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Nonlinear dynamic behavior of Pamukcay Earthfill Dam

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Abstract. Water and energy supplies are the key factors affecting the economic development and environmental improvement of Turkey. Given their important role and the fact that a large part of Turkey is in seismically active zones dams should be accurately analyzed since failure could have a serious impact on the local population environment and on a wider level could affect the economy. In this paper, a procedure is proposed for the static, slope stability, seepage and dynamic analysis of an earth dam and the Pamukcay embankment dam. The acceleration time history and maximum horizontal peak ground accelerations of the Bingöl (2003) earthquake data was used based on Maximum Design Earthquake (MDE) data. Numerical analysis showed that, the Pamukcay dam is likely to experience moderate deformations during the design earthquake but will remain stable after the earthquake is applied. The result also indicated that, non-linear analysis capable of capturing dominant non-linear mechanism can be used to assess the stability of embankment dams.

Keywords: earthfill dam; dynamic analysis; slope stability; seepage analysis

1. Introduction

According to the standard manual provided by the International Commission on Large Dams (ICOLD), in which about 63 member countries are now associated, dams with the height of more than 15m are referred to as “high dams”. To date about 14,000 high dams have been registered and more than 70 percent of these are embankment dams. A recent report on the construction of high dams has also noted that about 1,000 high dams constructed in recent two years, just 20 percent are concrete dams and the remainders are embankment dams. There are two major distinct features of embankment dams (Narita 2000):

(1) Rigorous conditions are not required for the dam foundation, while hard and sound rock foundation is necessary for concrete dams. Embankment dams can be constructed even on alluvial deposit and pervious foundations.
(2) Construction of embankment dams has an economic advantage, for example a dam project can be planned in the outskirts of city area since there is no need for specific foundations

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and the construction materials can be mainly supplied from the locality.

The responsibility for the construction of an earthfill (embankment) dam with maximum provisions for the safety and constant critical surveillance of dam, reservoir and foundation during its life time no longer is confined to engineers who built the dams, but is shared by those who have specialist knowledge of hydrology, geophysics, geology and soil mechanics (Ebrahimian 2011). The highest responsibility belongs to the seismic designers. However the design of dams is not easy task. There is a need to use dynamic analysis with different levels of sophistication in terms of the appropriate formulation, characterization of material properties and modeling stress-strain soil behavior.

As Gazetas (1985) commented in "the standard seismic design method for earth dams was based on the erroneous assumption that dams are absolutely rigid bodies fixed on their foundation and thus experiencing a uniform acceleration equal to the underlain-ground acceleration". However, research has shown that these dams deform under seismic forces, furthermore that is the materials from which they are constructed, the geometry and the nature of the base motion that determines their response during an earthquake. A significant amount of work has been undertaken to understand the seismic behavior of earth and rockfill embankment dams. Newmark (1965) and Seed (1973), were the first propose methods of analysis for predicting the permanent displacements of dams subjected to earthquake shaking.

Seed and Martin (1966), Ambraseys and Sarma (1967), Lin and Whitman (1983) used shear beam analysis to study the dynamic response of embankment dams. The failure of the Sheffield Dam (Seed *et al.* 1969) and San Fernando Dam (Seed 1973) prompted. Seed (1973) and other researchers to further review and modify Newmark's method of assessing the seismic stability of earth and rockfill dams. (Sarma 1975, Serff *et al.* 1976, Makdisi and Seed 1978, Abdel-Ghaffar and Scott 1979, Lin and Whitman 1986, Elgamal *et al.* 1990, Yan 1991, Gazetas and Dakoulas 1992, Bray and Travasarou 2007). Although Newmark (1965) treated the sliding mass as a rigid body, Seed (1966) and others recognized that an embankment dam responds as a flexible structure and introduced a technique to estimate the amplification of ground motions to the crest of the dam. Therefore, based on the developments in the research, in order to undertake a realistic prediction of the response of an earthfill dam to the particular shaking of an earthquake careful consideration must be given to the potential effects of the following major factors:

- Non-linear-inelastic soil behavior
- Dependence of soil stiffness on confining pressure
- Narrow canyon geometry
- Dam-alluvium interaction

Depending on the particular situation one or more of these factors can have a considerable influence on the response of dams to seismic forces. Since the raising of the awareness of the risk to earthfill dams the advent of fast computers facilitating effective modeling and testing, has brought increasing number of studies on these dams using numerical methods such as; finite element and finite difference methods with advanced nonlinear material models (Zienkiewicz *et al.* 1980, Vrymoed 1981, Mejia *et al.* 1982, Prevost *et al.* 1985, Gazetas and Uddin 1994, Martin *et al.* 1993, Martin and Sengupta 1994, Sengupta *et al.* 2010, Sengupta and Martin 1997, Li *et al.* 2008). In some cases, researchers (Mejia and Seed 1983, Elgamal and Abdel-Gaffer 1987, Gazetas and Dakoulas 1992, Papalou and Biejalak 2004) have even recommended particularly for the concrete dams, three-dimensional analysis to include effects of canyon, and other site-specific geometric irregularities on the dynamic stabilities. Sophisticated analytical tools, such as boundary elements, finite element and finite difference methods are the most recommended method. The other important studies include the following; Siyahi and Aslan (2008) who studied the non-linear dynamic behavior of the Alibey earth dam using a two dimensional finite element method. The authors modelled the dam using four node plane-strain finite elements (FE) and displacement-pore pressure coupled FE analyses. They also used nonlinear material models such as pressure dependent and independent multi yield materials were implemented during the analyses. Terzi (2011) evaluated the dynamic response of Damlapınar CFR dam. Terzi developed the time history and maximum horizontal peak ground acceleration values based on the maximum credible earthquakes over the previous 50 years from nearby seismic sources. He showed that the Damlapınar CFR dam should remain stable during a maximum credible earthquake. Based on these results it is also understood that the earthquake-induced deformations of the dam are expected to be within the safety margins. Sevim *et al*. (2011) examined the finite element calibrations of the Berke Arch Dam using Operational Modal Testing. Their studies consisted of both experimental and analytical investigations. In the analytical part they developed a 3D FEM of the Berke Arch Dam to determine the vibration characteristics of the dam body. They also conducted "Enhanced Frequency Domain Decomposition" technique on the dam body experimentally. Based on their studies they found inconvenience results between experimental measures and anaytical results. They calibrated the material properties for to obtain conveniences. Arici and Özel (2013) compared the results of 2D and 3D analysis methodologies for the evaluation of the performance of concrete faced rock-fill dams under dynamic loading. They found the results of 2D and 3D analysis agree well. However they commented that 3D analyses have advantages of such as the opening of the vertical construction and the crushing of the seismic action. Zhang *et al*. (2012) conducted a nonlinear finite element analysis using the ABAQUS software. They analyzed the stresses and deformations of the face of a rockfill dam during its completion, operation and the level draw down periods. They showed that all the results meet the requirements of the project.

