Seismic fragility and risk analysis of deep water bridges based on an improved endurance time method

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Abstract

Assessing the seismic fragility and risk probability of bridges is a computationally demanding part of performance-based earthquake engineering as it requires a large number of nonlinear time-history analyses. The endurance time analysis (ETA) has been successfully applied as a rapid and reliable method for the seismic analysis and assessment. Nevertheless, there is still a need for the efficient use of ETA method in the seismic fragility and risk analysis. In the ETA, the generation of endurance time acceleration functions (ETAFs) needs huge computational burden. The record-to-record variability estimated by ETA is extremely small compared to that of incremental dynamic analysis (IDA), which leads to unreliable fragility and risk estimates. Thus, the aim of this paper is twofold: (1) to reduce the time in generating the ETAFs based on the spectral modification procedures of ground motions and (2) to present two approaches for improving the reliable fragility and risk estimates. The application of presented approaches is illustrated using a computationally intensive example of a deep-water reinforced concrete (RC) bridge considering fluid-structure interaction. The feasibility of the proposed method is established by comparing the results with the IDA method, which can provide a pathway towards practical use of the ETA method in the seismic performance-based evaluation of bridges.

Keywords: Endurance time analysis, seismic fragility, seismic risk, deepwater bridge

1. Introduction

The seismic performance is usually defined by the performance-based earthquake engineering framework [1] as economic loss, life safety and recovery downtime. All of these decision variables are predicted based on the estimation of seismic risk, which is calculated based on structural fragility curves. Nowadays, the fragility curves are usually derived by the numerical methods [2-4] due to the insufficient empirical data. In the numerical methods, three frequently used approaches, namely cloud method [2], multiple strip analysis [5] and incremental dynamic analysis (IDA) [6], are implemented for developing the fragility curves. All of these methods need a large number of nonlinear time-history analyses to yield the similar results of fragility estimates, which takes a huge computational effort, especially for seismic assessment of deepwater bridges based on 3D finite element models [7]. Thus, developing an effective method to reduce the computational time appears to be an urgent need.

The endurance time analysis (ETA) is a newly developed method for seismic design and assessment of structures [8]. Commonly, the ETA only needs a few nonlinear time-history analyses in order to estimate the seismic responses using a few artificial endurance time acceleration functions (ETAFs) with the increasing amplitudes over time. The computational time associated with this method is very attractive and thus has been successfully applied in different areas of seismic engineering [8-10]. Due to distinctive feature of time-efficient computation, the ETA method has been also applied for seismic fragility and risk analysis [11]. However, there are still some disadvantages associated with the ETA method. For example, generating of ETAFs requires a large amount of computational effort when using an unconstrained optimization strategy. Moreover, for seismic fragility analysis, the previous studies [11-13] has revealed that the ETA method cannot predict the record-to-record variability accurately due to the use of small number of ETAFs. In order to deal with this problem, the previous study [13] adopted a recommended value of dispersion parameter to generate the fragility curves. However, this recommended parameter do not reflect the actual record-to-record variability of ground motions, and can be varied with different structure types and different suites of earthquakes.

Based on the above consideration, the objectives of the present paper are: (a) to generate ETAFs with an efficient and applicable method to reduce the huge computational time; (b) to present the fragility and risk analysis using the ETA method associated with proposing new and accurate approaches for estimating the damage probabilities of bridges accurately. The proposed methods are illustrated by using a case study of a typical deep-water reinforced concrete (RC) highway bridge located in high seismic zone near Wenchuan earthquake area of Sichuan province, China.

2. Endurance time analysis

The ETA is a dynamic pushover method which can estimate the seismic performance of structures through pre-defined artificial accelerograms with increasing intensities [8]. The ETAFs are artificially developed using the following scheme that both acceleration and displacement spectra are increasing with the time, t:

$$S_a(T,t)=\frac{t}{t_{Target}}S_{aT}(T) \tag{1}$$

$$S_d(T,t)=\frac{t}{t_{Target}}S_{dT}(T)\frac{T^2}{4\pi^2} \tag{2}$$

where $S_a(T, t)$ and $S_d(T, t)$ are the acceleration and displacement spectra of ETA records at time t respectively; $S_a(T, t)$ and $S_d(T, t)$ are target design spectra of acceleration and displacement; t_{Target} is the target time for scaling the acceleration functions and T is the fundamental period of the structure considered.

