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Time-Variant Seismic Fragility Analysis of Intake Tower Structure Based on Incremental Dynamic Analysis Throughout the Whole Life Cycle

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Abstract

High intake tower structures exhibit significant time-varying characteristics in their seismic performance during service life due to environmental erosion and material deterioration. This paper establishes a time-varying seismic fragility analysis framework for intake towers over their full life cycle based on the incremental dynamic analysis (IDA) method. By introducing time parameters, time-varying probabilistic seismic demand models based on displacement and local damage indices are constructed, and five performance levels are defined. The research results indicate that with increasing service life, the probability of the structure reaching critical performance levels exhibits a nonlinear growth. After 40 years of service, material strength and elastic modulus begin to decline significantly, with evident degradation of seismic performance. At a seismic acceleration of 0.8 g, the probability of the 60-year-service structure reaching the slight damage limit state (LS_1) has reached 99%, while the probability of reaching the collapse limit state (LS_4) exceeds 25%. The local damage index results demonstrate that under the same seismic intensity, the exceedance probability of tower-side damage exceeding LS_1 for the 60-year-service structure has increased by approximately 10% compared to that of the new structure (0-year service). Therefore, in the seismic design and retrofitting decision-making for intake towers, the time-varying characteristics over the entire service life must be fully considered. Particularly when the service life exceeds 40 years, seismic fortification standards should be appropriately enhanced or targeted strengthening strategies should be developed based on time-dependent fragility curves, so as to avoid underestimating long-term seismic risks. This study provides a quantifiable scientific basis for whole-life safety assessment and resilience enhancement of high-rise intake towers.

Keywords: intake tower; incremental dynamic analysis; full life cycle; probabilistic seismic demand model; time-varying fragility

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1. Introduction

Due to the large height-to-width ratio of intake tower structures, the concrete structure undergoes progressive performance degradation during its full life cycle under the coupled effects of environmental erosion, mechanical loads, and material deterioration when

subjected to seismic action, resulting in continuous attenuation of structural resistance and significant dynamic evolution characteristics of fragility. Chen et al. [1] established a strong correlation between ground motion duration parameters and the nonlinear response of intake towers. The results showed that there is a significant correlation between the elasto-plastic response of intake towers and duration-related composite intensity parameters. Liu et al. [2] conducted an analysis on the Guishi Reservoir dam and found that cracks caused significant economic losses, thus requiring safety monitoring. Mi et al. [3] took the Meixi Reservoir as an example and conducted systematic research on the stability and safety of the dam during its full life cycle based on existing data. If the time-varying patterns of structural performance are neglected in traditional seismic design, it will lead to systematic deviations in full-life safety assessment, significantly increasing the failure risk of buildings under extreme disasters and causing major economic losses; therefore, it is necessary to conduct seismic fragility research on high intake towers.

Seismic fragility analysis, as an important means for assessing structural seismic risk and performance, can intuitively describe the relationship between ground motion intensity and structural damage degree [4]. Incremental dynamic analysis is currently the most promising method for determining structural response under different intensity ground motions in performance-based earthquake engineering [5]. Zheng et al. [6] studied the main aftershock sequence of aqueducts using the incremental dynamic analysis method, conducting nonlinear dynamic time-history analysis of aqueduct structures to obtain main aftershock fragility curves. Zhang et al. [7] conducted in-depth research on the vulnerable parts of intake tower structures under seismic action through dynamic time-history analysis and explored the response variation patterns of these parts during earthquakes. Zhao et al. [8] selected the endurance time-history method and incremental dynamic method as calculation methods and made comparative analyses of the results. Huang et al. [9,10] established corresponding dynamic finite element models based on ABAQUS version 2020, considering the influence of site soil uncertainty, input ground motion uncertainty, and soil–structure contact effects, using the lining section moment capacity ratio as the damage index to obtain corresponding structural fragility curves. Shi et al. [11] systematically evaluated the seismic performance of three-dimensional isolated structures at both structural and non-structural component levels through incremental dynamic analysis, revealing the significant effect of multi-dimensional isolation technology in reducing system fragility. Zhang et al. [12] proposed a seismic design method for intake tower structures based on incremental dynamic analysis to more accurately assess structural limit states and seismic performance. Zhang et al. [13] conducted time-history analysis of transmission towers under seismic action using incremental dynamic analysis to obtain maximum tower top displacement and maximum segment displacement ratios at different peak accelerations. Amirpour et al. [14] based on the IDA method found that dam crest displacement ratio and peak stress in upstream–downstream overstress zones are more suitable as damage indices than other parameters. Liu et al. [15] took two different types of concrete-filled square steel tube frame structures as examples, considering ground motion uncertainty and structural uncertainty, and conducted performance-based seismic fragility analysis. Yao et al. [16] employed nonlinear dynamic time-history analysis with the crest displacement relative to the heel in the streamwise direction, the global damage index, and the cumulative sliding displacement along the dam-foundation interface as individual response indicators. Using the efficacy coefficient method, the authors applied a variable weight model to compute the comprehensive damage index of the dam body, proposed a four-level seismic damage classification criterion based on the comprehensive damage index, and conducted a comparative study on the seismic fragility curves of concrete gravity dams derived from individual response indicators versus the comprehensive damage index. The

comprehensive damage index was proposed to characterize the seismic performance of the gravity dam system, and probabilistic fragility curves were generated accordingly. Liang et al. [17] conducted parameter sensitivity and uncertainty analysis for gravity dams and arch dams based on the sliding instability failure mode of high arch dam-foundation systems and defined different limit states based on obtained IDA curves to conduct seismic fragility analysis. Wu et al. [18] took reinforced concrete frame structures as an example and proposed a method to determine structural seismic performance levels based on structural ultimate damage states, thereby conducting performance-based structural seismic fragility analysis. The above scholars only focused on the response characteristics of intake towers at the same period when studying seismic fragility, without systematically studying the seismic performance of intake towers throughout their full life cycle; fragility analysis based on single response indices is insufficient to reflect the actual failure modes occurring in the tower body. Zhang et al. [19] performed a parametric analysis with respect to service age and design parameters. The probability distributions of fragility function parameters (median and logarithmic standard deviation) were established. The evolution law of fragility parameters with increasing service age was determined, and a time-dependent fragility model for existing steel frame columns in marine atmospheric environments was proposed through regression analysis. Based on the developed FEA model and damage categories of existing columns, the influence of characteristic variables (service age, design parameters, and damage level) on the residual seismic capacity of earthquake-damaged columns was elucidated. Liang et al. [20] found that during the service period, the effects of time-varying durability damage and time-varying bond-slip effects on material mechanical properties cannot be ignored, with fragility and importance coefficients increasing with service years. However, existing research still faces the following common limitations: current vulnerability analyses predominantly focus on the initial structural state, failing to account for the progressive degradation of material properties over the service life. Existing studies predominantly characterize the failure state using either tower top displacement or a single damage index. Displacement-based indicators are insufficient in revealing the localized damage accumulation at critical interfaces; a single global damage index, on the other hand, tends to mask the severity at hazardous locations. Although some studies have referenced time-dependent factors, a time-variant probabilistic seismic demand model simultaneously incorporating both displacement and localized damage is yet to be established; it is necessary to study the time-varying fragility of intake tower structures during their full service life. This study requires a probabilistic time-varying fragility analysis, for which the incremental dynamic analysis (IDA) is precisely the standard methodology designed; conversely, the Endurance Time Analysis is more suitable for the rapid assessment of deterministic structural responses under specific rare earthquake events. Therefore, the incremental dynamic analysis method is selected for this research.

This paper established a three-dimensional finite element model of the intake tower, classified performance levels based on displacement and local damage indices according to the variation trends of IDA curves, considered the time-varying characteristics of the concrete material, constructed different time-varying probabilistic seismic demand models, plotted fragility curves of the intake tower structure at different service years, and conducted detailed analysis of full life cycle time-varying fragility.