Sica and Pagano (2008) studied the influence of past loading histories to the seismic performance of a zoned earth dam by coupled analysis. It is revealed in the study that pre-stress strain behavior affects the seismic performance by conducting seismic analysis. Hardening parameters was obtained by back analysis of a sesimic event. The study clearly showed that past loading conditions such as strong motions lead to hardenning in soils should be kept in mind during seismic performance analysis. In Rampello *et al*. (2009), evaluation of response of a homogeneous earth dam to the seismic loading was given by conducting displacement based analysis decoupling the ground response. They reported that acceleration responses obtained from FE analysis and equivalent analysis are in a fair agreement. In the study of Papadimitriou and Bielak (2004), a methodology was given for estimating seismic coefficients for performance-based design of earth dams and tall embankments which is used in pseudo-static analysis to define earthquake effect. Estimation of peak seismic coefficient and effective seismic coefficient was derived from allowable downslope displacements and sliding block analysis using result of 110 two dimensional FE analysis in statistical analysis. Elia *et al*. (2011) represented fully coupled dynamic analysis of a large earth dam by finite element effective stress approach. It is pointed out that after large strains accumulation induced by shaking followed by development of excess pore pressures. Sica and Pagano (2009) investigated the seismic response of the Camastra Dam by implementing an advanced constitutive law for the soil skeleton and coupled analysis between soil skeleton and pore water.

In this study, the dynamic response and earthquake resistance of the Pamukcay earth dam in south east, Turkey was investigated using non-linear dynamic time history and modal analysis methods. To verify the results the dam was first analyzed under static conditions and then acceleration-time histories of the Bingol (2003) earthquake were performed and the PGA responses caused by maximum design earthquake (MDE) was applied to the dam body, impervious core and foundation.

2. Pamukcay dam

During the last century, earth dam engineers have mainly focused their attention on the knowledge of empirical standards of design of these structures against earthquakes Sherard (1967). The safety of earth dams are mostly related on the proper design, construction, and monitoring of the actual behavior during the construction and operation of the structure. The most critical factor in the assessment of the safety threshold value of any structure is the deformation that occurs during seismic effects where the accelerations change at different locations in a structure. Therefore, the designed accuracy must fulfill requirements of detecting accelerations at critical locations of the dam structure under investigation. In this study the static, slope stability, seepage and dynamic analysis procedure for the Pamukcay earth dam was performed. The cross section of the dam is given in Fig. 1. and the properties are presented in Table 1.

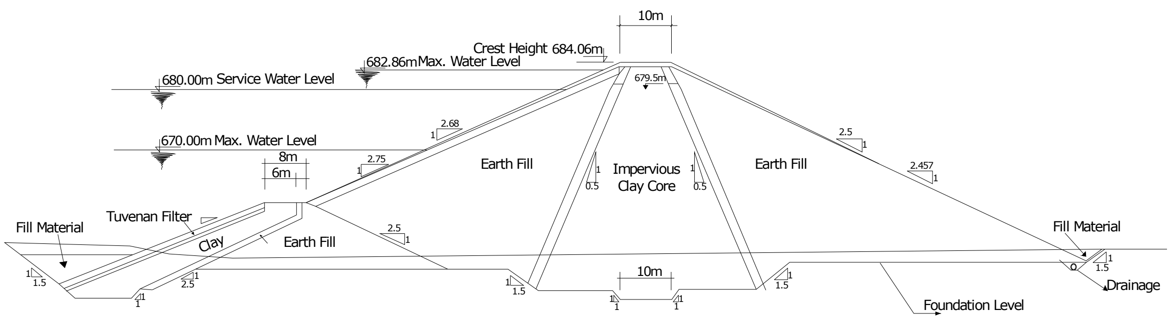


Fig. 1 Main cross section of Pamukcay Dam

Table 1 Properties of Pamukcay Earth Dam

Crest length	512.50 m
Crest level	683.50 m
Talveg level	652.0 m
Max. water level	682.86 m
Max. capacity	33.3 hm^3
Max. res. area	1.49 km^2
Upstream slope	2.75/1
Downstream slope	2.50/1
Eartfill volume	1401870 m^3

The Pamukcay dam on the river Pamukcay, a branch of the Dicle river is located about 40 km northeast of Diyarbakir city in the southeast of Turkey. The dam is now under construction and will be completed in 2015. It is an earth fill dam with an impervious clay core. The dam foundation and its associated earth structure are mainly Selmo formation. The main function of the dam is to irrigate an agricultural area of 5,134 ha.

3. Site geology

It should be emphasized that due to simplifications in the earthquake induced deformation analyzing procedures, an accurate assessment needs to be made of the geology of foundation, lithology of soil strigraphy and soil parameters of fill materials, for use in the analysis and that the degree of judgment will help to evaluate of soil characteristics through comprehensive field and laboratory tests (Ozkan *et al*. 1996).

Two field test methods were used in the investigation of this dam site. The dam site was geologically studied and mapped in detail. On the basis of these studies seven boreholes, totaling approximately 500 m were drilled. According to the borehole investigations, under the dam structure, between 4 m to 60 m, the Selmo formation is the main formation which was deposited in the basins associated with the Southeastern Anatolian Thrust Belt and East Anatolian Fault Zone in South East Turkey. The Selmo formation developed as a result of compressional stresses created by the movement of the Arabian plate to the north and the Eurasian plate to the west from the early Micone to late Pliocene. Soft sediment deformation structures were developed in the sandstone, siltstone, and marln of the deltaic and lacustrine units of the Selmo formation. These are slumps, recumbent folds, load casts, ball-and-pillow structures, flame structures, Neptunian dykes, chaotically associated structures and synsedimentary faults. In the foundation area, the Selmo formation is basically formed by the alteration of siltstone, mudstone, conglomerate and claystone. Mudstone in the formation, is generally light brown and in some places in purplish color. Mudstone is formed by carbonate cemented of clay, silt, sand and gravel materials. Conglomerate and Sandstone in the Selmo formation, are mottled gray color, in granular skeleton, and closely attached with carbonate cement. Claystone which is rarely seen in the Selmo formation is seen in some places with mudstone alteration.

Thirty pressiometer tests were also carried out in two boreholes to evaluate the possible settlement deflections and bearing capacity of the dam foundation. Based on the ASTM D4719 standard, the pressure initially applied was equivalent to 1 atmosphere, increasing to 3 atmospheres, for each 1m depth interval. The analysis of tests results indicated that for the Pamukcay dam, the settlements in the foundation would range between 12 to 16 mm the ultimate bearing capacity at the base of the dam was calculated as ranking between 650 to 830 kPa.

4. Seismic activity in the region

Estimating permanent displacements that an earthen/rockfill embankment dam will undergo during an earthquake shaking is a very difficult task (Sengupta and Martin 1997). It is made more difficult by the myriad of factors that are involved and the lack of reliable field data. The ground vibrations at a site are unique to the particular earthquake causing them and to the site-specific conditions existing at the dam.

There are two main methods for the quantification of an earthquake induced hazard,

(1) Probabilistic seismic hazard analysis considers all possible earthquake scenarios that could affect the site and the results from the hazard are represented by ground motion parameters at reference ground conditions, such as peak ground acceleration and spectral acceleration.
(2) In the deterministic assessment the composite probabilistic hazard is disaggregated to distinguish between the earthquake scenarios (magnitude, distance, factored, standard deviation) for a particular site that would contribute most to the particular hazard. The determistic earthquake hazard assessment methodology involves the determination of the earthquake scenario, identification of appropriate attenuation relationships and proper site response quantification. The hazard is evaluated using both intensity and PGA based attenuation relationships (Siyahi and Aslan 2008).

