales are used as a seismic intensity parameter for inelastic seismic response evaluation.

2. Seismic Analysis of Coupled and Decoupled Systems

The steam pipeline is connected at one end to the steam generator in the containment building and the other end to the turbine in the turbine building. The pipeline is supported in between by the auxiliary building. The containment building has prestressed cylindrical wall and hemispherical dome concrete structure. The containment building is surrounded by auxiliary building. Both the containment building and auxiliary buildings are seismically isolated. The auxiliary building usually has four quadrants. The turbine building is a conventional steel structure with reinforced concrete turbine pedestal.

A lumped-mass stick model of APR1400 reactor building is used for the seismic analysis. The reactor building model is composed of sticks representing the containment building structure and the internal structures including the primary and secondary shield wall, in-containment refueling water storage tank (IRWST) and reactor coolant system (RCS). The total height of the containment structure is 77.19m and the natural frequency of its first mode is 3.84Hz. The other stick represents the auxiliary building and the natural frequency of its first mode is 6.29Hz. The two sticks are structurally independent and are connected only at the base. The mass of the NPP reactor building is approximately 69,564,287kg. The coupled model of APR1400 main steam pipeline system is shown in Fig. 1.

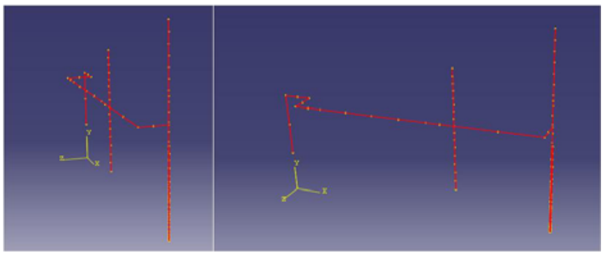

Fig. 1.The coupled model of APR1400 main steam pipeline system

The numerical models include representations of lead-rubber (LR) bearings. Bilinear elements are used for the LR bearings. To study a wide range of isolator properties, the values of characteristic strength, Q_d is set equal to 6 percent of the supported weight and the second-slope period (related to the yield stiffness, K_d through the supported weight) was assigned values of 2 sec [1,2].

A lumped mass stick model, whose first two natural frequencies are 1.34 and 1.69Hz, is used to model the turbine building[3]. The pipelines are assumed to be connected to the concrete pedestal. The roof of the turbine building is not considered, since the basic aim is to study the effect of seismic loading on pipelines. The pipelines are modeled as steel pipes having 813mm outer diameter and 12.7mm thickness. The steam pipe line connects the steam generators which are rigidly fixed to the primary and secondary shield walls. The pipeline passes through the auxiliary building to the turbine building, where it is fixed to the turbine.

Artificial earthquake ground motions which comply with the design ground response spectra (DGRS) requirements of USNRC RG. 1.60 [4] and SRP. 3.7.1 [5] are generated. Envelope function of artificial earthquake complies with the ASCE 4-98 [6] standards. The duration of strong ground motion is 13sec which satisfies the requirements of SRP. 3.7.1[5] and the total time duration is 24sec. The peak ground acceleration is 0.3g and the time step is 0.01sec.

Nonlinear time history analysis is conducted on the pipeline structure coupled with the nuclear building and the turbine building. The analysis is repeated for the decoupled model of the pipeline using the input accelerations generated at the appropriate levels. The results of both coupled and decoupled analysis are compared.

3. Evaluation of Seismic Intensity Parameter

PGA is a parameter which is used as a measure of the intensity of the seismic wave. The seismic waves consist of characteristics other than PGA, which can have different effects on structures. Therefore an alternate index which can reflect both seismic and structural characteristics is required. In this study, nonlinear time history analysis is conducted on the pipe line nuclear structure system to evaluate the inelastic seismic response. The scenario earthquake is normalized to PGA, PGV and SI as a measure of the intensity of the seismic wave. The displacement ductility demand and cumulative dissipated energy calculated for each earthquake ground motion are compared. SI scale which is obtained from integration by part of velocity response spectrum can be used as an index reflecting inelastic seismic response of structures [7].

In order to find out the failure mode of the piping system, dynamic loading tests will be conducted using the real piping system. The experimentally established failure mode of the pipeline system will be used for the validation of numerical model considered for the fragility analysis. Intense studies will be conducted to find out the accurate parameter among PGA, PGV and SI, for calculating the fragility.

4. Modeling of Pipeline Systems for Predicting Failure Modes

The main steam pipeline system is subjected to high steam pressure and temperatures, other than seismic loads. In order to determine the failure mode of the pipeline system, dynamic loading test is to be conducted on the real pipeline system. Therefore the effect of temperature and pressure has to be considered as equivalent static loads, to determine the failure mode using experiments. Equivalent similitude law is applied to the scaled models to simulate the stress effects in actual piping structure under seismic excitation. Therefore there is a need to modify the multiphase similitude modeling law to include the effects of the temperature. To study the combined effect of temperature, pressure and seismic loads, numerical studies will be conducted on the scaled models of the piping systems. The results will be validated using the full scale numerical model.

5. Conclusions

The steam piping system, containment building, auxiliary building and turbine building of next generation nuclear power plant APR1400 is modeled using lumped stick model. The properties of base isolation using lead rubber isolators are included in the models of base isolated containment building and auxiliary building. Nonlinear coupled and decoupled seismic analyses are conducted. The effect of interaction of primary structure on steam pipeline is found to be negligible. This may be due to the frequency difference between the primary structures and the piping system. The mass of the piping system is very less, when compared to the nuclear reactor building system. The main pipelines are subjected to internal pressure and high temperatures, other than seismic loads. The role of these loads during SSE vibration on the pipelines is not considered. Therefore further studies are required to consider the effect of temperature and internal pressure during seismic excitation.

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