2. Seismic Fragility Analysis Method

2.1. Incremental Dynamic Analysis

Incremental dynamic analysis is currently the most promising method for determining structural response under different intensity ground motions in performance-based earthquake engineering. The basic principle of this method is to input one or more ground

motion records multiplied by different scale factors to the structure; these ground motion records with different scale factors have become a series of ground motions with multiple intensities; through structural dynamic elastoplastic analysis, the nonlinear response of the structure under this series of ground motion records can be obtained; selecting appropriate ground motion intensity measure and structural performance parameter, and processing the calculated data, the IDA curve with IM as the independent variable and DM as the dependent variable can be obtained.

Through IDA calculation method [21] analysis of structures, the response and plastic development of structures under potentially achievable ground motion intensities can be described relatively accurately and continuously; important performance parameters of structures varying with ground motion intensity can be demonstrated and patterns discovered; for special or novel structural systems, more in-depth research on the ability of such structural systems to resist seismic action can be conducted through IDA calculation; based on IDA calculation results, seismic fragility analysis of structures can be conducted to assess structural seismic performance from a probabilistic perspective.

2.2. Seismic Fragility Analysis

Seismic fragility describes the probability that the seismic demand of a structure or component reaches or exceeds a specified damage limit state under different ground motion intensities. Seismic fragility analysis methods [22] include the following:

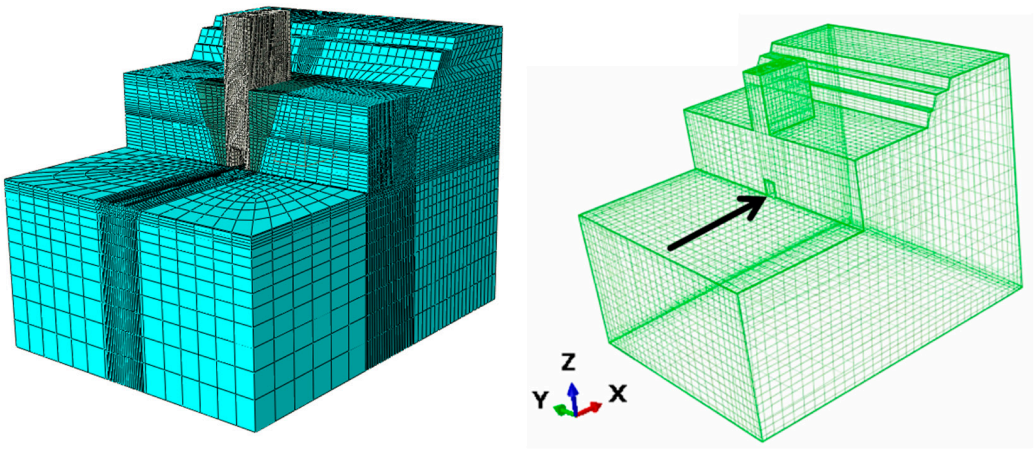
① Empirical fragility models;
② Statistical fragility models;
③ Expert system fragility models;
④ Physics-based fragility models.

This paper proposes time-varying fragility analysis methods based on displacement indices and damage indices, considering the randomness of intake tower structures and ground motions and material performance deterioration during the service period.

3. Finite Element Model

3.1. Establishment of Intake Tower Finite Element Model

This paper uses ABAQUS to construct a three-dimensional numerical model of the intake tower-foundation system, as shown in Figure 1. Hydrodynamic pressure is treated using the added mass method for internal and external water pressure loads.



(a) (b)

Figure 1. Three-dimensional finite element model of water intake tower. (**a**) Grid model diagram; (**b**) geometric model diagram.

Material parameters: The main structure uses C30 concrete, while backfill and tunnel lining use C25 concrete. The foundation scope is determined by extending each direction by one times the tower height. The tower body, backfill soil, and bedrock are all discretized using hexahedral solid elements, while connecting beams are discretized using beam elements. The tower body and bedrock constitute the main system; after discretization, the model generates a total of 129,749 elements and 128,659 nodes.

Dynamic calculation boundary conditions are set as: normal constraints on all four sides of the foundation, complete constraint at the bottom, and ground motion input through the massless foundation uniform input method.

The water intake tower of the dam is a shaft-type water intake structure standing in the reservoir. As shown in Figure 1b, the direction indicated by the arrow represents the flow direction. The X-axis is parallel to the flow direction, the Y-axis is horizontally perpendicular to the flow direction, and the Z-axis is vertically perpendicular to the flow direction.

3.2. Time-Varying Model of Concrete Material Strength and Elastic Modulus

International models usually focus on the influence of factors such as cement type and mineral admixtures on concrete strength variation over time and determine model parameters through test data.

Gao et al. [23] combined international multi-factor analysis concepts, through field testing and data analysis, and constructed a nonlinear model for concrete strength variation over time. This model can intuitively reflect the influence of concrete strength time-varying effects on design errors, and the model is applicable for longer durations; therefore, this paper selects this model for concrete material strength time-varying analysis:

$$f_c(t) = f_{cu,k}\left(-2.861 \times 10^{-4}t^2 + 1.384 \times 10^{-2}t + 0.8769\right) \quad (1)$$

where $f_c(t)$ is the concrete strength at service year t; $f_{cu,k}(t)$ is the standard compressive strength of concrete.

Selecting C30 concrete with service period of 5–60 years, its compressive strength time-varying pattern is shown in Figure 2.

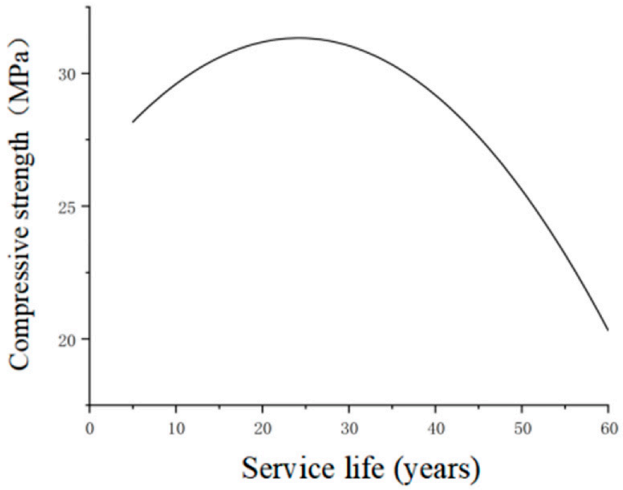


Figure 2. Time-varying characteristics of compressive strength of C30 concrete.

3.3. Time-Varying Model of Concrete Material Elastic Modulus

Changes in concrete material compressive strength simultaneously affect the elastic modulus of concrete materials. Considering the time-varying characteristics of concrete strength, based on the relationship between concrete material elastic modulus values

and compressive strength values in reference [24], the following material elastic modulus time-varying model is established:

$$E_t = \frac{10^5}{2.2 + \frac{33}{f_c(t)}} \quad (2)$$

where the unit of $f_c(t)$ is MPa; the unit of E_t is GPa.

From this concrete elastic modulus time-varying model, the variation curve of C30 concrete elastic modulus during 5–60 years of service is obtained, as shown in Figure 3. Comparing Figure 3 with Figure 2, it can be seen that concrete elastic modulus shows obvious time-varying characteristics during the service period with the same variation trend as compressive strength. However, even repeated seismic actions of relatively low intensity can cause gradual propagation of microcracks, thereby reducing the elastic deformation capacity of concrete.



Figure 3. Time-varying properties of elastic modulus of C30 concrete.

The time evolution of key mechanical parameters of concrete (compressive strength, elastic modulus) directly leads to time-varying characteristics in structural mechanical performance. To quantitatively analyze the influence of this time-varying characteristic on structural seismic performance, it is necessary to reasonably consider material time-varying factors and obtain structural responses when encountering earthquakes during the entire service period.

3.4. Seismic Motion Record and Level Categorization by Validity

This paper adopts selection method of ground motion suggested by Li et al. [25] and selects nine seismic records from the Pacific Earthquake Engineering Research Centre (PEER) database (Table 1). The category of the site involved in this article is Class 2.

