Incremental Dynamic Analysis of Koyna Dam under Repeated Ground Motions

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Abstract. This paper discovers the incremental dynamic analysis (IDA) of concrete gravity dam under single and repeated earthquake loadings to identify the limit state of the dam. Seven ground motions with horizontal and vertical direction as seismic input considered in the nonlinear dynamic analysis based on the real repeated earthquake in the worldwide. All the ground motions convert to respond spectrum and scaled according to the developed elastic respond spectrum in order to match the characteristic of the ground motion to the soil type. The scaled was depends on the fundamental period, $T_1$ of the dam. The Koyna dam has been selected as a case study for the purpose of the analysis by assuming that no sliding and rigid foundation, has been estimated. IDA curves for Koyna dam developed for single and repeated ground motions and the performance level of the dam identifies. The IDA curve of repeated ground motion shown stiffer rather than single ground motion. The ultimate state displacement for a single event is 45.59mm and decreased to 39.33mm under repeated events which are decreased about 14%. This showed that the performance level of the dam based on seismic loadings depend on ground motion pattern.

1. Introduction
Every dam location has its unique geological characteristics. The high cost is required for carrying out a geological survey to understand the geological characteristics of an area before deciding on a suitable location to construct a dam. A dam is usually built in a valley area that can be at active fault areas, such as the Himalayas, Southwest China, Iran, Turkey, and Chile [1]. Dams are damaged by earthquakes exceeding 6 M (Richter magnitude) occurred in Hsinfengking, China in 1962; Kariba, Zambia–Zimbabwe Border in 1963; Kremasta, Greece in 1966; and Koyna, India in 1967 [2]. In 1999, serious damage to the Shih-Kang dam caused the dam body to crack and separation of dam body from foundation bedrock to occur due to Chi-chi earthquake with 7.6 M [3] as shown in Figure 1. Severe damage to the structure of the dam would cause flooding to occur in the D/S direction and electricity and water supply will be interrupted for the area involved. Flooding is also able to cause the loss of life and a lot of the other structures and infrastructure damages. The person involved in the design, construction and operation of a dam should be sensitive to earthquake issues.
Seismic sequences characterised by the repetition of medium-strong earthquake ground motions occurring in a short time after other shocks have been observed in many parts of the world. The characteristic of repeated earthquake studied by Allen (1968), Sieh (1978) and Schwartz and Coppersmith, (1984), identifies the repeated earthquake events based on fault, location and magnitudes for the San Andreas fault and Wasatch faults. The structural damage has occurred in the middle of Italy caused by repeated earthquake events in 1997 investigated by Decanini et al. (2000), the primary characteristic and the impact of seismic sequences. Elnashai et al. (1998) expected the repeated earthquake event able considerably higher in ductility demand instead of a single earthquake event. This has been ratified by Faisal (2012), identify the ductility demand increased by 1.4 and 1.3 times when considering double and triple earthquake events. The dispersion of response demand of SDOF structure increased at the strong aftershock ground motions with respect to mainshock ground motions alone [10].

![Image](image_url)

**Figure 1.** Shih-Kang dam damage due to earthquake

From the repeated earthquakes considered in the previous studies is a time gap between two events is considered as zero acceleration, which means to stop the motion of any structure due to the damping before the start of the next event. The time gap 100 s has been used a few researchers [11–13] compared to 40 s introduced by Amadio et al. (2003). This is caused by non-movement on the structure before the next event. The examples of repeated earthquake shown are Figure 2 with a different time gap.

![Image](image_url)

**Figure 2.** Examples of repeated earthquake

The dam structure has already been damaged during the first individual seismic event, and the damage that is not yet repaired may increase the damage to the dam at the end of the seismic
sequences [15]. Seismic sequences will lead to greater accumulated damage to the structure; and therefore, the seismic design should be given significant attention [15–18].

The performance of structure under seismic loads can be approximated more details by using IDA which is a parametric analysis method. The ground motion record equals to or more than one, scale to multiple levels of intensity based on several intensities of response spectral applied to the structural model and hence producing the curves of response parameterized vs intensity level [19]. This concept has been implemented by U. S. Federal Emergency Management Agency (FEMA) guidelines and establish as the method to determine global collapse capacity [20]. IDA curve of the structure response is normally plotted as damage measure (DM) versus intensity measure (IM). The DM can be identified as peak roof drift ratio $\theta_{\text{roof}}$ or $\theta_{\text{max}}$ while the IM as peak ground acceleration (PGA), peak ground velocity (PVA) or the 5% damped the first mode spectral acceleration ($S_a(T_1, 5\%)$).