In order to meet the requirements of above two equations, unconstrained optimization procedures are usually formulated [8-10] as follows:

$$\min F\big(\mathrm{g(t)}\big)=\int_0^{T_{\max}}\int_0^{t_{\max}}\Big\{\big[S_a(T,t)-S_{aT}(T,t)\big]^2+\alpha\big[S_u(T,t)-S_{uT}(T,t)\big]^2\Big\}dtdT \tag{3}$$

in which $F(\bullet)$ = optimization target function; $g(t)$ = ETAFs; α = a weight parameter. The optimization method for generating the ETAFs is very time-consuming. Thus, this paper proposes a simply alternative method based on the spectral matching technique.

2.1 Developing ETAFs

The spectral matching technique is used to facilitate the generation of ETAFs. The spectral matching is an algorithm that modifies the spectral response of a ground-motion time history, $a(t)$, to match a target spectrum for various pairs of period and damping in the time domain. The *RspMatch2005* program [14] was applied to derive the ETAFs as following:

1) Generate a stationary random acceleration function, $g(t)$, using dt = 0.01 s and n = 3000 steps with a total duration of 30 s;

2) Converting the acceleration function to have non-stationary property and filtering the frequency content of random acceleration function in order to resemble real ground motions using the Fourier Transformation and filter functions;

3) Adjust the acceleration function to form the initial ETA record by using a linear profile function, $l(t) = t/10$, in order to make the acceleration intensity at various time intervals;

4) Compute the response spectrum R_i (T) of initial ETA record with different durations and define the target spectrum Q_i (T) over the period range from 0 to 4 s at 5% damping level (in this study, i=1, 2 and 3, meaning that three different durations considered).

5) Scale the initial ETA waves to compatible with target spectrum by the calculated scaling factor, SF, which is estimated by minimize the difference between the response spectra and target spectra in the step 4 using the following equation:

$$SF = \frac{\sum_j w(T_j)\ln\left(Q_i(T_j) / R_i(T_j) \right)}{\sum_j w(T_j)} \tag{4}$$

where w is a weight function for different period points; j is the number of the period points used.

6) Modify the initial ETA wave with different durations independently by adding the corrected tapered cosine wavelets in the specific time domain to match the corresponding target spectra.

In this paper, the design target spectrum in the seismic design code of highway bridges in China was applied for the developing the ETA record as following:

$$S_{aT}(T) = \begin{cases} S_{\max}(5.5T + 0.45) & T < 0.1s \\ S_{\max} & 0.01s \le T \le T_g \\ S_{\max}(T_g/T) & T > T_g \end{cases} \tag{5}$$

where T_g is the characteristic period of the site; $S_{\max}$ is the peak acceleration. In order to generate the ETA records, three seismic hazard levels, namely 10%50yr, 5%50yr and 2%50yr, were adopted according to different time domains or durations (namely 0-10s, 0-20s or 0-30s) of ETA wave separately. The initial ETA wave was scaled and then implemented for iterative spectral matching until a good quality of ETA wave was reached. An example of a generated ETAF has been shown in Fig. 1.

2.2 Approximate methods for seismic fragility analysis

By using the assumption of log-normal cumulative distribution function, the seismic fragility function can be mathematically estimated as:

$$P_f\left[DS \middle| IM\right] = \Phi\left\{ \frac{\ln(IM) - \ln(m)}{\beta} \right\} \tag{6}$$

in which P_f represents the damage probability; DS stands for the damage state; $\Phi(.)$ is the cumulative distribution function of standard normal distribution; m is the median fragility; β is the logarithmic standard deviation or fragility dispersion.

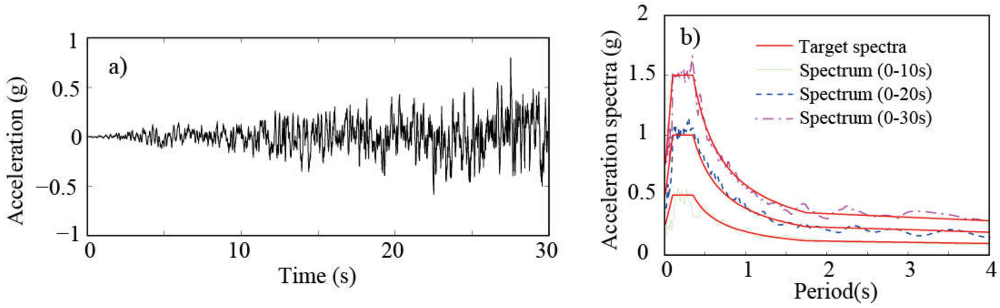

Fig. 1 – An example of a generated ETAF

Several previous researches [12-14] found that ETA is reliable for estimating the fragility median, but fails to predict the logarithmic standard deviation or dispersion β in Eq. (6) as shown in Fig. 2. Thus, in this paper, two efficient approximate methods are proposed to improve the estimation of logarithmic standard deviation.