In accordance with the Classification of Earthquake Damage to Buildings and Special Structures (GB/T 24335-2009) [26] and the Chinese Seismic Intensity Scale (GB/T 17742-2020) [27], the damage levels of the intake tower structure under seismic action are classified into five grades, as shown in Table 2:

Table 1. Seismic wave information table.

NO.	Seismic Event	Station Name	Magnitude	Shear Wave Velocity/ (m/s)	Fault Distance /km	PGA/g	PGV/ (m/s)	PGV/PGA
1	Duzce_Turkey	Ambarli	7.14	185	187.99	0.0380	0.0069	0.1816
2	Hector Mine	Altadena—Eaton Canyon	7.13	296.97	105.2	0.0732	0.0167	0.2281
3	Hector Mine	San Bernardino—E and Hospitality	7.13	375.16	166.11	0.0377	0.0068	0.1804
4	Hector Mine	San Bernardino—Mont. Mem Pk	7.13	358.92	104.95	0.0935	0.0171	0.1829
5	Hector Mine	Whittier Narrows Dam downstream	7.13	298.68	169.83	0.0608	0.0168	0.2763
6	Landers	Anaheim—W Ball Rd	7.28	269.29	144.9	0.0517	0.0169	0.3269
7	Landers	Arcadia—Arcadia Av	7.28	330.5	137.25	0.0285	0.0107	0.3754
8	Landers	Burbank—N Buena Vista	7.28	320.57	157.94	0.0561	0.0068	0.1212
9	Landers	Bell Gardens—Jaboneria	7.28	267.13	154.26	0.0369	0.0087	0.2358

Table 2. Seismic damage classification of intake tower structures.

Performance Level	Service Condition of Intake Tower Structure
Basically Intact	After experiencing seismic action, the materials of the intake tower structure remain in the linear elastic stage, with no obvious damage, and the structure can be used normally.
Slight Damage	The overall structure of the intake tower shows no obvious damage, but secondary components are damaged. The original function can be restored without repair or with simple repair.
Moderate Damage	The intake tower structure shows no obvious deformation, but the tower body suffers damage within a certain range. General repair is required to restore normal service condition.
Severe Damage	The tower body of the intake tower structure exhibits obvious plastic damage; the bedrock separates from the tower body. It loses basic functions, and it is difficult to restore the original functions after repair.
Destruction	The intake tower structure completely loses its original service performance. The tower body suffers obvious and severe damage, is on the verge of collapse or has already collapsed and completely loses the possibility of repair.

LS_1 is defined as slight damage, corresponding to the displacement threshold at which cracking initiates in the concrete structure. LS_2 is defined as moderate damage, corresponding to the displacement at which reinforcement yields for the first time. LS_3 is defined as severe damage, corresponding to the intermediate state between the equivalent yield displacement and the ultimate displacement, i.e., the stage at which the structure has entered significant plastic deformation but has not yet attained its peak load-bearing capacity. LS_4 is defined as collapse prevention, corresponding to the ultimate limit state at which the structure is approaching collapse.

4. Time-Varying Probabilistic Seismic Demand Model

4.1. Selection of Engineering Demand Parameters

The selection of appropriate engineering demand parameters is a crucial step in conducting seismic fragility analysis of intake towers. Based on the ground motion information provided in Table 1, ground motion records Nos. 2 and 5 were selected. This section will identify the indicators most correlated with the seismic response of intake towers from among the following four EDPs: relative displacement at the tower top in the streamwise direction, relative displacement at the tower top in the direction perpendicular to water flow, damage index at the junction between the tower side and backfill concrete, and damage index at the mid-section of the tower top.

From Figures 4 and 5, it can be observed that with increasing service years of the intake tower, the increment of relative displacement at the tower top in the streamwise direction is greater than that in the direction perpendicular to water flow, and the damage index at the junction between the tower side and backfill concrete is larger than that at the mid-section of the tower top. The relative displacement at the tower top in the streamwise direction and the damage at the junction between the tower side and backfill concrete cause more severe damage to the intake tower structure.

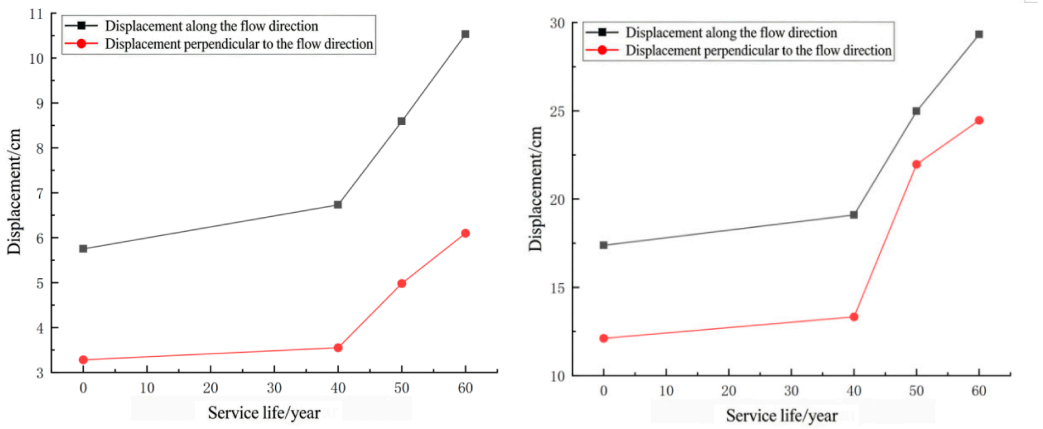


Figure 4. Comparison of maximum tower top displacements for intake towers of different service lives. (**a**) NO. 2; (**b**) NO. 5.

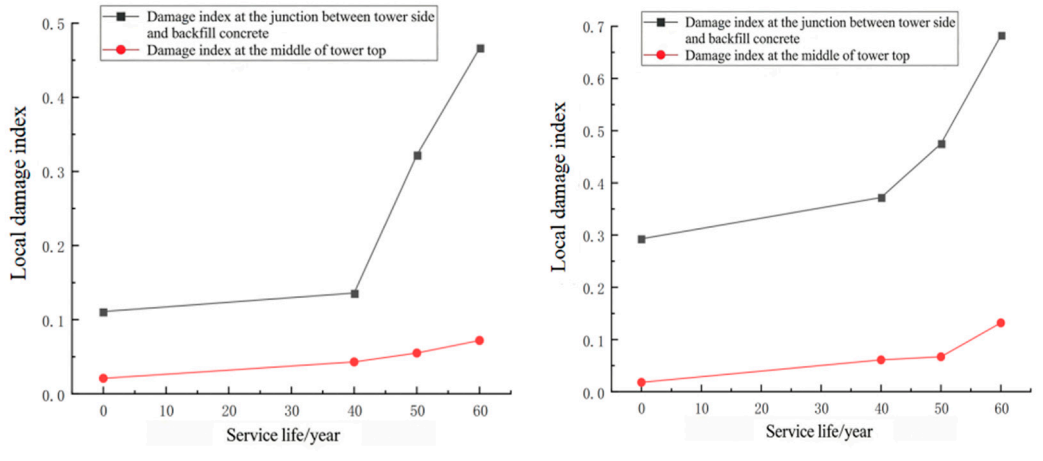


Figure 5. Comparison of local damage indices of intake towers with different service lives. (**a**) NO. 2; (**b**) NO. 5.

Therefore, the relative displacement at the tower top in the streamwise direction and the damage index at the junction between the tower side and backfill concrete can better reflect the damage effects of ground motion and time-varying characteristics on high-rise intake towers. In summary, this chapter will conduct probabilistic demand analysis and time-varying fragility analysis of intake towers based on the relative displacement at the tower top in the streamwise direction and the damage index at the junction between the tower side and backfill concrete.

4.2. Time-Varying Probabilistic Seismic Demand Model Based on Displacement and Damage Index

(1) Time-Varying Probabilistic Seismic Demand Model Based on Displacement

In probabilistic seismic demand analysis (PSDA), it is necessary to conduct hazard analysis based on real site conditions, statistically analyzing the probability that the structure exceeds given performance levels within any design period. The probabilistic seismic demand model refers to the statistical relationship between engineering demand parameters (EDPs) and ground motion intensity indices. According to Cornell et al.'s [28] research, assuming structural response follows log-normal distribution, the probabilistic seismic demand model for intake tower structures is established accordingly.

