Determining the Critical Intensity for Crack Initiation in Concrete Arch Dams by Endurance Time Method

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Abstract:
This study aims at determining the critical seismic intensity at which cracks are expected to develop in a concrete arch dam. This intensity is referred to as crack initiation intensity. The crack initiation intensity measure implies that earthquakes with the intensity measure higher than this value are expected to induce cracks in the arch dam. This quantity is an indicator for seismic evaluation of arch dams. Determining this parameter using conventional time history analyses requires multiple trials and errors applying several up and down scaling of a suite of ground motions which can be very time consuming. As an alternative method, endurance time method is well suited for this kind of study. In the endurance time method, structures are subjected to predefined intensifying acceleration time histories and all intensity measures are continuously covered in a single time history analysis. The continuous coverage of intensity measures in the endurance time method provides a tool to conveniently determine the transition points such as crack initiation in a single time history analysis. In this regard, a framework is proposed and then applied to Morrow point dam, a doubly curved arch dam, as a case study. Results are obtained by using three different endurance time excitation series; 'kn', 'kd', and 'lc'. The aim of using three endurance time series was to compare their differences in dynamic analysis of arch dams. Observations indicate the acceptable compatibility of different series of endurance time excitation. In order to investigate the accuracy of the results obtained by the endurance time method, the dynamic analysis of the arch dam subjected to ten ground motions scaled by the calculated crack initiation intensity measure is performed. It is shown that the proposed method can be conveniently applied for determining the crack initiation intensity.

1. Introduction

Concrete arch dams are critical infrastructures constructed for different purposes, such as irrigation, flood control, and power generation. The failure of dams can lead to heavy fatalities and financial consequences. Among the several hazards that threaten dams, earthquakes the most important ones. This matter shows the significance of evaluating the safety and structural integrity of concrete arch dams when they are subjected to earthquake ground motions. It is noteworthy that tensile cracking, excessive contraction joint opening, and abutment movement are the main possible seismic failure modes of this type of dam.

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There are several seismic analysis and design methods for dams. In quasi-static method, earthquake forces are treated in a static way [1]. The equivalent lateral force is another method assuming that the structures deformation conforms to the first mode of its natural vibration [2]. In fact, only one mode is considered in this analysis. In contrast to the equivalent lateral force method, response spectrum modal analysis includes several modes so that more than 90% of the total mass of the system is covered [3]. In this method, the earthquake is characterized by acceleration spectrum. The maximum responses of different modes are combined by different approaches, e.g. square root of sum of squares is one of them. Time history modal analysis is another method that receives the time history of earthquakes and outputs the time history of responses such as stress, displacement. This method is more accurate than the

response spectrum modal analysis because it directly sums the response of different modes. This method is limited to linear elastic behavior. By growth in the processing power of computers, the methods that are capable of considering nonlinear behavior of structures have been developed. Time history analysis can be directly used in nonlinear modeling. In this method, the motion equation is directly integrated.

To have proper understanding of dam behavior due to seismic loading, time history analysis has been extremely utilized by many researchers. Some of these researches can be listed as: The nonlinear behavior of dam using the crack band theory that was evaluated by Varga-Loi and Fenves [4] . The linear behavior of the Morrow point arch dam due to 1958 Taft earthquake that was studied by Tan and Chopra [5]. In their research, the effects of properties of dam and foundation rock, and impound water on the response of the dam were investigated. The effects of dam-reservoir interaction on the crack propagation in the dam based on the discrete crack method were studied by Wepf et al. [6]. In another study, Mirzabozorg and Ghaemian evaluated the nonlinear behavior of dam using smeared crack method including dam-reservoir interaction effects [7]. The seismic stability of arch dam abutment was studied by Mostafaei et al. [8].

Time history analysis is the most accurate method among the aforementioned analysis methods. The main drawback of time history analysis is the fact that the results strongly depend on the selected ground motions. This matter is intensified when the nonlinear models are employed. In order to alleviate this problem, scaled ground motions are used. In the scaling process, ground motions are multiplied by a factor so that their intensity measures become the same. Therefore, the results are dependent on the value of the considered intensity measure. If several intensity measures are considered, the method is called incremental dynamic analysis (IDA). The IDA illustrates the response of the structure at various intensity measure values. The results of IDA are summarized and expressed in a curve called the IDA curve. In the IDA curve, damage measure (DM), e.g. maximum tensile stress of the dam, is plotted against intensity measure (IM), e.g. spectral acceleration at the first mode period. The IDA requires a large number of dynamic analyses which is very time-consuming for complicated structures like arch dams. For example, Alembagheri and Ghaemian [9] investigated damage of the Morrow point arch dam.

Another analysis method that can be used for seismic analysis of dams is endurance time (ET) method. This method was initially developed by Estekanchi et al. [10].

This method was inspired from exercise test in medicine [11]. In the ET method, structures are subjected to predesigned intensifying acceleration functions called endurance time excitation functions (ETEF). The robustness and accuracy of the ET method results considerably rely on the accuracy of the generated ETEFs. The accuracy of ETEFs is defined as the degree of their consistency with real ground motions. Several studies have worked on the generation of ETEFs. Mashayekhi et al. [12] generated hysteretic compatible ETEFs called "kd" series. In "kd" series, acceleration spectra, nonlinear displacement, and hysteretic energy consistency are included in the generation process. Moreover, Mashayekhi et al. [13] generated duration consistent ETEFs called "lc" series. In "lc" series acceleration spectra, displacement spectra, and cumulative absolute velocity are included in the generation process. Mashayekhi et al. [14] employed discrete wavelet transformation in generating endurance time excitation functions. Mashayekhi et al. [15] adopted imperialist competitive algorithms for generating ETEFs. Mashayekhi et al. [16] employed the particle swarm optimization method for generating ETEFs.

Several studies have utilized the ET method for seismic analysis of different structures. For example, Valamanesh and Estekanchi [17] applied the ET method for seismic analysis of steel moment frames. Tafakori et al. [18] used the ET method for probabilistic seismic loss estimation. Mirfarhadi and Estekanchi [19] presented an ET-based methodology for value-based seismic design. Estekanchi et al. [20] investigated the application of ET method in linear seismic assessment, Basim and Estekanchi [21] applied ET method in performance-based optimum design, Hariri-Ardebili et al. [22] adopted ET method in performance-based seismic assessment of steel frames, and Foyuzat and Estekanchi [23] used the ET method to analyze frames equipped with friction dampers. Hariri and Mirzabozorg [24] applied the ET method for seismic analysis of concrete arch dams. Estekanchi et.al [25] employed the ET method to investigate the interaction of moment resisting frames in reinforced concrete dual systems.

