Structural Safety 58 (2016) 11–19

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Seismic fragility analysis of a typical Indian PHWR containment: Comparison of fragility models

Tushar K. Mandal, Siddhartha Ghosh *, Nikil N. Pujari

Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 1 July 2013
Received in revised form 17 August 2015
Accepted 21 August 2015
Available online 9 September 2015

Keywords:
Fragility
Seismic
Nuclear containment
Probabilistic safety assessment
Incremental dynamic analysis

ABSTRACT

The necessity of performing a detailed seismic fragility analysis of nuclear power plant components is well established in the nuclear industry. This paper focuses on the seismic fragility analysis of the primary containment structure of a typical Indian 700 MWe PHWR. The primary emphases of the fragility analysis adopted here are the detailed nonlinear modelling along with time-history analyses and the consideration of displacement-based failure limits. Three IDA-based methods and the conventional method using scaling/safety factors are used for fragility analysis and their results are compared. Among these, a new regression-based method proposed in this work provides better results than the existing methods. A modified version of this new method – for estimating fragilities for multiple limit states simultaneously – also provides similar results while reducing the level of statistical computation. The conventional method of fragility analysis fails to capture the (aleatory) randomness properly. In addition, compared to the peak ground acceleration, the fundamental mode spectral acceleration is found to have a better correlation with the damage measure for this structure, and is recommended for independent fragility analysis of such structures.

1. Seismic safety of nuclear power plants

The international fact finding expert mission [1] on the Fukushima nuclear power plant (NPP) related disaster, following the great east Japan earthquake and tsunami (March, 2011), categorically concluded, “There is a need for the nuclear community to increase effort in developing probabilistic safety assessments (PSA) for external events”. This mission also emphasised on a rigorous PSA treatment avoiding the screening of extreme events based on approximate criteria. The objective of a seismic PSA of a NPP is to examine the existence of vulnerabilities against postulated earthquake hazards [2]. It involves assessing the plant’s (or, its components’) safety numerically, in a probabilistic framework, so that appropriate measures can be taken to enhance the plant’s safety level, if required. One of the major components of this PSA, is the seismic fragility evaluation [3]. Seismic fragility is defined as the conditional probability of failure of a structure for a given seismic intensity level. These fragilities are typically expressed using conditional probability versus seismic intensity ‘fragility’ plots. Seismic fragilities can be defined both at component levels and at the system level in a NPP. The present work focuses on the seismic fragility analysis of the primary containment structure, which is considered to be the last barrier against radio-active leakage. Fragility definitions also change on the basis of how failure of a structure or a component is defined.

India has 20 operational nuclear reactor units, 18 of which are pressurised heavy water reactors (PHWR), with the earliest dating back to 1973. All of these are located in low to moderate seismic zones (Zones II and III as per the current seismological intensity map of India), except for those in Narora, which is in Zone IV [4]. Seismic re-evaluation of these reactors, including those in moderate seismic zones, is an extremely important task considering several factors, such as:

1. A change in the seismicity of the site based on newer information.
2. A requirement of checking the safety for greater seismic hazard than the one in the original design basis.
3. Lack of seismic design or, more commonly, poor seismic design and detailing not meeting the current standards.
4. Low level analysis adopted in the original qualification (many a times owing to the lack of computational tools necessary to perform intensive analyses).

As noted in the IAEA publication on the seismic evaluation of existing power plants [5], these are concerns across all countries

* Corresponding author. Tel.: +91 2225767309; fax: +91 2225767302.
E-mail addresses: tusharm78@gmail.com (T.K. Mandal), sghosh@civil.iitb.ac.in (S. Ghosh), pujarinikil@gmail.com (N.N. Pujari).

http://dx.doi.org/10.1016/j.strusafe.2015.08.003
0167-4730/

producing nuclear power. The requirement for such re-evaluations, although a part of the continuous regulatory process, has been recently highlighted in almost every forum after the Fukushima NPP related disaster.

From the early 1980s, seismic fragility analyses of nuclear power plant structures and other critical components typically have been based on the method proposed by Kennedy and Ravindra [6]. They had proposed the use of factors of safety (FoS) for estimating fragility parameters. The final FoS was defined as the ratio of the (random) actual capacity of the component/system to the (random) actual response, subjected to the safe shutdown earthquake (SSE). This FoS was modelled using a lognormal distribution with its median obtained from the median ground acceleration capacity. Logarithmic standard deviations were used to model the (aleatory) randomness and the (epistemic) uncertainty in estimating this median value. In this approach, the process of obtaining the median FoS starts with the containment design. Once the actual capacity of the containment is determined, a combination of different scale/safety factors are applied to take into account the uncertainties involved. The same principle was also recommended by various safety agencies, such as EPRI [7]. This method allows the user to consider different levels of damage and to treat system-level fragilities separately from component-level fragilities. However, there remain certain issues with the application of this basic methodology to a variety of scenarios. For example, often the fragility database that is used for the evaluation of a specific NPP is sourced from another specific plant or a set of plants, and this leads to a poor estimation of the actual uncertainties/randomness involved [8]. Also, uncertainties in estimating the factor(s) of safety are mostly based on judgement, as opposed to rigorous analyses [9]. The need for plant-specific probabilistic estimation of these factor of safety, using 'direct methods', was emphasised in more recent research publications on NPP fragility [9]. IAEA [5] specifically recommended the use of nonlinear analysis techniques in obtaining the seismic fragility of a containment structure.