As structural service time increases, structural seismic demand and seismic capacity continuously change. This paper considers time-varying seismic fragility by introducing time parameter t, obtaining the log-linear regression model of the structure:

$$\ln(S_D(t)) = \ln(a)(t) + b(t)\ln(IM) \tag{3}$$

Accordingly, the time-varying probabilistic seismic demand model for intake tower structures is established:

$$P[D(t) \geq LS_i(t) \,|IM, t] = \Phi\left(\frac{\ln(LS_i(t)) - \ln(S_D(t))}{\beta_{D\,IM}(t)}\right) \tag{4}$$

where $D(t)$ is the seismic demand of the structure at time t; $LS_i(t)$ is the limit state of the structure at time t; $S_D(t)$ is the median seismic demand of the structure at time t; and $\beta_{D\,IM}(t)$ represents the standard deviation of structural demand at time t.

Based on the established three-dimensional finite element model, this research selected nine ground motion records, calculated after amplitude modulation, with ground motion intensity gradually increasing from 0.1 g to 1 g in steps of 0.1 g. Through statistical analysis, the relationship between different engineering demand parameters and peak ground acceleration was analyzed, and corresponding probabilistic seismic demand models were constructed.

For probabilistic seismic demand analysis of the intake tower, the maximum relative displacement at the tower top in the streamwise direction was selected as the engineering demand parameter for probabilistic demand analysis.

The maximum relative displacement at the tower top in the streamwise direction was selected as the engineering demand parameter, and the peak ground acceleration (PGA) was adopted as the ground motion intensity measure. Through logarithmic transformation of the time-history analysis data and implementation of regression analysis on the nonlinear time-history analysis, the fitted curves are presented in Figures 6–9. The probabilistic seismic demand model for the intake tower structure in the streamwise direction displacement, as well as the corresponding logarithmic standard deviation, was obtained as shown in Table 3. In Table 3, the β values typically fall within the range of 0.60–0.85.

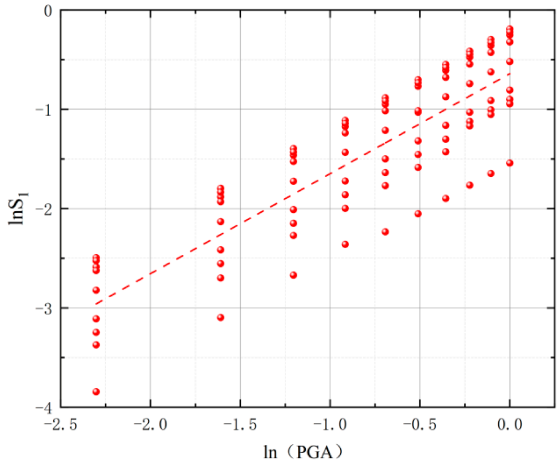


Figure 6. Probabilistic seismic demand modelling of the maximum value of displacement in the downstream direction at the top of the intake tower at 0 years of service.

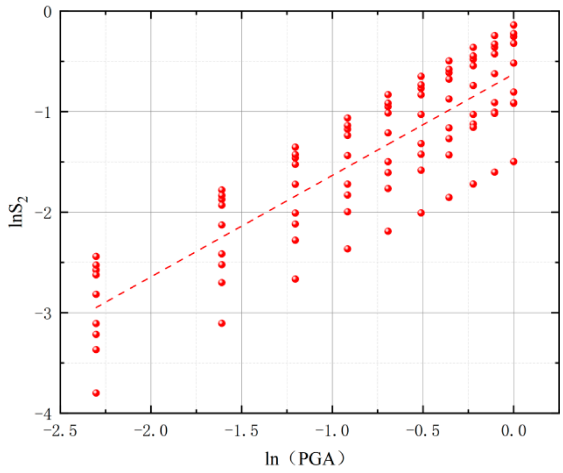


Figure 7. Probabilistic seismic demand modelling of the maximum value of displacement in the downstream direction at the top of the intake tower at 40 years of service.

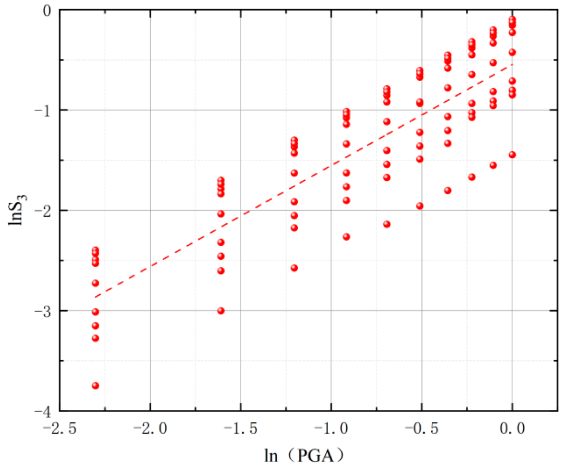


Figure 8. Probabilistic seismic demand modelling of the maximum value of displacement in the downstream direction at the top of the intake tower at 50 years of service.

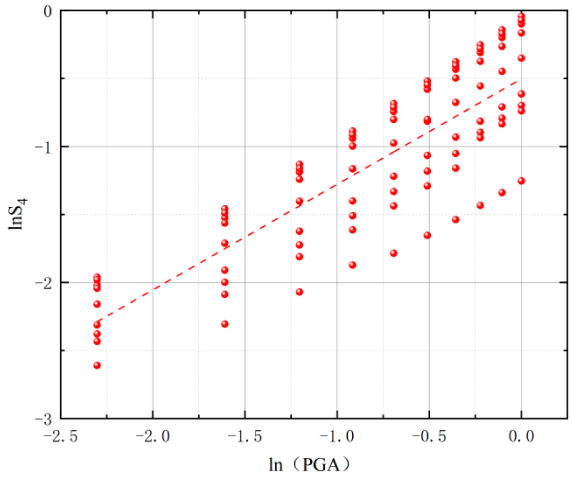


Figure 9. Probabilistic seismic demand modelling of the maximum value of displacement in the downstream direction at the top of the intake tower at 60 years of service.

Table 3. Probabilistic demand models based on displacement and corresponding logarithmic standard deviations for various years.

Year	Probabilistic Demand Model	β_{siPGA}
0 year	$\ln S_1 = 1.0067 \ln(PGA) - 0.6415$	0.8222
40 years	$\ln S_2 = 1.0087 \ln(PGA) - 0.6258$	0.8225
50 years	$\ln S_3 = 1.0067 \ln(PGA) - 0.5462$	0.8222
60 years	$\ln S_4 = 0.7756 \ln(PGA) - 0.5029$	0.6422

(2) Time-Varying Probabilistic Seismic Demand Model Based on Damage Index

Among damage models specified in concrete codes, damage magnitude and damage range can characterize the stiffness degradation and strength state of a structure. Local damage indices can be used to evaluate local damage conditions of structures, and overall damage indices obtained through weighting of local damage indices can be used to evaluate overall structural damage conditions [29].

Structural damage often has significant non-uniform distribution characteristics; local damage indices can accurately identify damage concentration areas and their severity, providing clear basis for targeted repair and reinforcement, while overall damage indices through weighted averaging will mask weak links in key parts, causing information from severely damaged areas to be "diluted", unable to reflect the true dangerous state of the structure.

Therefore, this section will determine local damage indices through tensile damage factors to explore the damage degree of intake towers under strong earthquakes and construct probabilistic seismic demand models based on damage indices.

