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Statistical Analysis of an RC Elevated Tank Damage by a Nonlinear Approach

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Abstract: In the seismic field, the seismic performance of a structure reflects its damage level under a given seismic demand. Thus, to evaluate this performance, many analysis and design techniques are used, such as nonlinear approach commonly called Pushover is used in this research. On the other hand, predicting the damage level is a random process, where only a probabilistic approach would allow predicting it, as the level of uncertainty, related to the seismic action is important. For this purpose, a statistical study was conducted through simulations with large number of seismic accelerations, generated from a probabilistic distribution law, inspired from the Monte Carlo method, to evaluate the damage rates corresponding to each damage domain. The results revealed the influence of the seismic zone and the location of the structure on the damage rate observed after seismic loading.

Keywords: Seismic acceleration, Performance, Damage, Pushover analysis, Statistical study, Monte Carlo.

Introduction

In the field of seismic engineering, the concept of damage is used to express the various responses of structures to the loads they experience throughout their lifecycle. This concept refers to a structure's susceptibility to damage caused in various ways, including excessive forces such as earthquakes, strong winds, or storms. Assessing damage requires qualifying and quantifying the expected level of damage in order to compare it to the maximum acceptable threshold.

In this context, mastering damage to achieve greater safety and security requires a better understanding and, consequently, better control and/or reduction of the multiple sources of uncertainty that one may encounter (Lemaire, 2005; Aoues, 2008; Aliche et al., 2019). It is within the framework of this overarching challenge that the present work is situated, with its primary objective being to propose an approach that combines nonlinear static analysis and probabilistic analysis to account for the uncertainties surrounding the assessment of structural damage levels under dynamic loading. For the purposes of probabilistic analysis, the Monte Carlo simulation method is employed in this research. A numerical example is presented to illustrate the calculation method described, along with an analysis and discussion of the obtained results.

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

Damage Assessment of an RC Elevated Tank

In this study, we propose a methodology for estimating the damage that can occur in an RC elevated tank under the influence of seismic loading. The approach developed is inspired by the concept presented in the RISK-EU method adopted for RC tanks. This approach will then be coupled with a probabilistic analysis process that considers the random nature of seismic loading to determine the estimate of the damage probability of occurring to our structure.

Assessment Methodology

It is common practice today to estimate the performance of a civil engineering structure by a deterministic approach on the (Sa, Sd) plane using nonlinear calculation methods. This procedure allows the construction of pushover curves for the studied structure by applying the capacity spectrum method, which then provides the maximum displacement of the structure during seismic loading (Hammoum et al, 2016). This parameter, considered as a key element, and helps to determine the state of damage in the RC structure through an associated damage index. The literature offers several models for characterizing structural degradation, such as the RISK-EU method. The principle of this method is to identify damage domains based on the maximum displacement that develops at the top of the tank under seismic action. We get inspired from of the RISK-EU method and FEMA 273 code, and we propose a classification of damage domains for RC elevated tank (Table 1). Consequently, there are six damage levels ranging from the green domain 1 to total failure of the structure corresponding to the red domain (see Table 1).

Table 1. Proposed Damages Domains for Elevated Tanks.

Degrees and damage domains	Formulas for differents spectrals displacements limits
Green 1 Domain (Negligible Damages)	$Sd < 0.4\ \delta e$
Green 2 Domain (Minor Damages)	$0.4\ \delta e \leq Sd < 0.8\ \delta e$
Orange 1 Domain (Moderate Damages)	$0.8\ \delta e \leq Sd < \delta e + 0.25\ (\delta u - \delta e)$
Orange 2 Domain (Signifiant Damages)	$\delta e + 0.25\ (\delta u - \delta e) \leq Sd < 0.75\ \delta u$
Orange 3 Domain (Severe Damages)	$0.75\ \delta u \leq Sd < \delta u$
Red Domain (Complete Structural Collapse)	$Sd \geq \delta u$
δe : Elastic limit displacement	
δu : Ultimate limit displacement	

The drawback of this approach lies in the fact that each step of the structure damage assessment process is affected by uncertainties primarily related to the definition of the hazard. To address this issue and better estimate the probability of damage to our structure, an approach based on the use of a probabilistic model that takes into account the uncertainties in seismic loading is developed. This approach, accurately estimates the degree of damage to an RC elevated tank by employing the Monte Carlo simulation method. Two types of seismic behaviour coefficients are considered for this purpose.