In order to assess the dynamic response of the Pamukcay Dam, it is necessary to take into account the seismic risk in the region. Anatolia is situated on one of the most seismically active regions in the world, named as Alpine-Himalayas Belt. According to McKenzie (1972); the Anatolian Peninsula is composed of Anatolian, Black Sea and Aegean micro-plates surrounded by the Eurasian, Arabian and African macro-plates. Due to the relative mutual movements of the micro and macro plates, the North Anatolian Fault zone and East Anatolian Fault zone were created. The south east part of the Turkey is also affected by the movement of the Eurasian and Arabian plates. The movement of the Arabian plate to the north and the Eurasian plate to the west as shown in Fig. 2 led to the formation of Southeastern Anatolian Thrust Belt and the sinistral East Anatolian Fault Zone structures in South East Turkey (Şengor *et al*. 1985, Şaroglu *et al*. 1992, Kaymakci *et al*. 2006). Several fault-bounded basins generally filled with alluvial-fan, fluvial and lacustrine deposits (Hempton *et al*. 1981, Önal 1995 a, b) were formed in relation to these major structures. The East Anatolian Fault System is a 600km long, approximately aligned NE-SW left lateral strike-slip fault zone, extending to the southwest from from the Karliova triple junction to another triple junction at the Amik basin.

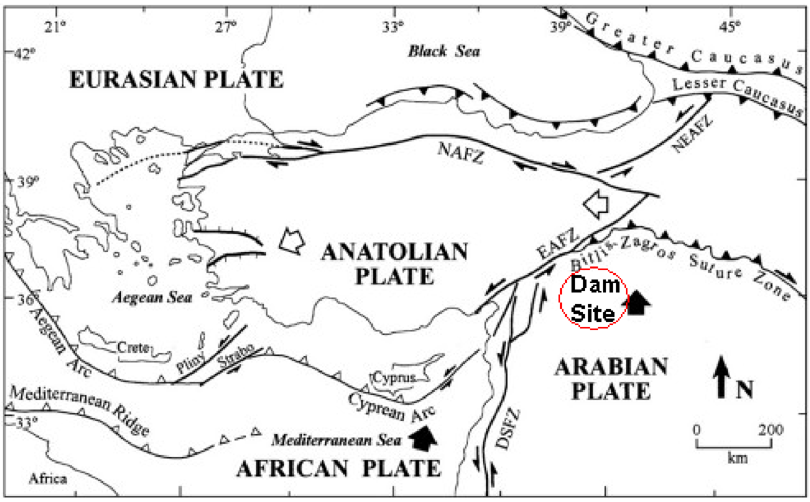


Fig. 2 Simplified map showing the location of the dam in relation to the major plates with their boundary faults

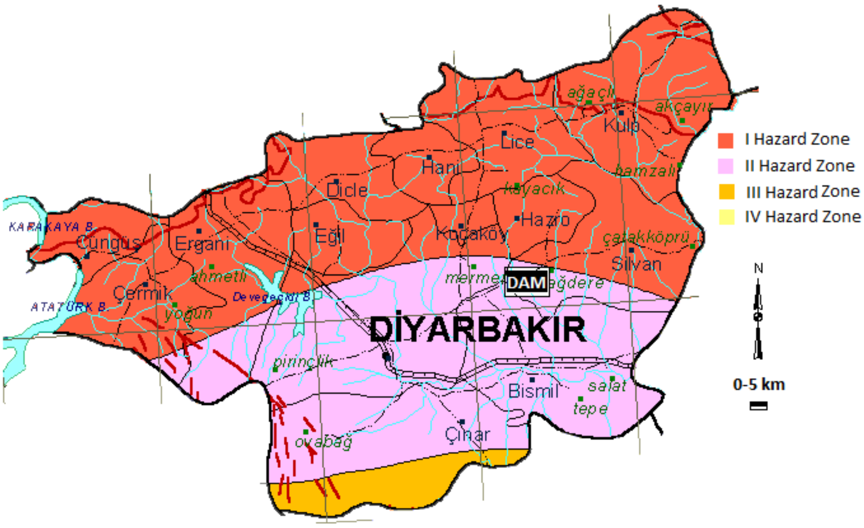


Fig. 3 Seismic hazard zone of Diyarbakır (Turkish Earthquake Code 2006)

According to historical sources more than 1,170 destructive earthquakes had occurred from B.C. 2100 to 1900 A.D. in Anatolia. Between the years 1903-1996 there were 168 strong and destructive in Turkey causing large numbers of fatalities, injuries and loss of property. Based on this data, in 1996 the Turkish Earthquake Zoning Map was prepared by the Ministry of Public Works and Settlement. The map divides Turkey into 5 risk zones, 95% of the total population and 92% of the existing or planned dams are in earthquake risk zones. Based on the Earthquake Zoning Map; Fig. 3. shows that the dam site is in II. Hazard Zone Area.

For the seismic design of dams, abutments and safety relevant components (spillway gates, bottom outlets, etc.) the following types of design earthquakes are used Wieland (2005);

(a) Operating Basis Earthquake (OBE): The OBE design is used to limit the earthquake damage to a dam project and, therefore, it is mainly a concern of the dam owner. Accordingly, there are no fixed criteria for the OBE although ICOLD has proposed an average return period of ca. 145 years (50% probability of exceedance in 100 years).

(b) Maximum Credible Earthquake (MCE), Maximum Design Earthquake (MDE) or Safety Evaluation Earthquake (SEE): The MCE is a deterministic event, and is the largest reasonably conceivable earthquake that appears possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. But in practice, due to the problems involved in estimating the corresponding ground motion, the MCE is usually defined statistically with a typical return period of 10,000 years.

Within all the frameworks of these assessments for the Pamukcay dam seismic design considering the MDE, the peak ground acceleration values and maximum horizontal earthquake coefficient was selected as 0.23 g and the input earthquake motion was sielected from a real acceleration time histories recorded on the Eastern Anatolian Fault considering the MDE. The Pamukcay dam construction site is subject to seismic activities from the East Anatolian Fault which is in a northeasterly direction, starting from the Maras province and ending at the Karlıova province where it meets the North Anatolian Fault. The Bingol earthquake occurred in 2003 on the East Anatolian Fault, with the epicentral distance close to dam site, this event was used in the dynamic analysis (Fig. 4). The input motion for the seismic analysis was selected considering the acceleration response spectrum given in Turkish Earthquake Code (TEC 2006).

The Bingol Earthquake (2003) affected Bingol Province in the Earstern part of Turkey. The epicentral coordinates were 38.99870 latitude and 40.46370 in longitude with a magnitude of *Mw* = 6.3 at the depth of 10 km. The earthquake motion was recorded in the Ministry of Environment and Urbanisation, located in the Bingol Province Directorates Building where the soil profile beneath the recording station has an average shear wave velocity of Vs 30 = 529 m/s determined by Republic of Turkey Prime Ministry Disaster and Emergency Management Presidency. The acceleration response spectrum of the North-South component of the Bingol Earthquake (2003) and the response spectrum given in Turkish Seismic Code 2006 for the 2nd Earthquake Zone with