The damage index at the junction between the tower side and backfill soil was selected as the engineering demand parameter, with the peak ground acceleration remaining as the ground motion intensity measure. Logarithmic transformation was performed on the damage index data, and the damage index distributions obtained through regression analysis are illustrated in Figures 10–13. Based on the fitting results, the probabilistic seismic demand model for the tower side damage index of the intake tower structure and the logarithmic standard deviation were established as shown in Table 4. The assessment of local damage represented by the β values in Table 4 is generally more stochastic than the global inter-story drift demand. Tower-side regions are typically subjected to the combined action of lateral deformations induced by the main frame and potential vertical loads,

rendering their damage evolution mechanisms more complex and further exacerbating the dispersion of damage responses in these regions.

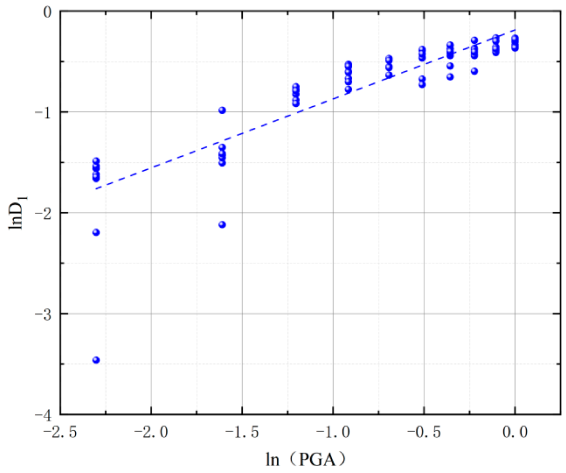


Figure 10. Probabilistic seismic demand modelling of tower side damage index at 0 years of service.

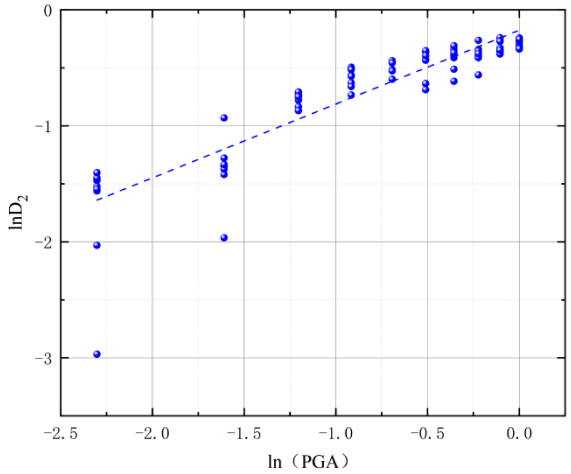


Figure 11. Probabilistic seismic demand modelling of tower side damage index at 40 years of service.

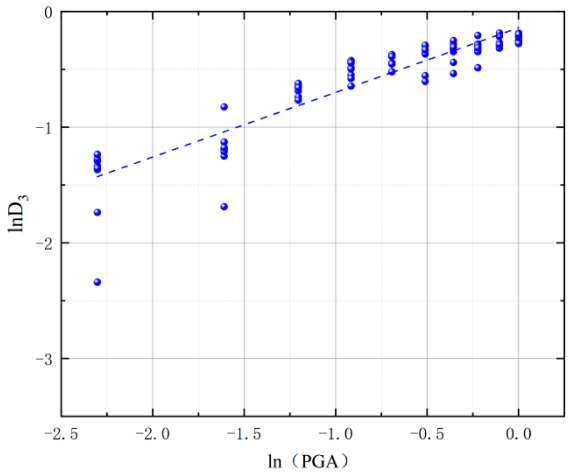


Figure 12. Probabilistic seismic demand modelling of tower side damage index at 50 years of service.

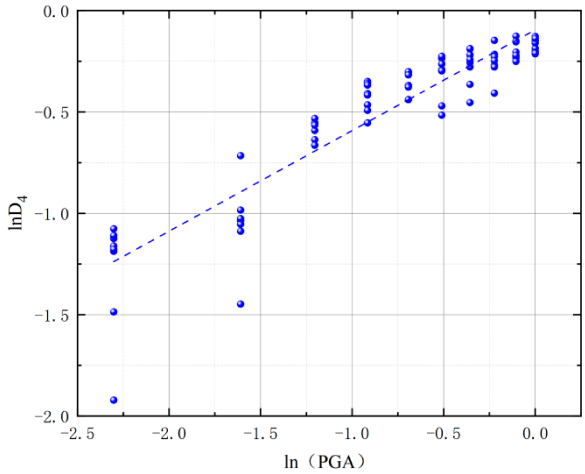


Figure 13. Probabilistic seismic demand modelling of tower side damage index at 60 years of service.

Table 4. Probabilistic demand models based on local damage and corresponding logarithmic standard deviations for various years.

Year	Probabilistic Demand Model	β_{DiPGA}
0 year	$\ln D_1 = 0.6837n(PGA) - 0.1874$	0.5390
40 years	$\ln D_2 = 0.6363n(PGA) - 0.1756$	0.4560
50 years	$\ln D_3 = 0.5589n(PGA) - 0.1397$	0.3551
60 years	$\ln D_4 = 0.4965n(PGA) - 0.0950$	0.3732

5. Full Life Cycle Time-Varying Fragility Result Analysis Under Ground Motion

5.1. Time-Varying Fragility Analysis Based on Displacement Index

This study employs the displacement index in the streamwise direction as the engineering demand parameter to further investigate the evolution law of seismic performance of intake tower structures over their full life cycle considering material degradation conditions. Fragility analysis can quantitatively characterize the probability of structures exceeding critical damage states under different intensity earthquakes, and when the time dimension is introduced, its core lies in revealing the dynamic correlation between damage index thresholds and seismic demand parameters with increasing service years. Therefore, this section will investigate the time-varying fragility analysis of intake tower structures based on displacement.

According to the probabilistic seismic demand analysis in Chapter 4, the cumulative probability that the structure reaches or exceeds a certain performance level or limit state at time t can be expressed by the formula:

$$P[D(t) \geq LS_i(t)|IM,t] = \Phi\left(\frac{\ln(IM,t) - \frac{\ln(LS_i(t)) - \ln(a(t))}{b(t)}}{\frac{\beta_{D\,IM}(t)}{b(t)}}\right) \quad (5)$$

Let: $m_{IM}(t) = \frac{\ln(LS_i(t)) - \ln(a(t))}{b(t)}$, $\zeta_{IM}(t) = \frac{\beta_{D\,IM}(t)}{b(t)}$

where m_{IM} represents the mean of ground motion intensity IM; ζ_{IM} represents its standard deviation.

Based on the ground motion information provided in Table 1, ground motion records Nos. 1, 2, and 5 were selected and scaled in increments of 0.1 g up to 1.0 g. Through analysis, the incremental dynamic analysis (IDA) curves for the maximum relative displacement at

the tower top of the intake tower in the streamwise direction were obtained. Drawing upon the performance-level quantification methods for concrete structures such as reservoir dams, this study defined four performance-level threshold values based on displacement for the intake tower structure at service years of 0, 40, 50, and 60 years, according to Figure 14:

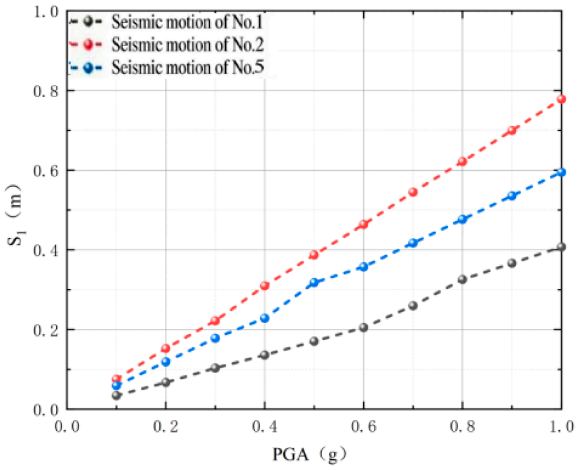


Figure 14. IDA curves of maximum displacement in the downstream direction at the top of the intake tower.

The fragility parameters for maximum displacement at the top of the intake tower structure in the streamwise direction at different performance levels for service years of 0, 40, 50, and 60 years are obtained, as shown in Table 5.

Table 5. Seismic susceptibility parameters for maximum displacement at the top of the intake tower structure at different performance levels.

