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RESEARCH ARTICLE

Impact of the pseudo-seismic coefficient on the finite element (FE) analysis of clay-core rockfill dam

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Abstract

Standards and approaches play a crucial role in assessing any engineering issue. This study highlights the differences between the maximum permitted seismic coefficients in various standards and approaches and examines how these differences affect the performance of clay-core rockfill dams. Specifically, the paper compares the behavior of a Clay Core Rockfill (CCR) dam under nine different pseudo-seismic coefficient standards. The dam is evaluated under two material conditions: elastic and plastic. For the analysis, the Düzçam CCR Dam, located in Karabük, Turkey, is chosen as a case study. The Düzçam Dam, with a height of 54 meters and an irrigation area capacity of 5,615 decares annually, is modeled for evaluation. The most critical section of the dam is selected for the two-dimensional model, which is constructed using the finite element method. The Düzçam Dam's two-dimensional finite element model is created using Phase2 software, and the material and soil mechanical properties are derived from experimental data. Numerical analyses are performed in four stages for each of the nine different standards: gravity loading, dam body construction, water application, and finally, the application of the pseudo-seismic coefficient to the dam body and rock foundation model. In cases where the pseudo seismic coefficient is 0.15 and 0.5, the displacement increases by approximately 61.5%, while the principal tensile and compressive stress increases by approximately 30% and 33%, respectively. The impact of selecting the maximum pseudo-seismic coefficient on the results is demonstrated.

1. Introduction

Water has been an essential resource for humanity throughout history. Dams are constructed for various purposes, including energy generation, agricultural irrigation, and providing drinking water to major urban areas. The significance of dams is particularly pronounced in terms of energy production, as they play a critical role in meeting a country's energy needs. However, the construction of dams involves substantial financial investments, making them a major factor in a nation's economic landscape. As a result, dams hold both strategic and economic importance. Selecting the most suitable type of dam to construct is a crucial decision. This process requires a comprehensive evaluation of several factors, including the seismic conditions of the region, its climate, and, most importantly, its geomorphological characteristics. Additionally, the potential long-term consequences of dam construction must be carefully considered. These include possible climate-related impacts on agricultural output and, most critically, the risks posed by earthquakes or other natural disasters that could lead to structural damage.

The selection of the appropriate dam type is influenced by several critical factors. Equally important as choosing the right type of dam is determining the optimal location for its construction. The key factors that impact this decision include the geomorphological characteristics of the area, the properties of the underlying soil and rock, the proximity to tectonic faults, the cost of construction, and the dam's production capacity. For example, the construction of an arch dam requires a narrow valley with strong and stable soil or rock conditions. In general, areas with firm soil and suitable valley structures are preferred for dam construction; however, fill dams can accommodate a broader range of soil types. Fill dams are further categorized into various types, such as clay core rockfill dams, earth fill dams, and front face concrete or asphalt-rock fill dams. The front face concrete-rock fill dam is often considered a viable alternative to clay core rockfill dams, especially in situations where suitable clay material is not readily available [1, 2].

The seismic stability of soils is typically analyzed using the pseudo-static approach, a method that originated in the 1920s [3]. In this approach, the potential destructive effects of seismic activity are represented by fixed horizontal and/or vertical accelerations. The structural behavior of dams can be estimated using pseudo-seismic coefficients [4]. Several factors influence the determination of the appropriate pseudo-seismic coefficient. For instance, the maximum potential earthquake acceleration and the distance to the site under analysis are directly related to the value of the horizontal seismic coefficient (kh). One of the most challenging aspects of pseudo-static stability analysis is selecting the correct pseudo-static coefficient. In practice, the coefficients used are typically much lower than the maximum acceleration (amax), as real slopes are not rigid, and peak accelerations have only a brief duration of effect. It is recommended to use a horizontal seismic coefficient (kh) of 0.1 for earthquakes of significant magnitude (magnitude IX on the Rossi-Forel scale), 0.2 for "severe, destructive" earthquakes (magnitude X on the Rossi-Forel scale), and 0.5 for earthquakes of "disaster level" intensity [5]. Slip beam models are utilized to analyze the inertia forces acting on a potentially unstable slope in an earth dam [6, 7]. These models demonstrate that the magnitude of the inertia force is influenced by the dam's response and the mean seismic coefficient corresponding to a deep slip surface. A list of pseudo-seismic design criteria was compiled for 14 dams across 10 countries located in earthquake-prone regions [8]. In 12 of these dams, the pseudo-seismic coefficients ranged between 0.10 and 0.12, with the minimum safety coefficient falling between 1.0 and 1.5. It has been suggested that the appropriate pseudo-seismic coefficient for dams, accounting for the magnification or reduction to which the dam is subjected, should range between one-third and one-half of the maximum amplitude [9]. The Newark slip block analysis was applied to over 350 accelerograms, revealing that the pseudo-static safety coefficient exceeded 1.0. Furthermore, it was found that "large-scale" deformations did not occur in the soil dams when the value of kh was set to 0.5 times the peak ground acceleration (PGA) divided by gravitational acceleration (g) [10]. As noted in the previous explanations, there are no definitive rules for selecting pseudo-static coefficients in design. The values of these coefficients are determined based on regulations and relevant studies. The optimal shape design of dams was investigated, with the study demonstrating that optimization was achieved through a combination of Simultaneous Perturbation Stochastic Approximation (SPSA) and Genetic Algorithm (GA) methods [11]. The effect of deconvolved stochastic seismic excitation on the nonlinear response of dams was investigated [12]. In this study, the mean absolute maximum displacement and stress values derived from three different earthquake input models were compared. The results indicate that the choice of input model leads to significant variations in the predicted structural responses of such structures. The nonlinear response of earth-fill dams was studied, and it was observed that variations in local soil conditions have a significant impact on the nonlinear behavior of these dams [13]. The dynamic analysis of concrete gravity dams was studied, and a modified, more efficient procedure was proposed that significantly simplifies the analysis process, resulting in substantial computational time savings [14]. It was found that the original efficient method, introduced in a previous study, can be considered a special case of the more general procedure presented in this research. One of the most significant risks that threaten earth dams, potentially leading to internal failure over an extended period, is the hydraulic fracturing factor [15]. This risk arises because the dam material undergoes settlement over time, and such settlements must be carefully evaluated to ensure the dam's safety. The stress and strain numerical analysis of a clay core rock-fill dam, located at a specific reservoir in Yunnan province, was conducted [16]. The analysis indicates that the current design of the dam is reasonable, as no abnormal stresses or deformations were observed in the structure. Additionally, a three-dimensional model of the topography and river valley at the dam site was developed to obtain more realistic results [17]. Seismic analysis, like for other dam types, should be conducted for clay-core rock-fill dams as well. Horizontal displacements of the dam body, particularly when the reservoir is full, must be carefully calculated. The geometry and material properties of dams are crucial not only for their static stability under hydrostatic pressure but also for their dynamic behavior, especially under conditions where the reservoir is full. Dams must be capable of securely retaining the volume of water within the reservoir. Any failures in the dam structure could pose a significant risk, potentially leading to severe loss of life and property in the surrounding area. Researchers focused on comparing the stochastic responses of asphaltic concrete core dams and asphaltic lining dams with clay core dams. The results indicate that asphaltic lining dams and asphaltic concrete core dams can potentially serve as viable alternatives to traditional clay core dams [18]. The focus of the study was on estimating seismic coefficients for the performance-based design of earth dams and tall embankments [19]. It was emphasized that the estimation of the horizontal seismic coefficient (kh) is based on the allowable permanent down-slope deviatoric displacement, along with a conservative approach to sliding block analysis. The seismic stability of slopes was investigated using the kinematical element method and the pseudo-static approach to study the effect of blasting on the stability of open-pit slopes [20]. The seismic response of earth dams was studied, with a particular focus on the estimation of seismic coefficients [21]. The findings revealed that the seismic coefficients decreased as the sliding mass became deeper and bulkier, increased when the mass was located upstream rather than downstream, and were significantly influenced by the characteristics of the seismic excitation and the stiffness of the foundation soil. The seismic stability of earth-rock dams was studied using finite element limit analysis [22]. In this approach, pore water pressures were modeled as external forces during the limit analysis to assess the seismic stability of earth-rock dams during the reservoir filling stage. The results show that the rigorous lower and upper bounds are closely aligned, even for rockfill materials with large internal friction angles. Additionally, failure surfaces can be effectively predicted by examining the contour of the yield function and the displacement field obtained through the limit analysis method. A study was conducted on concrete gravity dams, focusing on the optimization and safety evaluation of the largest sections of the dams using Indian standards [23]. The parametric analysis confirmed that the base width of the dam is proportional to its height and inversely proportional to both the internal friction angle and cohesion. A study was conducted on pseudo-dynamic testing of a concrete gravity dam. The investigation revealed that, despite significant cracking at the base of the monolith, no substantial sliding or stability issues were observed that could jeopardize the overall stability of the dam [24]. Researchers focused on the experimental seismic damage monitoring of dams, presenting a damage index matrix to assess the damage status of the dam across various paths. The findings demonstrated that the experimental results confirmed both the timeliness and effectiveness of the proposed method [25]. The dynamic response of dam-reservoir systems was investigated, with a practical alternative proposed through the Pseudo-Dynamic method. This method incorporates a simplified spectral response based on the fundamental mode of the system [26]. Researchers focused on the analysis of slopes using a modified pseudo-dynamic method [27]. The seismic stability of a homogeneous soil slope was evaluated by adopting the limit equilibrium approach, enhanced with the modified pseudo-dynamic method. A numerical analysis was conducted on the seismic stability of a high centerline tailings dam [28]. The results of the analysis indicated that the dam remains stable under weak ground motions but becomes unstable under stronger seismic inputs. The seismic stability of tailings dams was assessed using strain-dependent dynamic properties to evaluate their stability under seismic conditions [29]. The results from the proposed method were closely compared with those from the existing pseudo-static method of analysis. It was found that tailings dams are particularly vulnerable to damage from low-frequency input motions. A three-dimensional seismic displacement analysis of rock slopes was conducted using the pseudo-static method in conjunction with the Hoek-Brown Failure Criterion [17]. The results of the study were presented for a series of actual seismic waves and compared with outcomes calculated using empirical formulas. Pseudo-seismic and static stability analysis of Torul Dam was investigated [30]. In the study, the effects of different seismic coefficients and reservoir water levels were investigated. Dynamic analysis of Almagrera Tailings Dam under dry closure conditions was studied in two dimensions with finite element modeling [31]. The effect of galleries on the structural behavior of dams, along with the impact of viscous boundary conditions, the Westergard method, and the finite element analysis of three-dimensional dams, was investigated concerning seismic events. These factors were analyzed using the finite element method to assess their influence on the dam's response to earthquakes [32–35].

