TOP STRUCTURE OPTIMIZATION AND SEISMIC PERFORMANCE EVALUATION OF INLET TOWER BASED ON ENDURANCE TIME ANALYSIS

Shuliang GUO[1], Xiaodong ZHENG[2*], Xingguang ZONG[3]

Based on the endurance time analysis, the effect of the top structure of the inlet tower on the dynamic response of the tower is considered, and structural dynamic response indexes such as displacement, energy and damage are used to optimize the height and stiffness of the hoist room at the inlet tower top. The seismic performance of the inlet tower is evaluated by combining endurance time analysis and probability analysis. Taking the high inlet tower in southwestern China as the case background, endurance time analysis was carried out on the inlet tower. The results show that: During the whole seismic analysis process, when the height of the top hoist room reaches about 20m, the dynamic response of the inlet tower will decrease significantly;the dynamic response of the inlet tower decreases with the decreasing stiffness of the top structure, and top structure with smaller stiffness significantly lowers the dynamic response of the tower structure. For the optimized inlet tower, the peak ground acceleration corresponding to each limit state is greater than that under the maximum credible earthquake, which meets the functional guarantee level and safety guarantee level of the inlet tower. The research results provide new ideas for the seismic performance design and safety risk assessment of the inlet tower.

Keywords: endurance time analysis; structural performance parameters; high inlet tower; structure optimization; seismic performance evaluation

1. Introduction

Inlet tower is an independent towering structure. With complicated structural stress and boundary conditions, inlet tower plays an important role in the entire water conservancy project [1]. Hence, detailed structural optimization of the inlet tower has become a research hotspot of domestic and foreign scholars in recent years. Cao Wei et al. [2] analyzed the influence of different backfill materials and thicknesses of backfill concrete on the dynamic response of the inlet tower structure under the action of earthquake, and finally determined a reasonable backfill method. However, regarding hoist room at the inlet tower top,

[1] Lecturer, Chongqing Industry & Trade Polytechnic, 408000, Chongqing, China.
[2] Associate professor, School of Water Conservancy and Hydroelectric Power, Hebei University of Engineering, 056038, Handan, China. e-mail: 373048972@163.com
[3] Engineer, HeBei Province Water Conservancy Engineering Bureau Group Co. , Ltd., 050021, Shijiazhuang, China.

most previous studies make analysis according to the additive mass method [3-5], which ignores the effect of the top structure on the dynamic response of the main structure of the inlet tower, thus inconsistent with the actual project. The interaction between the inlet tower and the hoist room at the top is a non-negligible problem in the seismic analysis of the inlet tower [6-8]. Daniell[9] first studied the earthquake response of the entire inlet tower system including the hoist room. The hoist room structure will reduce the main structure response of the inlet tower under earthquake. On this basis, Zhang Hanyun, Zhang Liaojun et al. [10-11] considered the top structure of the inlet tower and analyzed the failure mechanism of the inlet tower. The influence of the hoist room at the inlet tower top on the dynamic response of the tower structure should be valued in the analysis process. According to the statistical data from existing hydropower station on inlet tower height and hoist room height at the inlet tower top, the height ratio between the top hoist room and the tower structure should be between one-fourth and one-half, generally between 10m and 40m[12]. Within this range, the damage state of the entire inlet tower structure will produce varying effects depending on the change of the hoist room height and stiffness. In order to improve the dynamic characteristics of the inlet tower structure, it is imperative to carry out dynamic optimization design of its structure.

In this paper, the Yangqu inlet tower in southwestern China is selected as the research object. Considering the influence of the hoist room at the inlet tower top on the earthquake response of the tower structure, seismic analysis of the inlet tower was carried out based on endurance time analysis. With displacement, damage and energy as the earthquake response indexes, and earthquake resistance time as the ground motion intensity parameter, a finite element model of the inlet tower was established with 7 groups of hoist rooms with different heights and 3 groups of hoist rooms with different stiffness to study the effect of hoist room on the earthquake response of the inlet tower. In this way, the top structure of the inlet tower will be optimized. At the same time, the seismic performance analysis of the optimized inlet tower was carried out by using endurance time analysis combined with quantile analysis and vulnerability analysis.