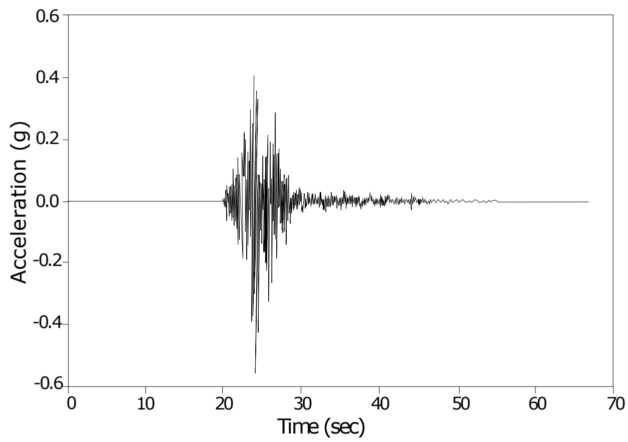


Fig. 4 Horizontal acceleration input data ofBingol earthquake (01.05.2003)

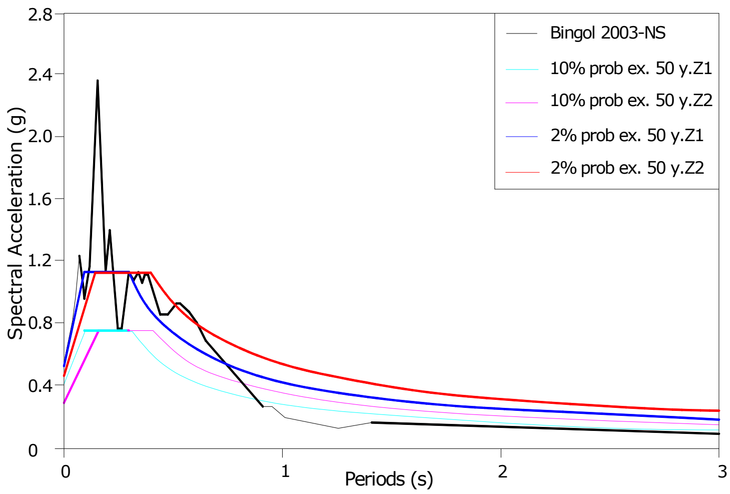


Fig. 5 Comparison of acceleration response spectrums of Bingol Earthquake (2003) and Turkish Seismic Code (2006)

respect to different local site conditions are given in Fig. 5. The local site class of Z1 stands for very dense or hard soils, and Z2 represents very stiff or dense soils. The spectrum given by the Seismic code is valid for ground motions having a 10% probability of exceedance within 50 years, in which the return period is 475 years for building type structures. According to the Seismic Code, ordinates can be increased by 1.5 times for important structures to satisfy the immediate occupancy criteria where the ground motions have a 2% probability of exceedance within 50 years, which has 2475 years of return period. Since there is no special seismic code for dams, the response spectrum of TEC2006 for 2nd earthquake zone is used to select input motion in order to be able to perform dynamic analysis. As can be seen in Fig. 5 the Bingol Earthquake (2003) is compatible with the response spectrum given in the seismic code.

5. Numerical analysis

In the last century, geotechnical earth dam engineers mainly focused their attention on the knowledge of empirical standards of design of dam structures against earthquakes guided by past experience. However, the study of seismic response of earth dams is complicated and requires the use of dynamic analysis at different levels of sophistication in terms of appropriate problem formulation, characterization of material properties and modeling of stress-strain soil behavior. The development of FE analyses permitted the evaluation of the overall patterns of dam behavior in terms of displacements and acceleration fields. The rapid development of computer programs has revolutionized earthquake engineering research. Computer programs such as, QUADAM4M, ITASCA, SHAKE2000, TELDYN are being used worldwide for the seismic analysis of earth dams.

This paper presents a numerical study of seismic behavior of earth dam overlaying bedrock subjected to real earthquake record using fully non-linear analysis. Seepage and earthquake induced failure possibility of the dam slopes were evaluated. The Bingol earthquake (2003) data was applied to the model for the dynamic analysis and to estimate the seismic behavior of the dam during earthquake loading.

In the calculations both the static and seismic of the Pamukcay dam were performed using the Quake/W FEM software package. This software consists of a two-dimensional, dynamic finite element that uses equivalent linear strain dependent modulus and damping properties. It uses a time-step analysis with Rayleigh damping and allows for variable damping for different elements. The software uses an iterative process to estimate nonlinear strain-dependent properties. Initially, the shear modulus and damping ratios are estimated for each element in the finite element model, and the system is analyzed using these initial properties. After each cycle, the values of the effective shear strain are computed for each element, and the corresponding modulus and damping properties, at the computed strain level, are compared with the estimated from the previous iteration. The analysis is repeated until convergence is achieved.

5.1 Static analysis

In non-linear problems the histories of stresses and strains at any point are necessary for comparison with the failure stresses or strain criteria. Therefore before any dynamic analysis, static analysis should be carried out to establish the existing in-situ stresses. The static stress distribution affects the seismic response and stability of the dam in two ways.

(1) The ratio of the initial static stress to the static normal stress affects the cyclic strength of the embankment and foundation materials (Duncan *et al*. 1984).
(2) The dynamic shear modulus of the dam structure and foundation materials depends on the static confining pressure.

In the first phase of the numerical studies; a sub-stage was modeled using the QUAKE/W 'in-situ stress' module and this is used to simulate the development of geostatic stresses in a dam in an empty reservoir condition (hence, just after construction). Pamukcay dam rests on a thick foundation rock. The bottom of the foundation rock has been restrained from both horizontal and vertical movements, while the far-off lateral boundaries have been restricted from only horizontal displacements. The static finite element mesh consisted of 2,319 elements and 2,848 nodes. The mesh geometry of the dam foundation system is given in Fig. 6.

In the second phase of the static analysis, hydrostatic pressure applied to the upstream face of the dam using the 'Load-deformation analysis' unit of the SIGMA/W module. Based on the full reservoir level, the hydrostatic pressure is calculated for a triangular variation towards the base of the reservoir (hydrostatic pressure, is calculated using ($P = h \times \gamma$) where "γ∀ is the unit weight of

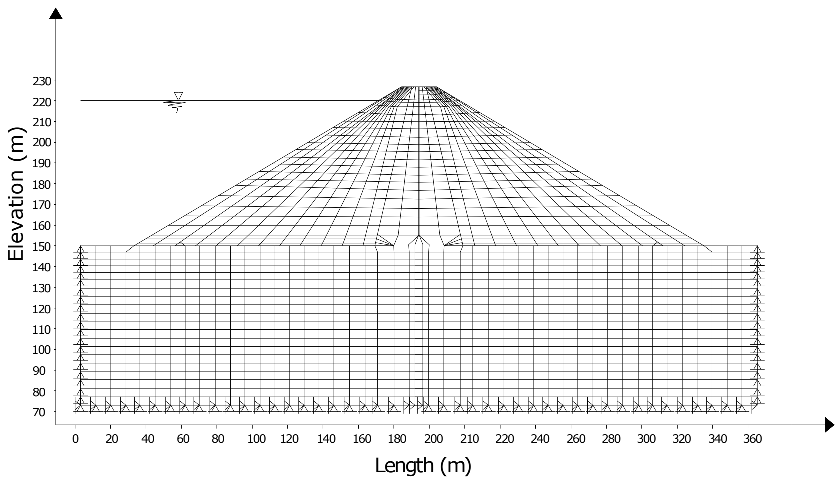


Fig. 6 Two Dimensional finite element mesh of the Pamukcay dam

Table 2 Geotechnical parameters used in the static analysis

	Earth fill	Fitler	Core	Shell	Şelmo formation
Bulk modulus (kPa*)	790	3850	1780	12000	17200
Poisson's ratio	0.30	0.27	0.40	0.35	0.45
Unit weight (kN/m^3)	18	19	19	20	20
Friction angle (°)	30	35	0	39	35
Cohesion (kPa)	15	0	70	0	500
Permeability (m/sn)	1 × 10-5	7	2 × 10-9	10-4	1 × 10-7

*Average stress values close the foundation level were used. The bulk modulus varies depending on shear stress conditions. Eq. (1) was used for the analysis water and "*h*" is the depth from the reservoir water level), with a zero value at the reservoir water level. Continuous hydrostatic pressure is applied as pressure on the upstream face of the dam.

