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Geotechnical risk analyses and evaluation of design criteria of embankment dam systems

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Abstract. The integrity of the state and national system of embankment dams and levees is a crucial component in ensuring the safety of protected communities in any country. The failure of such systems due to natural or man-made hazards can have monumental repercussions, sometimes with dramatic and unanticipated consequences on human life, property and the economy of the states and the country. For highly seismic areas such as Southern California, it is critical to investigate and study the seismic response of embankment dams and levees for the afore mentioned reasons. While experimental studies of embankment dams under seismic loads is expensive, very time consuming, and limited, numerical studies usually suffer from lack of legitimate real data for verification of the developed models. However, organizations such as the California Strong Motion Instrumentation Program (CSMIP) instrument lifeline structures such as earth dams and levees with accelerometers and actively collect strong-motion data. The data obtained from CSMIP accelerometers is then processed by the Center for Engineering Strong Motion Data (CESMD) and made public for earthquake engineering applications. In this study, numerical models of existing earth embankment dams verified with site specific CESMD data are created in order to analyze their stability for a future earthquake, for post-earthquake response purposes. The seismic fragility of the modelled dams was assessed, providing insight for decision makers regarding priority areas important for matters such as maintenance, dam retrofit, or first-aid response locations for a hypothetical major earthquake. Society can benefit from increased awareness of the seismic response of the modelled structures and can be better prepared for a potential catastrophic seismic event.

1 Introduction

The integrity of the state and national system of embankment dams and levees is a crucial component in ensuring the safety of protected communities in any country. Levees are constructed along water courses to provide protection against floods while dams are constructed to form reservoirs to store water for urban, industrial or agricultural consumptions. The failure of such systems due to natural or man-made hazards can have monumental repercussions, sometimes with dramatic and unanticipated consequences on human life, property and the economy of the states and the country. The failure of dams and levees during Hurricane Katrina in 2005, which led to the catastrophic flooding of the city of New Orleans, USA, is a highly illustrative example. About 2,000 people lost their lives due to the failure of the levees that were protecting the city, and the property damage was estimated at $81 billion (2005 USD) [1]. There are several other examples that reveal the critical role of embankment dams and levees, and the impacts of their failure on people's lives and properties. There are nearly 14,000 miles of levees under U.S. Army Corps of Engineers (USACE) jurisdiction in the US; but it does not include what is believed to be more than 100,000 additional miles of levees not covered by the USACE safety program. Some are little more than mounds of earth piled up more than a century ago to protect farm fields. Others extend for miles and are made of concrete and steel, with sophisticated pump and drainage systems. They shield homes, businesses and infrastructures such as highways and power plants [2].

Figure 1a shows that 881 counties with a total population of 160 million in the United States are protected by these dams and levees. Figure 1b presents a closer look at the levees (black lines) and the areas protected by them in Southern California, specifically, the Los Angeles metropolitan area. As it is illustrated in Figure 1b, there are large areas of Orange County between the Los Angeles River and Santa Ana River, which are heavily populated and are being protected by levees. Although Southern California has a relatively lower risk of experiencing hurricanes or typhoons compared to cities such as New Orleans, Louisiana or Houston, Texas, the existence of a large number of active faults, and the high likelihood of earthquakes, makes the assurance of a healthy and reliable dam and levee system a very important matter to the State of California. In the case of an earthquake, the induced seismic forces, failure of the slopes, and the ground rupture would be the main failure mechanisms. In the case of a hurricane or flood that happens relatively quickly, seepage and overtopping

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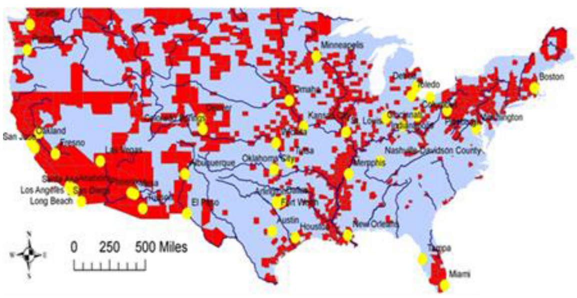
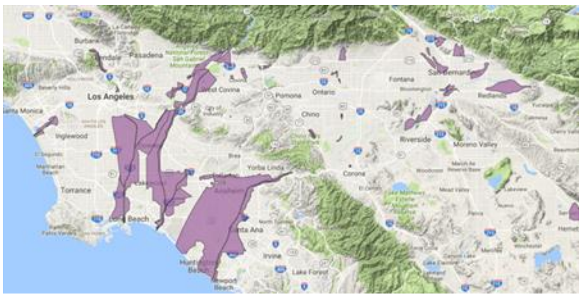
would be the most dominant and most probable failure mechanisms. While other failure mechanisms require more time to significantly damage a dam or levee, seismic loads would apply large deformation to the dams or levees in a relatively short time, and eventually lead to dam failure.