The present study aims to employ the ET method for determining the intensity measure value at which a crack in the concrete arch dam appears. A methodology for finding the crack initiation intensity measure using the ET method is proposed. This methodology is applied to the Morrow point arch dam. Results are presented and compared with ten ground motion-analyses.
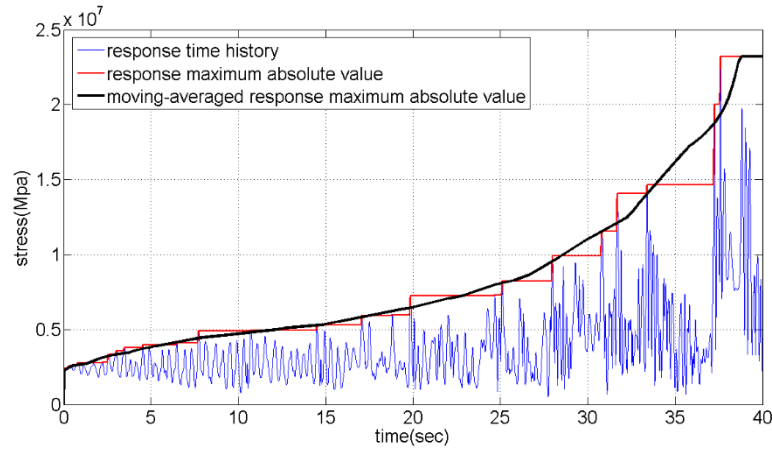
Fig. 1: A sample response time history, response maximum absolute value and moving-averaged maximum absolute value in the ET method
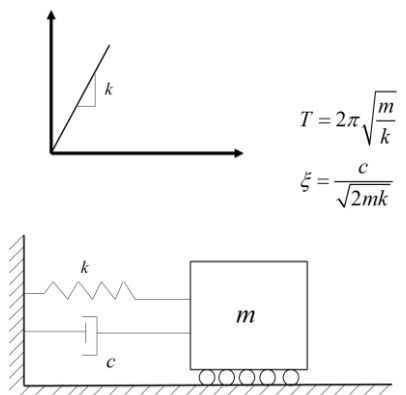

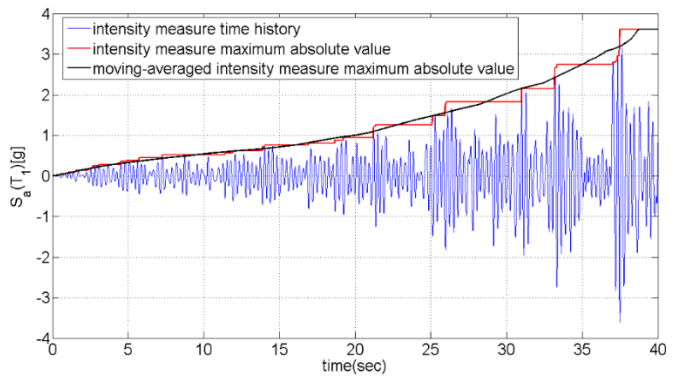**Fig. 2:** Schematic configuration of a single degree of freedom system

Fig. 3: A sample intensity measure time history, intensity measure maximum absolute value and moving-averaged intensity measure maximum absolute value of the ET method
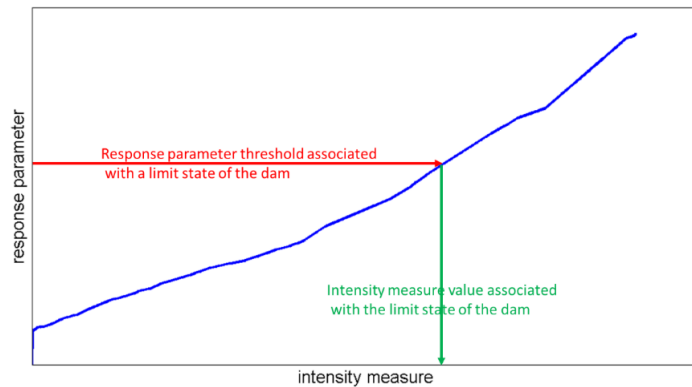

Fig. 4: Schematic procedure of determining the intensity measure value associated with a limit state of the dam

2. Methodology

In this section, the proposed method for determining the crack initiation intensity measure is explained. In the first step, the response parameter associated with crack initiation is identified. In this study, maximum tensile stress is chosen. It should be noted that other damage indices can also be utilized. In the next step, linear time history dynamic analysis of the dam subjected to

endurance time excitations is performed. At the end of this step, response time history is available. The response time history is transformed to the response maximum absolute value by using the formula given below. While response time history is the instantaneous response of the dam subjected to the ETEF, the response maximum absolute value is the maximum response occurred in the dam from the onset of dynamic analysis up to the desired time.

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$$\Omega\big(f(t)\big) = Max\big(\big|f(\tau)\big|\big) \quad 0 \le \tau \le t \tag{1}$$

In the above equation, Ω is the maximum absolute response in the time span $[0, t]$ and f is the response history as a function of time. The response maximum absolute value is an ascending function with horizontal steps. The maximum absolute value in the horizontal steps is constant. The existence of these steps is both unavoidable and undesirable. After producing the response maximum absolute value, moving average process is performed in order to make this function smoother and remove these steps. A sample of the moving averaged response maximum absolute value along with the raw response time history and the response maximum absolute value is presented in Fig. 1. It should be noted that the 40-sec endurance time excitation is used in the ET analysis in this figure. Moving average process is performed by "smooth" command in MATLAB software [26].

The significance of time in the ET method differs from the significance of time in conventional time history analyses. Time in the ET method is an indicator of intensity level and can be transformed to intensity. The following formula can be used to convert time to spectral acceleration at the first mode period of the structure.

$$S_a(T,t) = \max\big(a(\tau)\big) \quad 0 \le \tau \le t \tag{2}$$

where t is the time, T is the structural first mode period, $a(\tau)$ is the acceleration response time history of the single degree of freedom system with the period T and damping coefficient 5%. The single degree of freedom system is given in Fig. 2.

Similar to the response time history, intensity measure, and spectral acceleration at the first mode period, must be transformed to the intensity measure maximum absolute value and then be smoothed. This procedure is completely similar to the procedure explained for the response time history. A sample moving averaged intensity measure maximum absolute value is depicted in Figure 3.

Result of the ET method is presented by ET curve. In the ET curve, moving-averaged response maximum absolute value is plotted against the moving averaged intensity measure maximum absolute value. This curve expresses the response parameter value at each intensity measure value. This curve is called the ET curve and is counterpart of the IDA-curve in the IDA method. The next step is to specify the threshold of the response parameter associated with crack initiation or other limit states of the arch dam. If this response parameter threshold is specified in the ET curve, the intensity measure associated with this limit state will be determined. This procedure is schematically shown in Fig. 4.