Over the last decade, incremental dynamic analysis (IDA) [10] has emerged as a favoured approach for rigorous (and specifically probabilistic) analysis for estimating the seismic demands on buildings and similar other structures. In the recent past, IDA was used for estimating the seismic fragility of different kinds of structure, such as, steel and RC building frames [11,12] and bridges [13]. IDA as a tool for seismic fragility analysis gives the advantages of

- demand estimation using the most (computationally) accurate analysis method (nonlinear response/time-history analysis, NLRHA),
- selection of site-specific ground motion records (recorded, artificial or synthetic),
- direct demand estimation at any intensity of the hazard (no scaling of demand parameters), and
- simple frequentist computation of failure probabilities for any type of limit state.

This study focuses on obtaining the seismic fragility of a nuclear primary containment structure and exploiting these advantages provided by the IDA based approaches.

2. Objective and main features

The primary objective of this work is to perform a seismic fragility analysis of the primary containment structure of an Indian PHWR using IDA. No seismic fragility analysis has so far been conducted for this structure. The highlights of these fragility analyses are: demand estimations based on nonlinear response-history analysis, the consideration of displacement-based performance limits to define failure, the use of multiple real (recorded) ground motion records suitable for the actual site, and the use of two different seismic intensity measures. Seismic fragility of this structure is estimated from the multi-IDA data using: (a) a nonlinear regression based method suggested by Ellingwood et al. [11], (b) a maximum likelihood based method suggested by Shinozuka et al. [14], and (c) a modification of the regression based method proposed in this work. The emphasis is on a comparative study of the fragility estimates from these three methods and their effectiveness.

3. Mathematical modelling of the study structure

The primary containment (PC) structure considered for this study consists of a prestressed concrete cylindrical wall capped by a segmental prestressed concrete dome connected through a massive ring beam. The containment shell is supported on a circular raft foundation. The containment structure considered for the study is depicted schematically in Fig. 1a. This structure responds to base excitations like a 'deep' cantilever beam with a circular cross-section. The segmental dome along with the ring beam acts to stiffen the circular cross section and also adds to the mass of the system.

The structure is mathematically modelled as a 2D stick/beam with lumped masses, following the standard practices in the Indian nuclear industry [15,16], and elsewhere. Researchers in the past (e.g., [17,18]) compared the seismic responses of a containment shell based on its 2D stick idealisation to those based on a detailed 3D shell finite element model, and found the 2D stick model to adequately represent the seismic responses of the containment structure. This idealisation allows a great reduction in computation which is otherwise unavoidable in the case of nonlinear response-history analyses for multiple ground motion records at multiple intensities. Simplifications in terms of modelling the domical part with vertical elements are justified on the basis that the failure (even any nonlinearity) of the structure never occurs in this zone. A careful modelling – specifically, that of the shear deformation behaviour of the thin annular shell – provided modal characteristics very close to those obtained from a detailed 3D shell model.

Fig. 1a also shows the 2D cantilever structure with lumped masses at elevations of mass concentrations, connected by 2-dimensional beam-column elements with actual sectional geometry (thin annular cross-sections of varying dimensions). The structure is assumed to be fixed on a rigid raft foundation, without any soil-foundation-structure interaction (which is typical of the rocky sites the NPPs are situated in).

The cantilever structure is modelled using the open-source structural analysis programme OpenSees (version 2.3.1) [19] using *NonLinearBeamColumn* elements. These elements can handle spread of plasticity along the length of the member. The cross-section of this element is modelled using the *FiberSection* approach, with circular concrete patches and circular layers of reinforcement (Fig. 1b). A total of 60 integration points across the thickness and 200 integration points along the circumference of the cross-section are used in the analysis. Concrete is characterised by modified Kent and Park models for both confined (within the inner and outer layers of reinforcements) and unconfined (outside the layers of reinforcements) behaviour, using the *Concrete02* properties in OpenSees [19]. For a best estimate of the structural resistance, the resistance parameters are modelled at their mean values. The mean 28-day strength of concrete is obtained from the reported characteristic strength (f_{ck}) as per the Indian Standard IS:10262 [20]. The mean cracking strength (f_{cr}) is similarly adopted following Indian Standard IS:456 [21]. The tension softening stiffness (E_{st})