2. Endurance Time Analysis (ETA)

2.1 Basic principles of the ETA method

ETA method is a dynamic pushover process based on the nonlinear time history analysis method. That is, an endurance time acceleration curve with ground motion intensity gradually increasing over time is applied to the structure, and the response spectrum is proportional to target spectrum under different endurance time. An endurance time history contains the characteristics of multiple response spectra, which can be input as the acceleration time history under different peak accelerations [13-15]. While applying the designed ground motion time history to the structure, the seismic performance level of the structure is determined by monitoring the displacement, acceleration, stress, energy, damage volume and some other corresponding structural performance parameters, until structural failure is detected. In the process of endurance time analysis, the ground peak acceleration g is abandoned as the index of ground motion intensity, but the seismic wave duration t is used as the index of ground motion intensity. That is, the ground motion intensity input to the structure increases proportionally with the passage of time.

2.2 Synthesis of endurance time

The displacement response spectrum is closely related to the acceleration response spectrum, so acceleration response spectrum can be solved therefrom [16].

$$S_{aT}\left(T,t\right)=\frac{t}{t_{T\arg et}}S_{aC}\left(T\right) \tag{1}$$

$$S_{uT}\left(T,t\right)=\frac{T^{2}t}{4\pi^{2}t_{T\arg et}}S_{aC}\left(T\right) \tag{2}$$

Where, $S_{aC}\left(T\right)$ is the pre-specified standard response spectrum; $S_{aT}\left(T,t\right)$ is the response spectrum of the endurance time curve; $t_{T\arg et}$ is the target time point; T is the natural vibration period of the structure; $S_{uT}\left(T,t\right)$ is the displacement response spectrum of the endurance time curve.

The ultimate purpose of the ETA method is to make any point on the endurance time acceleration curve conform to formula (1) and formula (2). However, it is quite complicated and impossible for the prior art to make each point meet the above requirements, so this problem can be converted into an optimization problem with unconstrained variables:

$$\min F\left(a_{g}\right)=\int_{0}^{T_{\max}}\int_{0}^{t_{\max}}\left\{\left[S_{a}\left(T,t\right)-S_{aT}\left(T,t\right)\right]^{2}+\rho\left[S_{u}\left(T,t\right)-S_{uT}\left(T,t\right)\right]^{2}\right\}dtdT \tag{3}$$

Where, a_g is the initial endurance time, $T_{\max}$ is the maximum response spectrum time, $t_{\max}$ is the maximum ground motion time, and ρ is the weight.

The endurance time acceleration is specifically generated as follows [17]: First, select a target response spectrum conforming to local geological conditions according to the seismic design code of hydraulic structures, use the artificial wave generation program compiled in Python to generate artificial waves conforming to the actual engineering, and finally use the MATLAB optimization tool to perform unconstrained optimization on the generated artificial waves, thereby generating the required endurance time acceleration curve.

2.3 Quantile analysis

In the quantile analysis, it is hypothesized that each IM-DM point on the IDA curve obeys log-normal distribution [18-19], and for each IM value, the mean and log standard deviation of different DM values can be obtained. In this way,16%, 50%, 84%quantile line and mean quantile line can be obtained. Finally, the serviceability limit state and the bearing capacity limit state can be determined according to the limit of each quantile line.

2.4 Vulnerability analysis

Vulnerability analysis is to fit each IDA curve separately, calculate the IM value corresponding to each performance level on each IDA curve through interpolation, and finally establish the vulnerability curve with IM as the abscissa and $F(x)$ as the ordinate [20].

$$F(x) = P\left[LS \mid IM = x\right] \tag{4}$$

Where: $F(x)$ is the fragility function; P is the failure probability; LS is the structural performance level; IM is the peak ground acceleration PGA.