Probabilistic Concept

Damage Criterions and Limit State Functions

The evaluation of vulnerability involves quantifying the damages that can occur in a structure or structural component following a given seismic load. In the case of an elevated tank, which is considered as an inverted pendulum with mass concentrated at the top, its stability is affected by ground motion at the base during seismic loading, resulting in a maximum displacement, Sd, at the top, thus resulting damage to certain structural components or complete structural collapse. However, to quantify the probability of a certain level of damage occurrence, considering the non-linear behaviour of the structure and the variability in seismic loading, we employ the Monte Carlo method (Lemaire, 2005).

Random Variable

The modeling of the nonlinear behaviour of an RC elevated tank is affected by numerous uncertainties, which can sometimes be difficult to estimate quantitatively. Accounting for these uncertainties leads to a certain complexity in the formulation. Therefore, a simplification focused on essential parameters becomes essential. In this study, where the probability of reaching or exceeding a damage level is calculated, the parameter that exerts the most influence on the structure's behaviour is the seismic loading. This variable is considered as the primary source of uncertainty in our study and follows a probability distribution law.

Goodness-of-Fit Test

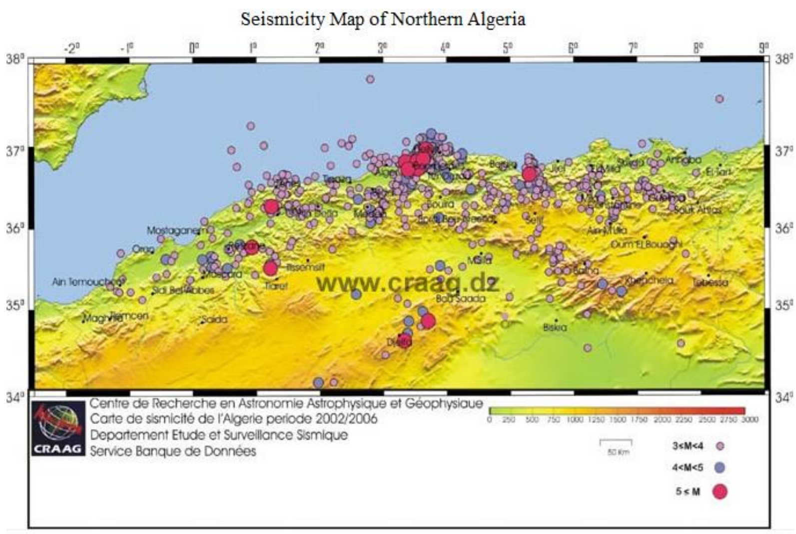

Figure 1. Seismicity map of Northern Algeria

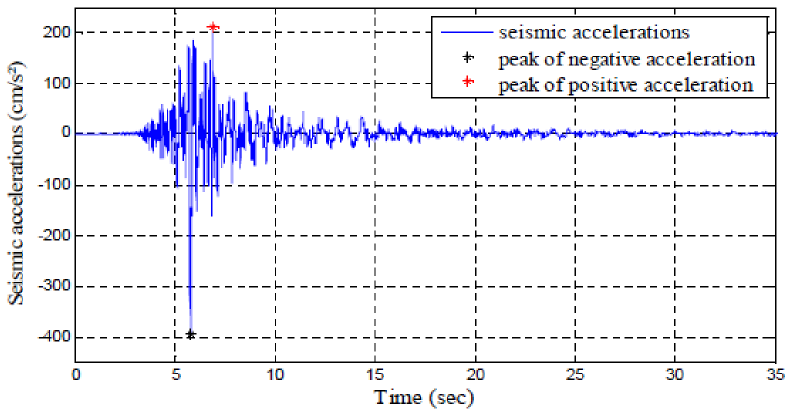

Figure 2. Accelerogram recorded at the Kheddara Dam Site (CGS) (Aliche et al., 2016)

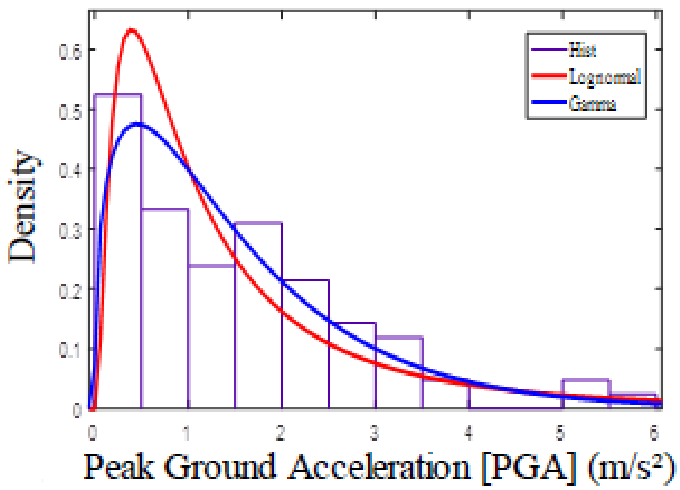

Figure 3. Histogram of peak accelerations and probability distribution laws.