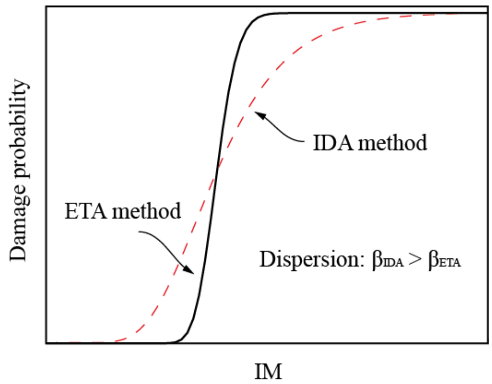

Fig. 2 – Unreliable fragility estimate by ETA method compared to IDA method

2.2.1 Proposed method 1 to estimate β

In this paper, an additional IDA point is adopted to help to determine the dispersion β. The proposed method 1 is summarized as following:

1) Generate the initial fragility curves using Eq. (6) by the ETA method under the assumption of a lognormal probability distribution for fragility function. The median and dispersion value is obtained according to the previous study [13];

2) Based on this initial fragility curve, identify the intensity level, IM_1, at which the full area (orange in Fig. 3) above the fragility curves reaches unit as shown in Fig 3;

3) Conduct the nonlinear time-history analyses using the selected ground motions scaled to this intensity level IM_1 and predict the damage probability $p_f[\, DS|\, IM_1\,]$ at the intensity level of IM_1;

4) Use the probability point $p_f[\, DS|\, IM_1\,]$ to estimate the new dispersion β_u in step 3 as following:

$$\beta_u = \frac{\ln\left(IM_1/m_i\right)}{\Phi^{-1}\left(p_f\left[DS|IM_1\right]\right)} \tag{7}$$

where m_i is the initial estimate of fragility median;

5) Update the fragility curve by the dispersion β_u under the assumption of a lognormal distribution as:

$$P_f\left[DS\middle|IM\right]=\Phi\left\{\frac{\ln(IM)-\ln(m_i)}{\beta_u}\right\} \tag{8}$$

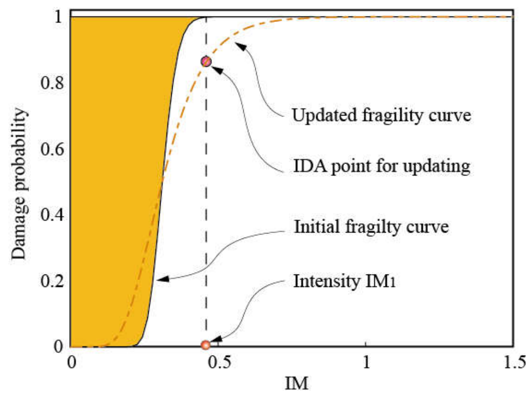

Fig. 3 – Identification of the specified intensity level to update the fragility curve

2.2.2 Proposed method 2 to estimate β

Assuming that the selected intensity measure (IM) has good correlation with the EDPs, the record-to-record variability, β_{RTR}, can be reflected by the standard deviation of $S_a(T_1)$ for the selected ground motions and calculated by the transferred equivalent time from the mean ETA curve as following:

1) Select a suite of as-recorded ground motions compatible with the target spectrum, which is used to generate the ETAFs, as shown in Fig 4;

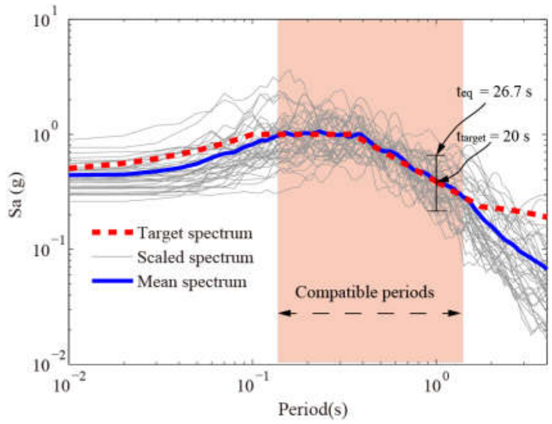

Fig. 4 – Selected ground motions and target design spectrums with equivalent time