It is accepted that the geotechnical parameters of earth materials play a significant role in the stability of a dam body. In particular the compaction and gradation quality is essential to minimize deformations and leakage. The geotechnical parameters used in the numerical analysis for the earthfill, impervious zone and foundation are presented in Table 2.

To obtain the bulk modulus (G) of the dam material the equation created by Seed *et al*. (1985) was used as shown in the following equation

$$G = 1000 \times K_2 \times (\sigma'_m) \tag{1}$$

Where K_2 and σ_m are the constant and effective mean stress, respectively. For the K_2 constant 150 was selected, according to the recommendation made by Seed *et al*. (1985). For the effective stress the average was calculated as 1 atm (100 kPa). Initially the static analysis of the dam for dead weight was performed using the parameters given above. The corresponding static stress vector and load are stored for the earthquake analysis of the dam. Fig. 7. shows the contours of stress distribution obtained from the numerical studies.

As seen in the Fig. 7 maximum stress distributions occurred in the middle of the dam body and stresses appeared to concentrate in the basement of dam body, similar to the dam behaviors reported in the literature. The calculated vertical stresses are consistent with the weight of the rock fill material. In addition, the calculated stress distributions are lower than 0.1%, therefore no problems would be expected in terms of the stability of the dam for static conditions.

5.2 Dynamic analysis

In this study, Quake/W FEM software was used to evaluate the seismic dam-foundation response. This two dimensional dynamic finite element software uses equivalent linear strain dependent modulus and damping properties. In general, material damping in a soil body is generated by the viscous properties, internal friction angle and development of plasticity. The role of damping in the numerical models is to generate energy losses in the natural system when subjected to a dynamic load. The dynamic damping in the model is provided by the Rayleigh damping option available in Quake/W. The program uses an iterative process to estimate non-linear strain dependent properties. At the beginning the shear modulus and damping ratios are estimated for each element in the finite element model and the system is analyzed using

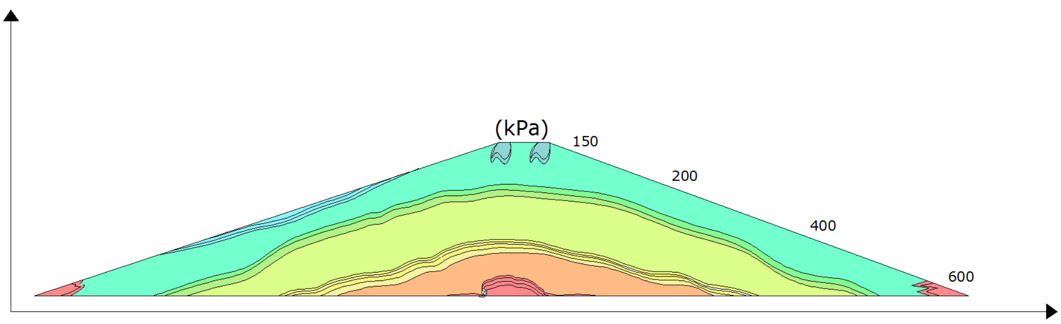


Fig. 7 Stress distribution for initial static analysis

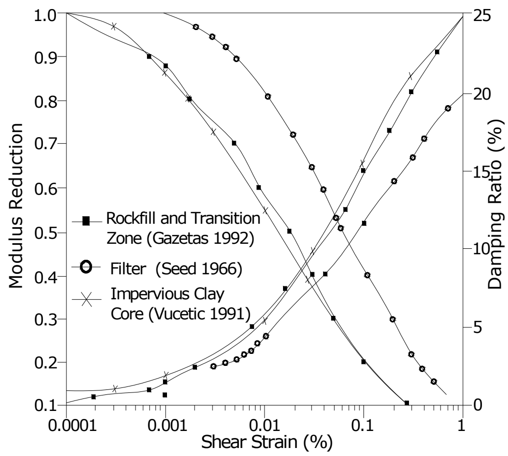


Fig. 8 Damping factor

these initial properties. After each cycle the values of effective shear strain are computed for each element, then the corresponding modulus and damping properties at the computed stain level are estimated from the previous iteration. The analysis is repeated until convergence is achieved. In all the analysis standard earthquake boundary conditions were used as suggested by the software manual (Geostudio 2007).

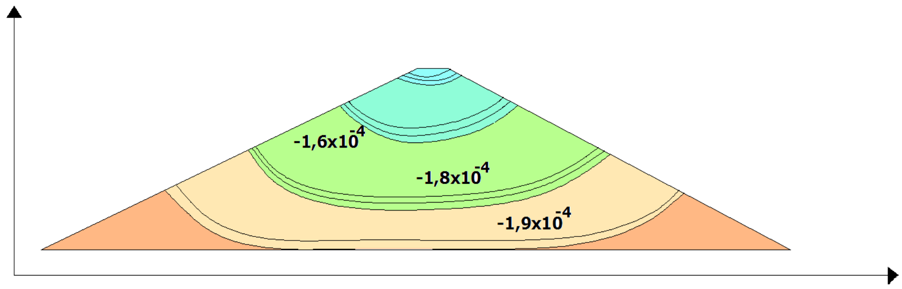
Dynamic shear modulus values at low strain can either be measured in the laboratory using a resonant column test or obtained from field measurements of the shear wave velocity. When available, estimates of Gmax based on the field measurements are preferable to laboratory test data.

The strain dependency of the shear modulus and damping ratios used in this analysis for rockfill and transition zone are based on the curve suggested by Gazetas and Dakoulas (1992), filter materials by Seed *et al*. (1985) and the impervious core by Vucetic and Dobry (1991). The relationships between the modulus reduction factor G/Gmax and damping ratio are given in Fig. 8.

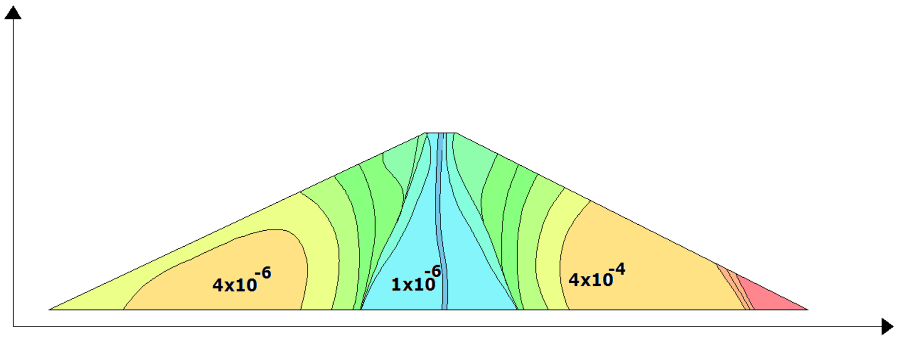
Dynamic deformation analysis was considered incremental stresses as a driving force for permanent deformation based on stress redistribution. As it is mentioned in Rampello *et al*. (2009), permanent displacement are resulted from plastic strains that accumulate during the earthquake because of progressive plastic loading which are influenced by the duration of the strong motion.