	Performance Level	LS_1: 0.06 m	LS_2: 0.23 m	LS_3: 0.33 m	LS_4: 0.78 m
0 year	m_{IM}	−2.16	−0.82	−0.46	0.39
	ζ_{IM}	0.82	0.82	0.82	0.82
40 years	m_{IM}	−2.17	−0.84	−0.48	0.37
	ζ_{IM}	0.81	0.81	0.81	0.81
50 years	m_{IM}	−2.25	−0.91	−0.56	0.30
	ζ_{IM}	0.82	0.82	0.82	0.82
60 years	m_{IM}	−2.98	−1.25	−0.78	0.32
	ζ_{IM}	0.83	0.83	0.83	0.83

Substituting the seismic fragility parameters from Table 4 into Formula (5), the cumulative probability of reaching a certain performance level can be obtained as follows:

$$P[D(t) \geq LS_i(t)|IM, t] = \Phi\left(\frac{\ln(IM, t) - m_{IM}(t)}{\zeta_{IM}(t)}\right) \quad (6)$$

The seismic fragility curves for intake tower structures at 0, 40, 50, and 60 years of service reaching different performance levels under different intensity earthquakes are shown in Figure 15.

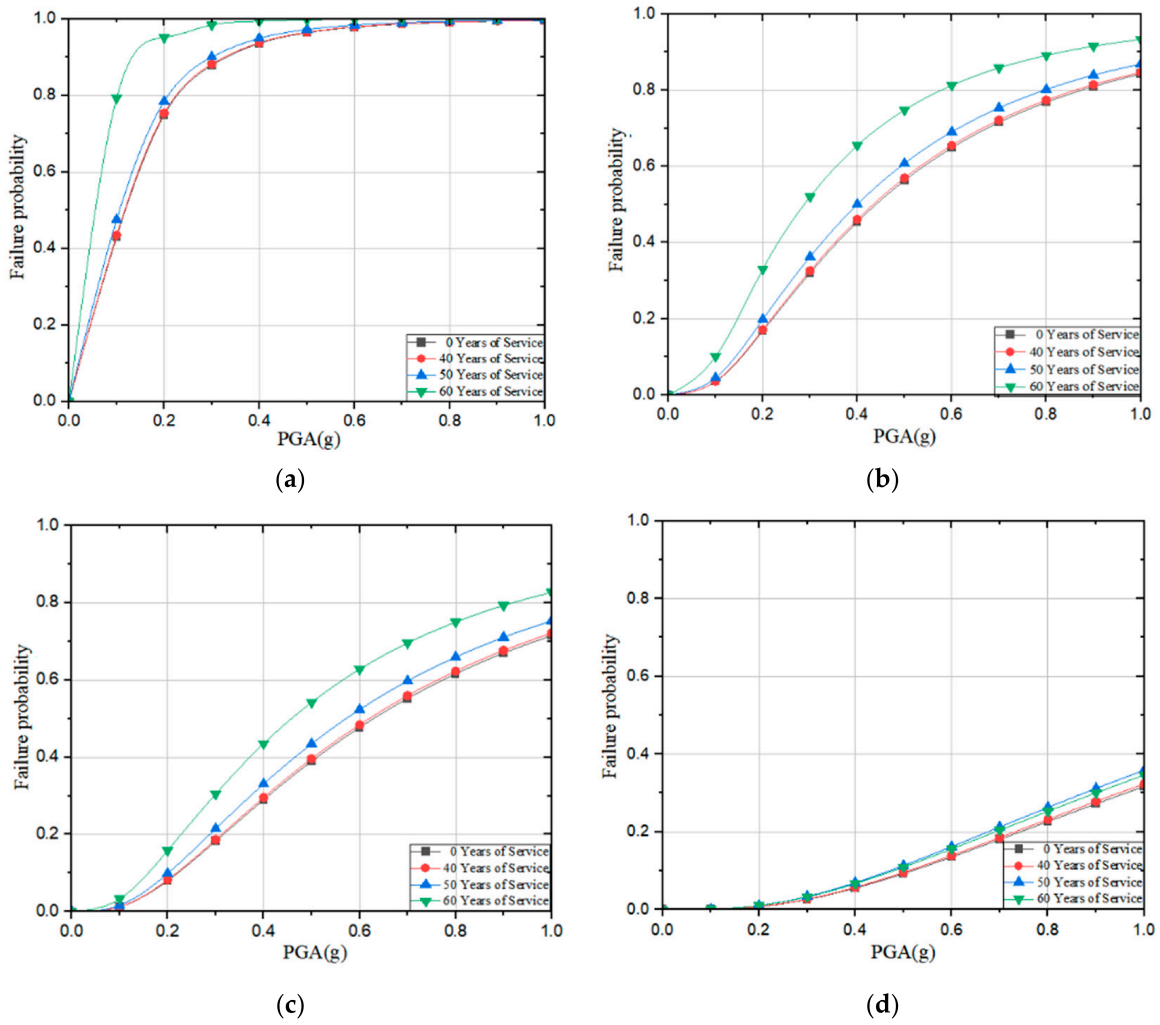


Figure 15. Displacement-based time-varying susceptibility curves for intake towers in different damage states. (**a**) LS_1; (**b**) LS_2; (**c**) LS_3; (**d**) LS_4.

In the time-dependent fragility analysis of the maximum displacement at the intake tower structure's top in the direction of water flow, the probability of the structure's maximum relative displacement at the top reaching performance levels LS_1 through LS_4 generally increases with service time. At a design earthquake acceleration of 0.2 g, the probability of reaching LS_1 for the 60-year-service structure increased by approximately 21% compared to the new structure (0-year service), while the probability of reaching LS_4 increased by 2%. Under 0.4 g and 0.8 g earthquake accelerations, the probabilities of the 60-year-service structure reaching critical performance levels were significantly higher than those of the new structure (0-year service), particularly at 0.8 g, where the probability of reaching LS_1 approached 99% and the probability of reaching LS_4 exceeded 25%.

With increasing service years, the probability of the intake tower structure reaching critical performance levels shows nonlinear growth. Specifically, taking reaching performance level LS_1 as an example, growth is slow from 0 to 40 years of service, while growth is rapid from 40 to 50 years and from 50 to 60 years of service. This is mainly because with increasing service years, the strength and elastic modulus of concrete materials gradually decrease, leading to degradation of structural seismic performance.

5.2. Time-Varying Fragility Analysis Based on Local Damage Index

Furthermore, the time-varying fragility analysis method based on local damage index is introduced. Although the displacement index can macroscopically reflect the degradation

of overall structural deformation capacity, it is difficult to reveal the influence of damage accumulation in key component details on the seismic performance of the system. Therefore, this study selects the junction between the tower side and backfill concrete and considers the time-varying deterioration of material performance over the full life cycle to establish time-varying fragility curves of structural local damage at different service years.

The ground motion records Nos. 1, 2, and 5 are still adopted. The performance levels based on the damage index are defined by analyzing the variation trends of IDA curves of the intake tower structure under the action of these three ground motions, and the fragility of the intake tower based on the damage index is analyzed. According to Figure 16, this paper defines the threshold values for classification of local damage index performance levels of the intake tower structure at 0, 40, 50, and 60 years of service as follows:

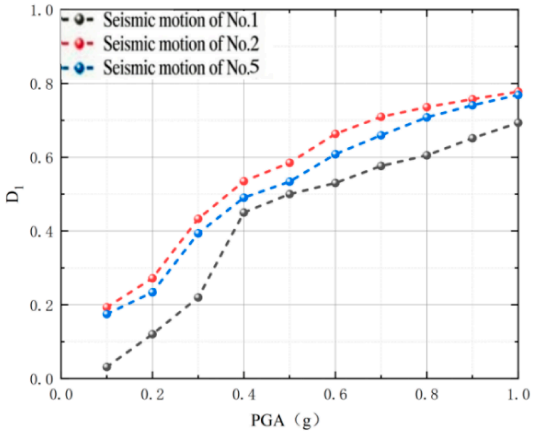


Figure 16. IDA curves of tower-side damage indices for intake tower structures.