2.5 Seismic evaluation mechanism of endurance time analysis

The seismic performance of structures under strong earthquake is evaluated by combining endurance time analysis, probability-based quantile analysis and vulnerability analysis methods. At present, scholars at home and abroad usually employ incremental dynamic analysis to evaluate the structural performance. As a combination of the incremental dynamic analysis method and the pushover analysis method, endurance time analysis method can use a set of endurance time history to calculate dynamic response under different intensity, demonstrating obvious advantages in analyzing structure damage and failure under any intensity.According to the vulnerability analysis mechanism of the IDA method, Xu Shutong [21] determined the structural vulnerability assessment method based on the ETA method. According to its analysis process, this paper summarizes the seismic performance evaluation steps of the inlet tower based on the ETA method as follows:

(1)Establish a three-dimensional model of the inlet tower, and input reasonable material parameters and boundary conditions;

(2)According to the standard response spectrum, synthesize a plurality of corresponding three-dimensional endurance time accelerations, and determine the intensity index (IM) of the action of earthquake;

(3)Define the seismic structure performance index (DM) of the inlet tower； In this paper, the ratio D_E of plastic energy consumption to total deformation energy, which is based on the overall energy of the structure, is used for analysis.

(4)Input the endurance time acceleration curve synthesized in to the established inlet tower model, implement finite element simulation, and output the IM and DM of the structure under the action of earthquake;

(5)According to the relationship corresponding to the output IM and DM, plot the endurance time curve under the action of each ground motion and define the limit state point on the curve;

(6)Analyze the endurance time curve by statistical method, and perform quantile analysis to calculate the ground motion intensity of the inlet tower under different limit states;

(7)Perform vulnerability analysis on the seismic performance of the inlet tower, and calculate the structure failure probability under different ground motion intensities.

3. Case analysis

3.1 Calculation model and parameters

This paper selects the inlet tower of the Yangqu as a model case. The tower has a height of 85.5 meters, a length of 14 ~15 meters, a width of 15 meters and a wall thickness of 2.2 ~2.9 meters. The tower base material is C30 concrete, the tower concrete strength grade is C25, and the tower top hoist room material is C30 concrete embedded with steel reinforcement. The seismic fortification category of the inlet tower is Class A, the basic earthquake intensity is 7 degrees, and the fortification intensity is 8 degrees. The ground motion with the exceedance probability $P_{100} = 2\%$ under base period of 100 years is taken as the design ground motion. The horizontal peak ground acceleration for the maximum design earthquake is 0.15g and the maximum reliable earthquake is 0.20g. The model is built as shown in Fig. 1. In the process of endurance time analysis, the ground peak acceleration g is abandoned as the index of ground motion intensity, but the seismic wave duration t is used as the index of ground motion intensity. The artificial ground motion design is shown in Fig. 2.

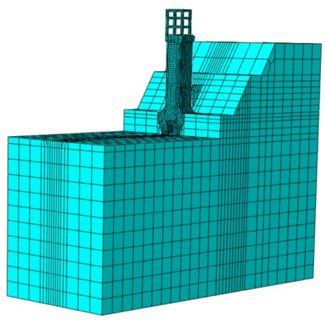
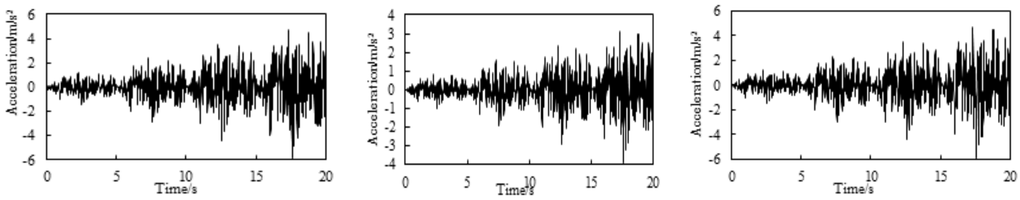