To determine the type of distribution of accelerations, we perform a statistical analysis based on Kolmogorov-Smirnov (K-S) tests (Ahmadi et al, 2015). These tests are conducted using a database composed of 45 accelerograms recorded following the May 21st, 2003 earthquake in Boumerdes, Algeria, by various seismographs installed by the National Center for Applied Research in Seismic Engineering (CGS) in the central region of Algeria (see Figure 1). In Figure 2, we provide an example of an accelerogram recorded at the Kheddara dam site (50 km east of Algiers) and used for the statistical analysis (Hammoum et al, 2021).

The result of the goodness-of-fit test, namely the K-S Test, indicates that the gamma distribution is the most appropriate for approximating the distribution of the peaks accelerations sample (Table 2). The shape and scale parameters of the distribution are, respectively, k = 1.41427 and θ = 1.08846.

The representation of the sample density along with the overlay of the cumulative distribution function on the sample (Figure 3) confirms the choice of the distribution law. In fact, the gamma distribution appears to be much more suitable than the log-normal distribution.

Table 2. Kolmogorov-Smirnov Goodness-of-Fit test results for acceleration

Distribution Laws	P-values	k-s stat	Test Decision
Log normal	0.6737	0.0769	accepted
Gamma	0.6987	0.0753	accepted

Practical Application

Description of the Studied Elevated Tank

To apply the methodology described above, we consider a concrete elevated tank with a capacity of 200 m3 and a support height of H=15m. The tank is located in seismic zone IIa and on a loose soil site (S3). The behavior coefficient provided by RPA is R=2, and the value of R obtained through the nonlinear approach is R=2.63 (Ider, 2023). A three-dimensional finite element model has been developed to simulate the tank's behaviour under lateral loading of the progressive thrust type, using the ETABS© software.

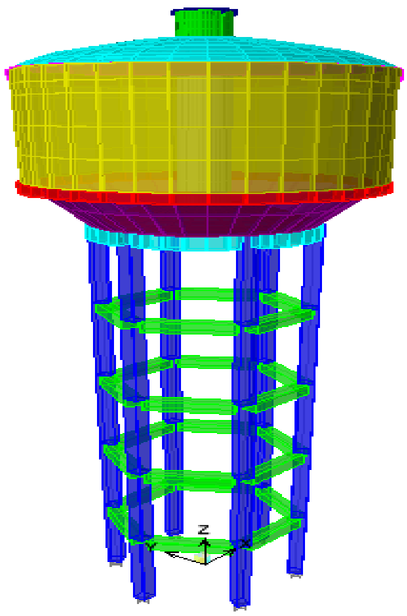

Figure 4. Finite element modelling of the RC elevated tank

Performance Point Evaluation

For each spectrum representing a simulated seismic loading, we obtain the displacement induced at the top of the structure, considering two types of seismic behaviour coefficients, namely R_{RPA}=2 and $R_{power\ law}$ which varies depending on the seismic zone (Table 3) (Ider, 2023). Figure 5 displays the maximum displacements experienced by the tank for 150,000 seismic loading simulations.

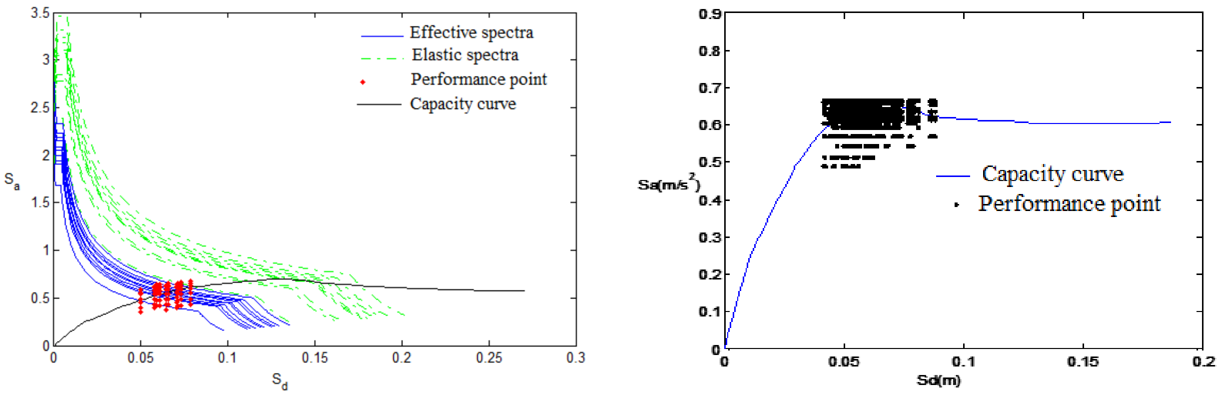

Figure 5. Performance points in the form of a scatterplot from the 150000 simulations.