In this study; dynamic deformation analysis the crest behavior was selected as the parameter to represent earthquake related deformations because it is the most frequently mentioned quantified measurement of damage presented in dam studies. The amount of crest settlement is related primarily to two factors; the peak ground acceleration at the dam site and the magnitude of the causative earthquake. The computed displacements and stress distribution along the dam body are shown in Figs. 9(a)-(b) and Figs. 10(a)-(b).

As seen in Figs. 9(a)-(b) and Figs. 10(a)-(b) displacements increased with the increased height of the dam. When most of the dam section is under strong base excitation a distributed slumping may take place rather than failure along a discrete surface. Permanent deformations appear to concentrate in the upper third of the dam crest. In general, according to the literature, under the earthquake shaking the crest settlements of embankment dams should not exceed 1 or 2% of the dam height. From the static and seismic analysis in Quake/W, it can be concluded that seismic

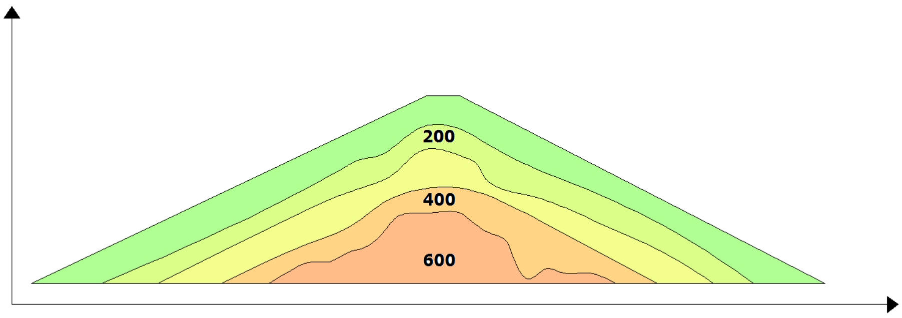


(a) Relative vertical displacement (m)

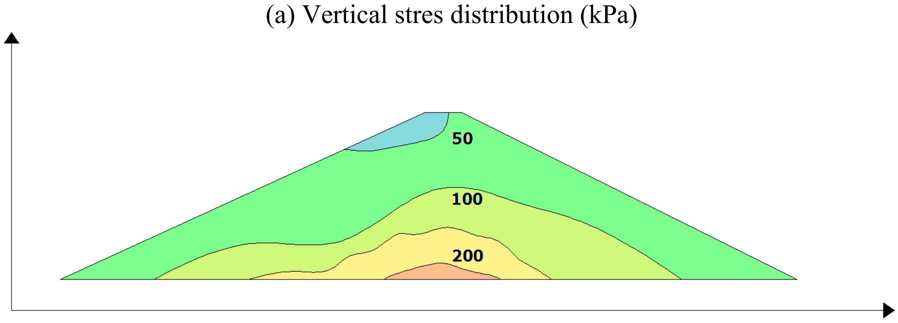


(b) Relative horizontal displacement (m)

Fig. 9 Earthquake induced deformation behavior of Pamukcay Dam



(a) Vertical stres distribution (kPa)



(b) Horizontal stress distribution (kPa)

Fig. 10 Earthquake induced stress behavior of Pamukcay Dam

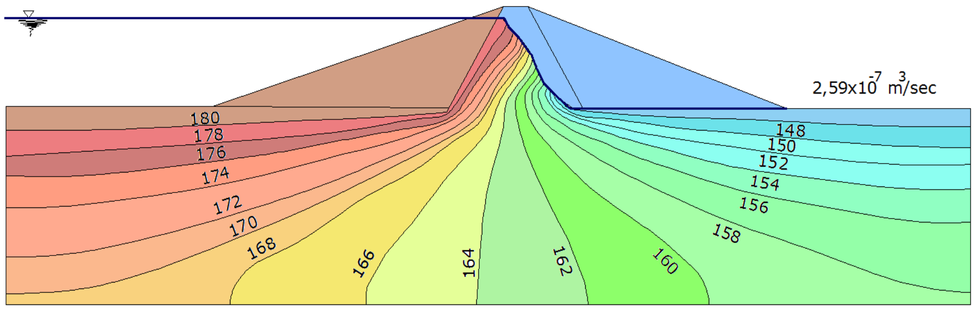


Fig. 11 Seepage analysisDamping Factor

loading has a notable effect on the deformation of the dam. As seen from the dynamic analysis, the maximum shear deformations at the dam body and foundation are under 0.1%. These results show that a seismic loading is unlikely to present a serious problem in terms of the overall stability of the dam.

5.3 Seepage analysis

All dams on earth foundations are subject to under-seepage. Seepage control is necessary to prevent excessive uplift pressures and piping through the foundation. Generally, siltation of the reservoir tends to diminish under-seepage over time. In this study, the Pamukcay dam site is modeled with SEEP/W model which could be used to analyze both simple and complex seepage problems. The SEEP/W model uses the finite element method for two dimensional Darcy's flow in both saturated- unsaturated soils.

The application of dam model was made by sketching the earth dam cross section which is discrete into a finite element mesh as shown in Fig. 11 consisting of triangular and quadrilateral regions. According to the seepage analysis, the flow of the water is obtained as 0.022 m^3/day/m.

5.4 Slope stability

Evaluating the stability of the upstream and downstream slopes of dam structures is one of the most important issues in dam engineering. A stable slope under static conditions is thought to have resistance to sliding which is greater than the driving forces that exist due to the slope geometry. However, seismic loading of a slope can induce greater driving forces that will potentially make a once stable slope unstable. A slope that fails under seismic loading usually does so rapidly, and due to the nature of earthquakes, unexpectedly, with potentially great losses. The permanent slope displacement from seismic force depends on dam geometry, material properties, reservoir water level, and ground motion parameters. In this study, static and dynamic slope stability analyses were performed using SLOPE/W software. The safety factor corresponding to the critical failure surface was calculated according to the Bishop simplified method (1955) for each case. The seismic coefficient was computed as the maximum value of the ratio of the earthquake induced force along the slip circle to the mass of the failure surface. Based on the recommendations made by Makdisi and Seed (1978) the horizontal seismic coefficient (k_h) value was selected as 0.14 for the analysis. The vertical seismic coefficient (k_v) value was applied as 50% of the horizontal

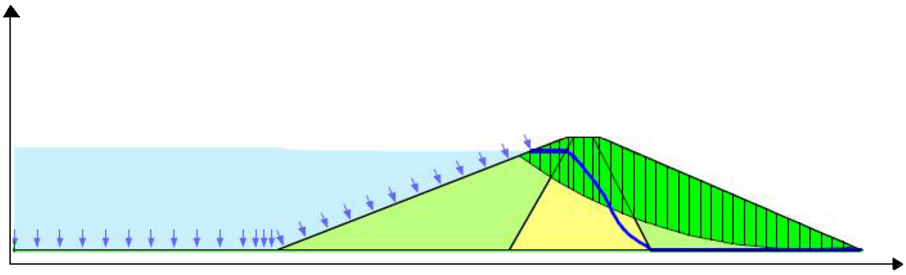


Fig. 12 Slope stability analysis

Table 3 Slope stability of Pamukcay Dam

	Safety factor	
	Upstream	Downstream
After Construction	1.701	1.243
Maximum Reservoir Level	1.163	1.458
Max Res. Level + Seismic Load	1.156	1.151

seismic coefficient (k_h) value = 0.070. The factor of safety values downstream and upstream of the dam body are presented in Fig. 12 and Table 3.