Fig.1. The inlet tower model

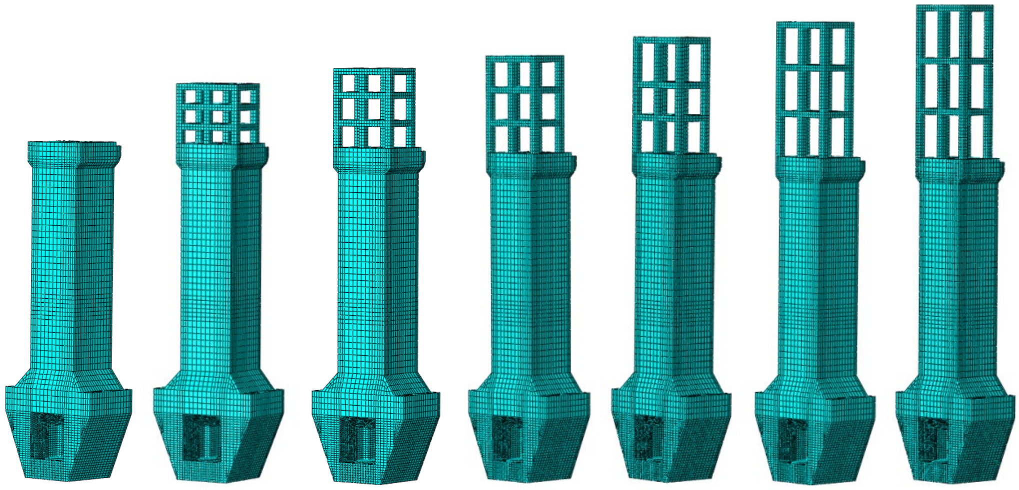


X-direction | Y -direction | Z -direction

Fig.2.The synthesized seismic time history acceleration curve

3.2 Influence of the top hoist room on the earthquake response of the inlet tower

In order to study the effect of different hoist room heights of the inlet tower on the tower structure, seven groups of inlet tower models with zero hoist room, hoist rooms of 15m, 20m, 25m, 30m, 35m and 40m in height are established. The model of different hoist room heights is shown in Fig. 3.



zero hoist machine room | 15m | 20m | 25m | 30m | 35m | 40m

Fig.3.Schematic diagram of the calculation example model of different hoist room heights

By processing and analyzing ratio D_E between the plastic energy consumption and the total deformation energy of the inlet tower with hoist room of different heights, D_E under different heights are calculated and compared as shown in Table 1.

Table. 1

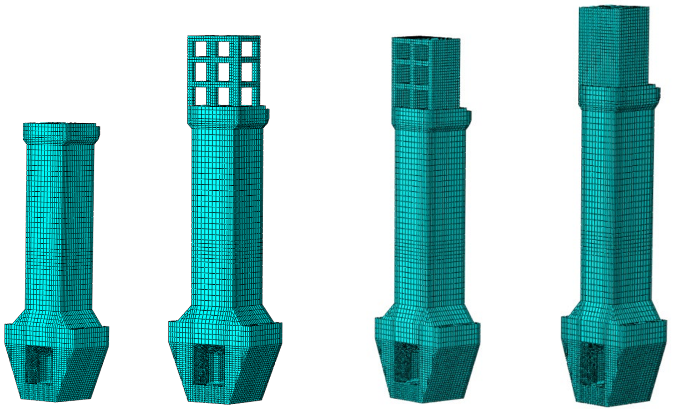
Energy ratio under the influence of different height hoist room

Time \ Height	Zero	15m	20m	25m	30m	35m	40m
0s	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1s	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2s	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3s	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4s	0.0000	0.0080	0.0000	0.0000	0.0000	0.0000	0.0000
5s	0.0114	0.0176	0.0183	0.0040	0.0000	0.0170	0.0000
6s	0.0204	0.0410	0.0512	0.0155	0.0000	0.0291	0.0200
7s	0.0471	0.0914	0.1000	0.0500	0.0300	0.0671	0.0700
8s	0.0966	0.2285	0.1886	0.1898	0.2109	0.1886	0.1856
9s	0.2623	0.3770	0.3420	0.3406	0.3586	0.3398	0.3416
10s	0.4402	0.4745	0.4605	0.4536	0.4622	0.4572	0.4647
11s	0.5970	0.5418	0.5478	0.5340	0.5364	0.5461	0.5566
12s	0.7173	0.5926	0.6100	0.5894	0.5924	0.6127	0.6222
13s	0.7981	0.6357	0.6542	0.6282	0.6379	0.6630	0.6681
14s	0.8445	0.6757	0.6870	0.6582	0.6780	0.7025	0.7011
15s	0.8659	0.7146	0.7143	0.6856	0.7154	0.7354	0.7273
16s	0.8731	0.7525	0.7404	0.7148	0.7511	0.7648	0.7514
17s	0.8756	0.7884	0.7677	0.7476	0.7847	0.7924	0.7761
18s	0.8805	0.8211	0.7969	0.7835	0.8149	0.8184	0.8022
19s	0.8911	0.8492	0.8268	0.8200	0.8404	0.8419	0.8285
20s	0.9071	0.8721	0.8549	0.8530	0.8595	0.8613	0.8526