Clay core-rock fill dams are modeled and designed using appropriate software such as ANSYS, ABAQUS, PHASE, PLAXIS, and FLAC, employing finite element and discrete element methods to accurately determine the stress and deformation characteristics of the dams. Ensuring dam safety under all conditions is a primary concern. The main objective of this study is to assess the effect of the seismic coefficient on numerical results, such as displacements and stresses. To achieve this, the elastic and plastic pseudo-dynamic behavior of the Düzçam Dam was investigated. Numerical analysis was performed using the Phase2 (2007) program, based on the finite element analysis method in two dimensions. A detailed investigation is provided in the following sections.

The pseudo-seismic analysis method is widely used for the dynamic evaluation of large structures such as dams. As a result of advancements in computer capabilities, reduced processing times, and the development of software, there is a clear need to enhance this method to achieve more realistic results. To ensure consistency, the seismic coefficient values selected for seismic analysis must be carefully scrutinized. There is a significant discrepancy in the maximum allowed values of the pseudo-seismic coefficient between various standards and approaches, indicating that more detailed studies are necessary. Determining an appropriate pseudo-seismic coefficient is critical for the seismic analysis of dams. Therefore, the primary aim of this study is to highlight the importance of the selected pseudo-seismic coefficient on the stresses and displacements derived from the numerical analysis results of dams. Furthermore, the study suggests that the optimum pseudo-seismic coefficient should be chosen based on the stress and displacement results obtained. Given that the pseudo-seismic coefficient values permitted by current standards and approaches vary significantly, this inconsistency will directly influence the stress and displacement values, leading to inconsistent results in safety assessments. In this context, nine different regulations and approaches for the maximum seismic coefficient value are evaluated in this study. The Düzçam CCR Dam, located close to the North Anatolian fault line (as shown in Fig. 1), is modeled using the finite element method to examine the effects of the pseudo-seismic coefficient on stresses and displacements. The finite element model represents the dam body, foundation, and water in the reservoir, enabling the analysis of the differences in principal stress and horizontal displacements obtained from the numerical simulations.

2. Geometry and material properties of Düzçam Dam

The Düzçam Dam is one of six dams planned for the Karabük province in Turkey. These six dam projects are part of an initiative in the western Black Sea region, spanning the provinces of Zonguldak, Karabük, Bartin, and Kastamonu. The Düzçam Dam is situated within the boundaries of Düzçam village, and its location is shown in detail in Fig. 1. It is important to note that the dam is located very close to the North Anatolian Fault Line, which emphasizes the need for a thorough evaluation of the dam's seismic behavior about potential seismic events originating from this fault.

The Düzçam Dam is a Clay Core Rock Fill (CCR) dam, with a dam body height of 54 meters and a crest length of 208.5 meters. The crest width starts at 6 meters and increases to 10 meters at the largest cross-section of the dam. The crest elevation is 717 meters, while the maximum water level is 715.92 meters. Additionally, the Düzçam Dam has an irrigation capacity of 5,615 decares annually. The upstream and downstream slopes of the dam are 2.25:1 and 2:1, respectively, while the slopes of the rockfill and transition zones are 1:4. The most critical section and the depth variations of the dam body are presented in detail in Fig. 2.