3. Endurance time excitations description

In this section, several explanations regarding the employed endurance time excitations are presented. Three ETEFs series are utilized in this study, namely, "lc" series, "kn" series, "kd" series.

"lc" series ETEFs are cumulative absolute velocity consistent endurance time excitation functions. The comprehensive characteristics of this series are available in [27]. "ETA40loc01", "ETA40lc02", and "ETA40lc03" are the members of this series. Acceleration time histories of these ETEFs are demonstrated in Fig. 5. As shown in this figure, exponential form has been used for generating the excitations of this series. This form guarantees the consistency of cumulative absolute velocity variation between endurance time excitations and real ground motions. The objective function used for generating this series is presented in Equation (3). The consistency of acceleration spectra, displacement spectra, and cumulative absolute velocity are considered in the objective function.
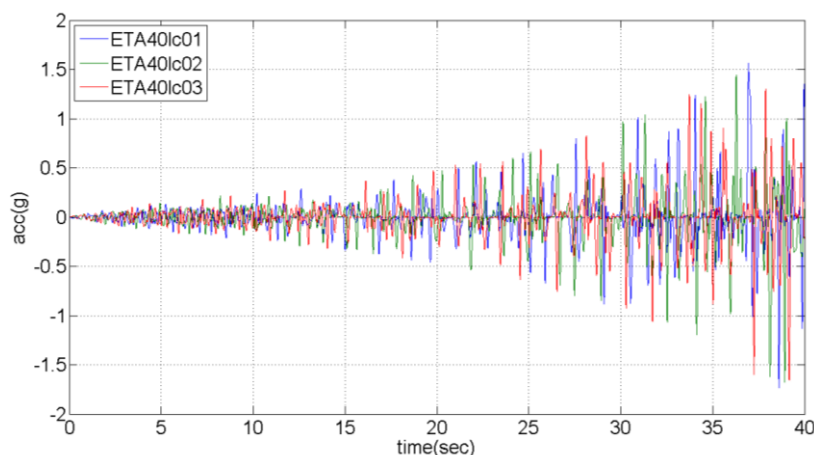

Fig. 5: Acceleration time history of ETA40lc01, ETA40lc02, and ETA40lc03
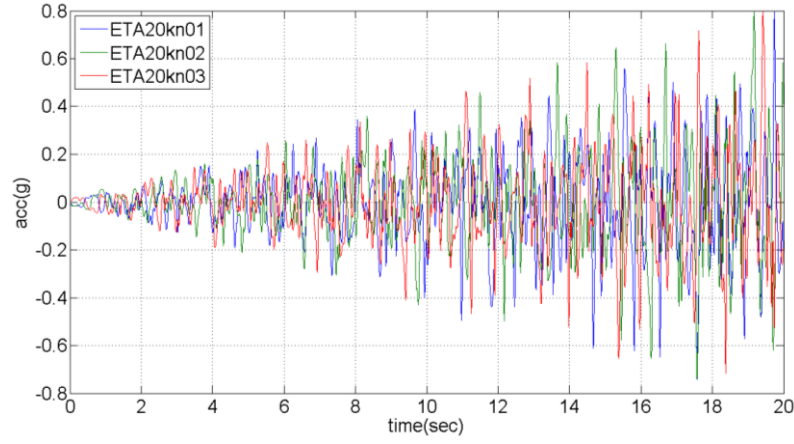
Fig. 6: Acceleration time history of "kn" series, ETA20kn01, ETA20kn02, and ETA20kn03
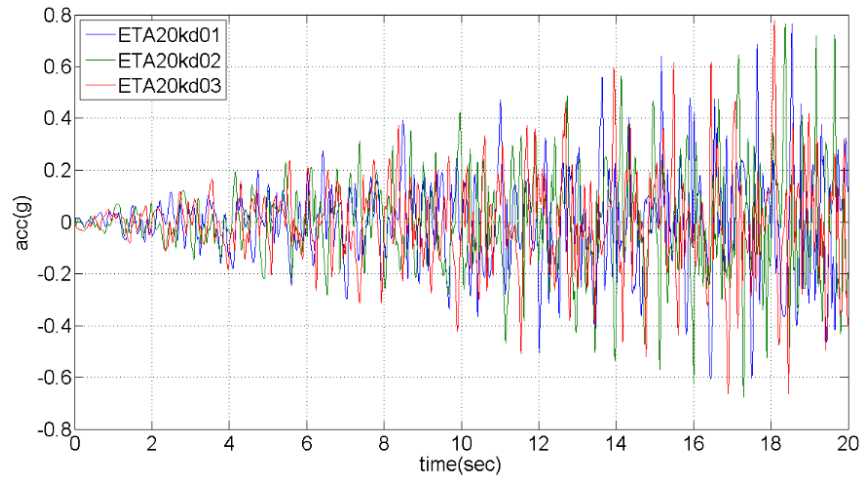

Fig. 7: Acceleration time history of "kd" series, ETA20kd01, ETA20kd02, and ETA20kd03

$$F_{\text{CAV-M}}\left(a_g\right)=\int_{T_{\min}}^{T_{\max}}\int_{0}^{t_{\max}}\left\{\begin{array}{l}\left[\dfrac{S_a(T,t)-S_{aC}(T,t)}{S_{aC}(T,t)}\right]^2+\\[6pt]\left[\dfrac{S_u(T,t)-S_{uC}(T,t)}{S_{uC}(T,t)}\right]^2\\[6pt]\left[\dfrac{CAV(t)-CAV_C(t)}{CAV_C(t)}\right]^2+\\[6pt]\left[S_a(T,t)-S_{aC}(T,t)\right]^2\\[6pt]+\alpha_{S_u}\left[S_u(T,t)-S_{uC}(T,t)\right]^2+\\[6pt]\alpha_{CAV}\left[CAV(t)-CAV_C(t)\right]^2\end{array}\right\}dtdT \qquad (3)$$

where $S_a(T,t), S_u(T,t)$ and $CAV(t)$ are respectively, acceleration spectra, displacement spectra, and cumulative absolute velocity of the excitation. $S_{aC}(T,t), S_{uC}(T,t)$ and $CAV_C(t)$ are, respectively, target acceleration spectra, target displacement spectra, and target cumulative absolute velocity that are computed based on the selected ground motions. α_{S_u} and α_{CAV} are weighting factors determining the contribution of residual associated with displacement spectra and cumulative absolute velocity in the objective function. a_g is the acceleration time history of ETEFs. These objective functions take a_g as the input.