2) Calculate the median and standard deviation of $S_a(T_1)$ for the corresponding structures, and transfer the median plus standard deviation value of $S_a(T_1)$ to the equivalent time by the following equation:

$$\frac{t_{eq}}{\alpha_m S_{\mu+\sigma}(T_1)}=\frac{t_{Target}}{S_t(T_1)} \tag{9}$$

in which t_{eq} = equivalent endurance time; α_m = scale factor; $S_{\mu+\sigma}(T_1)$ = median plus standard deviation value of spectral acceleration at the fundamental period; $S_t(T_1)$ = target spectrum at the fundamental period; T_{target} = target time in the ETAFs, which was adopted as 20 s;

3) Use the equivalent time to obtain the median and standard deviation of EDPs from the mean ETA curve and estimate the dispersion β_{RTR};

4) Update the fragility curve by the dispersion β_{RTR}.

3. Application to an example bridge

The 3D finite element (FE) model of the example pier with surrounding water is established in software ADINA, as shown in Fig 5. The 3D 8-node solid elements are applied for modeling the pier, while the 3D 8-node potential-based fluid elements are used for simulate the water as shown in Fig. 5. The meshes for both pier and water produce a total of 81,900 elements. The interface between pier and water was achieved by balancing the velocity and pressure at the interface between water and pier as:

$$\begin{bmatrix} M_s & 0 \\ 0 & -M_w \end{bmatrix}\begin{bmatrix} \ddot{U} \\ \ddot{\Psi} \end{bmatrix}+\begin{bmatrix} C_s & C_{sw} \\ C_{ws} & 0 \end{bmatrix}\begin{bmatrix} \dot{U} \\ \dot{\Psi} \end{bmatrix}+\begin{bmatrix} K_s & 0 \\ 0 & -K_w \end{bmatrix}\begin{bmatrix} U \\ \Psi \end{bmatrix}=\begin{bmatrix} -M_s\ddot{u}_g(t) \\ -C_{ws}\dot{u}_g(t) \end{bmatrix} \tag{10}$$

where M_s and M_w are mass matrices for pier and water, respectively; K_s and K_w are stiffness matrices for pier and water, respectively; C_s is the Rayleigh damping matrix for pier; C_{sw} and C_{ws} are water-pier interaction matrix; $\ddot{u}_g(t)$ is the time-history acceleration of selected ground motion.