As for the effect of the reservoir water level, it was found that the horizontal displacement increases as the reservoir water level increases. However, the affect is not significant in terms of the safety of the dam.

6. Conclusions

This study has shown that, a non-linear analysis capable of capturing dominant non-linear elasto-plastic response mechanism can be very effective in assessing the stability of a earth fill dam structure. A preliminary study of the dynamic response of Pamukçay Dam was achieved via a 2-D finite element analysis using a real earthquake motion. The dynamic properties of the dam were calculated based on the available dam properties. Seismic response of the dam was performed by nonlinear analysis using an iterative process to estimate non-linear strain dependent properties. Plasticity of soil is taken into consideration by changing corresponding modulus and damping properties at the computed strain level at each cycle. A dynamic analysis is performed by using a spectrum compatible earthquake motion which is selected from the earthquakes that have occurred in the closest fault have strongly affected the dam site. The results show that the dynamic behavior of the Pamukcay Dam appears to provide an adequate basis to upon which the stability and deformations of the dam body under the Bingöl earthquake (2003). The results of the analysis showed that, even though the dam was excited by the Bingol earthquake record, the responses found in this study showed no significant dam hazard. It was seen on results that deformations increased with the increasing dam height in which the magnitude of displacements are very limited. Earthquake induced crest settlements and permanent deformations appear to concentrate in the upper third of the dam crest. In the view of findings of the slope stability analysis, the horizontal displacement increases as the reservoir water level increases. It was found that there is no significant change in terms of the safety of the dam. Furthermore, according to seepage analysis performed seepage per unit volume and magnitude of the seepage forces under the dam are in low range.

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References

Abdel-Ghaffar, A.M. and Scott, R.F. (1979), "Analysis of earth dam response to earthquakes", *J. Geotech. Eng. Div. ASCE*, **105**(12), 1379-1404.

Ambraseys, N.N. and Sarma, S.K. (1967), "The response of earth dams to strong earthquakes", *Geotechnique*, **17**(2), 181-213.

Arici, Y. and Özel, H.F. (2013), "Comparison of 2D versus 3D modeling approaches for the analysis of the concrete faced rock-fill CokalDam", *Earthq. Eng. Struct. Dyn.*, **42**(15), 2277-2295.

Bishop, A.W. (1955), "The use of the slip circle in the stability analysis of slopes", *Geotechnique*, **5**, 7-17.

Bray, J.D. and Travasarou, T. (2007), "Simplified procedure for estimating earthquake-induced deviatoric slope displacements", *J. Geotech. Eng., Div. ASCE*, **133**(4), 381-392.

Duncan, J.M., Seed, R.B., Wong, K.S. and Ozawa, U. (1984), "FEADAM: A computer program for finite-element analysis of dams", Department of Civil Engineering, Stanford University; Geotechnical Engineering Research Report No. Su/GT/84-03, November.

Ebrahimian, B. (2011), "Numerical analysis of nonlinear dynamic behavior of earth dams", *Front. Archit. Civ. Eng. China*, **5**(1), 24-40.

Elgamal, A.M. and Abdel-Ghaffar, A.M. (1987), "Elasto-plastic seismic response of 3-D earth dams: applications", *J. Geotech. Eng. Div. ASCE*, **113**(11), 1309-1325.

Elgamal, A.M., Scott, R.F., Succarieh, M.F. and Yan, L. (1990), "La Villita dam response during five earthquakes including permanent deformation", *J. Geotech. Eng. Div. ASCE*, **116**(10), 1443-1462.

Elia, G., Amorosi, A., Chan, A.H.C. and Kavvadas, M.J. (2011), "Fully coupled dynamic analysis of an Earth dam",*Geotechnique*, **61**(7), 549-563.

Gazetas, G. (1985), "Seismic response of earth dams: Some recent developments", Keynote Address; *Proceedings of the 2nd International Conference on Soil Dynamics and Earthquake Engineering*, New York, NY, USA, June.

Gazetas, G. and Dakoulas, P. (1992), "Seismic analysis and design of rockfill dams: State of the art", *Soil Dyn. Earthq. Eng.*, **11**(1), 27-61.

Gazetas, G. and Uddin, N. (1994), "Permanent deformation on preexisting sliding surfaces in dams", *J. Geotech. Eng. Div. ASCE*, **120**(11), 2041-2060.

Hempton, M.R., Dewey, J.F. and Şaroğlu, F. (1981), "The east anatolian transform fault: Along strike variations in geometry and behavior", *EOS Trans.*, **62**, 393 p.

Kaptan, C. (1999), "Basic criters for selection of seismic design coefficient in dam project", *Proceedings of the 2nd Balkan Geophsical Congress and Exhibition*, Istanbul, Turkey, July.

Kaymakçı, N., İnceöz, M. and Ertepınar, P. (2006), "3D-architecture and Neogene evolution of the Malatya Basin: inferences for kinematics of the Malatya and Ovacık fault zones", *Turkish J. Earth Sci.*, **15**(2), 123-154.

Lin, J.S. and Whitman, R.V. (1983), "Decoupling approximation to the evaluation of earthquake-induced