Two other used ETEF series in this study are "kn" and "kd" series. In "kn" series, acceleration spectra and nonlinear displacement were considered in generating this series. In "kd" series, hysteretic energy consistency was also included in the generating objective function of the "kn" series. In fact, the objective function of generating "kn" series was a special case of the objective function of generating "kd" series. The objective function of generating "kd" series is expressed in Equation (4). It should be mentioned that the linear profile was used for simulating "kn" and "kd "series. This property of "kn" and "kd" series is different from "lc" series where exponential profile was adopted for generating it.

$$F_{\text{ETEF}}\left(a_g\right)=\int_{0}^{T_{\max}}\int_{0}^{t_{\max}}\left\{\left[S_a(T,t)-S_{aC}(T,t)\right]^2\right\}dtdT$$
$$+\int_{1}^{\mu_{\max}}\int_{0}^{T_{\max}}\int_{0}^{t_{\max}}\left\{\begin{array}{l}\alpha_{u_m}\left[u_m(t,T,\mu)-u_{mC}(t,T,\mu)\right]\\[4pt]\alpha_{E_H}\left[E_H(t,T,\mu)-E_{HC}(t,T,\mu)\right]\end{array}\right\}dtdTd\mu \qquad (4)$$

where $u_m(t,T,\mu)$ and $E_h(t,T,\mu)$ are respectively the nonlinear displacement demand and hysteretic energy demand of

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nonlinear SDOF with period of T and yield strength of $F_y(T,\mu)$ subjected to ETEFs. $u_{mc}(t,T,\mu)$ and $E_{Hc}(t,T,\mu)$ are respectively the target nonlinear displacement and target hysteretic energy demand which are calculated based on the selected ground motions. α_{u_m} and α_{E_H} are weight factors associated with the contribution of nonlinear displacement and hysteretic energy in the objective function respectively. In the objective function of generating "kn" series, the value of α_{E_H} was assigned to zero so that only acceleration spectra and nonlinear displacement demand contributed in the objective function value.

ETA20kn01, ETA20kn02, and ETA20kn03 are the members of "kn" series. The acceleration time history of these excitations is shown in Fig. 6. ETA20kd01, ETA20kd02, and ETA20kd03 are the members of "kd" series. The acceleration time history of these excitations is depicted in Fig. 7. "kn" series and "kd" series are 20-sec ETEFs while "lc" series is 40 sec ETEFs.

4. Model description

In this paper, the Morrow point dam, which is a 144-m-high double curvature arch dam, is studied as a case study for applying the proposed method. Fig. 8 shows a view of the Morrow point dam. The thickness of dam in the crest and the base are 3.7 m and 16 m, respectively, and 16 m base thickness.

Fig. 8: A view of Morrow point dam

A finite-element model of the dam is presented in Fig. 9. In this case, the dam body and the surrounding foundation rock are modeled by eight-node brick elements (C3D8R). It is worth noting that the current numerical model consists of 675 and 6,630 elements for the dam body and the foundation rock, respectively. In addition, the reservoir is modeled using 2,310 acoustic elements (AC3D8). The reservoir is truncated at sufficient distance from the dam upstream face, which is about two times the dam height, and the transmitting boundary conditions are applied at the far truncated far-end surface. A set of ETEFs is applied at foundation boundaries in stream direction.
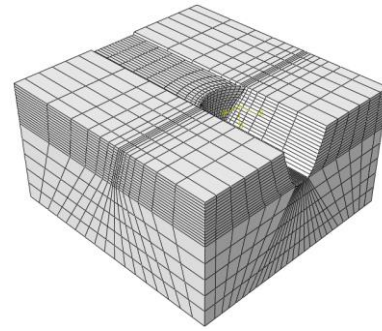

Fig. 9: 3-D finite element model of morrow point dam

It is noteworthy that the behavior of the dam is assumed to be linear. The material properties of concrete and foundation are tabulated in Table 1. Moreover, the tensile strength of the concrete is assumed to be σ_t =3 MPa. In addition, the mass density and Bulk modulus of water are considered to be ρ_w= 1000 kg/m³, and $K_w = 2.2 GPa$, respectively. Besides, the transmitting boundary condition is exerted at the far-ends of the reservoir.
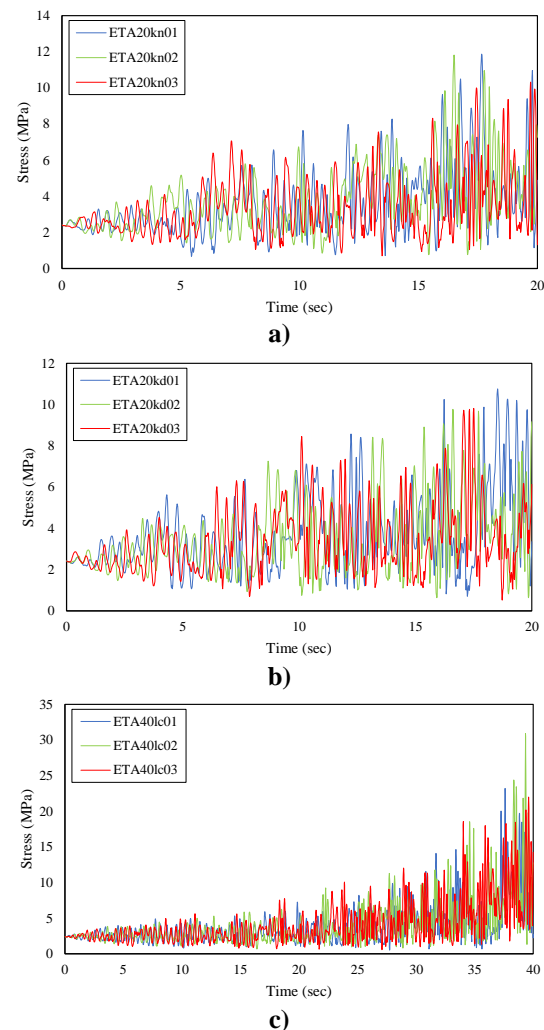

Fig. 10: The time histories of the maximum tensile stress of the dam body due to different ETEFs. a) "kn" series, b) "kd" series, c) "lc" series.

Table 1: Material properties of the dam concrete and the foundation rock

Materials	Density (kg/m³)	Elastic modulus (GPa)	Poisson ratio
Concrete	2483	34.5	0.2
Rock	2643	26.2	0.2

Rayleigh-damping factors are employed based on the first two natural frequencies of dam system, and the energy dissipation is computed by setting damping ratio to 5%. It should be noted that the stiffness proportional and the mas-proportional coefficients are obtained as 0.001078 and 1.5238, respectively.

5. Result and discussion

In this section, by implementation of the endurance time method, the spectral acceleration corresponding with the initiation of cracking is obtained through a set of ETEFs. Afterwards, the achieved value is used to investigate the correlation between endurance time and time history analyses.