Concrete dams are one of the largest structures constructed by humanity, which their seismic response can be affected by the presence of various contingency. Since limited data is available for the actual concrete dams on the field and laboratory tests, the limit state of concrete dams in light of uncertainties calculation is based on theoretical and numerical methods [21]. Alembagheri and Ghaemian (2012) introduced a new concept to verify the limit state of the damage in concrete dams by using IDA and SPO analysis that not only consider initial loads but also the hydrodynamic loads. The methods can be applied to obtain indexes for seismic performance evaluation and damage assessment.

The effects of the repeated earthquake to the structures have been studied since 1990’s. The damage of the structure due to the first earthquake event will be accumulated after the second earthquake happened. Most of the researchers focus on the structure of buildings and bridges to define the performance of structure due to the repeated earthquake. Since limited data is available for seismic sequences, the previous study creates the artificially repeated earthquake as seismic loading was not adequate. Therefore, the repeated earthquake should be significant attention to the concrete dam as analysed the structure of buildings and bridges subject to real seismic sequences, for example, Chi-Chi earthquake in 1999 cause the serious damage to Shih-Kang dam. The seismic sequences data have been recorded within short duration with the same station, direction and fault distance.

2. Numerical modeling

Koyna dam is located on Koyna River in the west of the Indian Peninsula. The dam has experienced with the crack damage caused by Koyna earthquake in December 1967 with magnitude 6.5 [23,24]. However, the dam not in danger from a major failure and only required of repairs and permanent strengthening. The structure of the dam has an elongated geometry with constant cross section. The structure of the dam can be determined by plane strain condition because the loading position does not differ along the trend. The depth of the reservoir for Koyna dam is 91.8m and the height of the dam is 103m. The full dimension of Koyna dam as illustrated in Figure 3. The rigid foundation has been considered for this model and the material properties for this model are tabulated in Table 1. The present study uses the concrete damage plasticity (CDP) model to evaluate the nonlinear seismic performance of the concrete gravity dam [25,26]. The concrete damage plasticity model is to simulate the nonlinear constitutive behaviour of concrete by presenting scalar damage variable to describe the irreversible damage during loading process [27–30].
Figure 3. Dimension of Koyna Dam

| Table 1 Concrete properties |
|-----------------------------|
| Material parameter          | Value      |
| Modulus of elasticity (E)   | 31513 MPa  |
| Poisson’s ratio (ν)         | 0.2        |
| Density (ρ)                 | 2643 kg/m³ |
| Dilation angle (ψ)          | 36.31°     |
| Compressive initial yield stress (σ₀) | 13.0 MPa |
| Compressive ultimate stress (σᵤ)    | 24.1 MPa   |
| Tensile failure stress (σₜ₀)  | 2.9 MPa    |
| Damping for the first mode vibration | 3%        |

3. Incremental dynamic analysis (IDA)

IDA is the performance-based earthquake engineering approach for seismic performance evaluation. IDA involves applying a series of nonlinear time history analysis to a structure for numerous ground motion records by scaling every record to several levels of intensity to determine the full range of the structure’s performance from elastic to yielding, nonlinear inelastic and ultimately leading to global instability [19].

The real ground motion is scaled with the design respond spectrum according to Eurocode 8 (2004). The concrete dam is subjected to a set of ground motion which are scaled to multiple levels of intensity until the structure failed [22,32]. The IDA curve represented the maximum crest displacement to monitors the dynamic response of the structure with different concrete strength caused by degradation process. In this study, IDA carried out has covered: (i) fourteen ground motion which is seven real repeated and seven real single ground motions, and (ii) twenty types peak ground accelerations. Total numbers of 196 nonlinear time history analysis have been carried out in the IDA.

The seismic input in this study is divided into two categories which are a single ground motion; and the real repeated ground motion. The criteria for selecting the ground motion are as follows: (i) the distance from the epicenter is considered less than 15km, (ii) the events more than one in the same direction and fault distance (repeated earthquake), (iii) the magnitude is equal to or greater than 5.5, and (iv) the PGA is equal to or greater than 0.15g. Seven earthquake records based on these criteria are
downloaded from the strong-motion database of the Pacific Engineering Research Center [33] as shown in Table 2. The single ground motion is picked the highest PGA for repeated events.