In the two-dimensional model of the Düzçam Dam, the most critical section was selected for analysis. It is recommended that in the finite element method, the dam was measured according to specific dimensions. The height of the dam was denoted as "H." The dam foundation was modeled with extensions up to "H" downstream, "3H" upstream, and "H" in the vertical (gravity) direction. These dimensions for the dam and soil modeling were adopted based on the finite element method. For the finite element modeling, the dam ground was represented with fixed boundary conditions, meaning the structure and ground were restricted from movement in both the x and y directions. The right and left sides of the dam, in both the downstream and upstream directions, were modeled with moving boundary conditions. In this moving boundary model, movement was restricted in the x-direction, while vertical (y-direction) movement was allowed. A typical section of a clay core rockfill dam, representing the most critical section of the Düzçam Dam, is shown in Fig. 2.

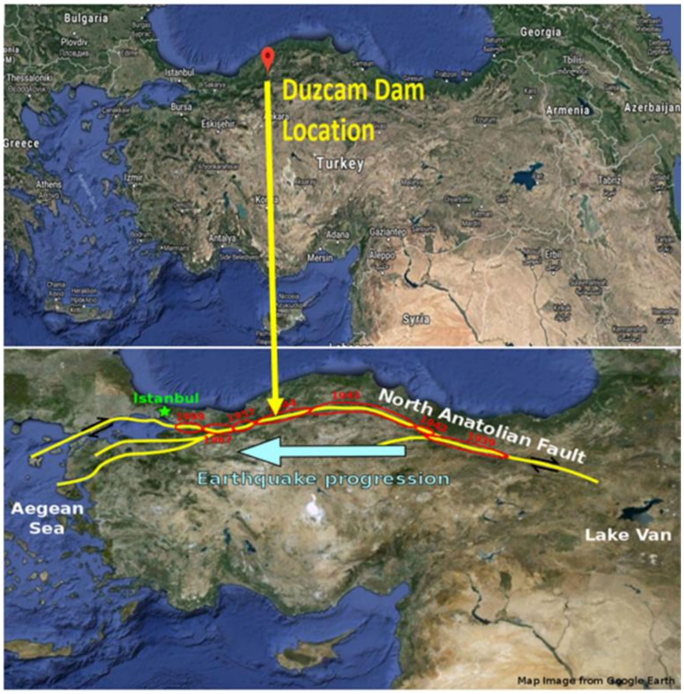


Fig. 1. Düzçam Dam location and North Anatolian Fault locations

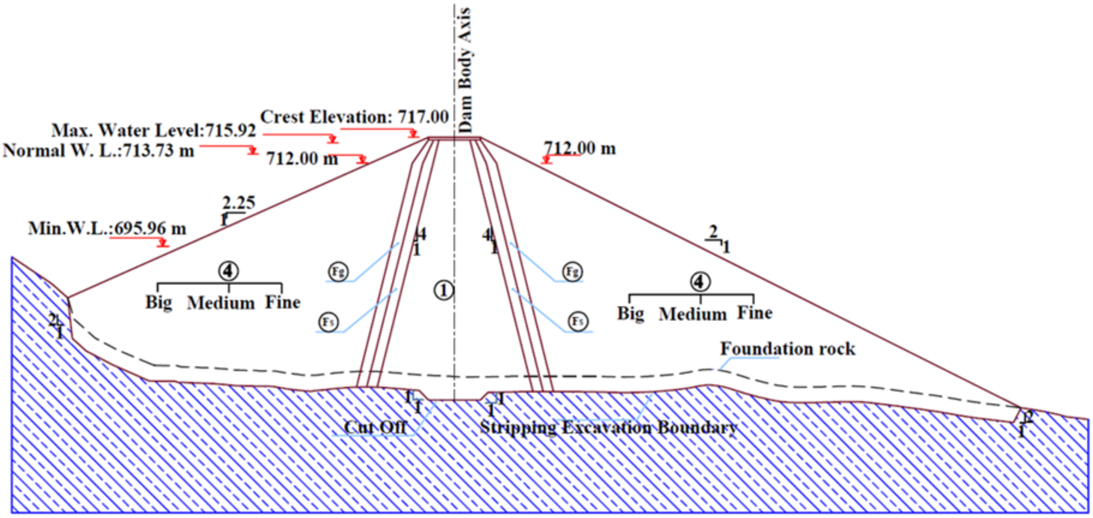


Fig. 2. The most critical section of Düzçam CCR Dam

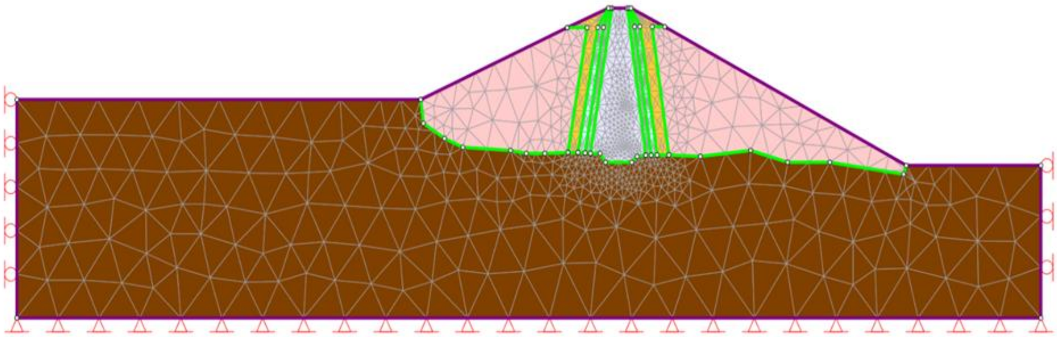


Fig. 3. Empty reservoir model of unfavorable section of Düzçam Dam and soil

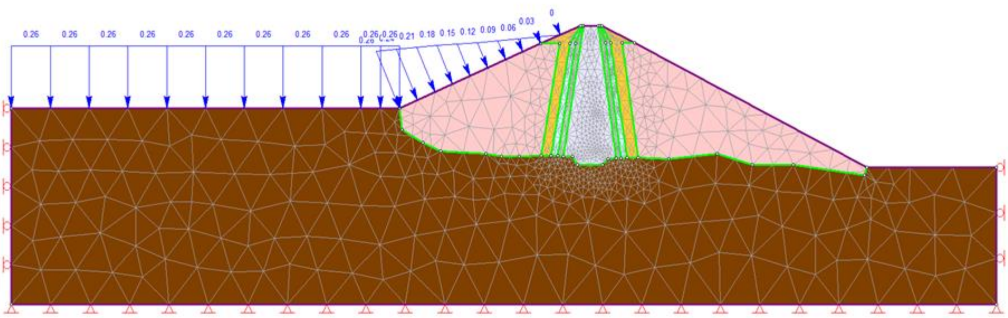


Fig. 4. Full reservoir model of an unfavorable section of Düzçam Dam and soil

The analysis consists of four stages for each standard and approach. The analysis type employed is plane strain, and the solver used is Gaussian Elimination. The mesh type is graded, which ensures the generation of a well-distributed mesh for most models, utilizing the quadtree nodal insertion technique [36]. The element type is three-noded triangles. In most cases, a graded mesh type is recommended. When a graded mesh is selected, it is necessary to specify the Element Type, Gradation Factor, and the Number of Excavation Nodes in the Mesh Setup dialog [36]. Both plane strain and Gaussian Elimination are the recommended methods for solving the problem, as specified by the Phase2 program. For the foundation portion of the dam, the number of elements is 630, with 365 nodes. The dam body contains 1,888 elements and 987 nodes. Similarly, the reservoir section includes 1,888 elements and 987 nodes. All elements have been verified to be of satisfactory quality. Elements considered poor quality are defined as those exhibiting the following characteristics:

- Side length ratio (maximum/minimum) > 30.00; Minimum interior angle < 2.00 degrees
- Maximum interior angle > 175.00 degrees
- Impermeable material was used in zone 1 located in the dam body.
- Filter sand material was used in the Fs-numbered zone in the dam body.
- Filter gravel material was used in the Fg region located in the dam body.
- Fine, medium, and big rock fill material was used in Region 4 located in the dam body.