5.1 Endurance time analysis

As mentioned before, three ETEFs series are utilized in the present work, namely, "lc" series, "kn" series, "kd" series. These ETAFs are applied at foundation boundaries in stream direction, and the time history of the maximum principal stress in the dam is obtained, as shown in Fig. 10. It should be noted that because of linear assumption for materials, high stress is observed in the dam body. On the basis of the dam response provided in Fig. 10, the maximum tensile stress in the dam is obtained for diverse spectral acceleration at the first mode, as shown in Fig. 11. This procedure is explained in detail in the methodology section.

The average of spectral acceleration at which the tensile stress in the dam body reaches the tensile strength is 0.135g, 0.146g, and 0.161g for "kn", "kd" and "lc" series, respectively. It should be noted that for the obtained results, the maximum difference between the aforementioned ETEFs series doesn't exceed 16.1%. Also, Fig. 12 shows the contours of maximum principal stress through the dam body at the moment the maximum tensile stress reaches the tensile strength.
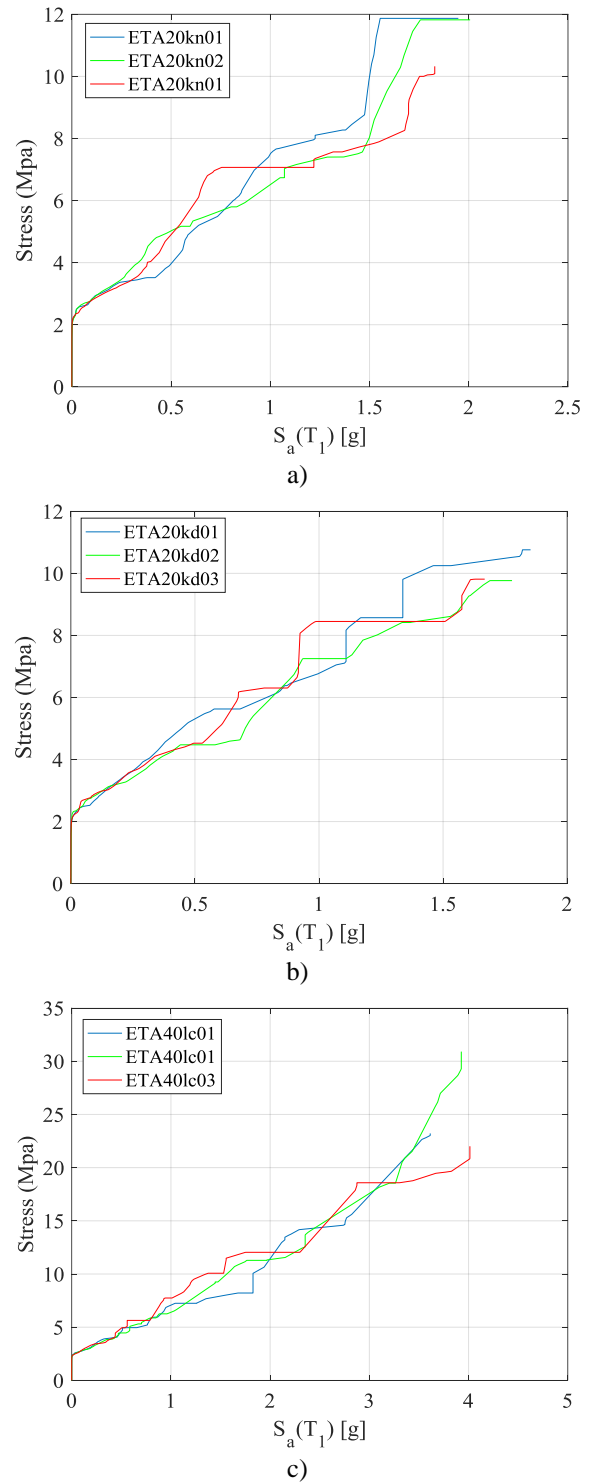

a)

b)

c)

Fig. 11: Maximum tensile stress versus spectral acceleration at the first mode period by different ETEF seriess. a) "kn" series, b) "kd" series, c) "lc" series.
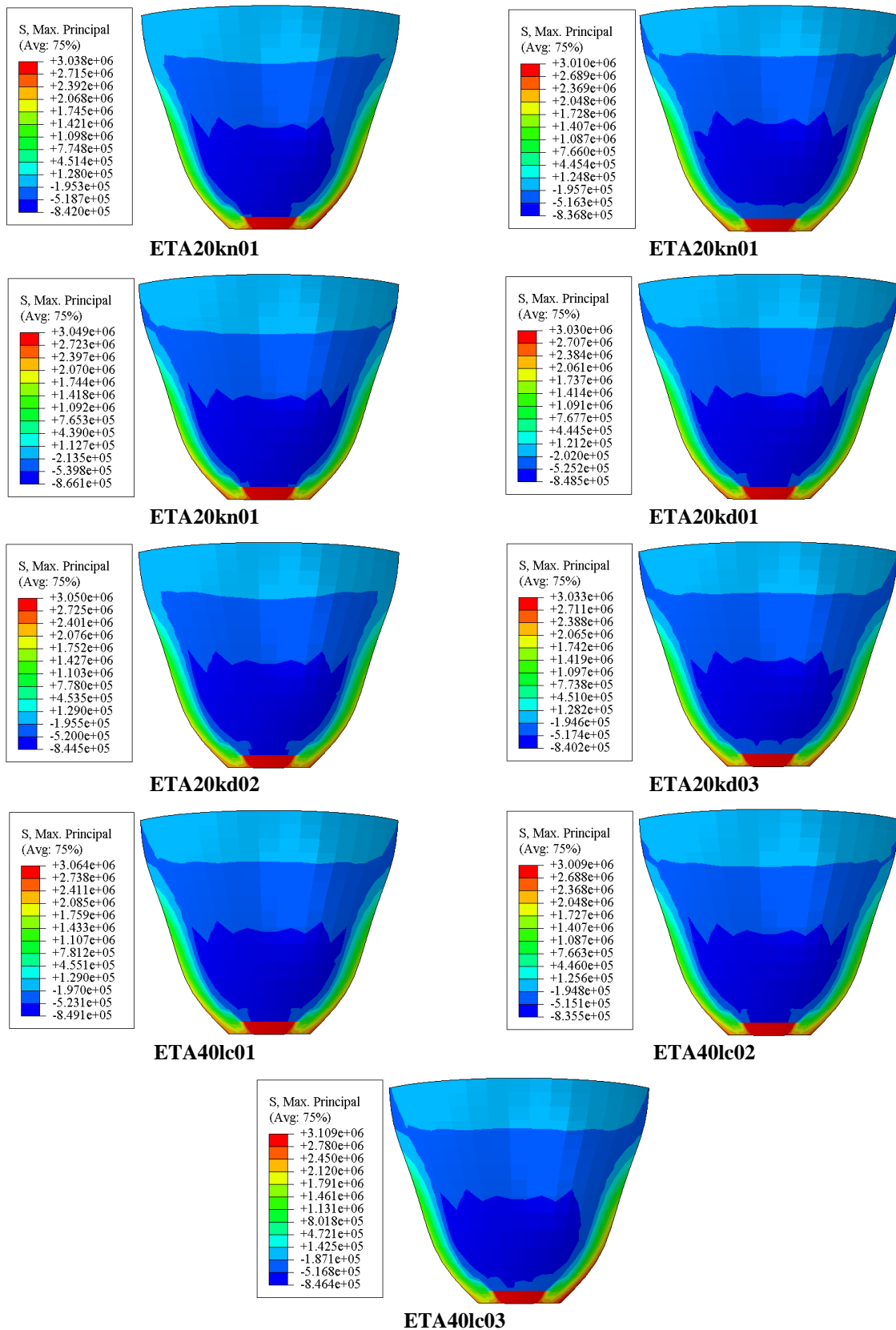
Fig. 12: The stress contours of dam due to various ETEFs at intensity that the tensile stress in the dam body reaches the tensile strength

