Influence of Foundation Stiffness on the Fragility Curves of a Concrete Gravity Dam Subjected to Near-Field Ground Motions Using Finite Element Method

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ABSTRACT

A concrete gravity dam is being investigated to determine the fragility curves during near-field ground motions under various foundation stiffness conditions. This is accomplished using the finite element method for modeling the Latyan dam and its dam-reservoir-bed complex interaction system. The nonlinear constitutive model of concrete, plastic damage, is used to simulate the cyclic behavior of tensile and compressive failures in concrete. An acoustic element is used to model the propagation of compressive waves in the reservoir to account for the hydrodynamic effects of the lake reservoir. A total of 100 real and scaled accelerograms are used to simulate near-filed seismic loading in eight different concrete-to-foundation stiffness ratios. Based on the peak ground acceleration (PGA) of the earthquake, numerical models are applied to obtain the probability density function (PDF) and cumulative distribution function (CDF) for lognormal distributions and to determine and analyze the fragility curves of the dam. According to the findings, the seismic performance of the dam is improved for stiffness ratios of 0.75, 1, and 1.5, and the best seismic performance is determined for stiffness ratios of 1. Concrete dams with stiffness ratios of 0.75, however, perform better when the peak ground acceleration is greater than 0.74g compared to those with stiffness ratios of 1.

Keywords: Concrete gravity dam; Fragility curve; Foundation stiffness; Near-field ground motion.
1. INTRODUCTION
In recent decades, the increased demands for water resources and major droughts have made concrete gravity dams one of the most important and costly infrastructures in human and industrial civilizations. As most concrete gravity dams are subject to near-field and far-field earthquakes, seismic performance studies are increasingly being considered in geotechnical and structural engineering. Since concrete gravity dams are known to be fragile in the event of earthquakes, numerous researchers have investigated both numerically and experimentally the parameters that determine their fragility [1–5]. Researchers are particularly interested in near-field ground motions, which are earthquakes recorded near a ruptured fault plane, because their seismic response differs significantly from that of ground motions recorded at a distance from the source of the earthquake. As a result of the "forward-directivity" and "fling-step" effects related to rupture mechanism and slip direction and the permanent ground displacement at the site, respectively, the pulse-type feature of near-field ground motions is triggered [6–8]. As opposed to non-pulse ground motions, pulse-type ground motions exhibit a ratio of peak ground velocity (PGV) to peak ground acceleration (PGA) greater than 0.1 second, leading to high energy inputs of the earthquake at the beginning of the event [7, 9, 10]; hence, the structures are at risk of severe damage. In this regard, some studies have examined how near-field ground motions impact the seismic performance of concrete gravity dams under various conditions. [7–13]. Zhang and Wang [7] investigated the effect of near-field and far-field ground motions on the response of a concrete gravity dam using finite element analysis. Their study indicates that displacement histories in near-field ground motions differ substantially from those in far-field motions. In addition, analysis of the cracking profiles has shown that the cracks in the near-fault ground motions are more widely dispersed throughout the dam body than in the far-fault ground motions. A recent study by Gorai and Maity [10] examined the influence of near-field and far-field ground motion on the seismic response of concrete gravity dams by response spectrums analysis, induced stress throughout the dam, and cumulative inelastic durations (CIDs) using finite element methods. It is well known that structural characteristics affect the dynamic response of concrete gravity dams, but dam-reservoir-foundation interactions have also had a significant impact on analyses, as shown by some researchers in the past three decades [11, 12, 14–20]. Consequently, it is well understood that various parameters affect the overall system response by changing the energy dissipation level, such as water compressibility, P-wave refraction at reservoir-foundation boundaries, and dam-foundation interfaces. Moreover, modeling the dam-reservoir-foundation system could highlight the foundation characteristics in the seismic response dam. In this regard, a limited number of studies have partially examined the effect of foundation stiffness on the seismic response of concrete gravity dams, including Yazdchi et al. [21], Arabshahi and Lotfi [22], Bybordiani and Arıcı [13]. A study conducted by Yazdchi et al. [21] compared the seismic response of concrete gravity dams with different
foundation stiffness through time history of dam displacement, accumulated damage, and induced stresses and damage patterns of the dam body using a hybrid finite element-boundary element technique. Arabshahi and Lotfi [22] investigated the effects of foundation flexibility and some other parameters (e.g., base deformation, water compressibility, sliding modes) through the envelope of maximum tensile principal stresses, as well as the time history of base sliding displacement on seismic analyses of concrete gravity dams using nonlinear finite element calculations. In a more recent study, Bybordiani and Arıcı [13] evaluated the efficiency of ground motion scaling techniques in predicting the results of a concrete gravity dam using the finite element method. This issue was investigated under various conditions, and some parameters, such as foundation stiffness, were analyzed to determine their effect on the accuracy of ground motion scaling techniques. It should be noted, however, that these three studies represent deterministic analyses, and no stochastic reliability studies have examined the effect of foundation stiffness on concrete gravity dam seismic responses systematically.