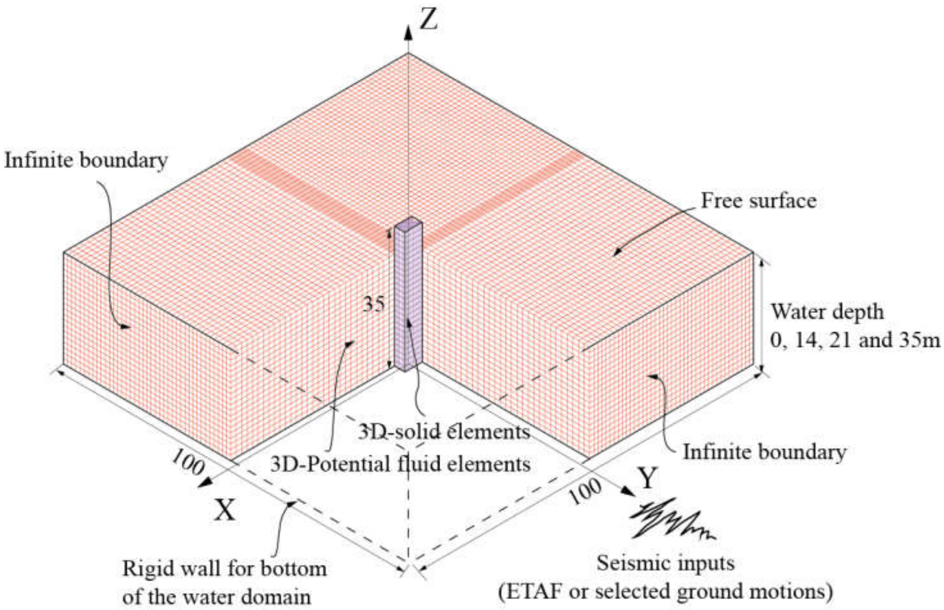

Fig. 5 – 3D finite element model of pier-water coupled system

3.1 Validation of generated ETAFs

In this study, IDA was used as a basis to validate the efficiency and accuracy of generated ETA records by the proposed method. Based on the selected 40 ground motions, the median IDA curve were employed for comparison with average ETA results, which were obtained using three ETA records for illustrating the effectiveness of the proposed ETAFs. Fig. 6 shows the comparison of seismic displacements of top pier from both IDA and ETA methods with no water and different water depths. From Fig 6, it can be depicted that the ETA curves have jagged lines in which the seismic responses are constant over a specific time duration. This is because the maximum seismic responses of ETA records remain the same over a specific time interval during the nonlinear time-history analysis. Due to the intensifying property of both ETA and IDA methods, the continuous increasing tendency can be found in both median curve of ETA and IDA curves. Moreover, it can be observed from Fig 6 that the average ETA curve coincides well with median IDA curve, indicating that the ETA method with the proposed ETAFs is an appropriate method to accurately estimate the seismic responses of deepwater bridge piers.

In addition, with regard to the efficiency of computational time, the spectral modification can reduce the time of generating the ETAFs. For instance, it only took only 3 hours for modifying one ground motion to match the target spectrum, which is very efficiency compared to around 1 week by using the optimization procedures.

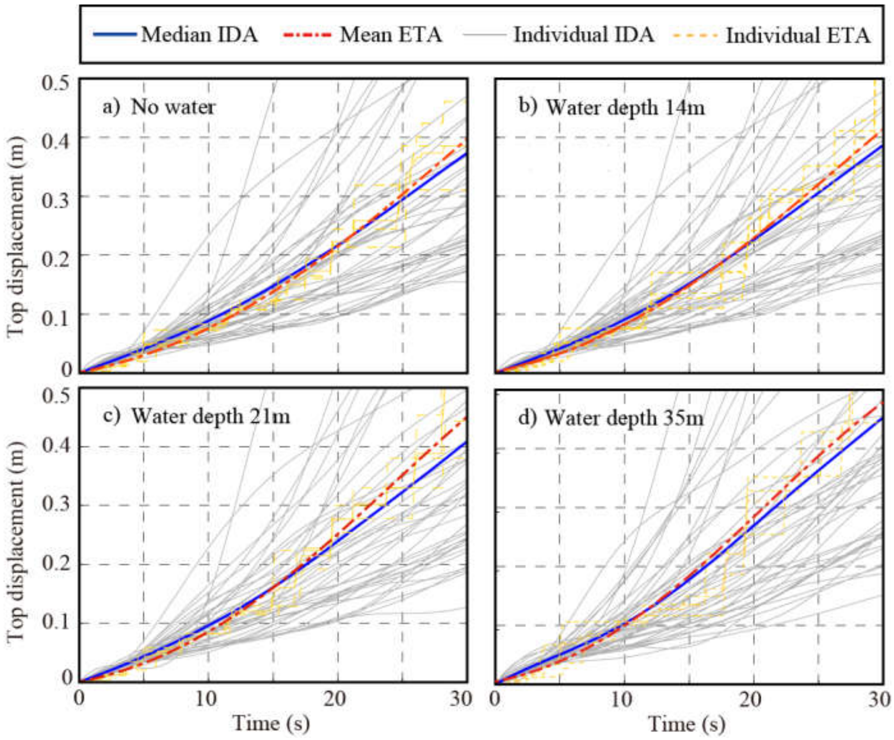

Fig. 6 – Comparison of seismic displacements of top pier from both IDA and ETA methods with no water and different water depths

3.2 Comparison of fragility curves

The damage states in the present paper is defined as slight, moderate, extensive and complete damage. The limit states are defined in terms of maximum drift (%) of the top pier as depicted in Table 1. The seismic fragility curves are developed for different methods, namely ETA, IDA, proposed method 1 and proposed method 2.