Table 2: Characteristics of the ten ground motion records selected.

| No.	Earthquake	Station	Magnitude (M)	Year	Un-scaled PGA (g)	Scale factor
EQ1	Northridge	Beverly Hills - Mulhol	6.7	1994	0.52	0.129
EQ2	Northridge	Canyon Country-WLC	6.7	1994	0.48	0.198
EQ3	Duzce, Turkey	Bolu	7.1	1999	0.82	0.074
EQ4	Hector Mine	Hector	7.1	1999	0.34	0.287
EQ5	Imperial Valley	Delta	6.5	1979	0.35	0.270
EQ6	Imperial Valley	El Centro Array #11	6.5	1979	0.38	0.122
EQ7	Kobe, Japan	Nishi-Akashi	6.9	1995	0.51	0.119
EQ8	Kobe, Japan	Shin-Osaka	6.9	1995	0.24	0.337
EQ9	Kocaeli,Turkey	Duzce	7.5	1999	0.36	0.228
EQ10	Kocaeli,Turkey	Arcelik	7.5	1999	0.22	0.430
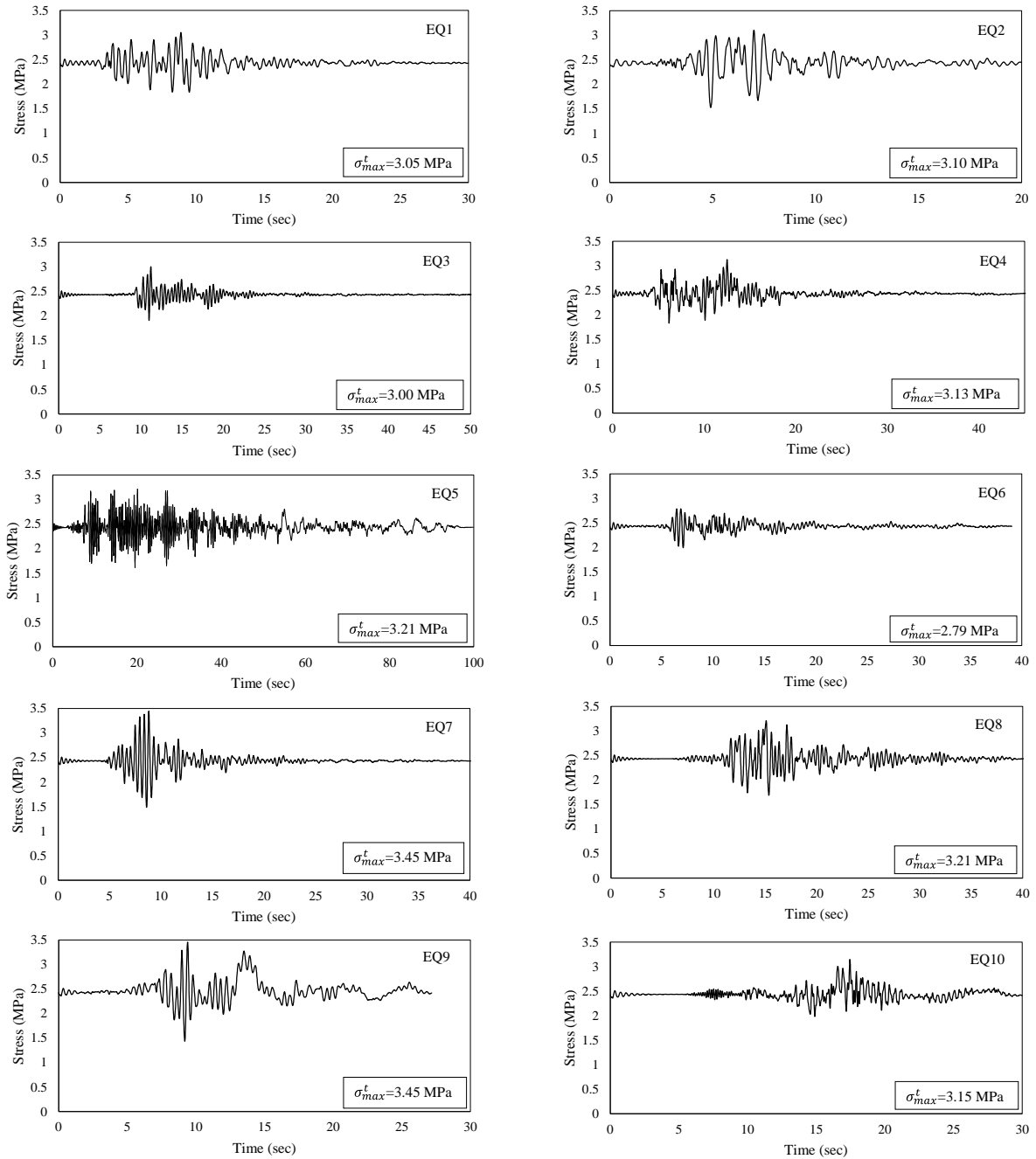
Fig. 13: The time histories of the maximum tensile stress of the dam body due to various earthquakes
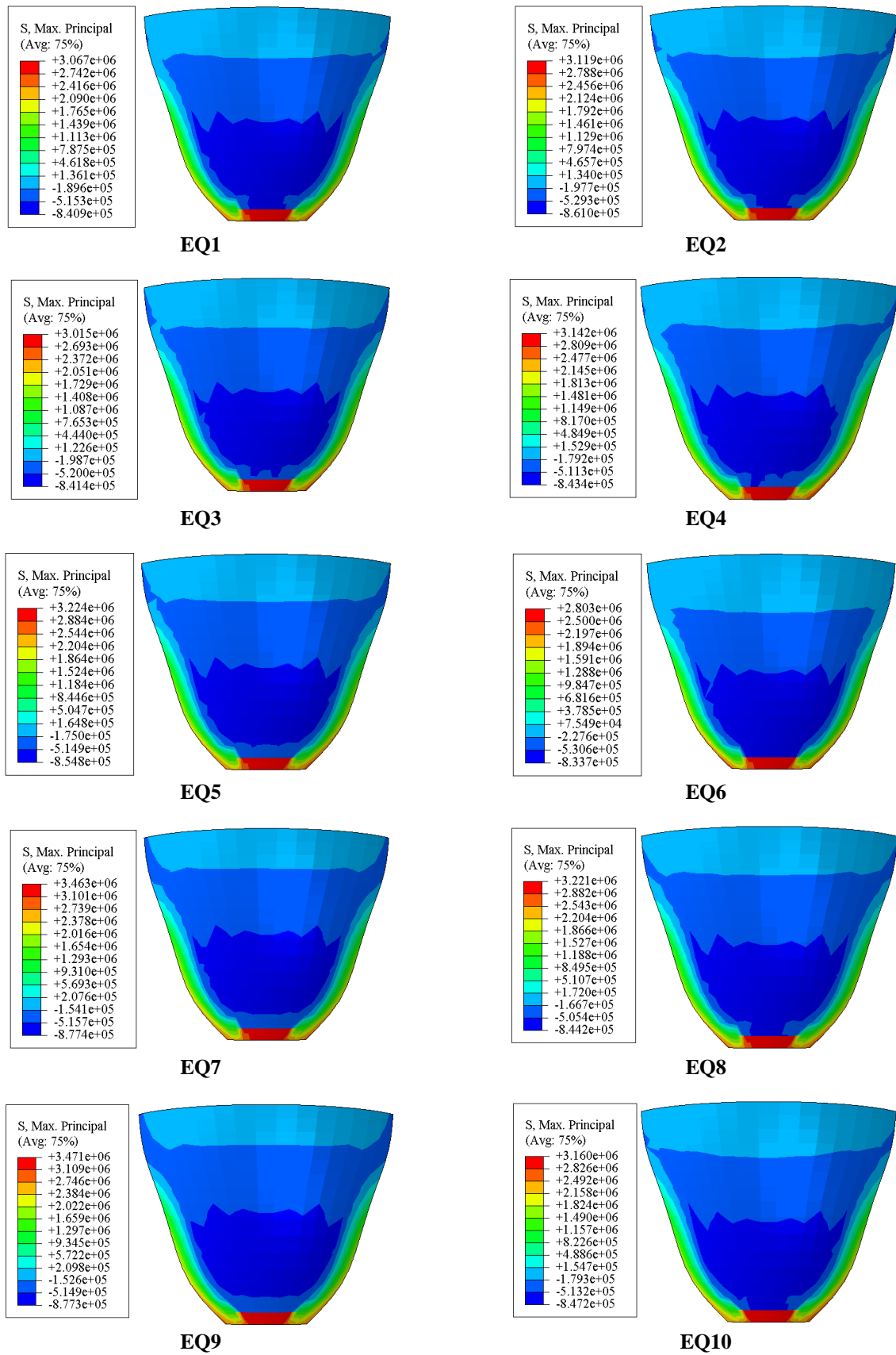
Fig. 14: The stress contours of dam due to various earthquakes.