There is a lack of consideration of all perspectives of structural safety in deterministic analyses, particularly for large projects such as concrete gravity dams, where the stability of systems is estimated in the presence of dangerous conditions and in very low probability of limit states occurrences. The cause of this is the uncertainty associated with the structures' applied loads, geometry, and materials. It is, therefore important to note that probabilistic safety assessments consider multiple sources of uncertainty that may affect a dam's performance, particularly in seismic vulnerability analyses of concrete gravity dams. For this reason, fragility curves have been developed for reliability problems in order to estimate a structure's probability of being safe. Fragility curves show a correlation between damage probability and the intensity of a parameter leading to failure. In this regard, many researchers have examined the seismic performance of concrete gravity dams by considering different parameters in various conditions in light of the fragility curves [8, 15, 23–28]. Also, a small number of studies have examined the fragility curves as a function of peak ground acceleration, PGA [2, 18, 29–33]. In a study conducted by Hariri-Ardebili and Saouma [34], the seismic fragility curves for concrete gravity dams have been examined with or without the vertical component of ground motion using the finite element method. In this regard, various parameters, including peak ground acceleration, have been examined in relation to seismic fragility curves. The authors studied the impact of reservoir elevation on the probability of collapse and found that for full and empty reservoirs, the PGA values are 0.25g and 0.3g, respectively. More recently, Li et al. [33] have studied the uncertainty of ground motions and improved fragility curves in order to estimate the seismic performance and risk of a concrete gravity dam. As a result, they examined the fragility curves versus peak ground acceleration and the accuracy of the prediction of collapse probabilities for curves with varying numbers
of ground motion records. They found that the prediction of collapse probabilities is closely related to the total number of ground motion records used. The literature review revealed that the influence of foundation stiffness on the fragility curves of concrete gravity dams has not yet been investigated. Thus, this paper aims to investigate the seismic probability collapse of a concrete gravity dam with varying foundation stiffness. In this regard, the Latyan dam, which is a concrete gravity dam in Iran, has been modeled with the finite element method as a complete dam-reservoir-foundation system. A simulation of seismic loading is based on near-field scaled records of ten different earthquakes in terms of vertical and horizontal acceleration. Results have been presented through the fragility curves as the probability density function (PDF) and cumulative density function (CDF) versus the peak ground acceleration for eight foundation stiffnesses. The probability of collapse details have been presented through some tables.

2. METHOD OF ANALYSIS

2.1. Numerical model

This study uses the Latyan dam located on the Jajrood River in Iran as its empirical example (Fig. 1a). The basin of this concrete gravity dam covers an area of 69,800 km², with a mean annual flow of 350,000,000 m³. An illustration of the geometry of this dam can be seen in Fig. 1b, which shows the dam's cross-sectional view.
This study involves the use of a 2D plane strain finite element method to model the dam-reservoir-foundation system of the Latyan concrete gravity dam. Fig. 2 shows the mesh pattern for the dam, reservoir, and foundation discretized using linear and bilinear elements with an average dimension of 7.5 cm. The system's foundation is composed of finite and infinite elements that act as an energy-absorbing boundary to prevent seismic wave reflection in distant domains. The meshing of the dam and foundation is based on a Lagrangian formulation, which is a displacement-based element. Additionally, in order to simulate the compressive wave propagation and account for the hydrodynamic effects of the lake, an Eulerian formulation is used with acoustic elements to model the reservoir.
Table 1. Material characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concrete</th>
<th>Foundation</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity, $E$ (MPa)</td>
<td>26500</td>
<td>$E_d/E_f$</td>
<td>2070</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$= 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4$</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.15</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>2400</td>
<td>3000</td>
<td>1000</td>
</tr>
<tr>
<td>Bulk modulus, $K$ (MPa)</td>
<td>-</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>Tensile strength, $\sigma_t$ (MPa)</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In order to prevent an unrealistic seismic response as a result of linear concrete behavior, the nonlinear behavior of concrete in body dams (i.e., degradation of stiffness as a result of microcracking and unrecoverable deformation under earthquake loading) is considered in the current study using the concrete damage plasticity (CDP) model. The model presented in this study is a basic constitutive model proposed by Lubliner et al. [35] and updated by Lee and Fenves [36]. It is important to note that the concrete model includes both tension and compression behavior. Two failure mechanisms are therefore used to simulate concrete damage and plastic deformation: tensile cracking and compressive crushing. A detailed description of this constitutive model, including the damage evolution, the yield criteria, and
the flow rule, has been published in the literature, where the CDP model has been established to evaluate the seismic performance of concrete gravity dams [4, 7, 12, 32, 37, 38].