Figs. 3 and 4 present empty and full reservoir models of unfavorable sections of the Düzçam Dam and soil, respectively. In dynamic analyses, the material types are chosen as elastic and plastic. The material parameters used for the analyses are selected from the threshold values given in the Rocdata program.

2.1. The Drucker-Prager model

There are many criteria for the determination of the yield surface or yield function of materials. The Drucker-Prager criterion is widely used for frictional materials such as rock and concrete. Drucker and Prager [37] obtained a convenient yield function to determine the elastoplastic behavior of concrete smoothing Mohr-Coulomb criterion (Fig. 5). The formulas are presented in Eqs. 1-7 [38] as:

$$f = \alpha\ I_1 + \sqrt{J_2} - k \tag{1}$$

where α and k are constants which depend on cohesion (c) and angle of internal friction (φ) of the material given by

$$\alpha = \frac{2\ Sin\varphi}{\sqrt{3}\,(3 - Sin\varphi)} \qquad\qquad k = \frac{6c\ Cos\varphi}{\sqrt{3}\,(3 - Sin\varphi)} \tag{2}$$

In Eq. 1, I_1 is the first invariant of stress tensor (σ_{ij}) formulated as follows,

$$I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33} \tag{3}$$

$$J_2 = \frac{1}{2} s_{ij}\ s_{ij} \tag{4}$$

where s_{ij} is the deviatoric stresses as yielded below.

$$s_{ij} = \sigma_{ij} - \delta_{ij}\sigma_m \qquad\qquad (i,j\ = 1,2,3) \tag{5}$$

In Eq. (5), δ_{ij} is the Kronecker delta, which is equal to 1 for i=j and 0 for $i \neq j$. σ_m is the mean stress and obtained as follows:

$$\sigma_m = \frac{I_1}{3} = \frac{\sigma_{ii}}{3} \tag{6}$$

If the terms in Eq. 5 are obtained by Eq. 6 and replaced in Eq. 4, the second invariant of the deviatoric stress tensor can be obtained as follows:

$$J_2 = \frac{1}{6}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2] + {\sigma_{12}}^2 + {\sigma_{13}}^2 + {\sigma_{23}}^2 \tag{7}$$

3. Suggested pseudo seismic coefficient values in standards and approaches

The categorization of the pseudo-seismic coefficient according to various standards and approaches is presented. This study includes nine different standards and approaches, as detailed in Table 1 below. The pseudo-seismic coefficient recommended by JCOLD is proposed to range from a minimum of 0.12 to a maximum of 0.25 in the horizontal direction [39]. The equation presented in the study is based on the acceleration due to gravity (g) and the peak ground acceleration (PGA) [9]. According to [8], different pseudo-seismic coefficients were suggested and categorized according to the magnitude of the earthquake. It is made [10] a similar suggestion to [9] which correlated the pseudo-seismic coefficient with the gravitational acceleration gravity (g) and peak ground acceleration (PGA). According to the California Division of Mines and Geology, the maximum permissible pseudo-seismic coefficient value is 0.15. This value is the lowest value among the maximum permissible pseudo seismic coefficients. The pseudo-seismic coefficient value suggested by the Indian Standard for Seismic Design of Earth may vary according to the three parameters [39]. These three parameters are zone, importance, and amplification factors. The zone factor varies from 0.1 to 0.36, while the importance and amplification factors range from 1 to 2. According to the IRI Road and Railway Bridges Seismic Resistant Design Code, the pseudo seismic coefficient is associated with the ratio of design acceleration to acceleration of gravity (0,2 to 0,35) [39]. It is suggested that three different pseudo-seismic coefficients according to the magnitude of the earthquake, 0.1, 0.2, and 0.5 [5]. The maximum recommended pseudo-seismic coefficient is the 0.5 value of Terzaghi. According to the Corps of Engineering, the pseudo seismic coefficient is taken as two different values according to the magnitude of the earthquake [39].

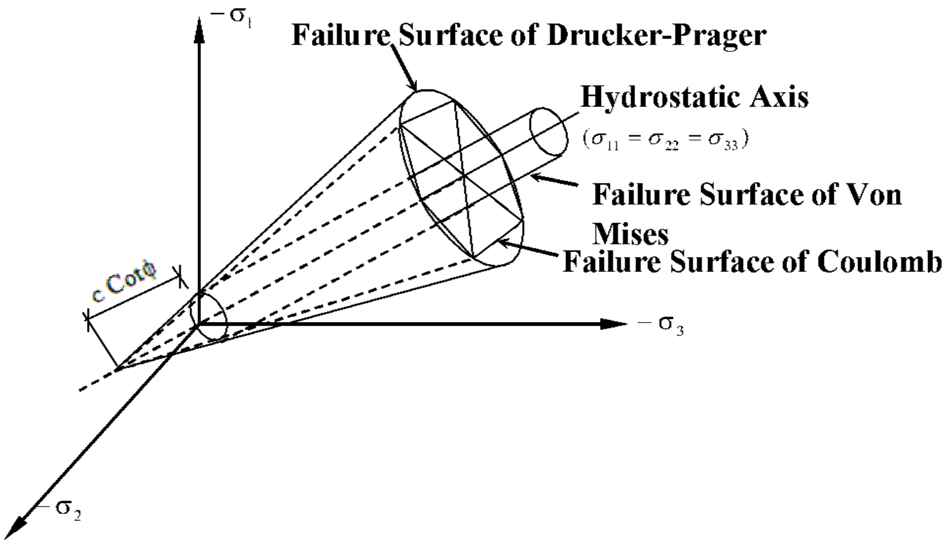


Fig. 5. Failure criteria for Coulomb, Drucker-Prager and von Mises

Table 1. Pseudo-static coefficients from various studies

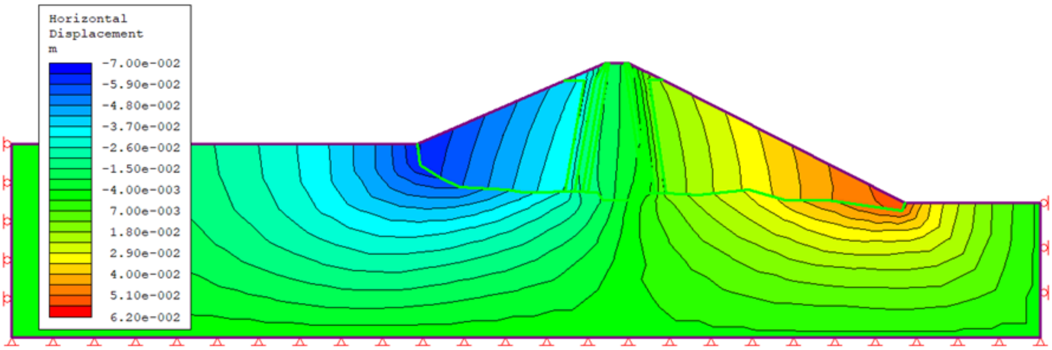
Investigator	Recommended Pseudo static horizontal coefficient (k_h)	Recommended factors of safety	Earthquake effect