Table 1 – Damage states of bridge piers in terms of top drift (%)

Damage state	Slight	Moderate	Extensive	Complete
Median S_c	0.23	0.78	1.15	2.52
Dispersion β_c	0.25	0.25	0.46	0.46

Fig. 7 shows the comparison of fragility curves obtained from different method. From this figure, it can be found that the original ETA method cannot capture the damage probability of bridge pier accurately at four damage states considered. As mentioned above, it is due to underestimation of fragility dispersion by a few of ETAFs [13]. It can also be seen from Fig. 7 that the two proposed methods are found to match the IDA method well at four damage states. The match quality of two proposed methods are much better than the original ETA method, indicating that the fragility estimate is improved by the two proposed methods. Note that the difference between the proposed methods and IDA method can be observed to increase with damage states. This is caused by the increased difference between median IDA and ETA curves, which leads to the bias of median fragility value.

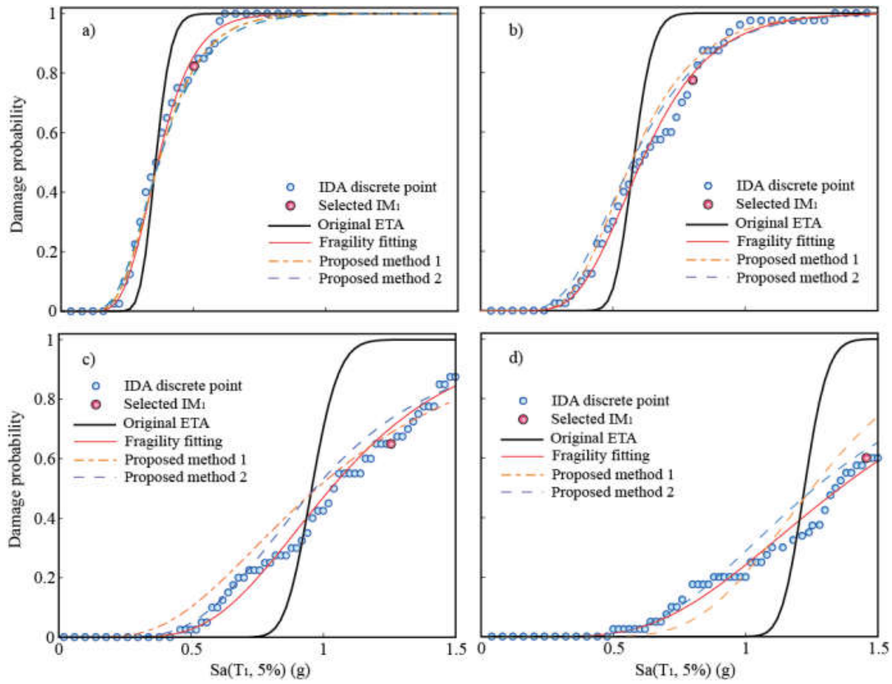

Fig. 7 –Accuracy and efficiency of fragility curves for bridge piers with 21 m water depth by two proposed methods compared to the IDA and original ETA and at different limit states: a) slight damage; b) moderate damage; c) extensive damage and d) complete damage

3.3 Seismic risk and recovery downtime

In this study, the seismic risk, λ, is defined as the annual probability of pier exceeding a prescribed damage state level. Calculating λ involves the seismic hazard of bridge site and fragility probability as:

$$\lambda = \int_0^{\infty} P_f[DS|im] \cdot \left| \frac{d\gamma_{IM}(im)}{d(im)} \right| d(im) \tag{11}$$

where P_f = fragility probability at a specified damage state; $d\gamma_{IM}(im)/d(im)$ = slope of the seismic hazard curve. Fig. 8 shows the calculated seismic risk of bridge pier at water depth 21m at four damage states. From Fig. 8, it can be illustrated that the original ETA method underestimates the seismic risk of bridge pier, while the proposed method can improve the prediction accuracy of the seismic risk.

One decision variable, recovery downtime, is also adopted to demonstrate the accuracy of the proposed methods, which can be calculated as following:

$$RDT = \sum_{t=1}^{SL} \sum_{j=1}^{4} \left[\lambda_j \exp(-\lambda_j t) \cdot \tau_j \right] \tag{12}$$

where τ_j is the repair time (days) at a specified damage state j; λ_j represents the seismic risk at jth damage state; SL is the service life of the considered bridge. The definition of repair time at each damage states is listed in Table 2 according to the previous study [15].

Table 2 – Repair time for four damage states

Damage state	Slight	Moderate	Extensive	Complete
Repair time (days)	1	7	30	365

Fig. 9 depicts the results of recovery downtime predicted by four considered methods in this paper. From this figure, it can be seen that the two proposed methods improve the accuracy of estimate of recovery downtime compared to the original ETA method, and the proposed method 1 shows better results than the proposed method 2.