Table 2 Summary parameters of the selected ground motion

| No | Seismic          | Date            | M   | PGA-H (g) | PGA-V (g) |
|----|------------------|-----------------|-----|-----------|-----------|
| 1  | Mammoth Lakes    | 25 May 1980     | 5.7 | 0.485     | 0.312     |
|    |                  | 27 May 1980     | 5.9 | 0.315     | 0.190     |
| 2  | Chalfant Valley  | 20 July 1986    | 5.8 | 0.270     | 0.201     |
|    |                  | 21 July 1986    | 6.2 | 0.447     | 0.324     |
| 3  | Northwest - China| 5 April 1997    | 5.9 | 0.274     | 0.192     |
|    |                  | 6 April 1997    | 5.9 | 0.125     | 0.081     |
| 4  | Northridge       | 17 Jan 1994     | 6.7 | 0.474     | 0.265     |
|    |                  | 17 Jan 1994     | 6.0 | 0.235     | 0.031     |
| 5  | Coalinga         | 22 July 1983    | 5.8 | 0.124     | 0.083     |
|    |                  | 25 July 1983    | 5.8 | 0.143     | 0.153     |
| 6  | Chi-chi          | 20 Sept 1999    | 7.6 | 1.009     | 0.320     |
|    |                  | 20 Sept 1999    | 6.2 | 0.139     | 0.050     |
| 7  | Loma Prieta      | 18 Oct 1989     | 6.9 | 0.179     | 0.095     |
|    |                  | 18 Oct 1989     | 6.9 | 0.484     | 0.089     |

Figure 4. Repeated earthquake with 100 seconds gap

The repeated earthquakes in this study are based on the real repeated events in worldwide with the same seismic station and the duration of the events between 2 to 3 days are as tabulated in Table 2. The gap between two consecutive ground motions is 100 seconds with zero acceleration of amplitude Figure 4. This gap has been suggested by Hatzigeorgiou and Liolios (2010) and is absolutely enough to achieve for the structure to be brought to rest after vibration due to its inherent damping. The single earthquake input for this study was chosen based on the maximum horizontal PGA of each seismic event. For example, the PGA for Mammoth Lake event on 25 May 1980 was 0.485g and 0.315g on 27 May 1980. The single event for this case was 0.485g.

The response spectrum of the 14 ground motion input data which are single and repeated events as tabulated in Table 2, has to be scaled according to the site elastic response spectrum to correspond with the characteristics of the ground motion records to the site condition. The scaling method utilised the spectrum acceleration at fundamental period of the structure, $S_e(T_1)$ as the intensity measurements of the ground motion as suggested by Shome et al. (1998). The time history record of each ground motions is converted to the acceleration response spectrum (g) by using the SeimoSignal software. Then, the acceleration response spectrum of each ground motion is scaled to the same pseudo-spectrum acceleration at the fundamental period of the structure, $T_1$ in the elastic response spectrum Figure 5.
Plotting an IDA curve required scaled up or scaled down of the ground motion intensity measure (IM) and structural state variable which is damage measure (DM) or engineering demand parameter. An IM is the intensity of a ground motion record by increasing the scalar factor and using peak ground acceleration (PGA) for this study. A DM is the state of the structural model to a specified seismic loading that can be determined from the output of the nonlinear dynamic analysis [19]. The output considered in this study is the maximum crest displacement of the dam to identify the limit states of the concrete dam. The limit state was based on the structural behaviour from the early elastic to the failure.

**4. Results and discussion**

*4.1 Validation*

The dam has been analysed using two-dimensional plane strain formulations. To validate the accuracy of the numerical model, the results available for the Koyna dam were considered [35]. The assumed material properties as tabulated in Table 1. The comparisons of the results indicate the validity of the present numerical model based on the natural period as tabulating in Table 3 which is the percentage difference is less than 3 percent.

| Mode | Present | Nayak and Maity (2013) | % of deviation |
|------|---------|------------------------|---------------|
| 1    | 18.87   | 19.27                  | 2.08          |
| 2    | 50.09   | 51.50                  | 2.74          |
| 3    | 68.17   | 67.56                  | -0.90         |
| 4    | 98.70   | 99.73                  | 1.03          |

*4.2 Comparison single and repeated ground motions*

The original model which is an unscaled ground motion for single and repeated earthquakes are shown in Figure 6. The cracking trend performs at the neck of the dam from the D/S face and the cracking appeared at the heel of the dam from the U/S face. The displacement under repeated ground motion increase about 3% to 51% compared with the single event. The highest displacement increase is Chalfant Valley event where the single event is 40.87 mm and increases to 82.62 mm for the repeated events. However, there is some ground motion event shows the displacement decreased under repeated ground motions which are Northridge and Coyote events. This happened cause of the PGA value for the second ground motion event lower than the first event. Damage accumulation on structures under repeated ground motion as mention by Zhang et al.
4.3 Incremental dynamic analysis (IDA)

A total number of 198 analysis was conducted to develop the IDA curve for Koyna dam. The cracking patterns were recorded for each analysis with different ground motions. Figure 7 and Figure 8 shows the cracking patterns for Koyna dam under single and repeated ground motions event with different intensity measure (IM).