The overall stability of levees and embankment dams is a very complicated matter and depends on several multidisciplinary factors such as stability of slopes (Geotechnical Engineering), characteristics and impacts of flooding events (Water Resources Engineering), and erosion properties of the surface and covers (Construction Engineering), among others. Therefore, it is critical to investigate and study the behavior of the system of levees and embankment dams in Southern California using a multidisciplinary research team. This can help to more realistically identify the locations with most critical problems in the levee system and accordingly reevaluate the current existing seismic design criteria in regards to the embankment dam systems. Precisely modeling the structure of dams under seismic loads would help engineers to be able to predict the most probable failure sections, and take the appropriate actions to minimize the risk of failure.



(a)



(b)

Fig. 1. Areas protected by levees, (a) United States counties protected by levees and major cities, (b) Los Angeles greater metropolitan area.

One method to model the seismic response of earth dams is through shaking table tests of scaled models. One of many examples is the work performed by Yuan et al. [3]. The large size of the dams and levees would generally create a great limitation on the experimental and laboratory studies of these structures. Accurate construction of the laboratory models, lack of precise control on the boundary conditions, difficulties of performing tests with various seismic loads, and large number of required stress and strain sensors, among others are some of the main challenges of experimental investigations of embankment dams and levees [4, 5].

Numerical models, on the other hand, can overcome almost all of the mentioned limitations of the experimental studies, although a thorough verification of the results is an essential part of any numerical study [6, 7]. Alberti et al., [8] analyzed the seismic performance of the San Pietro dam in Southern Italy using a numerical method. The dam was modeled and analyzed through dynamic 2D finite difference analyses using the computer code FLAC 2D. Crosshole tests were performed on various portions of the dam to obtain small strain shear modulus (*Go*) values to model the dam. Prior to the seismic analyses, a static analysis was performed to simulate the dam construction and reproduce the total and effective state of stress at the end of the dam construction. The input motions were obtained from several accelerograms from a worldwide database including a record from the 1994 Northridge earthquake in California. Permanent deformations smaller than 50 cm (20 in) were calculated, based on the input parameters.

Rampello et al., [9], performed a set of finite element analyses to evaluate the behavior of the Marana Capacciotti earth dam in Southern Italy, under seismic load. A constitutive model capable to reproduce soil non-linearity, and calibrated against laboratory measurements of the stiffness of small strains, was used for their investigations. The models were developed in Plaxis software and both artificial and real accelerograms were considered for seismic input values. With respect to the real accelerogram data, the finite element analysis only considered data from a single accelerogram from the 1976 Friuli earthquake in northeast Italy. Prior to seismic analyses, a static model of the construction of the dam was also simulated to produce initial state of stress conditions. The static model was checked with observed settlements during and after construction from extensometers installed on the dam. Material property inputs were obtained from results of recent in situ investigation. Ultimately, the seismic analyses returned acceptable results specifically due to computed settlements at the crest being considerably smaller than the service freeboard.

Other researchers have performed seismic analyses of earth dams using numerical methods in recent years to investigate various aspects of embankment design [10-14].

While the studies mentioned above provide important information regarding seismic numerical analysis procedures for earth dams, they were mainly limited to historical seismic input values that have occurred at other sites. However, due to the complexity of the interactions of various sections of embankment dams, it would be very beneficial to analyze a dam using seismic parameters previously experienced by the specific dam in order to verify that the model responds similarly to the actual occurrence.

Zeghal and Abdel-Ghaffar [15], performed numerical analyses to investigate the behavior of the Long Valley earth dam in California, using data from 22 accelerographs instrumented on the dam, primarily to address existing methods of seismic modeling of earth dams. The authors noted that it was a complex task to choose a model for a real structure, especially under seismic conditions. Using the accelerograph data, the dam was determined to behave nonlinearly and having seismic wave propagation at its boundaries. The study also found that constitutive hysteretic models are insufficient to account for dam dissipation mechanisms. The study highlighted the benefit of having strong-motion data to produce information not available by other means.

More recently, Castelli et al. [16] modeled the Lentini earth dam in southeast Sicily, Italy with strong-motion data from a nearby accelerometer recorded during the 1990 Santa Lucia earthquake, which had caused notable damage to the dam. Using Plaxis, a 1D analysis was preformed resulting in the maximum horizontal acceleration versus depth.