5.2 Comparison between endurance time and time history analyses

In order to investigate the reliability of the results obtained by endurance time analysis, a comparison study is performed between endurance time and time history analyses. For this purpose, the first ten records specified by FEMA P695 [28] as far-field ground motion records are chosen. These earthquakes and corresponding scale factors are listed in

Table 2, which are scaled on the basis of the spectral acceleration at the first mode period ($S_a(T_1) = 0.15g$). This value is the average crack initiation intensity measure obtained by the ET method.

Fig. 13 shows the time histories of the maximum tensile stress through the dam body for different earthquakes.

The results illustrate that, except for the EQ6 record, the maximum tensile stress exceeds the tensile strength in all other records. It should be noted that the average of the maximum tensile stress in the dam is more than the tensile strength as it equals 3.15 MPa. So, the ET method is capable of predicting the spectral acceleration corresponding a desired performance level. In order to determine the spectral acceleration that the dam response reaches a certain performance level, a large number of time history analyses is required. However, the ET method can predict the spectral acceleration at a certain performance with acceptable precision. Furthermore, the contours of maximum principal stress through the dam body at the moment that the maximum tensile stress occurs are presented in Fig. 14. It can be inferred that the maximum tensile stress occurs at the base of the arch dam.

6. Conclusions

In this study, a method for determining critical seismic intensity for crack initiation which is used for evaluating the seismic performance of concrete arch dams is proposed. The crack initiation intensity measure indicates that earthquakes with higher intensity measure than this value induce cracks in the dam. This parameter value can be considered for the performance evaluation of arch dams. Determining this parameter value using conventional time history analyses requires several up and down scaling of a suite of ground motions which is time consuming. In order to avoid this obstacle, Endurance Time (ET) method is utilized in place of conventional time history analyses. In the ET method, the structure is subjected to predesigned intensifying acceleration time histories. In this study, a framework for determining the crack initiation intensity measure value using the ET method is proposed. The proposed method is applied to the Morrow point arch dam by using three different endurance time excitation series, namely, 'kn', 'kd', and 'lc'. A 3-D finite element model of the dam was developed, including the dam body, its foundation, and reservoir. The foundation was modeled to be a massless medium. and a set of endurance time excitations were applied at foundation boundaries in stream direction. In order to investigate the reliability of the proposed method, the time history analysis of the arch dam is performed by ten ground motions scaled to the crack intensity measure value obtained by the ET method. The concluding remarks are given below:

- The ET curve obtained by three different endurance time excitation series are shown in the same figure. Their compatibility is obvious in spite of the fact that they are generated based on different approaches.
- It is demonstrated that the crack initiation intensity measure value obtained by different endurance time excitations are compatible with each other. Their maximum differences do not exceed 16.1%.
- Principal stress contours at the crack initiation instant are shown for different endurance time excitation series. It is demonstrated that the desirable consistency exists among the considered endurance time excitation series.
- Time history analysis of the arch dam subjected to ten ground motions scaled by the crack initiation intensity measure indicates that crack in the dam appears in nearly all ten ground motions. This observation shows that the ET method conservatively predicts the crack initiation intensity measure.
- Time history analysis of the dam subjected to the scaled ground motions depicts that the crack in the dam under 6 ground motions (more than half of ground motions) was at the early stage. This observation shows that the ET method well predicts the average value of the crack initiation intensity measure.
- Comparison between principal stress contours obtained by the ET method and the scaled ground motions at the crack initiation stage shows acceptable compatibility, indicating the high potential of the endurance time method in seismic analysis of concrete arch dams.