### 2.1. Earthquake loading

Ten modified and baseline-corrected accelerograms have been selected to simulate the actual earthquake excitation, each scaled in ten steps with a magnitude of 0.125g for dynamic analysis. In total, 100 real and scaled accelerograms were collected for seismic loading. An overview of the accelerograms used is presented in **Table 2**. As can be seen, the magnitude of the earthquakes (M) and the velocity of their shear waves (V<sub>s (30)</sub>) exceed approximately 5 Richter and 200 meters per second, respectively. It should be noted that considering that the current study is concerned with near-field ground motions, the selected stations are within 10 km of the source of excitation.

**Table 2.** Accelerogram information of the selected ground motions

<table>
<thead>
<tr>
<th>RSN</th>
<th>V&lt;sub&gt;s (30)&lt;/sub&gt; (m/s)</th>
<th>R&lt;sub&gt;jB&lt;/sub&gt; (km)</th>
<th>M (Richter)</th>
<th>Station</th>
<th>Date</th>
<th>Location</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>4276</td>
<td>310.68</td>
<td>5.96</td>
<td>5.5</td>
<td>Buia</td>
<td>1976</td>
<td>Italy</td>
<td>Friuli</td>
</tr>
<tr>
<td>143</td>
<td>766.77</td>
<td>1.79</td>
<td>7.35</td>
<td>Tabas</td>
<td>1978</td>
<td>Iran</td>
<td>Tabas</td>
</tr>
<tr>
<td>180</td>
<td>205.63</td>
<td>1.76</td>
<td>6.53</td>
<td>El Centro arry</td>
<td>1979</td>
<td>Mexico City</td>
<td>Imperial Valley</td>
</tr>
<tr>
<td>99</td>
<td>198.77</td>
<td>8.85</td>
<td>5.14</td>
<td>Hollister City Hall</td>
<td>1989</td>
<td>USA</td>
<td>Hollister</td>
</tr>
<tr>
<td>879</td>
<td>1369</td>
<td>2.19</td>
<td>7.28</td>
<td>Lucerne</td>
<td>1992</td>
<td>USA</td>
<td>Landers</td>
</tr>
<tr>
<td>1045</td>
<td>285.93</td>
<td>2.11</td>
<td>6.69</td>
<td>Newhall - W Pico Canyon Rd</td>
<td>1994</td>
<td>USA</td>
<td>Northridge</td>
</tr>
<tr>
<td>1120</td>
<td>256</td>
<td>1.46</td>
<td>6.9</td>
<td>Takatori</td>
<td>1995</td>
<td>Japan</td>
<td>Kobe</td>
</tr>
<tr>
<td>1176</td>
<td>297</td>
<td>1.38</td>
<td>7.51</td>
<td>Yarimca</td>
<td>1999</td>
<td>Turkey</td>
<td>Kocaeli</td>
</tr>
<tr>
<td>1511</td>
<td>611.98</td>
<td>2.74</td>
<td>7.62</td>
<td>TCU076</td>
<td>1999</td>
<td>Taiwan</td>
<td>Chi-Chi</td>
</tr>
<tr>
<td>4040</td>
<td>487.4</td>
<td>0.05</td>
<td>6.6</td>
<td>Bam</td>
<td>2003</td>
<td>Iran</td>
<td>Bam</td>
</tr>
</tbody>
</table>

According to these recorded earthquakes (**Table 2**), a scaled time history of acceleration with both the vertical and horizontal components of ground motion is shown in **Fig. 3**. There is also an indication of the vertical and horizontal peak ground acceleration of the corresponding earthquake in time history figures (**Fig. 3**), as PGA is most effective in indicating the vulnerability of a structure during an earthquake [32, 39]. In comparison with considering only one component of acceleration, considering both vertical and horizontal components of acceleration leads to a more realistic simulation of the earthquake [34].
Note that explicit dynamic analysis is used in the current study in order to solve the time integration of the equation of motion. In order to avoid instability and reduce computational efforts, this model uses the explicit central-difference time integration rule. This approach allows large models with relatively short dynamic response times, such as concrete gravity dams, to be efficiently simulated [11, 30, 40, 41].