The fragility parameters for tower-side damage index of intake tower structures at 0, 40, 50, and 60 years of service at different performance levels are obtained, as shown in Table 6.

Table 6. Seismic susceptibility parameters for the tower-side damage index of intake tower structures at different performance levels.

	Performance Level	LS_1: 0.22	LS_2: 0.45	LS_3: 0.6	LS_4: 0.76
0 year	m_{IM}	−1.94	−0.89	−0.47	0.13
	ζ_{IM}	0.79	0.79	0.79	0.79
40 years	m_{IM}	−2.10	−0.98	−0.53	0.16
	ζ_{IM}	0.72	0.72	0.72	0.72
50 years	m_{IM}	−2.46	−1.18	−0.66	0.24
	ζ_{IM}	0.64	0.64	0.64	0.64
60 years	m_{IM}	−2.86	−1.42	−0.84	0.36
	ζ_{IM}	0.75	0.75	0.75	0.75

Similarly, substituting the fragility parameters into Formula (5), the time-varying fragility curves for tower-side damage index of intake tower structures at 0, 40, 50, and 60 years of service reaching various damage states under different ground motion intensities can be obtained, as shown in Figure 17.

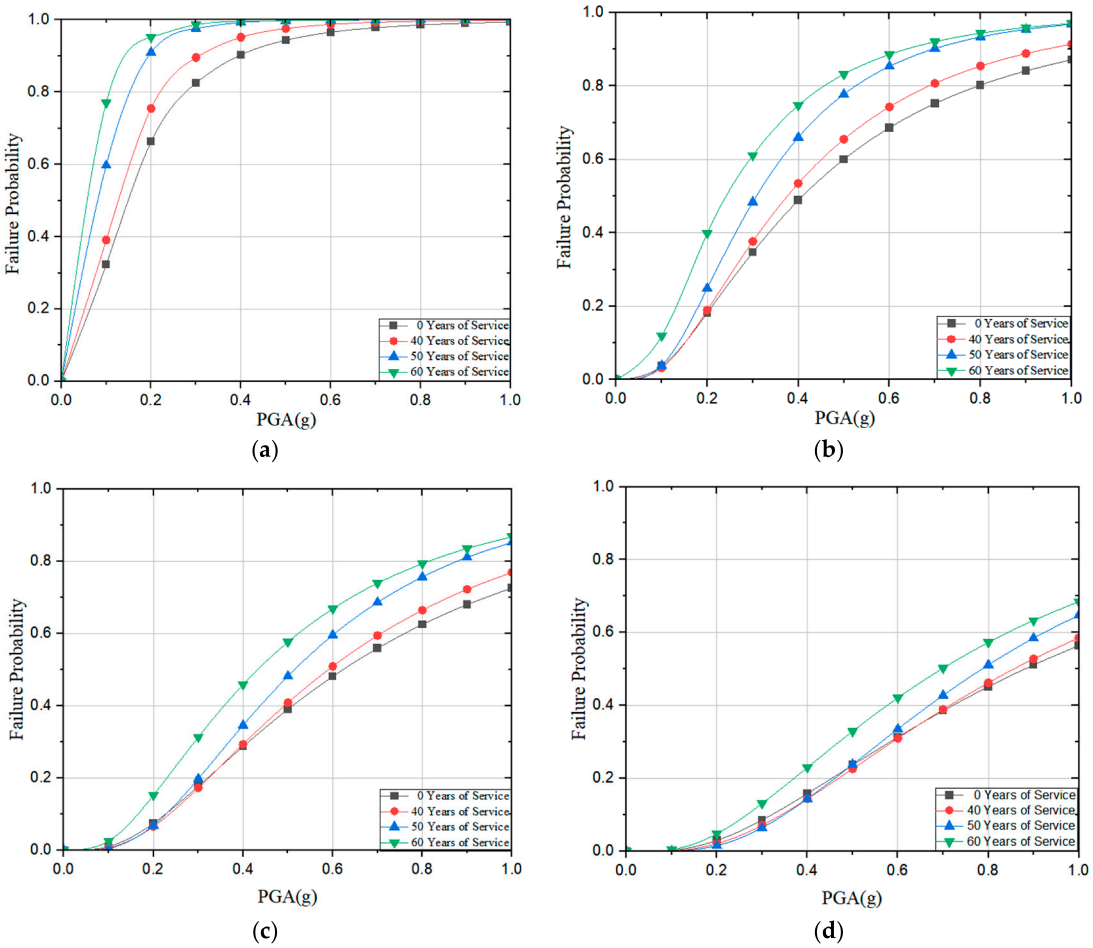


Figure 17. Time-varying susceptibility curves based on localized damage for intake towers in different damage states. (**a**) LS_1; (**b**) LS_2; (**c**) LS_3; (**d**) LS_4.

In the time-dependent fragility analysis based on local damage indices of the intake tower structure, the probabilities of the tower-side damage index reaching performance levels LS_1 through LS_4 increased with service time under design earthquake accelerations of 0.2 g, 0.4 g, and 0.8 g. Specifically, at 0.2 g and 0.4 g earthquake acceleration, the probability of LS_1 increased from 66.27% to 75.47%, while at 0.8 g earthquake acceleration, the probability of LS_1 approached 100%. Concurrently, the probabilities of LS_2 through LS_4 also increased significantly, indicating that the risk of tower-side damage in the intake tower structure gradually increases with extended service time, with this risk increase being more pronounced at higher earthquake accelerations.

In summary, with the enhancement of earthquake acceleration and the increase in service years, the probability of intake tower structures reaching critical performance levels increases significantly. Therefore, time-varying characteristics over the full life cycle should be fully considered in seismic design and reinforcement strategies, which helps to improve the seismic performance and safety of structures.

6. Conclusions

Based on the incremental dynamic analysis method, this study systematically investigated the time-varying seismic fragility of high-rise intake tower structures over their full life cycle. The main conclusions are as follows:

(1) Influence law of service years on fragility curves: With increasing service years, the probability of intake tower structures reaching critical performance levels shows

nonlinear growth. Growth is slow from 0 to 40 years of service, while growth is rapid from 40 to 50 years and from 50 to 60 years of service. This is mainly because concrete strength increases with time during the initial service period until 40 years when concrete strength decreases to near its original strength; therefore, structural response changes little from 0 to 40 years of service. After 40 years of service, concrete strength and elastic modulus begin to decrease, and structural seismic performance degradation becomes obvious. This is because the durability degradation of structures (e.g., steel reinforcement corrosion, concrete freeze–thaw damage) can significantly reduce the material's resistance to high-cycle fatigue, while the cumulative damage induced by high-cycle fatigue will, in turn, accelerate the deterioration of durability issues. There exists a strong interconnection between the two, characterized by a mutually reinforcing, vicious cycle.

(2) Time-varying fragility analyses based on displacement and local damage indicate that with increasing earthquake acceleration and service years, the probability of intake tower structures reaching critical performance levels increases significantly. In terms of tower top displacement, under design earthquake acceleration of 0.2 g, the probability of LS_1 at 60 years of service increases by 21% compared to 0 years of service; at four times design earthquake acceleration of 0.8 g, the probability of LS_1 reaches 99% and LS_4 exceeds 25%. For local tower-side damage, under earthquake acceleration of 0.2 g, the probability of LS_1 at 40 years of service increases by 10% than 0 years; at four times design earthquake acceleration of 0.8 g, the probability of LS_1 approaches complete failure. Research results indicate that with increasing service time, the failure probabilities of the water intake tower structure reaching critical performance levels in terms of tower top displacement and damage index both exhibit an upward trend.