Through the three indexes of the maximum relative displacement of the tower top, the ratio D_E between plastic energy dissipation and total deformation energy, and the damage area at key position of the tower, it thoroughly explains the influence of hoist room height at the inlet tower top on earthquake response of the tower from the three perspectives of displacement, energy and damage. The results show that, the top structure of the inlet tower significantly reduces the dynamic response under the earthquake. When the hoist room height of the inlet tower is about 20 meters, the top structure can significantly reduce the dynamic response of the tower.

3.3 Influence of the stiffness of the top hoist room on the earthquake response of the inlet tower

In order to study the influence of different hoist room stiffness at the inlet tower top on the dynamic response of the tower structure, three groups of inlet tower models with different hoist room stiffness are established in this section, and the height of the top hoist room is 20 meters. The model of each example in this group is shown in Fig. 4.



Zero hoist room Stiffness example I Stiffness example II Stiffness example III

Fig.4.Schematic diagram of hoist room models with different stiffness

By analyzing the ratio D_E between plastic energy dissipation and total deformation energy of the inlet tower with different hoist room stiffness, D_E values of hoist rooms with different stiffness are calculated and compared as shown in Table 2.

Table.2

Comparison of D_E of inlet tower under the influence of hoist room with different stiffness

Stiffness / Time	Zero hoist room	Stiffness I	Stiffness II	Stiffness III
0s	0	0	0	0
1s	0	0	0	0
2s	0	0	0	0
3s	0	0	0	0
4s	0	0	0	0
5s	0	0	0	0
6s	0	0	0	0
7s	0	0	0	0
8s	0.3166	0.4419	0.4218	0.4597
9s	0.4306	0.5129	0.3758	0.3916
10s	0.599	0.6155	0.6334	0.7099
11s	0.807	0.5049	0.4876	0.482
12s	0.7793	0.6751	0.6118	0.6445
13s	0.7935	0.6241	0.7403	0.7704
14s	0.7645	0.7351	0.7671	0.8238

15s	0.9061	0.7676	0.8481	0.8837
16s	0.9093	0.7037	0.7448	0.768
17s	0.946	0.8889	0.9215	0.943
18s	0.9209	0.8486	0.8865	0.8986
19s	0.834	0.8379	0.8638	0.8801
20s	0.9394	0.8572	0.8766	0.8958

Through the three indexes of the maximum relative displacement of the tower top, the ratio D_E between plastic energy dissipation and total deformation energy, and the damage area at key position of the tower, it thoroughly explains the influence of hoist room stiffness at the inlet tower top on earthquake response of the tower from the three perspectives of displacement, energy and damage. The results show that structural stiffness at the inlet tower top exerts a significant impact on the dynamic response of the inlet tower under the action of earthquake; the dynamic response of the inlet tower decreases with the decrease in top structural stiffness.

4. Seismic performance evaluation

According to the above analysis results, the top structure height of 20 meters and the stiffness of example stiffness I form the optimal top structure of the inlet tower in seismic performance evaluation. Considering randomness of ground motion, 15 synthetic endurance time accelerations are used in nonlinear dynamic analysis of the inlet tower. According to the basic principle of endurance time analysis, the corresponding structural performance parameters are extracted to plot quantile curve and vulnerability curve for seismic performance analysis.

4.1 Input of endurance time

According to the synthesis principles and steps of endurance time curve introduced above, the standard response spectrum in the seismic design code of hydraulic structures in China is used as the target response spectrum to generate 15 groups of endurance time acceleration curves with consistent characteristic period of the response spectrum in which seismic wave lasts for 20 seconds.