2.2. Dam-reservoir-foundation interactions

The equation of motions for the dynamic interaction of the fluid-solid system (dam-reservoir and foundation-reservoir interactions) is derived using a Lagrangian approach in the present study. The lake water is assumed to behave as a linear-elastic, inviscid, and irrational fluid. Stress-strain equations for two-dimensional finite elements of fluid are expressed as follows [11]:

\[
\begin{pmatrix}
    P \\
    P_w
\end{pmatrix} =
\begin{bmatrix}
    C_{11} & 0 \\
    0 & C_{22}
\end{bmatrix}
\begin{pmatrix}
    \varepsilon_v \\
    w
\end{pmatrix}
\]

Assumed that \( P, C_{11}, \text{ and } \varepsilon_v \) refer to the pressure, the bulk modulus, and the volumetric strain of the fluid, respectively. \( w \) is the rotation about the axis normal, \( P_w \) is the rotational stress, and \( C_{22} \) is a constant coefficient related to \( w \) [7, 16].

In the current study, the equation of the fluid motion system is based on energy principles through the use of the Lagrange equation which is expressed as Eq. (2).

\[
\frac{\partial}{\partial t} \left( \frac{\partial T}{\partial q_i} \right) - \frac{\partial T}{\partial \dot{q}_i} + \frac{\partial \Pi_t}{\partial q_i} = Q_i; \quad i = 1, ..., n
\]

where \( T \) is the kinetic energy of the system, \( \Pi_t \) is the total potential energy, including the total strain energy (\( \Pi_e \)) and the increase in the potential energy of the system due to the free surface motion (\( \Pi_s \)), and \( q_i \) and \( Q_i \) are the generalized coordinate and force, respectively [15]. In this regard, the final form of the equation of fluid motion can be obtained by defining the corresponding parameters and substituting them into Eq. (2) as follows:

\[
M_f \ddot{U}_f + K_f^* U_f = R_f
\]

where \( U_f \) and \( \dot{U}_f \) are the nodal displacement and acceleration matrices of the fluid system, respectively. \( M_f \) and \( K_f^* \) are the system mass and stiffness (including the free-surface stiffness) matrices, respectively. In addition, \( R_f \) is a time-varying nodal force vector defined as \(-M_f a_g\), where \( a_g \) is ground acceleration vector during earthquake [11].
Furthermore, the following equation describes the motion of a coupled fluid-structure system under ground motion that contains damping effects using the interface condition [7, 16]:

\[ M_c \ddot{U}_c + C_c \dot{U}_c + K_c U_c = R_c \]  (4)

where \( M_c, C_c, \) and \( K_c \) are the matrices of mass, damping, and stiffness in the coupled system, respectively. \( \dot{U}_c, \ddot{U}_c, \) and \( U_c \) are the displacement, velocity, and acceleration vectors of the coupled system, respectively. Also, \( R_c \) is the ground acceleration vector of the time-varying nodal forces. A more detailed formulation of the fluid-structure interaction system can be found in the literature [7, 11, 15, 16, 32, 33].

It is necessary to consider the following finite element formulation of the dynamic equilibrium equations between dam and foundation in general form using the direct stiffness method in order to model the dynamic dam-foundation interaction system:

\[
\begin{bmatrix}
[M_{SS}] & [M_{SB}] & \{\ddot{u}_S\} \\
[M_{BS}] & [M_{BB}] & \{\ddot{u}_B\}
\end{bmatrix}
+ \begin{bmatrix}
[C_{SS}] & [C_{SS}] & \{\dot{u}_S\} \\
[C_{SS}] & [C_{SS}] & \{\dot{u}_B\}
\end{bmatrix}
+ \begin{bmatrix}
[K_{SS}] & [K_{SS}] & \{u_S\} \\
[K_{SS}] & [K_{SS}] & \{u_B\}
\end{bmatrix}
= \begin{bmatrix}
0 \\
\{F_B\}
\end{bmatrix}
\]  (5)

where \([M], [C], \) and \([K]\) are the mass, damping, and stiffness matrices of the dam-foundation system, respectively. The acceleration, velocity, and displacement vectors are denoted by \(\{\ddot{u}\}, \{\dot{u}\}, \) and \(\{u\}\), respectively. In addition, \(\{F\}\) is the interaction forces vector acting at the dam-foundation interface. Note that subscript \(S\) indicates nodes for finite areas while subscript \(B\) indicates nodes at boundaries for both finite and infinite areas. The model is also composed of three node groups: nodes shared between the dam and the foundation, nodes in the dam, and nodes in the foundation. An extensive description of the dynamic dam-foundation interaction can be found in the literature [20].