plastic slip in earth dams", *Earthq. Eng. Struct. Dyn.*, **11**, 667-678.
Lin, J.S. and Whitman, R.V. (1986), "Earthquake induced displacements of sliding block", *J. Geotech. Eng. Div. ASCE*, **105**(12), 1427-1434.
Li, H., Chi, S., Lin, G. and Zhong, H. (2008), "A modified approach for determination of nonlinear properties in seismic response analyses for 200 m high core rock-fill dams", *Can. Geotech. J.*, **45**(8), 1064-1072.
Makdisi, F.I. and Seed, H.B. (1978), "Simplified procedure for estimating dam and embankment earthquake induced deformations", *J. Geotech. Eng. Div. ASCE*, **104**(7), 849-867.
Martin, P.P., Niznik, J.A. and Sengupta, A. (1993), "Prediction of static and dynamic deformation response of blue ridge dam, Georgia, USA", *International Workshop on Dam Safety Evaluation*, Switzerland.
Martin, P.P. and Sengupta, A. (1994), "Numerical analysis of bath county upper reservoir dam", *The 3rd ICOLD Benchmark Workshop on Numerical Analysis of Dams*, Paris, France, September.
Masing, G. (1926), "Eigenspannungen und der merfestgungbeim messing", *Proceedings of the 2nd International Congress for Applied Mechanics*, Zürich, Switzerland, September, pp. 332-335.
McKenzie, D. (1972), "Active tectonics of the Mediterranean, Geophys", *J. R. Astr. Soc.*, **30**(2), 109-185.
Mejia, L.H. and Seed, H.B. (1983), "Comparison of 2D and 3D dynamic analyses of earth dams", *J. Geotech. Eng. Div. ASCE*, **109**(11), 1383-1398.
Mejia, L.H., Seed, H.B. and Lysmer, J. (1982), "Dynamic analysis of earth dam in three-dimensions", *J. Geotech. Eng. Div. ASCE*, **108**(12), 1586-1604.
Mircevska, V. and Bickovski, V. (1998), "Two dimensional nonlinear dynamic analysis of rockfill dam", *Internatioanl Symposium of Dam Safety*, Barcelona, Spain, 2, pp. 859-866.
Narita, K. (2000), "Design and construction of embankment dams", Lecture Notes; Department of Civil Engineering, Aichi Institute of Technology, Toyota, Japan.
Newmark, N.M. (1965), "Effects of earthquakes on dams and embankments", *Geotechnique*, **15**(2), 139-160.
Önal, M. (1995a), "Malatya Grabenhavzasıkuzeyininstratigrafisi, kömür potansiyeli ve neotektoniği", Süleyman Demirel Üniversitesi, *Müh. Mim. Fak. Jeoloji Müh. Seksiyonu*, Isparta, s.8, pp. 159-175.
Önal, M. (1995b), "Miocene stratigraphy and lignite potential of the northern part of the Malatya graben, Eastern Anatolia – Turkey", *Proceedings of International Earth Sciences Colloquıum on the Aegean Region*, İzmir, Turkey, October, pp. 607-621.
Ozkan, M.Y., Erdik, M., Tuncer, M.A. and Yilmaz, C. (1996), "An evaluation of Surgu Dam response during 5 May 1986 earthquake", *Soil Dyn. Earthq. Eng.*,**15**(1), 1-10.
Papalou, A. and Bielak, J. (2004), "Nonlinear seismic response of earth dams with canyon interaction", *J. Geotech. Eng. Div. ASCE*,**130**(1), 103-110.
Papadimitriou, A.G., Bouckovalas, G.D. and Andrianopoulos, K.I. (2014), "Methodology for estimating seismic coefficients for performance-based design of earth dams and tall embankments", *Soil Dyn. Earthq. Eng.*, **56**, 57-73.
Piao, R., Rippe, A.H., Myers, B. and Lane, K.W. (2006), "Earth dam liquefaction and deformation analysis using numerical modeling", *Proceeding of the Geo Congress 2006*, *ASCE*, Atlanta, GA,USA, February-March.
Prevost, J.H., Abdel-Ghaffar, A.M. and Lacy, S.J. (1985), "Nonlinear dynamic analyses of an earth dam", *J. Geotech. Eng. Div. ASCE*, **111**(7), 882-897.
Rampello, S., Cascone, E. and Grosso, N. (2009), "Evaluation of seismic response of a homogenous earth dam", *Soil Dyn. Earthq. Eng.*, **29**(5), 782-798.
Roa, F.R. and Gamboa, L.A. (1996), "Seismic analysis of concrete-faced gravel fill dams", *Proceedings of the International Symposium on Seismic and Environmental Aspects of Dams Design*, (Volume 1), Santiago, Chile, October.
Sarma, S.K. (1975), "Seismic stability of earth dams and embankments", *Geotechnique*, **25**(4), 743-761.
Şaroğlu, F., Emre, O. and Kuşçu, I. (1992), "The east anatolian fault zone of Turkey", *Ann. Tectonicae*, **6**, 99-125.
Seed, H.B. (1966), "Method for earthquake resistant design of earth dams", *J. Soil Mech. Found. Div.*, *ASCE*, **92**(SM1), 13-41.
Seed, H.B. (1973), "Analysis of the slides in the San Fernando Dams during the Earthquake of February 9,

1971", Report No. EERC 73-2; Earthquake Engineering Research Center, University of California, Berkeley, CA, USA.
Seed, H.B. and Martin, G.R. (1966), "The seismic coefficient in earth dam design", *J. Geotech. Eng., ASCE*, **92**(3), 25-58.
Seed, H.B., Lee, K.L. and Idriss, I.M. (1969), "Analysis of the sheffield dam failure", *J. Soil Mech. Found. Div. ASCE*, **95**(6), 1453-1490.
Seed, H.B., Seed, R.B., Lai, S.S. and Khamenehpour, B. (1985), "Seismic design of concrete-face rockfilldams", *Proceedings of Symposium on Concrete-Face Rockfill Dams-Design, Construction and Performance, ASCE*, New York, NY, USA, pp. 459-478.
Şengör, A.M.C., Gorur, N. and Saroglu, F. (1985), "Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study", *Soc. Econ.*; *Paleontol Mineral*, Special Publication, **37**, 227-264.
Sengupta, A. (2010), "Estimation of permanent displacements of the Tehri dam in the Himalayas due to future strong earthquakes", *Sadhana*, **35**(3), 373-392.
Sengupta, A. and Martin, P.P. (1997), "Earthquake-induced permanent deformations in earth dams: From a challenge to practice", *ICOLD 97*, Madrid, Spain, pp. 745-768.
Serff, N., Seed, H.B., Makdisi, F.I. and Chang, C.Y. (1976), "Earthquake induced deformations of earth dams", Report No. EERC 76-4; Earthquake Engineering Research Center, University of California, Berkeley, CA, USA.
Sevim, B., Bayraktar, A. and Altunişik, A.C. (2011), "Finite element model calibration of berke arch dam using operational modal testing", *J. Vib. Cont.*,**17**(7), 1065-1079.
Sherard, J.L. (1967), "Earthquake considerations in earth dam design", *J. Soil Mec. Foun. Div., ASCE*, **83**(SM-4), 377-401.
Sica, S. and Pagano, L. (2009), "Performance-based analysis of earth dams: Procedures and application to a sample case", *Soils Found.*, **49**(6), 921-939.
Sica, S., Pagano, L. and Modaressi, A. (2008), "Influence of past loading history on the seismic response of earth dams", *Comput. Geotech.*, **35**(1), 61-85.
Siyahi, B. and Arslan, H. (2008), "Earthquake induced deformation of earth dams", *Bull. Eng. Geo. Env.*, **67**(3), 397-403.
Terzi, N.U. (2011), "Evaluation of the dynamic response of the Damlapinar CFR dam", *Bull. Eng. Geo. Env.*, **70**(3), 429-438.
Turkish Earthquake Code (2006), Ministry of Public Works and Resettlement, Ankara, Turkey.
Vrymoed, J. (1981), "Dynamic FEM model of Oroville dam", *J. Geotech. Eng. Div. ASCE*, **107**(8),1057-1077.
Vucetic, M.V. and Dobry, R. (1991), "Effect of soil plasticity on cyclic response", *J. Geotech. Eng. Div. ASCE*, **117**(1), 89-107.
Wieland, M. (2005), "Review of seismic design criteria of large concrete and embankment dam", *Proceedings of the 73rd Annual Meeting of ICOLD*, Tehran, Iran, May.
Yan, L. (1991), "Seismic deformation analysis of earth dams: A simplified method", Report No. SML 91-01; Soil Mechanics Laboratory, California Institute of Technology, Pasadena, CA, USA.
Zhang, J.W., Cheng, S.Z., Yuan, S.F. and Zhao, Y. (2012), "3D finite element analysis of concrete face rockfill dam", *Appl. Mech. Mater.*, **238**, 264-267.
Zienkiewicz, O.C., Leung, K.H. and Hinton, E. (1980), "Earth dam analysis for earthquakes: Numerical solutions and constitutive relations for nonlinear (damage) analysis", *Conference on Design of Dams to Resist Earthquake, ICE*, London, UK, October, pp. 141-156.

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