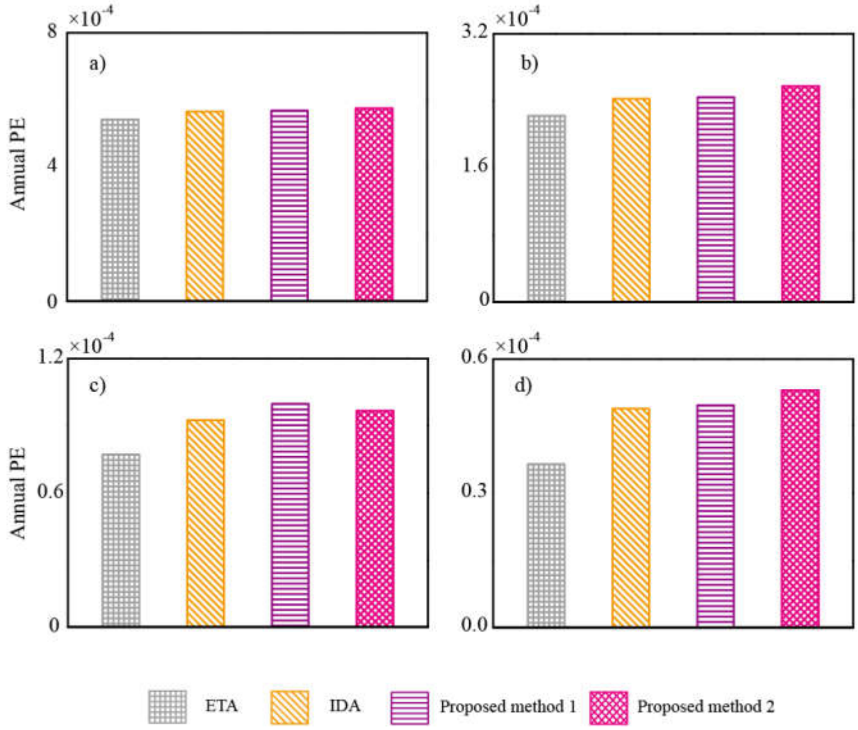

Fig. 8 Seismic risk of bridge pier at water depth 21m at four damage states: a) slight damage; b) moderate damage; c) extensive damage and d) complete damage;

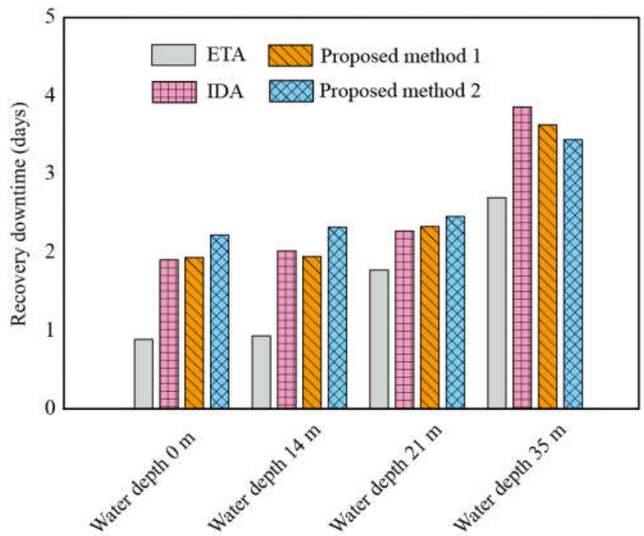

Fig. 9 Results of recovery downtime predicted by four considered methods

4. Conclusions

This paper proposes an ETA-based approach for improving the efficiency and accuracy of seismic fragility and risk analysis. Based on the spectral matching technique, the ETAFs can be easily generated and the associated computational time is massively reduced. Due to the reason that the original ETA method cannot capture the fragility dispersion accurately, two effective approaches are proposed to improve the accuracy of fragility estimates. From the results of fragility analysis, risk analysis and recovery downtime prediction, it can be concluded that the two proposed method can be used for ETA method to conduct the seismic fragility, risk analysis and estimate of decision variables with high prediction precision. In general, the proposed modified approach based on the ETA method can be applied as a fast and effective method for evaluating the seismic performance of bridges.

5. Acknowledgements

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