JCOLD	0.12-0.25	>1.0	Unspecified
Marcuson (1981)	0.33-0.50 PGA/g	>1.0	Unspecified
	0.1 (M=6.5) 0.15 (M=8.25)	>1.15	<1m displacement in earth dam
	0.1	>1.2	Sheffield Dam (completely collapsed)
Seed (1979)	0.15	>1.3	San Fernando Dam (upstream site slope defeat)
	0.15	2-2.5	San Fernando Dam (Downstream face shifted 1.83 m (6 ft) with cret)
	0.2	1.3	Mine waste dam in Japon (dam collapse)
Hynes-Griffin and Franklin (1984)	0.5×PGA/g	>1.0	<1m displacement in earth dam
California Division of Mines and Geology (1997)	0.15	>1.1	Unspecified
Indian Standard for Seismic Design of Earth	0.33×Z×I×S	>1.0	Unspecified
IRI Road and Railway Bridges Seismic Resistant Design Code	0.5×A	>1.0	Unspecified
Terzaghi (1950)	0.1 (R-F=IX) 0.2 (R-F=X) 0.5 (R-F>X)	>1.0	Unspecified
Corps of Engineering	0.1 (Major earthquake) 0.15(Great earthquake)	>1	Unspecified

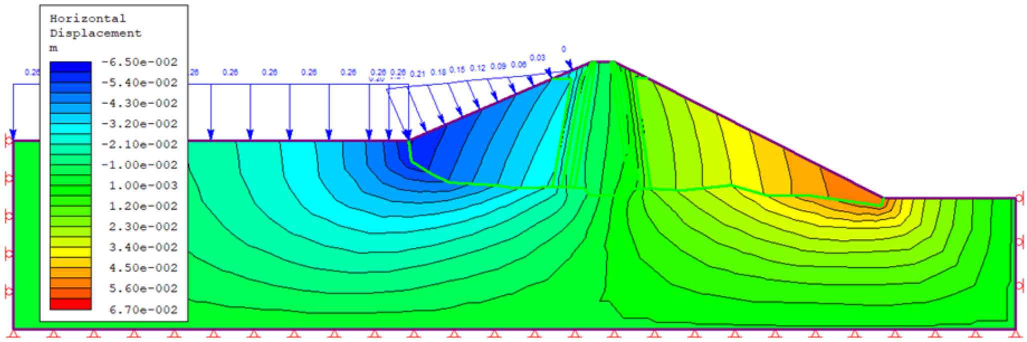
R-F: Rossi-Forel earthquake intensity scale; M: Earthquake magnitude; PGA: Peak Ground Acceleration;
g: Acceleration of gravity; A: Ratio of design acceleration to acceleration of gravity (0.2 to 0.35);
Z: Zone factor (0.1 to 0.36); I: Importance factor (1.0 to 2.0); S: Site amplification factor (1.0 to 2.0)

4. Stability assessment

In the static analysis using the finite element method, the stability of the dam is assessed at various stages. The stresses and displacements observed in the dam body are presented in Figs. 6-8 below. For the static analysis under the empty reservoir condition, the maximum displacement observed in the dam is 6.2 cm, as shown in Fig. 6(a). When the Düzçam Dam is filled to the crest, the greatest displacement occurs in the downstream surface of the bottle section, as revealed by the static analysis. The numerical stress analysis indicates a horizontal displacement of 6.7 cm, as shown in Fig. 6(b). According to the results of the static analysis, the greatest horizontal displacement occurs in Fig. 6(b), where the reservoir is filled to the crest and the dam is in an elastic condition. The displacement results from the elastic analyses for both empty and filled reservoir conditions are larger. The principal stresses in the dam body and rock foundation are presented in Fig. 8(a) and 8(b) for the static analyses. It can be observed that the principal stress values are higher on the upstream side due to water pressure. As a result of the static analysis in the elastic state, the maximum stress value obtained was 7.7 MPa, while for the plastic state, the maximum stress was 7.2 MPa.

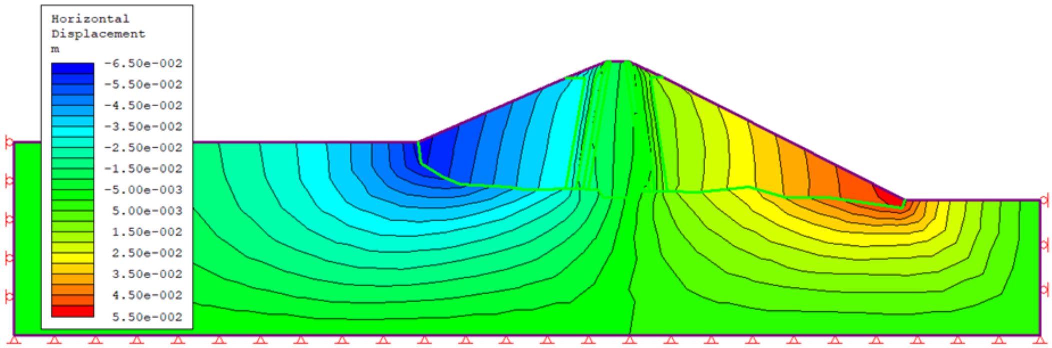


(a)



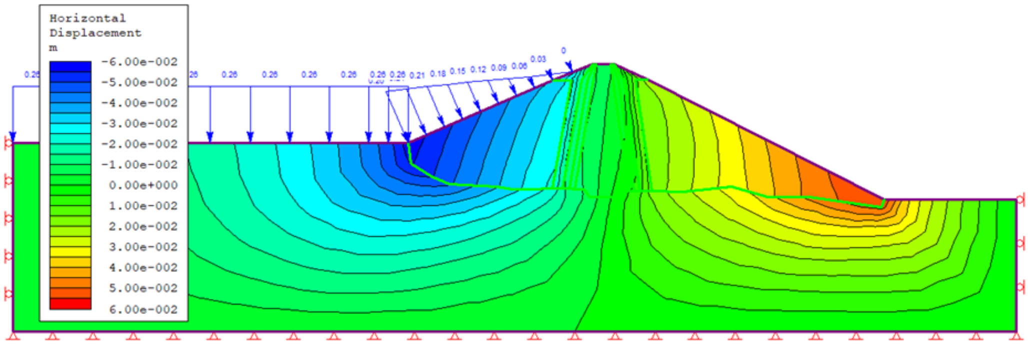
(b)