Strong-motion earthquake data is constantly being collected for various structures in the State of California, USA. The primary reason for collecting strong-motion earthquake data is that society could greatly benefit from an increased understanding of how certain structures would respond to specific strong-motion values or seismic events [17]. This is especially true for lifeline structures in Southern California. Figure 2 shows the locations of the dams in southern California that are currently being monitored by the Center for Engineering Strong Motion Data (CESMD) and its partners, and the behavior of these dams have been recorded during the past earthquakes in the region. In lack of accurate laboratory work, the available data can be a great source to verify and validate developing numerical models.

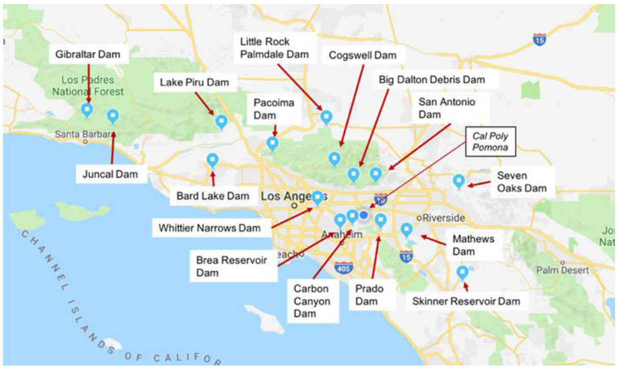


Fig. 2. Dams in Los Angeles greater metropolitan area that are being monitored by the Center for Engineering Strong Motion Data (CESMD) and its partners.

The objective of this investigation is to develop sets of numerical models that simulate different failure mechanisms of these dams under seismic loads. The results can reveal the areas of the dams and levees with higher risks in respect to overall stability, which would eventually lead to the measurement of potential impacts on properties and lives in affected areas. These could lead to the development of action plans for remediation of the system of the dams and reduce the risk of failure in the case of an earthquake or other natural and man-made catastrophes [18].

2 Problem definition

One of the main goals of this investigation is to revisit and improve the seismic design criteria of embankment dams and levees. This goal can be achieved by developing precise models of embankments, using site specific soil characteristics, and considering the overall behavior of dams under previous seismic loads.

2.1 Input motions

Site specific accelerometer data is used for this study. There are currently a few organizations such as the California Geologic Survey (CGS), Department of Conservation that use a large number of instruments to continuously record the responses of select structures since 1972. More than 125 structures instrumented with accelerometers by the California Strong Motion Instrumentation Program (CSMIP) are lifeline structures [19]. The data obtained from CSMIP accelerometers is then made public by the Center for Engineering Strong Motion Data (CESMD). The CESMD is a cooperative center established by the United States Geological Survey (USGS) and the CGS to integrate earthquake strong-motion data from the CSMIP. The CESMD provides raw and processed strong-motion data for earthquake engineering applications [20]. In order to analyse an existing structure for post-earthquake response, significant earthquakes that have occurred in Southern California are applied to the model, such as the 1994 Northridge earthquake (6.7 Mw). The CESMD provides records from numerous accelerometers with data from this earthquake and many others. Figure 3 displays a typical output of processed accelerometer data displaying the acceleration, velocity, and displacement during the 1994 Northridge earthquake from an accelerometer located on the Pacoima Dam in California.

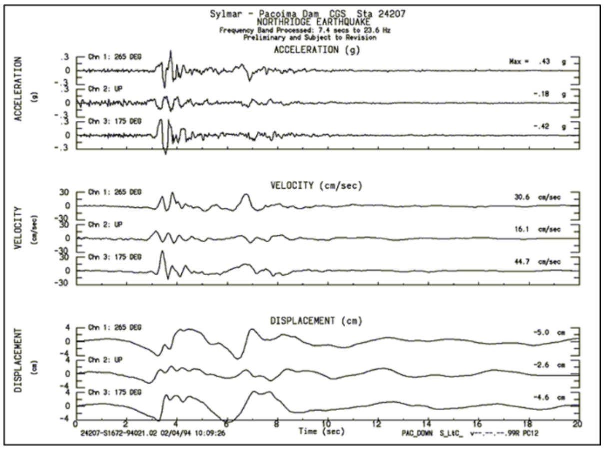


Fig. 3. Sample CESMD processed accelerometer data output.