(3) Sensitivity analysis of different quantification indices on fragility assessment results: There are differences in fragility analysis results based on displacement and local damage. Pursuant to the Unified Standard for Reliability Design of Building Structures (GB 50068) [30], the 50-year time point represents the performance state of the structure at the end of its conventional service life. Regarding tower top displacement, at a design seismic acceleration of 0.2 g, the probability of attaining LS_1 increases by 12.51% relative to the local lateral damage index, whereas the probability of attaining LS_2 increases by 5.06%; at twice the design seismic acceleration, the probability of attaining LS_1 increases by 4.34%, and the probability of attaining LS_2 increases by 15.97%. The displacement index mainly reflects the overall deformation capacity of the structure, while the local damage index reflects damage conditions at key structural locations. In actual engineering, appropriate damage indices should be selected according to specific assessment purposes and structural characteristics to obtain more accurate fragility assessment results.

In summary, the time-varying models for concrete strength and elastic modulus adopted in this study are primarily based on empirical relationships under general atmospheric environments, without considering the coupled effects of complex environmental factors such as freeze–thaw cycles and chemical attacks (e.g., sulfate and chloride ingress). Furthermore, the seismic input has not systematically accounted for the effects of special ground motion types, including near-fault pulse-like ground motions and directivity effects. Additionally, soil–structure interaction has not been incorporated. These factors all exert certain influences on the seismic fragility of the intake tower throughout its entire service life, and they represent directions for the author's future research.

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References

1. Chen, X.; Zhou, B.; Liu, X. An Investigation into the Effect of Near-Fault Ground Motion Duration Parameters on the Nonlinear Seismic Response of Intake Towers. *Buildings* **2024**, *14*, 580. [CrossRef]
2. Liu, C.; Jiang, G. Analysis of Dam Safety State Assessment Based on Monitoring Data from Guishi Reservoir. *Pearl River* **2024**, *45*, 29–33. (In Chinese)
3. Mi, C.; Xiong, G. Monitoring Data Analysis on Dam Safety of Meixi Reservoir. *Zhejiang Hydrotech.* **2018**, *46*, 50–54. (In Chinese)
4. Yu, H.; Li, X.; Yuan, Y. Seismic Vulnerability Analysis Method for Longitudinal Response of Immersed Tunnels. *China J. Highw. Transp.* **2022**, *35*, 13–22. (In Chinese)
5. Lü, X.; Su, N.; Zhou, Y. IDA-based seismic fragility analysis of a complex high-rise structure. *Earthq. Eng. Eng. Dyn.* **2012**, *32*, 19–25. (In Chinese)
6. Zheng, X.; Shen, Y.; Zong, X. Vulnerability Analysis of Main Aftershock Sequence of Aqueduct Based on Incremental Dynamic Analysis Method. *Buildings* **2023**, *13*, 1490. [CrossRef]
7. Zhang, X.; Dang, K.; Tao, W. Dynamic Response Analysis of Intake Tower Considering Contact Nonlinearity. *Shaanxi Water Resour.* **2021**, *2*, 20–22+26. (In Chinese) [CrossRef]
8. Zhao, J.; Yang, J.; Li, X. Seismic Performance Analysis of Intake Tower Structure Based on Endurance Time History Method. *China Earthq. Eng. J.* **2021**, *43*, 1244–1250. (In Chinese)
9. Huang, Z.-K.; Pitilakis, K.; Tsinidis, G.; Argyroudis, S.; Zhang, D.-M. Seismic vulnerability of circular tunnels in soft soil deposits: The case of Shanghai metropolitan system. *Tunn. Undergr. Space Technol.* **2020**, *98*, 103341. [CrossRef]
10. Huang, Z.; Zhang, D. Seismic Vulnerability Analysis of the Shallow-buried Shield Tunnel in Soft Soil Stratum. *Mod. Tunn. Technol.* **2020**, *57*, 51–60. (In Chinese)
11. Shi, Y.D.; Wei, W.W.; Ding, Y.; Li, Z.X. Seismic Fragility Study of Three-Dimensional Isolated Steel Frame Structure and Non-Structural Components. *Eng. Mech.* **2024**, *41*, 149–159. (In Chinese)
12. Zhang, H.; Zhang, L. Seismic performance assessment and potential failure modes of intake towers. *Nat. Hazards* **2016**, *83*, 1321–1340. [CrossRef]
13. Zhang, X.; Niu, J.; Liu, F.; Zhang, Y.; Yang, Q.; Feng, D. Seismic fragility analysis of transmission towers considering soil-structure interaction. *World Earthq. Eng.* **2026**, *42*, 100–111. (In Chinese) [CrossRef]
14. Amirpour, A.; Mirzabozorg, H. Quantifying the qualitative limit-states using IDA approach in concrete arch dams. *Arab. J. Sci. Eng.* **2014**, *39*, 7729–7740. [CrossRef]
15. Liu, J.; Liu, Y.; Yan, Q.; Huang, Q. Performance-based seismic fragility analysis of CFST frame structures. *China Civ. Eng. J.* **2010**, *43*, 39–47. (In Chinese)
16. Yao, Q.; Song, Z.; Wang, F.; Zhao, W. Vulnerability of concrete gravity dams based on a comprehensive destruction index. *Chin. J. Appl. Mech.* **2022**, *39*, 104–112. (In Chinese)
17. Liang, H.; Zhao, W.; Guo, S.; Tu, J.; Li, D.; Liao, J. Probabilistic Seismic Risk Analysis of Overall Stability of High Arch Dam-Foundation System. *J. Hydraul. Eng.* **2021**, *52*, 310–322. (In Chinese)
18. Wu, Q.; Zhu, H.; Fan, J. Performance-Based Seismic Fragility Analysis of Rc Frame Structures. *Eng. Mech.* **2012**, *29*, 117–124. (In Chinese)

19. Zhang, X.; Zhao, X.; Zheng, S.; Yang, Q. Time-Dependent Fragility Functions and Post-Earthquake Residual Seismic Performance for Existing Steel Frame Columns in Offshore Atmospheric Environment. *Buildings* **2025**, *15*, 2330. [CrossRef]
20. Liang, Y.; Yan, J.L.; Qian, W.X.; Cheng, Z.Q.; Chen, H. Analysis of collapse resistance of offshore rigid frame—Continuous girder bridge based on time-varying fragility. *Mar. Struct.* **2021**, *75*, 102844. [CrossRef]
21. Jiang, J.; Wang, S.; Xu, C.; Du, X.; Chen, G. Application of incremental dynamic analysis and the cloud method in the seismic vulnerability analysis of underground structures. *J. Harbin Eng. Univ.* **2023**, *44*, 1445–1452. (In Chinese)
22. Ma, Z. Seismic Fragility Analysis Method for Gravity Dams Based on Deformation and Damage. Master's Thesis, Guangxi University, Nanning, China, 2016.
23. Gao, X.; Yan, Y.; Li, J. Change Law of Time-Dependent Concrete Compressive Strength in the Atmospheric Environment. *China Civ. Eng. J.* **2015**, *48*, 19–26. (In Chinese)
24. Zhu, Y. *Design Principle of Concrete Structures*; Chongqing University Press: Chongqing, China, 2022; p. 357. (In Chinese)
25. Li, X.H.; Wang, W.K.; Wu, D.; Xu, X.L.; Li, Z.J.; Li, Y.X. The bounded method and characteristics analysis for long period ground motions. *J. Vib. Eng.* **2014**, *27*, 685–692. (In Chinese)
26. *GB/T 24335-2009*; Classification of Earthquake Damage to Buildings and Special Structures. Standards Press of China: Beijing, China, 2009. (In Chinese)
27. *GB/T 17742-2020*; The Chinese Seismic Intensity Scale. Standards Press of China: Beijing, China, 2020. (In Chinese)
28. Cornell, C.A.; Jalayer, F.; Hamburger, R.O.; Foutch, D.A. Probabilistic Basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines. *J. Struct. Eng.* **2002**, *128*, 526–533. [CrossRef]
29. Li, J.; Chen, J.Y.; Xu, Q.; Ji, L.Q. Study on Index of Seismic Performance Evaluation of Arch Dam. *J. Hydraul. Eng.* **2015**, *46*, 118–124. (In Chinese)
30. *GB 50068-2018*; Unified Standard for Reliability Design of Building Structures. China Architecture & Building Press: Beijing, China, 2018. (In Chinese)

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