4.2 Selection of performance evaluation indexes and definition of performance levels

According to the selection basis of structural performance parameters in existing literature, the maximum relative displacement cannot precisely and accurately describe the dynamic response of the structure under the action of strong earthquakes. Therefore, the ratio D_E between plastic energy dissipation and total deformation energy is selected as the structural performance index to evaluate the seismic performance of the inlet tower. At the same time, 0.2 and 0.7

proposed in this literature are used as the critical values for the serviceability limit state and bearing capacity limit state. Fig. 5 shows the limit state points of 15 endurance time curves with D_E as energy index.

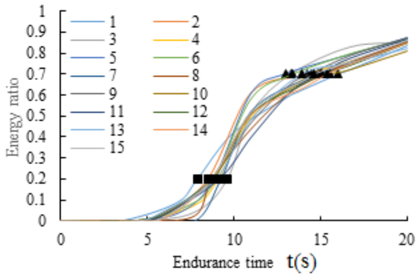


Fig.5. ETA curve of different performance points

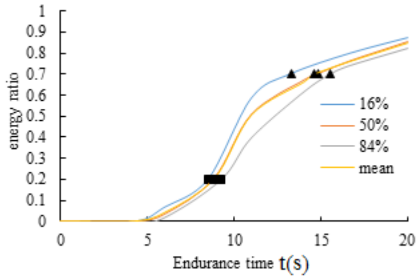


Fig.6. IDA curves for different quantiles

4.3 Probability analysis

4.3.1 Quantile analysis

When conducting quantile analysis on the ETA, the 16%, 50%, 84%, mean quantile curve and the corresponding serviceability limit state points and bearing capacity limit state points on each quantile can be obtained according to the formula as shown in Fig. 6, Table3.

Table 3

Peak ground acceleration corresponding to each limit state under different fractile probabilities

Quantile probability	Serviceability limit state	Bearing capacity limit state
84%	0.256g	0.399g
50%	0.265g	0.445g
mean	0.265g	0.437g
16%	0.278g	0.465g

Take the quantile of 84% as an example (at this time, there is a guarantee rate of 84%). The inlet tower structure is in the normal use stage under the peak ground acceleration of 0.256g, which meets the functional guarantee requirement; the dam is in the damage control stage under a peak ground acceleration of 0.399g, which meets the safety guarantee requirement. The peak ground acceleration in both limit states is greater than peak ground acceleration 0.20g under the maximum credible earthquake, indicating that the applicability and safety of the dam can be met.

4.3.2 Vulnerability analysis

According to the ETA analysis results of the inlet tower, the exceedance probability of the inlet tower under different seismic intensities is calculated respectively, and the seismic vulnerability curve of the gravity dam can be plotted by direct fitting method, as shown in Fig. 7.

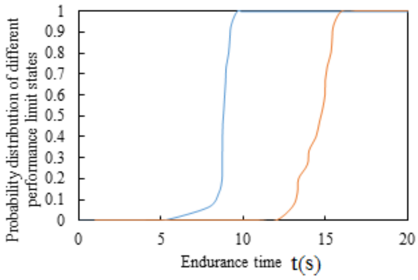


Fig.7. Fragility curve

Table 4

Surpass probability of different waterproofing standards

Fortification level （g）	Exceedance probability (%)	
	Function guarantee point	Safety guarantee point
0.1	0	0
0.15	0	0
0.2	0	0
0.25	6.67	0
0.275	73.33	0
0.3	100	0
0.39	100	6.67
0.40	100	13.33
0.45	100	66.67
0.5	100	100
0.6	100	100

Table 5

Failure probability of different waterproofing standards

Fortification level （g）	Failure probability (%)		
	Normal use stage	Damage control stage	Collapse prevention stage
0.1	100	0	0
0.15	100	0	0
0.2	100	0	0
0.25	93.33	0	0
0.275	16.67	0	0
0.3	0	100	0
0.39	0	11.11	93.33
0.40	0	22.22	86.67

0.45	0	77.78	33.33
0.5	0	100	0
0.6	0	100	0

Note: The peak ground acceleration of the maximum design earthquake of the inlet tower is 0.15g, and the peak ground acceleration of the maximum credible earthquake is 0.20g.