Influence of the Seismic Zone and the R Coefficient on the Level of Damage

The probabilistic analysis of the seismic vulnerability of the tank, which was the subject of the deterministic study, is carried out by varying its location from Zone I to Zone III. The results of calculating the probability of damage to the study tank are given in the following table 3 (Table 3):

Table 3. Probabilistic variation of the damage level of a support tank with H=15m for different R.

R - RPA		**R=2**			
zone		I	II a	II b	III
		0.12	0.2	0.25	0.3
Pf	Green 1 Domain	0	0	0	0
	Green 2 Domain	0.05758	0	0	0
	Orange 1 Domain	0.846213333	0.03386667	0	0
	Orange 2 Domain	0.09616	0.95366667	0.13144667	0
	Orange 3 Domain	4.66667E-05	0.01246667	0.80427333	0.00771333
	Red Domain	0	0	0.06428	0.99228667

R-law Power		**R=2.05**	**R=2.63**	**R=2.98**	**R=3.35**
zone		I	II a	II b	III
		0.12	0.2	0.25	0.3
Pf	Green 1 Domain	0	0	0	0
	Green 2 Domain	0.115846667	0	0	0
	Orange 1 Domain	0.821846667	0.47072	0	0
	Orange 2 Domain	0.06226	0.52928	1	1
	Orange 3 Domain	4.66667E-05	0	0	0
	Red Domain	0	0	0	0

The results of the damage analysis of the tank under consideration in our application, identified by evaluating each simulation using the damage index as defined by the limit state functions for failures or damages, are presented in Table 3. These results are also summarized by presenting a histogram illustrating the probability distribution of damage occurrences within the elevated tank. Thus, the Figure 6 illustrates the probability distribution of tank damage based on the two values of the behaviour coefficient considered. This representation provides a detailed insight into the statistical distribution of damage within the sample used. It is evident that for both coefficients (R-RPA and R-Power Law), the probability of damage occurrence in the structure is significantly different.

The structure is at risk of experiencing Orange 2-type damages with a probability of 95.36% in the case of a coefficient (RRPA =2). However, with a coefficient of (R-Power Law = 2.63), the risk of damage is 52.92% in the Orange 2 domain and 47.07% in the Orange 1 domain. this comes from the fact that the coefficient proposed in the calculation code overestimates the seismic risk, resulting in significant displacements, unlike the R-Power Law coefficient. Moreover,the results have demonstrated that the probability of damage occurrence is highly sensitive to changes in the seismic zone

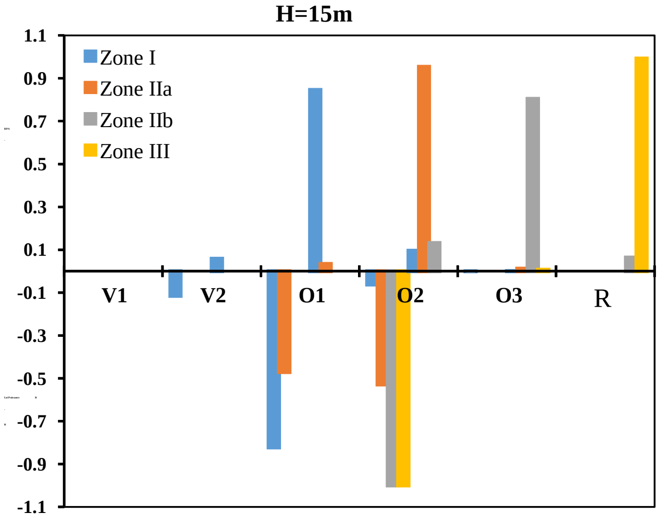

Figure 6. Probabilistic histogram of the variation in damage level of a support tank with H=15m for different R and seismic zone..

Conclusion

The concept of probabilistic analysis and the notion of damages are employed in this research to assess the probabilities of damage to the elevated tank subject of this study, within each of the predefined domains outlined in Section 1. Two behaviour coefficients are used, namely R=2 as recommended by the RPA, and the R values obtained from the power law. The limit state functions are defined by the damage domains associated with the spectral displacement Sd.

The random variable associated with seismic action is generated by a Gamma distribution, deduced from a statistical analysis performed on a sample of peak accelerations obtained from 45 accelerograms recorded following the Boumerdes earthquake in 2003. The results have highlighted a redistribution of the risk probabilities of damage occurrence between the value of R=2 and the values derived from the power law. Furthermore, the results have shown that the probability of damage occurrence is highly sensitive to changes in the seismic zone.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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