The cracking began at the dam body from the neck of the dam on the downstream (D/S) face. Later on, a partial crack occurred at the base of the dam at the upstream (U/S) face and as a general trend. When the PGA of the motion increased, the cracking was created at the neck of the dam from the U/S face and then moved forward from the both face until cracks were joined, that can be concluded as collapse. In the meantime, the cracking at the heel area increased around 15% to 40% from the width of the dam. The first crack occurred on the neck at displacement around 20.72mm to 27mm with PGA around 0.100g to 0.175g which is considered as a yielding state. The ultimate state of the dam with 36.27mm to 47.31mm displacement and the PGA value between 0.225g to 0.275g. Meanwhile, the yielding and ultimate state under repeated ground motions, the maximum crest displacement are significantly different with a single ground motion which is the values between 20.72mm to 29.43mm and 36.27mm to 40.14mm with the same PGA value under single ground motions.

The IDA curves have been plotted in Figure 9 for a single ground motion and the repeated in Figure 10. The slope of the graphs start from 0 to 0.05g are shown the maximum crest displacement are same values for 7 ground motions. Later on, the curves start change according to the ground motion pattern. The yielding and ultimate region have been marked in the graphs Figure 9 and Figure 10 for single and repeated ground motions. It is shown that the yielding state under single ground motion is the lower displacement values rather than repeated. However, the ultimate state results under repeated ground motions outstrip a single earthquake loading. Figure 11 shows the IDA curves for Chalfant Valley to comparing the repeated and single ground motions. The maximum displacement under repeated ground motion increased about 7% for the yielding state while 14% decreased for the ultimate state. That is mean, the ultimate state of repeated ground motion reached earlier than single ground motion.

| Earthquake Events | Mammoth Lake | Chalfant Valley | Northridge | Chi-chi | Coyote |
|-------------------|--------------|----------------|------------|--------|-------|
| Single            |              |                |            |        |       |
|                   | 42.04 mm     | 40.87 mm       | 29.85 mm   | 165.71 mm | 43.64 mm |
| Repeated          |              |                |            |        |       |
|                   | 42.04 mm     | 82.62 mm       | 28.81 mm   | 172.27 | 42.13 mm |

Figure 6. Cracking patterns and maximum crest displacement results with original ground motions.
**Figure 7.** Cracking patterns and maximum crest displacement from IDA for Koyna dam under single ground motion
Mammoth Lake | Chalfant Valley | Northridge | Coalinga | Chi-chi | Coyote
---|---|---|---|---|
0.100g  
$u = 20.72$mm

| 0.125g  
$u = 23.24$mm

| 0.125g  
$u = 22.31$mm

| 0.125g  
$u = 21.99$mm

| 0.150g  
$u = 29.43$mm

| 0.150g  
$u = 26.43$mm

| 0.175g  
$u = 28.71$mm

| 0.200g  
$u = 32.78$mm

| 0.175g  
$u = 29.82$mm

| 0.225g  
$u = 28.78$mm

| 0.200g  
$u = 39.71$mm

| 0.175g  
$u = 30.99$mm

| 0.200g  
$u = 31.36$mm

| 0.225g  
$u = 36.27$mm

| 0.200g  
$u = 37.99$mm

| 0.250g  
$u = 41.99$mm

| 0.200g  
$u = 35.30$mm

| 0.225g  
$u = 33.94$mm

| 0.250g  
$u = 42.07$mm

| 0.225g  
$u = 49.44$mm

| 0.250g  
$u = 44.33$mm

| 0.225g  
$u = 39.63$mm

| 0.250g  
$u = 39.33$mm

| 0.275g  
$u = 48.80$mm

| 0.250g  
$u = 42.33$mm

| 0.275g  
$u = 47.76$mm

**Figure 8.** Cracking patterns and maximum crest displacement from IDA for Koyna dam under repeated ground motion

**Figure 9.** IDA curves for Koyna dam under single ground motion

**Figure 10.** IDA curves for Koyna dam under repeated ground motions
5. Conclusions
Incremental dynamic analysis (IDA) is the performance-based earthquake engineering approach for seismic performance evaluation. IDA involves applying a series of nonlinear time history analysis to a structure for numerous ground motion records by scaling every record to several levels of intensity until an ultimate condition is reached. It was observed that the dam started to perform at the neck area on the downstream (D/S) face. Later on, a partial crack occurred at the base of the dam at the upstream (U/S) face and as a general trend. When the PGA of the motion increased, the cracking was created at the neck of the dam from the U/S face and then moved forward from the both face until cracks were joined, that can be concluded as collapse. In the meantime, the cracking at the heel area increased around 15% to 40% from the width of the dam. The maximum displacement under repeated ground motion increased about 7% for the yielding state while 14% decreased for the ultimate state. That mean, the ultimate state of repeated ground motion reached earlier than a single ground motions event in the same PGA. The results show that the repeated ground motion should not be neglected in analysed of a concrete gravity dam. Further study will have to be investigated by comparing the IDA curves and static pushover analysis to identify the minimum values reached for yielding and ultimate state for concrete gravity dam.

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