Fig. 6. Static analysis of dam; (a) elastic analysis and empty reservoir (b) elastic analysis and full reservoir



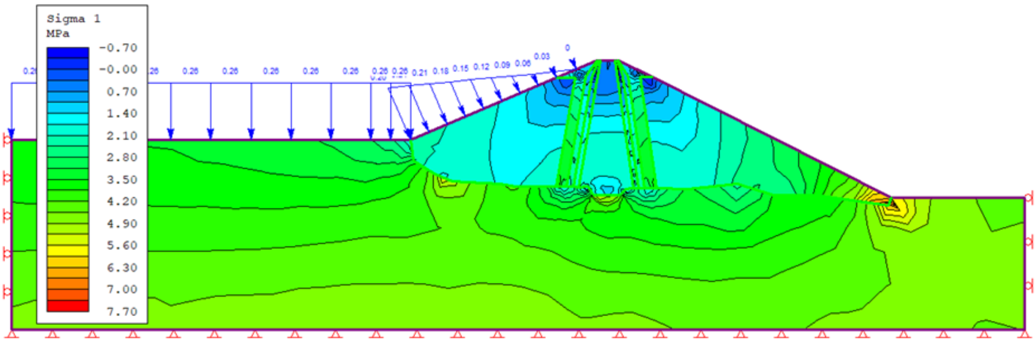
(a)

Fig. 7. Static analysis of dam; (a) plastic analysis and empty reservoir (b) plastic analysis and full reservoir

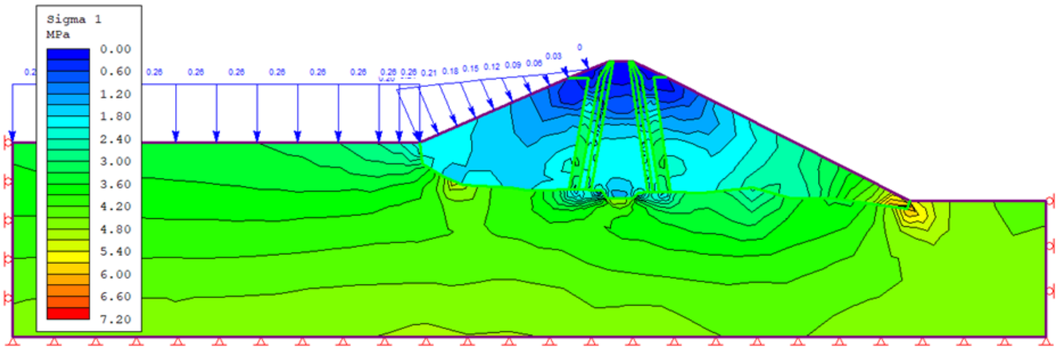


(b)

Fig. 7. Continued



(a)



(b)

Fig. 8. Stresses for static analysis of dam; (a) elastic analysis and full reservoir (b) plastic analysis and full reservoir

5. Pseudo-seismic analysis of Düzçam Dam

This study investigates the elastic and plastic numerical analysis of Düzçam Dam using the pseudo-seismic method. In the fourth stage, different pseudo-seismic coefficients, which represent earthquake accelerations, are applied to the model. This approach allows for the evaluation of the potential earthquake impacts under both conditions. The values of the pseudo-seismic coefficients used in the analysis are provided in Table 2 below. These coefficients range from 0.15 to 0.5 and are applied exclusively in the fourth stage. Nine different standards and approaches are compared for both elastic and plastic solutions under the specified conditions.

Table 2. Used pseudo seismic coefficient in numerical analysis

Standards and Approaches	Maximum Pseudo Seismic Coefficient
California Division of Mines and Geology	0,15
Corps of Engineering	0,15
IRI Road and Railway Bridges Seismic Resistant Design Code	0,18
Seed	0,2
JCOLD	0,25
Marcuson	0,35
Hynes-Griffin and Franklin	0,4
Indian Standard for Seismic Design of Earth	0,48
Terzaghi	0,5

The numerical analysis results indicate that the effect of the pseudo-seismic coefficients, which are associated with the maximum values of earthquake accelerations, on displacement is approximately linear. The maximum displacement value in the Düzçam Dam body, influenced by the pseudo-seismic coefficient, is calculated to be 13.2 cm.

In comparison to the pseudo-seismic analysis, the displacement in the dam reservoir is approximately two and a half times greater under the condition with the maximum pseudo-seismic coefficient applied. This demonstrates that the pseudo-seismic coefficients have a significant impact on the displacement of the dam body. Therefore, selecting the appropriate pseudo-seismic coefficient is crucial. Further studies should be conducted to accurately determine the correct pseudo-seismic coefficient. To determine the appropriate pseudo-seismic coefficient, it is recommended that boundary conditions be modeled as viscous or that three-dimensional analyses be performed, as these factors have a substantial influence on the results. The results of the pseudo-seismic analysis are presented in Figs. 9-14, with the displacements varying according to the pseudo-seismic coefficient shown in Fig. 13(a) and (b).

The principal stress values along the height of the dam body are presented in Fig. 15 and 16 for both elastic and plastic analyses. Upon examining the results of the numerical analysis, it is evident that the stress values obtained from the elastic analyses are higher than those from the plastic analyses.

The standards and approaches of the California Division of Mines and Geology, JCOLD, and Terzaghi are compared for both the elastic and plastic analyses. The California Division of Mines and Geology recommends the lowest permissible maximum pseudo-seismic coefficient, with a value of 0.15 for the pseudo-seismic coefficient kh. The pseudo-seismic coefficient recommended by JCOLD is 0.25, while Terzaghi suggests a value of 0.5. The stresses along the dam body, based on these recommended values, are shown in Fig. 15 and 16. It is observed that the stresses along the height of the dam body increase with depth. On the other hand, an increase in the pseudo-seismic coefficient corresponds to higher stress values.

In the elastic analyses performed using the seismic coefficient proposed by the California Division of Mines and Geology, the maximum stress value in the dam body is calculated to be approximately 7 MPa. When the seismic coefficient recommended by JCOLD is applied, the maximum stress value increases to nearly 8 MPa. With the maximum seismic coefficient value suggested by Terzaghi, the maximum stress value in the dam body approaches 10 MPa. In the plastic analyses, as shown in Fig. 16, it is observed that the principal stress values decrease when the pseudo-seismic coefficients recommended by the three approaches are applied. In the plastic analysis, the maximum tensile stress value obtained using the seismic coefficient suggested by Terzaghi is approximately 8 MPa. According to JCOLD, the maximum calculated stress value is 7 MPa, while the maximum stress value in the dam body, using the pseudo-seismic coefficient proposed by the California Division of Mines and Geology, is 5 MPa. While it was observed that the stress values obtained along the dam height according to the California and JCOLD data were close to each other and more compatible, it was determined that the results of the finite element analysis performed according to the Terzaghi data were quite different. Considering the maximum stress in the dam body, the analyses performed according to Terzaghi seismic acceleration resulted in stress values approximately 42% and 30% larger than those in California and JCOLD, respectively.