According to Table 4, under the action of the maximum design earthquake, the probability for the inlet tower to exceed the serviceability limit state is 0. Under 2 times of the design earthquake intensity, the inlet tower can basically guarantee safety. Under the maximum credible earthquake, the probability for the inlet tower to exceed the serviceability limit state is still 0. Under 2 times of the maximum credible earthquake, the probability for the inlet tower to exceed the bearing capacity limit state is 13.33%, which can basically guarantee the safety of the entire inlet tower system.

According to the formula, the vulnerability curve of the key position is plotted, as shown in Fig. 7. Table 5 shows the probability of each failure state for the inlet tower structure under different intensity. Under the maximum design earthquake, the probability of availability and safety is close to 100%, while under the maximum credible earthquake, the probability of availability is 100%, and the probability of safety is close to 100%. Under 2 times of the maximum credible earthquake, the probability of guaranteed safety is 86.67%. For the entire inlet tower structure, safety can be guaranteed under both the maximum credible earthquake and the maximum design earthquake.

To sum up, through quantile analysis, it is concluded that the peak ground acceleration PGA under each limit state in the IDA curve is greater than the peak ground acceleration under the maximum credible earthquake, so the functional guarantee and safety guarantee of the inlet tower are met. Through the vulnerability analysis, it is concluded that under the maximum design earthquake, the probability of being in the normal use stage is close to 100%; under the maximum credible earthquake, there is a 100% probability of being in the damage control stage, so safety requirements are met.

5. Conclusion

A finite element model of the inlet tower with different top structure heights and stiffness is established. By calculating and analyzing the seismic dynamic response of the main structure of each inlet tower model, the influence of different top structure height and stiffness on the dynamic response of the main structure of the inlet tower is discussed in terms of displacement, energy and damage. The top structure is optimized, and its seismic performance is evaluated. The relevant conclusions are as follows:

(1) Compared with the inlet tower without hoist room, the inlet tower top structure significantly reduces the dynamic response of the main structure of the inlet tower under the action of earthquake. During the earthquake, when the hoist room height at the inlet tower top is about 20 meters, the top structure significantly reduces the dynamic response of the tower structure.

(2) The dynamic response of the inlet tower decreases with the decrease in top structure stiffness; the top structure with smaller stiffness significantly reduces the dynamic response of the tower structure. Hoist room with smaller stiffness on the inlet tower top adds to earthquake resistance of the main structure.

(3) By combining ETA method with quantile analysis and vulnerability analysis, we use the structural performance parameter D_E to evaluate the seismic performance of the optimized inlet tower model. The results are as follows: in the case of 16% quantile, the inlet tower is in the normal use stage under the peak ground acceleration of 0.256g, which meets the functional guarantee requirement; the inlet tower is in the damage control stage under the peak ground acceleration of 0.399g, which meets the safety guarantee requirement. The peak ground acceleration in both limit states is greater than peak ground acceleration 0.20g under the maximum credible earthquake, indicating that applicability and safety of the inlet tower can be met after optimization. Under the maximum design earthquake, there is nearly 100% probability of being in normal use stage; under the maximum credible earthquake, there is 100% probability of being in damage control stage and safety requirements are met.

Acknowledgements

This research was supported by the Open Fund Project of State Key Laboratory of Eco-hydraulics in Northwest Arid Region (Grant No.2019KFKT-15), Science and Technology Research Program of Chongqing Education Commission (KJQN202103602), Chongqing Industry & Trade Polytechnic Project, (ZR202014), Natural Science Foundation of Hebei Province (E2020402087), Postdoctoral Fund (SJ200100105).

R E F E R E N C E S

[1]. *Yang Guang, Li Shouyi, Li Lang, et al.* Influence of backfill height of towering inlet tower on its seismic performance. Journal of Water Resources and Water Engineering, 2019, 30(06): 180-5.

[2]. *Cao Wei, Liu Yunhe, Dang Kangning, et al.* Seismic design optimization and dynamic response in backfilling of inlet towers. South-to-North Water Transfers and Water Science & Technology, 2017, 15(03): 151-7.