2.3. Fragility analysis

In order to determine the vulnerability of the concrete gravity dam with the presented properties, a fragility analysis for future events has been performed to determine the potential damage to the system. The concept of fragility quantifies the conditional probability that an engineered system will reach or exceed a structural limit state at a given level of ground motion intensity [11, 18, 24, 25, 34, 40, 41]. In this regard, The probability density function (PDF) of fragility analysis for limit state functions based on random variables of strength and load is schematically illustrated in Fig. 4.
In order to analyzing the vulnerability of a structural system to collapse, the damage zone is defined as $g(R, Q) = R - Q < 0$, in which $R$ and $Q$ denote the random variables of strength and structural load, respectively (Fig. 4). Accordingly, the probability of structural damage and structural reliability, based on the joint probability density function ($f_{RQ}$), is the following fundamental relation:

$$P_f = P[g(R, Q) < 0] = P(R < Q) = \int_{g<0} f_{R,Q} \, dR \, dQ \approx \Phi(-\beta)$$  \hspace{1cm} (6)

Where $\beta$ and $\Phi$ are the reliability index and the cumulative distribution function of the standard normal probability, respectively. The fragility curves are then calculated by cumulating the probability density function, and the ground motion intensity measure in this study is defined as the peak ground motion (PGA). Considering a lognormal distribution, the probability density function (PDF) is as follows [42]:

$$PDF = exp\left(-\frac{1}{2} \frac{(\ln(x - \gamma) - \mu)^2}{\sigma} \right) \frac{(x - \gamma)\sigma\sqrt{2\pi}}{\sigma\sqrt{2\pi}}$$  \hspace{1cm} (7)

Where $\sigma$ is the standard deviation, and $\mu$ is the mean ratio. The cumulative distribution function (CDF) for a lognormal distribution is as follows:

$$CDF = \Phi\left(\frac{\ln(x - \gamma) - \mu}{\sigma}\right)$$  \hspace{1cm} (8)

3. NUMERICAL RESULTS
3.1. Analysis of dam fragility curves

Based on near-field accelerograms and fragility curves for a variety of stiffness ratios, defined as the dam stiffness, $E_d$, over the foundation stiffness, $E_f$ ($E_d/E_f = 0.25, 0.5, 0.75, 1, 1.5, 2, 3,$ and $4$), a series of dam collapse analyses are presented in Fig. 5 and 6 and Table 3. Table 3 shows the peak ground acceleration (PGA) values at which the dam collapses as determined by finite element analyses of the system based on near-field accelerograms taken from ten different earthquakes. A histogram of the dam collapse is presented in Fig. 5, along with the probability density function (PDF) based on Eq. (7) and the PGA data of collapse presented in Table 3. According to Eq. (8), for the lognormal distributions of the PDF results in Fig. 5, a cumulative distribution function (CDF) is presented in Fig. 6.

As can be seen in Table 3, the worst earthquake for the Latyan dam is the Landers earthquake, which has a devastative peak ground acceleration ranging between $0.25g$ and $0.33g$. Therefore, earthquakes such as this one could pose a threat to the stability of the dam. However, the Northridge earthquake, which has a devastative peak ground acceleration of $0.72g$ to $1.03g$, is generally less catastrophic; therefore, the dam is more resilient to earthquakes of this type than other types. Nevertheless, the dam-to-foundation stiffness ratio plays a crucial role and can, for example, cause a dam subject to a severe earthquake to be more stable than a dam subject to a moderate earthquake.

Table 3. PGA value of the severe damage for near-field accelerograms in the studied earthquakes

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>$E_d/E_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Friuli, 1976</td>
<td>0.4g</td>
</tr>
<tr>
<td>Tabas, 1978</td>
<td>0.8g</td>
</tr>
<tr>
<td>Imperial Valley, 1979</td>
<td>0.46g</td>
</tr>
<tr>
<td>Hollister, 1989</td>
<td>0.5g</td>
</tr>
<tr>
<td>Landers, 1992</td>
<td>0.28g</td>
</tr>
<tr>
<td>Northridge, 1994</td>
<td>0.79g</td>
</tr>
<tr>
<td>Kobe, 1995</td>
<td>0.26g</td>
</tr>
<tr>
<td>Kocaeli, 1999</td>
<td>0.52g</td>
</tr>
<tr>
<td>Chi-Chi, 1999</td>
<td>0.35g</td>
</tr>
<tr>
<td>Bam, 2003</td>
<td>0.35g</td>
</tr>
</tbody>
</table>
Fig. 5. The probability density function of peak ground acceleration in the stiffness ratio \( \frac{E_d}{E_f} \) of a) 0.25 b) 0.5 c) 0.75 d) 1 e) 1.5 f) 2 g) 3 h) 4