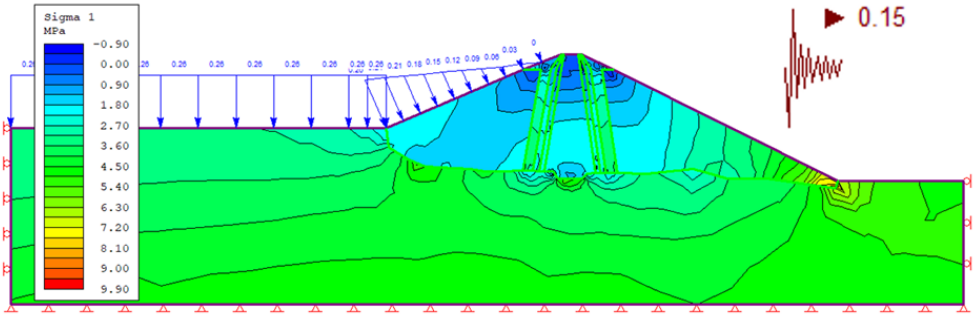


Fig. 9. Minimum pseudo seismic analysis of dam under elastic and full reservoir condition in California Division of Mines and Geology

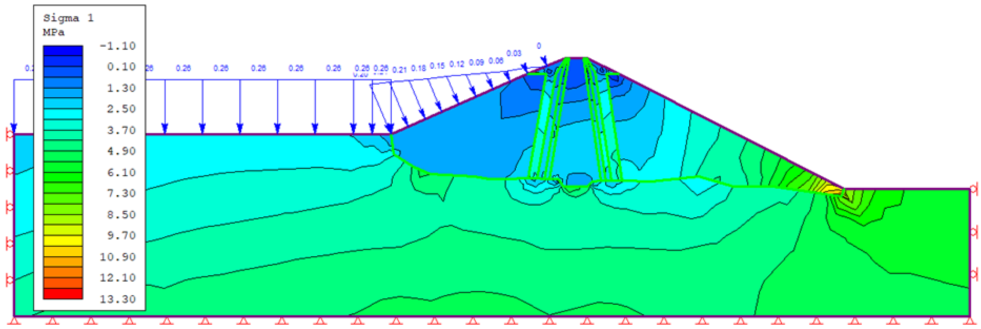


Fig. 10. Maximum pseudo seismic analysis of dam under elastic and full reservoir condition in Terzaghi

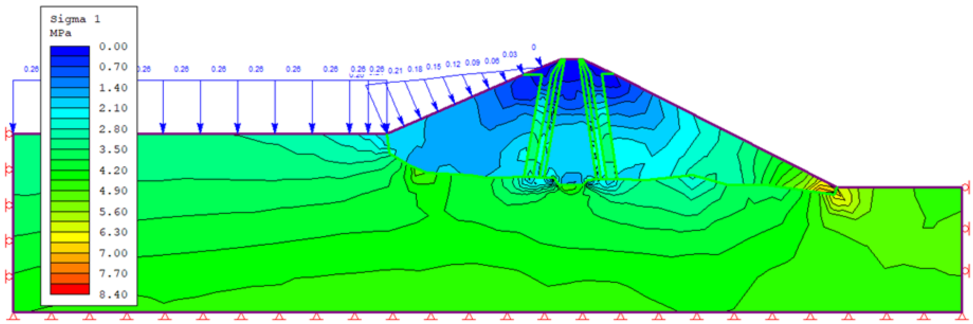


Fig. 11. Minimum pseudo seismic analysis of dam under plastic and full reservoir condition in California Division of Mines and Geology

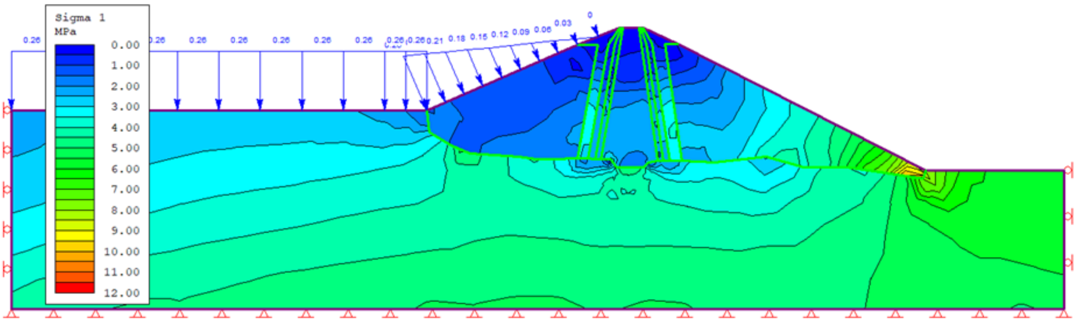
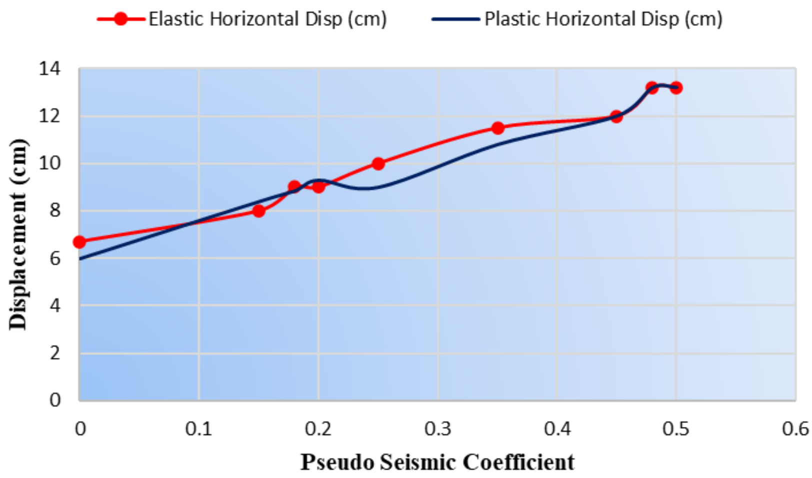
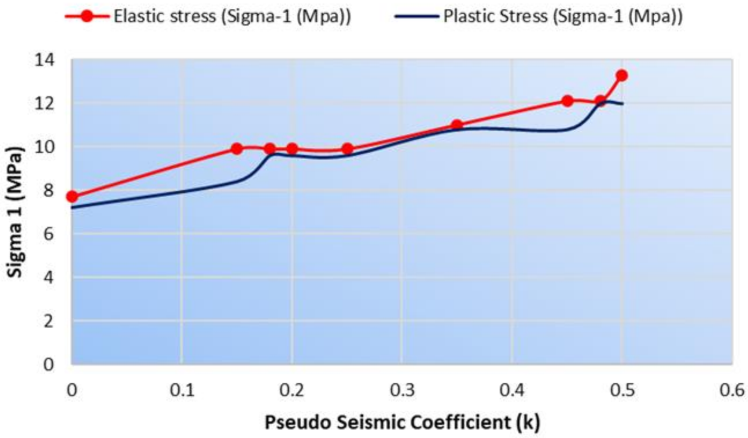