Computing (HPC) Center of Sharif University of Technology for providing a robust and fast platform to run our simulation cases of this research.

References

[1] H. Mostafaei, M. Sohrabi Gilani, and M. Ghaemian, "A Comparative Study between Pseudo-static and Dynamic Analyses on Rock Wedge Stability of an Arch Dam," Civ. Eng. J., vol. 4, no. 1, p. 179, 2018.

[2] N. Bouaanani and C. Perrault, "Practical Formulas for Frequency Domain Analysis of Earthquake-Induced Dam-Reservoir Interaction," J. Eng. Mech., vol. 136, no. 1, pp. 107–119, 2010.

[3] D. Wagle, "Earthquake response of concrete gravity dams," 2010.

[4] G. L. Fenves, "Effects of Concrete Cracking on the Earthquake," Earthq. Eng. Struct. Dymamics, vol. 18, no. July 1988, 1989.

[5] H. Tan and A. K. Chopra, "Dam-Foundation Rock Interaction Effects in Earthquake Response of Arch Dams," J. Struct. Eng., vol. 122, no. 5, pp. 528–538, 1996.

[6] D. H. Wepf, G. Feltrin, and H. Bachmann, "Influence of Time-Domain Dam-Reservoir," Earrthquake Eng. Struct. Dyn., vol. 22, no. May 1991, pp. 573–582, 1993.

[7] H. Mirzabozorg and M. Ghaemian, "Non-linear behavior of mass concrete in three-dimensional problems using a smeared crack approach," Earthq. Eng. Struct. Dyn., vol. 34, no. 3, pp. 247–269, 2005.

[8] H. Mostafaei, M. Sohrabi Gilani, and M. Ghaemian, "Stability analysis of arch dam abutments due to seismic loading," Sci. Iran., vol. 24, no. 2, pp. 467–475, 2017.

[9] M. Alembagheri and M. Ghaemian, "Damage assessment of a concrete arch dam through nonlinear incremental dynamic analysis," Soil Dyn. Earthq. Eng., vol. 44, pp. 127–137, 2013.

[10] H. E. Estekanchi, A. Vafai, and M. Sadeghazar, "Endurance Time method for seismic analysis and design of structures," Sci. Iran., vol. 11, no. 4, pp. 361–370, 2004.

[11] M. Mashayekhi, S. A. Mirfarhadi, H. E. Estekanchi, and H. Vafai, "Predicting probabilistic distribution functions of response parameters using the endurance time method," Struct. Des. Tall Spec. Build., vol. 28, no. 1, p. e1553, 2019.

[12] M. Mashayekhi, H. E. Estekanchi, H. Vafai, and S. A. Mirfarhadi, "Development of hysteretic energy compatible endurance time excitations and its application," Eng. Struct., vol. 177, no. April, pp. 753–769, 2018.

[13] M. Mashayekhi, H. E. Estekanchi, A. Vafai, and S. A. Mirfarhadi, "Simulation of Cumulative Absolute Velocity Consistent Endurance Time Excitations," J. Earthq. Eng., vol. in press, 2018.

[14] M. Mashayekhi, H. E. Estekanchi, and H. Vafai, "Simulation of Endurance Time excitations via wavelet transform," Iran. J. Sci. Technol. - Trans. Civ. Eng., 2018.

[15] M. Mashayekhi, H. E. Estekanchi, H. Vafai, and G. Ahmadi, "An evolutionary optimization-based approach for simulation of endurance time load functions," Eng. Optim., pp. 1–20, 2019.

[16] M. Mashayekhi, M. Harati, and H. E. Estekanchi, "Development of an alternative PSO-based algorithm for simulation of endurance time excitation functions," Eng. Reports, no. October, pp. 1–15, 2019.

[17] V. Valamanesh and H. E. Estekanchi, "Nonlinear seismic assessment of steel moment frames under bidirectional loading via Endurance Time method," Struct. Des. Tall Spec. Build., vol. 23, no. 6, pp. 442–462, 2014.

[18] M. Mashayekhi, H. Estekanchi, H. Vafai, and S. Mirfarhadi, "Development of hysteretic energy compatible endurance time excitations and its application," Eng. Struct., vol. 177, pp. 753–769, 2018.

[19] A. Mirfarhadi and H. E. Estekanchi, "Value Based Seismic Design of Structures using Performance Assessment by the Endurance Time Method," Struct. Infrastruct. Eng., pp. 1–19, 2020.

[20] H. E. Estekanchi, V. Valamanesh, and A. Vafai, "Application of Endurance Time Method in Linear Seismic Analysis," Eng. Struct., vol. 29, no. 10, pp. 2551–2562, 2007.

[21] M. C. Basim and H. E. Estekanchi, "Application of endurance time method in performance-based optimum design of structures," Struct. Saf., vol. 56, pp. 52–67, 2015.

[22] M. A. Hariri-Ardebili, S. Sattar, and H. E. Estekanchi, "Performance-Based seismic assessment of steel frames using Endurance Time analysis," Eng. Struct., vol. 69, pp. 216–234, 2014.

[23] M. A. Foyouzat and H. E. Estekanchi, "Application of rigid-perfectly plastic spectra in improved seismic response assessment by Endurance Time method," Eng. Struct., vol. 111, pp. 24–35, 2016.

[24] M. A. Hariri-Ardebili and H. Mirzabozorg, "Estimation of probable damages in arch dams subjected to strong ground motions using endurance time acceleration functions," KSCE J. Civ. Eng., vol. 18, no. 2, pp. 574–586, 2014.

[25] H. E. Estekanchi, M. Harati, and M. Mashayekhi, "An investigation on the interaction of moment- resisting frames and shear walls in RC dual systems using endurance time method," Struct. Des. Tall Spec. Build., vol. 27, no. 12, pp. 1–16, 2018.

[26] I. The MathWorks, "MATLAB 2018a." The MathWorks, Inc., Natick, Massachusetts, United States., 2018.

[27] M. Mashayekhi, H. E. Estekanchi, A. Vafai, and S. A. Mirfarhadi, "Simulation of Cumulative Absolute Velocity Consistent Endurance Time Excitations," J. Earthq. Eng., 2018.

[28] Federal Emergency Management Agency (FEMA), Quantification of Building Seismic Performance Factors, FEMA P-695. Washington, D.C., 2009.