The results of the peak ground acceleration of dam collapse during ten earthquakes can be found in Table 3 for \( \frac{E_d}{E_f} = 0.25 \). It appears that the Landers earthquake poses the greatest threat to the safety of the dam for this dam-to-foundation stiffness, while the Tabas earthquake poses a modest threat (Table 3). Lognormal distributions fit the frequency of probability density function data for \( \frac{E_d}{E_f} = 0.25 \) in Fig. 5a with a good degree of agreement, and Fig. 6a illustrates the corresponding cumulative distribution function of the fragility curve. In Fig. 5a, it is shown that a peak ground acceleration of 0.38g results in the maximum probability density function of 0.53. The fragility curve in Figure 6a exhibits 15 percent collapse under 0.3 of gravity acceleration (0.3g), and 50% collapse under 0.44g. As the ground acceleration increases abruptly, the collapse probability increases to 75% when...
the peak ground acceleration is at 0.56g and can reach 90% in the range of 0.56g to 0.71g (Fig. 6a).

In Table 3, the near-field peak ground accelerations associated with each earthquake when the dam collapses in the case of \( E_d/E_f = 0.5 \) are presented. According to the results, the Landers earthquake is the worst earthquake that could threaten the stability of the dam, and Tabas is the most modest earthquake that could threaten the stability of the dam. Figure 5b presents the probability density function with the best-fitted lognormal distribution, while in Fig. 6b, the fragility curve is presented as a cumulative distribution function. A probability density function with a maximum value of 0.48 occurs during the peak ground acceleration of 0.36g (Fig. 5b). In this stiffness ratio, the fragility curve indicates that 15% collapse probability has occurred when the peak ground acceleration is 0.28g. However, the fragility curve indicates that this probability is less than 50% at PGA = 0.43g. With a peak ground acceleration of 0.58g and 0.74g, the collapse probability is 75% and 90%, respectively (Fig. 6b).

The peak ground acceleration under the influence of a stiffness ratio of 0.75 is shown in Table 3. For this dam-to-foundation stiffness ratio, the Landers earthquake is the worst earthquake that threatens the safety of the dam, while Northridge is the most modest. Fig. 5c illustrates the frequency distribution of probability density function data as well as the best-fitted lognormal function of fragility in the \( E_d/E_f = 0.75 \) condition overlaid on the histograms. According to Fig. 5c, 0.48 represents the maximum probability function with a peak ground acceleration of 0.52g. Based on the results of the fragility curve in Fig. 6c, it can be concluded that the collapse threshold for 15% occurs at 0.4 times the acceleration of gravity (0.4g), and after that, the collapse threshold increases to 50% at 0.6g. The fragility curve continues to increase up to 0.79g acceleration, at which point 75% of the system will collapse. As a result of the peak ground acceleration of g, a collapse probability of 90% has been reported. (Fig. 6c).

For \( E_d/E_f = 1 \) and 10 different earthquakes, Table 3 shows the peak ground acceleration that results in the dam collapsing. The Landers earthquake presents the greatest threat to the safety of the dam for this dam-to-foundation stiffness, and Northridge presents the modest threat. An analysis of the best-fit lognormal function on the histogram data in Fig. 5d indicates that the maximum probability density function of 0.5 occurs at a peak ground acceleration of 0.57g. According to Fig. 6d, the fragility curve of the dam at the stiffness ratio of 1 lies between 0.22g and 0.97g of peak ground acceleration. It is estimated that 15% of the dam will collapse at PGA of 0.45g, while 50% and 75% will collapse at PGAs of 0.63g and 0.78g, respectively. Furthermore, the results indicate that 90 percent of the collapse of the dam is caused by a peak ground acceleration of 0.95g (Fig. 6d).

PGA values of dam collapse in 10 different earthquakes are reported in Table 3 for stiffness ratios equal to 1.5 (\( E_d/E_f = 1.5 \)). This dam-to-foundation stiffness makes the Landers
earthquake the worst seismic event that threatens the dam's safety, while Northridge is the least severe. For stiffness ratios of 1.5, Fig. 5e gives a distribution of probability density functions (PDF) versus peak ground accelerations (PGA) with histogram data and the best-fitted lognormal curve. In this stiffness ratio, the maximum probability function is 0.52, occurring during the peak ground acceleration of 0.55g (Fig. 5e). The fragility curve is represented by Fig. 6e in the form of a cumulative distribution function for the condition $E_d/E_f = 1.5$. There have been 15% collapses in the case of 0.43g and 50% collapses in the case of 0.6g. If the peak ground acceleration is increased to 0.74g, the probability of collapse increases to 75%. Taking an average of 0.89g as a reference, the collapse probability of 90% is calculated.