2.2 Site and dam characteristics

To investigate the behavior of embankment dams under seismic loads, a few existing dams in Southern California were analyzed. For the purposes of this study, the selected dams were limited to homogeneous earth embankments, currently well instrumented with CSMIP accelerometers, and with existing subsurface investigation for model parameters. Figure 4 displays a typical cross section and plan view of an appropriate dam obtained from the CESMD.

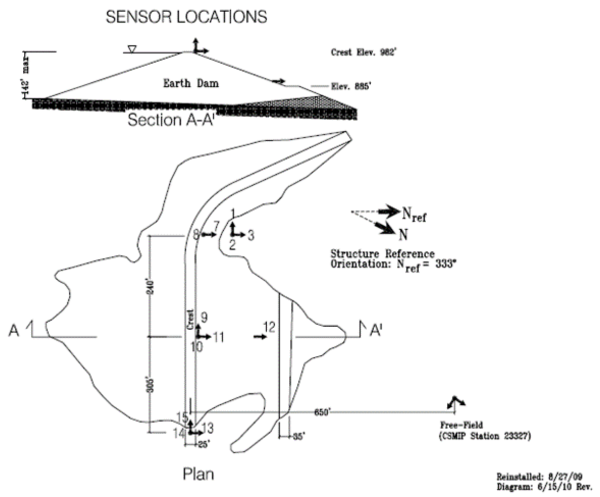


Fig. 4. Typical cross section and plan view of earth dam instrumented with accelerometers [20].

The typical dam presented in Figure 4 is instrumented with 12 accelerometers throughout the structure, as shown with the numbered indicators. The dam geometric features including total volume, water storage, crest length and width, height of the dam, freeboard, and various slopes were all obtained to create accurate models.

3 Finite element modelling

The numerical models are developed using the finite element modeling software RS2 by Rocscience [21]. The selected dams were modeled geometrically based on the actual conditions of the respective dams. Material properties were then introduced based on the performed subsurface investigations, and obtained values from field and laboratory experiments. The dams were modeled using an appropriate constitutive model. A strain-hardening model with non-linear stiffness was found to be the most appropriate constitutive model for these investigations [9, 11-13, 16], and was used in this study. Subsequently, the appropriate boundary conditions and a uniform mesh were applied to the models. Figure 5 illustrates the cross section of a typical modeled dam with mesh and boundary conditions. Prior to running any analysis, the strong-motion data obtained from the CESMD must be properly applied. In RS2, similar to other finite element models, the seismic motions are applied at the base of the model. However, the strong-motion values obtained from the CESMD are the recorded motions experienced at the location of the accelerometer. To properly evaluate the validity of the models, the strong-motion data must be deconvoluted such that the motions inputs at the base of the embankment dam, results in the motion recorded by the accelerometer at the actual location of the accelerometer. Afterwards, the strong-motion data was filtered so that the high frequency components, which do not provide significance would be eliminated from the analyses. This is done to reduce computing time. Finally, appropriate Rayleigh damping coefficients, α_M and β_K, were computed for the model.

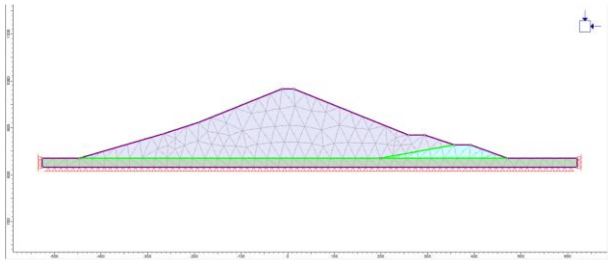


Fig. 5. Typical RS2 model input.

The analysis generally consisted of two major stages. First, the model was analyzed under static conditions (gravity) to achieve an existing (after construction) state of stress. The next stage was the dynamic stage where displacements were calculated based on the input parameters.

3.1 Model verification

Prior to running an analysis on any probable, significant, earthquake, the developed model must be verified to have confidence in the results. The benefit of picking a dam well instrumented with accelerometers is the possibility of using the recorded data from smaller earthquakes in the past. The developed models in this research were validated with CESMD data recorded by select accelerometers on the dam. The actual displacements of the dam at those selected locations were known from the processed data. The motions input for verification were the recent, previously occurred earthquakes of less magnitude, and the majority of the recorded displacement values were less than 1 cm (0.4 in). The water level of the dams on the days the input motion was experienced was also obtained and modelled accordingly in an effort to create the most representative models possible.