Fig. 12. Maximum pseudo seismic analysis of dam under plastic and full reservoir condition in Terzaghi

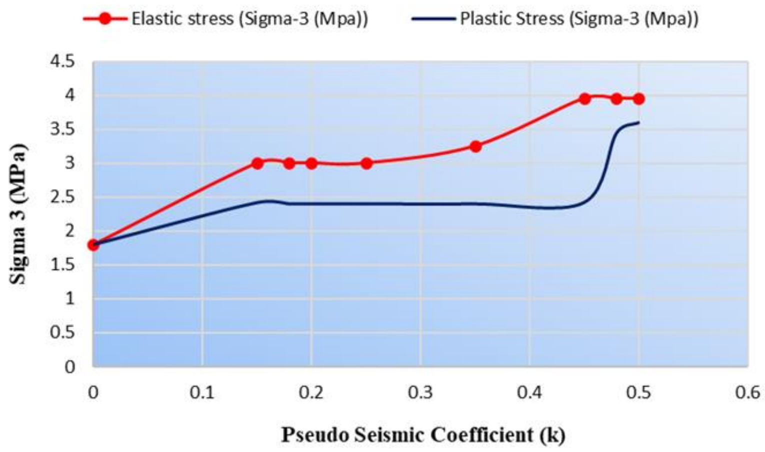


(a) Displacements for elastic and plastic cases

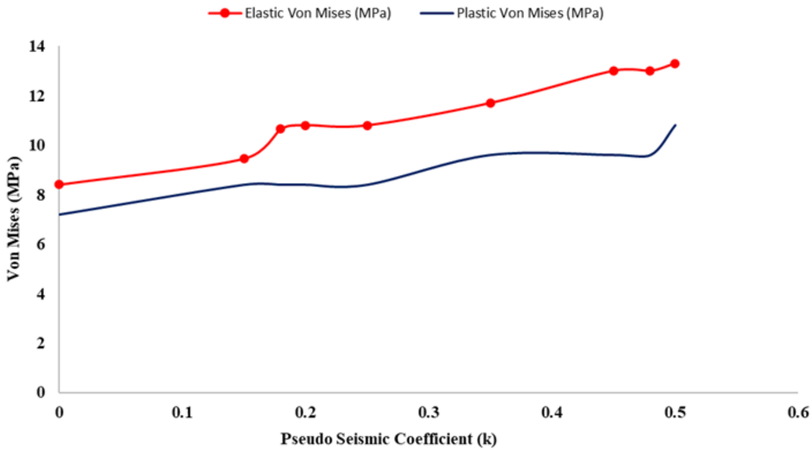


(b) Principal tensile stress (sigma 1)

Fig. 13. Pseudo seismic- displacements and principal tensile stress (sigma 1) analyses for elastic and plastic cases



(a) Principal compressive stress (Sigma 3)



(b) Stress (Von Mises)

Fig. 14. Pseudo seismic stress analyses (principal compressive stress and Von Mises) for elastic and plastic cases

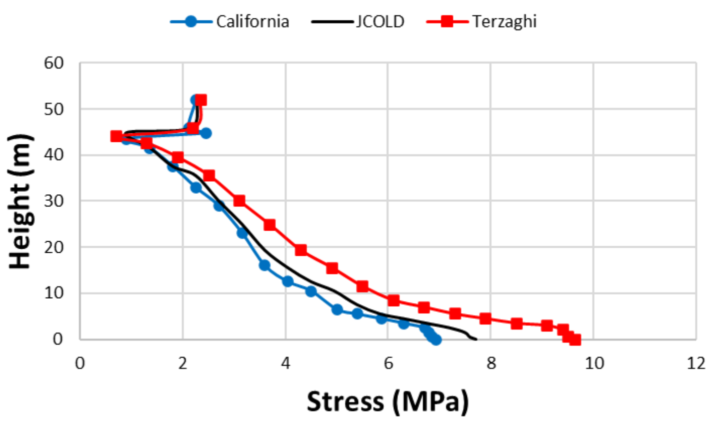


Fig. 15. Principal stress changing by dam body height in elastic analyses

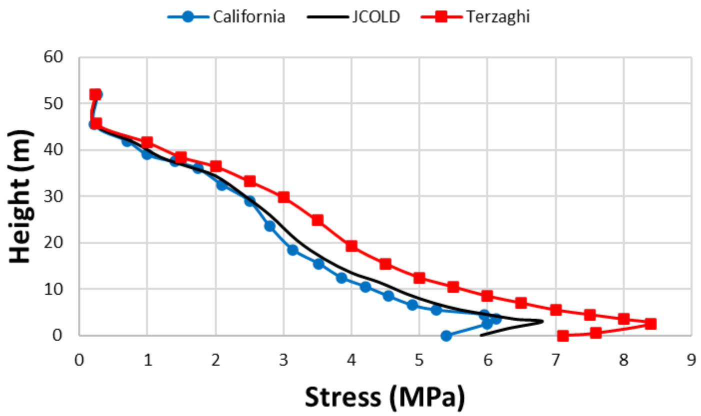


Fig. 16. Principal stress changing by dam body height in plastic analyses

6. Conclusions

This study is conducted using the maximum pseudo-seismic coefficient values outlined in the relevant standards and approaches. The analysis provides insights into the different stress and displacement values that may arise when the seismic coefficients prescribed by these standards and approaches are applied to a dam-foundation model. The effect of water is also evident in both the elastic and plastic states. The stress and displacement values obtained from models with a full reservoir are consistently higher than those from analyses conducted in the absence of water. Furthermore, the plastic solution results in smaller displacements compared to the elastic solution when both cases are compared.

The significance of the pseudo-seismic coefficient is demonstrated, as it is more than double the horizontal displacement and stress values derived from the analysis. Additionally, the tensile values observed in the plastic analysis are lower than those in the elastic analysis.

Considering the dam body damage that occurred in recent years during earthquakes and the collapse of dams due to hydrostatic pressure caused by sudden rainfalls, it is recommended that Terzaghi pseudo seismic coefficient 0.5, which suggests the maximum seismic acceleration in terms of dam structural safety, be used in future dam analysis studies.

The primary objective of this study is to highlight the importance of selecting the appropriate seismic coefficient. The study demonstrates the substantial impact of changes in the seismic coefficient. To further validate these findings, a dynamic analysis of the Düzçam CCR Dam could be conducted to compare the results and assess which standards provide the most consistent results. More detailed studies should be undertaken to determine the maximum permissible pseudo-seismic coefficient. Additionally, three-dimensional dam models and alternative boundary conditions, such as viscous conditions, should be considered for future analyses.

1. Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

2. Funding

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3. Data availability statement

Data generated during the current study are available from the corresponding author upon reasonable request.

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