Table 3 shows the PGA values for various earthquakes in which the dam collapses in $E_d/E_f = 2$ condition. According to the results, the Landers earthquake is the most severe earthquake that threatens the safety of the dam for this dam-to-foundation stiffness, while the Northridge earthquake is the most moderate earthquake. In Fig. 5f, the PGA values are also represented by a probability density function (PDF) and a best-fitted lognormal curve. According to this figure, the maximum probability function is 0.51 when the peak ground acceleration reaches 0.53g. Based on the cumulative distribution function on the fragility curve in Fig. 6f for stiffness ratio of 2, collapses of 15% and 50% are observed at peak ground accelerations of 0.41g and 0.55g, respectively. It should also be noted that for PGA=0.67g, the collapse probability is 75%, while for PGA=0.8g, the collapse probability is 90%.

Table 3 reports the PGA values for near-field accelerograms where the dam collapses as a result of different earthquakes at a stiffness ratio of 3. In terms of this dam-to-foundation stiffness, Northridge is considered modest, while Landers is considered to be the most hazardous. Fig. 5g shows the PDF value of PGA using the histogram and a best-fitted lognormal distribution. Based on the results, the maximum probability density function is 0.58, corresponding to the peak ground acceleration of 0.47g. It is determined from the fragility curve in Fig. 6g that the peak ground accelerations of 0.38g and 0.52g are associated with collapses of 15% and 50%, respectively. It is considered that in the case of PGA=0.63g, there is a 75% probability of the dam collapsing. After this point, the fragility curve rises until the extreme of the CDF is reached at a value of 0.88g. Near-field earthquakes with a peak ground acceleration of 0.77g have a 90% likelihood of collapse under $E_d/E_f = 3$ condition.

According to Table 3, the near-field accelerogram PGA values for dam collapse under $E_d/E_f = 4$ conditions for some earthquakes are presented with PDF values in Fig. 5h. A dam-to-foundation stiffness of this magnitude makes the Landers earthquake the greatest threat to the dam's structural integrity, whereas the Northridge earthquake poses the least threat. A maximum PDF of 0.54 in Fig. 5h corresponds to a PGA value of 0.45g. Fig. 6h
represents the fragility curve using the CDF values of the corresponding PGAs. Based on the results, there is a collapse probability of 15% for a peak ground acceleration of 0.37g, and the probability increases to 50% when the ground acceleration is increased to 0.49g. This fragility curve has a 75% collapse probability when the ground velocity reaches 0.59g, while a 90% collapse probability is attained when the ground velocity reaches 0.7g.

Fig. 6. The fragility curves of Latyan dam in the stiffness ratio \(E_d/E_f\) of a) 0.25 b) 0.5 c) 0.75 d) 1 e) 1.5 f) 2 g) 3 h) 4

4. Discussion

Fig 7 illustrates the different fragility curves of the Latyan dam for seismic forces in various stiffness ratios so that the effect of foundation stiffness may be evaluated and compared. Observations indicate that the most safe seismic performance can be achieved at stiffness
ratios of 0.75, 1, and 1.5. The unit stiffness ratio has, however, generally been found to provide the best seismic performance \((E_d/E_f = 1)\). As long as the peak acceleration of the ground is less than 0.74g, a stiffness ratio of 1 will be safer than that of 0.75; however, when the peak ground acceleration increases, the stiffness ratio of 0.75 will improve the seismic response of the concrete dam. In addition, the stiffness ratio of 1.5 is safer for dams performing at peak ground accelerations less than 0.56g compared to 0.75; however, when peak ground accelerations increase, the stiffness ratio of 0.75 improves the seismic response of concrete dams. As a result of the stiffness ratio of 1, the dam's performance is more stable than that of 1.5 when it is subjected to all-ground acceleration. If the foundation stiffness was increased by a factor of three or four compared to the dam stiffness \((E_d/E_f = 3\) and 4), the dam's seismic response would be more critical. As a result, poor performance resulted from reducing the foundation stiffness by a factor of 0.25 or 0.5 compared to the dam stiffness \((E_d/E_f = 0.25\) and 0.5) so that in the case of the 0.8g stiffness ratio, the probability of damage is approximately 95%, whereas at the 0.75 and 1 stiffness ratios, the probability of damage is approximately 75%. Generally, Dams are considered unsafe if they are overly stiff or soft, and improving the dam's performance by building it in zones with a stiffness ratio of 0.75 to 1.5 has been shown to enhance its safety significantly. Furthermore, it is important to note that the Landers earthquake would generally be considered one of the worst-case earthquake scenarios for a dam in the future, whereas the Northridge earthquake would generally be considered one of the moderate earthquake scenarios; however, the different dam-to-foundation stiffness ratios may result in different stability conditions.