[3]. *Chen Houqun, Xu Zeping, Li Min*. Wenchuan earthquake and dam seismic safety. Journal of Hydraulic Engineering, 2008, 10: 1158-67.

[4]. *Zhang H Y, Zhang L J, Wang H J, et al*. Influences of the duration and frequency content of ground motions on the seismic performance of high-rise inlet towers. Engineering Failure Analysis, 2018, 91(4): 81-95.

[5]. *Zhao J, Yang J, Li X N. (2021).* Seismic performance of inlet tower structures based on endurance time method. China Earthquake Engineering Journal, Vol. 43, No.5, P: 1244-1250. DOI: N/A

[6]. *Morteza Aghaeipoor; Mohammad Alembagheri*. Seismic Damage of Submerged Inlet tower under the Sequence of Mainshocks and Aftershocks. Journal of Earthquake Engineering, 2021, 1-25

[7]. *Soroush Resatalab; Mohammad Taghi Ahmadi; Mohammad Alembagheri*. Seismic response sensitivity analysis of inlet towers interacting with dam, reservoir and foundation. Magazine of Civil Engineering, 2020, Vol. 99(7): 9901

[8]. *Pezhman Pirhadi; Mohammad Alembagheri*. The influence of bridge–tower interaction on the dynamic behavior of intake–outlet towers.SN Applied Sciences, 2019, Vol. 1(12)

[9]. *Daniell W T.,* Developing a numerical model for a UK inlet tower seismic assessment. Proc Inst Civil Eng Water Marit Eng, 2003, 56(01): 63-72.

[10]. *Zhang H Y, Zhang L J, Wang H J, et al.* Influences of the duration and frequency content of ground motions on the seismic performance of high-rise inlet towers. Engineering Failure Analysis, 2018, 91(4): 81-95.

[11*]. Zhang H Y, Zhang L J.* Seismic performance assessment and potential failure modes of inlet towers. Natural Hazards, 2016, 83: 1321-1340.

[12]. *Dang Kangning, Liu Yunhe, Wang Yuan, et al.* Vibration characteristics of hoist room frame on inlet tower of hydroelectric power station. South-to-North Water Transfers and Water Science & Technology, 2016, 14(04): 129-34.

[13]. *Xu Qiang, Xu Shutong, Chen Jianyun, Li Jing*. Analysis method of endurance time damage factors of concrete gravity dam. Journal of Vibration Engineering, 2019, 32(03): 452-461.

[14*]. Zhang L W, Lu Z H, Chen C*. Seismic fragility analysis of bridge piers using methods of moment. Soil dynamics and earthquake engineering, 2020, 134: 106-150.

[15]. *Li Yongmei, Wang Hao, Peng Lingyun, et al.* Advanced displacement-based seismic design method for reinforced concrete frame structures with infill wall. Journal of Building Structures, 2019, 40(06): 125-32.

[16]. *Du Ke, Yan Deng, Gao Jiawei, et al*. Seismic and seismic isolation performance evaluation of RC frame structures based on FEMA P-58. Engineering Mechanics, 2020, 37(08): 134-47.

[17]. *Wang Mengfu, Long Si*. Endurance time method for seismic response analysis of steel-concrete hybrid structures. Earthquake Resistant Engineering and Retrofitting, 2016, 38(04): 1-11.

[18]. *Cai Yurong, Wang Huiling*. Research on the influence mechanism of innovation input on industrial structure upgrade——analysis based on quantile regression. Inquiry into Economic Issues, 2018, (01): 138-46.

[19]. *Wang Xiuzhen, Qian Yongjiu, Shao Changjiang, et al.* QRNN importance analysis of structural seismic demand. Journal of Basic Science and Engineering, 2020, 28(04): 953-65.

[20]. *Kong Xianjing, Pang Rui, Zou Degao, et al.* Seismic performance evaluation of high CFRDs based on incremental dynamic analysis. Chinese Journal of Geotechnical Engineering, 2018, 40(06): 978-84.

[21*]. Xu Shutong*. Vulnerability analysis of concrete dam based on endurance time method. Dalian University of Technology, 2019.