4 Results and discussions

Two different embankment dams with various soil properties were investigated in this paper using a developed finite element model. The numerical models were verified using site specific recorded seismic responses. The behaviors of these dams were then studied under predicted future seismic events. Figure 6 shows a typical deformation response of one of the modeled dams. The weaker sections of the dams were identified and checked against the current seismic design criteria. The developed model can also be used to analyze the responses of other earth embankment dams with similar soil properties in the case of a major earthquake event, and assess the possibility of future failure in existing conditions. Displacements throughout the dam are measured and assessed. The crest of the dams are specifically an area of interest in assessing the stability of dams as large deflections of the crest would greatly affect the service freeboard.

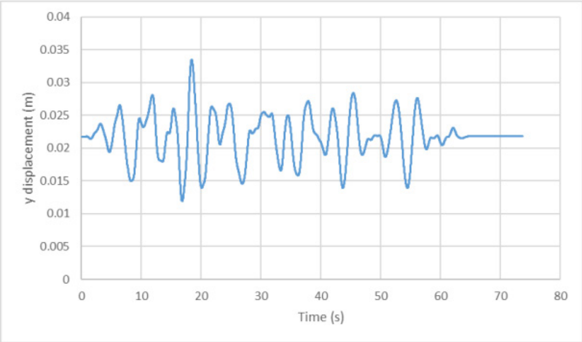


Fig. 6. Typical embankment deformation under seismic load.

Seismic fragility analysis, with fragility curves as the outcome, is an efficient approach for seismic risk analysis of engineering structures. However, as far as embankment dams in seismically active regions are concerned, there still lacks a well-established method. As a result of this study, fragility curves for the subject dams were also generated. Figure 7 presents a typical fragility curve result. The seismic vulnerability for the dams under the proposed study were determined by combining the probabilities of various levels of the seismic hazard at the dam location, with the damage probabilities to the dam corresponding to the seismic hazard levels at the site.

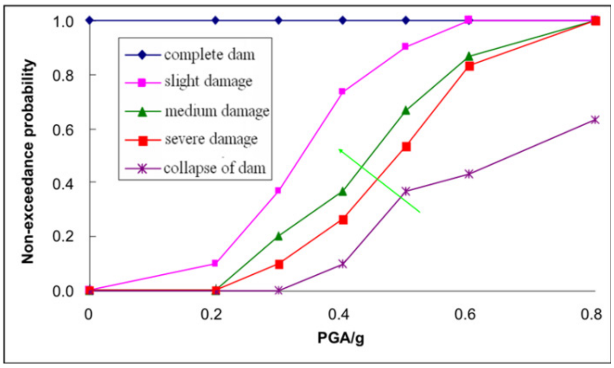


Fig. 7. Typical embankment deformation under seismic load.

Seismic hazard is represented by the peak ground acceleration (PGA) using a number of near field earthquake records in the CSMIP database. The records include different PGA levels and frequency contents that represents a creditable earthquake in active seismic sites. The analyses were carried out using the calibrated models described in the section above. The fragility curves will assist a decision maker for section priorities for dam retrofit and maintenance, and it will be used as a tool for first aid respondents to mobilize their resources more effectively at sites susceptible to the risk of higher damage. The ultimate goal is to expand this study in future research for a series of earth dams and levees in a region such as the Los Angeles Basin to identify the key structures that are in emanate risk.

5 Conclusions

In this paper, a set of numerical models were developed that simulate different failure mechanisms of embankment dams and levees under seismic loads in Southern California, USA. The results revealed the areas of the dams and levees with higher risks in respect to overall stability, which would eventually lead to the measurement of potential impacts on properties and lives in affected areas. These could lead to the development of action plans for remediation of the system of the dams and reduce the risk of failure in the case of an earthquake or other natural and man-made catastrophes. The following specific conclusions can be drawn from the study:

1. The finite element modeling method was performed to precisely simulate the existing, at risk dams in Los Angeles metropolitan area, using the available recorded data of the response of the same dams during previously occurred seismic activities. The results showed a good consistency with the previous earthquakes.

2. The data produced over the course of this research validated the behavior predicted by the numerical models. Although the deformations and stresses were recorded during previous earthquakes in the region, the developed model in this research can be used to predict the dam's responses in the case of future earthquakes.

3. The analyses showed that the maximum settlement (vertical deformation) would happen under the crest of the embankment. This can be due to the fact the crest is the highest elevation on the dam, and the underlying soil would carry the largest stresses in the structure.

4. Maximum lateral (horizontal) deformation would occur about mid-height of the embankment on the slope face and away from the center on either side. As the embankment settles, it extends outward laterally.

5. This study serves as an example for other earth embankment dams to be numerically modelled using strong-motion data to assess the need for post-earthquake response.

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