**Fig. 7.** A comparative presentation of the fragility curves of Latyan dam in the various stiffness ratio \((E_d/E_f)\) from 0.25 to 4
5. CONCLUDING REMARKS
In this study, a finite element model of a dam-reservoir-bed interaction was examined on the Latyan dam to evaluate the influence of dam and foundation stiffness on the seismic collapse of the dam based on ten different earthquake data sets. The results were presented as the fragility curves for the various stiffness ratios \(E_d/E_f\) within the CDF-PGA plane. It has been found that bed stiffness significantly affects the fragility curve of the dam-reservoir-bed interaction system. It is concluded that the Landers earthquake is likely to be the most dangerous earthquake for possible future earthquakes, while Northridge may have a modest magnitude; however, the different dam-to-foundation stiffness ratios could change the stability scenario. The best results were obtained when the stiffness ratios were close to the unit value, which resulted in a safer seismic system. In spite of this, it is concluded that the bed's overly hard or soft nature reduced the safety of the dam. Therefore, in order to perform preliminary studies of dam construction projects, it is recommended that beds be selected with a stiffness ratio of one unit.

LIST OF NOTATIONS
\n\begin{align*}
\alpha_g & \quad \text{Ground acceleration vector during an earthquake} \\
C & \quad \text{Damping matrix of the dam-foundation system} \\
C_{11} & \quad \text{The bulk modulus of the fluid} \\
C_{22} & \quad \text{Constant coefficient related to } w \\
C_c & \quad \text{Matrix of damping in the coupled system} \\
E & \quad \text{Elasticity modulus} \\
E_d & \quad \text{Stiffness of dam} \\
E_f & \quad \text{Stiffness of foundation} \\
F & \quad \text{Interaction forces vector acting at the dam-foundation interface} \\
f_{R,Q} & \quad \text{Joint probability density function} \\
K & \quad \text{Stiffness matrix of the dam-foundation system} \\
K_c & \quad \text{Matrix of stiffness in the coupled system} \\
K_f^* & \quad \text{Stiffness matrix} \\
M & \quad \text{Mass matrix of the dam-foundation system \ earthquake magnitude} \\
M_c & \quad \text{Matrix of mass in the coupled system} \\
M_f & \quad \text{System mass matrix} \\
P & \quad \text{Fluid pressure} \\
P_f & \quad \text{Probability of structural damage} \\
P_w & \quad \text{Rotational stress} \\
Q_i & \quad \text{Generalized force} \\
q_i & \quad \text{Generalized coordinate}
\end{align*}
\( Q \) Random variables of strength and structural load  
\( R \) Random variables of strength and structural load  
\( R_c \) Ground acceleration vectors of the time-varying nodal forces  
\( R_f \) Time-varying nodal force vector  
\( \text{RJB} \) Joyner-Boore distance  
\( T \) The kinetic energy of the system  
\( U_c \) Displacement vectors of the coupled system  
\( \dot{U}_c \) Velocity vectors of the coupled system  
\( \ddot{U}_c \) Acceleration vectors of the coupled system  
\( U_f \) Nodal displacement matrices of the fluid system  
\( \dot{U}_f \) Nodal acceleration matrices of the fluid system  
\( u \) Displacement vector  
\( \dot{u} \) Velocity vector  
\( \ddot{u} \) Acceleration vector  
\( V_s \) Shear wave velocity  
\( w \) Rotation of the normal vector of the element plane  
\( \beta \) Reliability index  
\( \varepsilon_v \) Volume strain of the fluid  
\( \mu \) Mean ratio  
\( \nu \) Poisson’s ratio  
\( \zeta \) Material damping  
\( \Pi_e \) Total strain energy  
\( \Pi_s \) Increase in the potential energy of system due to the free surface motion  
\( \Pi_t \) Total potential energy  
\( \rho \) Volumetric mass  
\( \sigma \) Standard deviation  
\( \sigma_t \) Tensile stress  
\( \phi \) The cumulative distribution function of the standard normal probability

**LIST OF ABBREVIATION**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CDF</td>
<td>Cumulative density function</td>
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<tr>
<td>CDP</td>
<td>Concrete damage plasticity</td>
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<tr>
<td>CID</td>
<td>Cumulative inelastic duration</td>
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<tr>
<td>DCR</td>
<td>Demand capacity ratio</td>
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<tr>
<td>PDF</td>
<td>Probability density function</td>
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<tr>
<td>PGA</td>
<td>Peak ground acceleration</td>
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PGV  Peak ground velocity
RSN  Regional seismograph networks

REFERENCES


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