Review on Seismic Design of Concrete Gravity or RCC Dams with Design Examples

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SUMMARY:
Evaluation of seismic behaviour of concrete gravity or RCC dams are discussed by giving examples of designed dams. Information is given on the performance criteria required for operating basis earthquake and maximum design earthquake, with the relevant solution methods that can be used accordingly. The seismic coefficient method is discussed and the related design of Cindere Dam of H_{max} = 107 m is summarized. Time history analyses, widely used in recent years are widely covered, which allow to determine the stress levels by linear models, but also can be used to estimate post-earthquake damage especially for dams in high seismic areas. The issues about modelling of the system composed of dam body, foundation and reservoir are briefly reviewed. The seismic design of Pervari Dam of RCC type with H_{max} = 180 m is presented. The related earthquake parameters, load conditions, performance criteria and the results are given in detail.

Keywords: Concrete dam, time-history, seismic

1. INTRODUCTION

International specifications suggest, the methods to be followed and scope of the seismic calculations for the seismic design of dams, to be determined based on the properties such as the dam location, type, height and seismicity. In parallel to the advancement of computer hardware technologies and analysis programs in the recent years, researchers and engineers prefer to use advanced analysis methods in the evaluation of earthquake behaviour for dams. Accordingly, in the seismic design of the concrete gravity dams, different approaches ranging from conventional simplified pseudo-static methods to improved non-linear analyses where various fracture mechanics algorithms can also be employed are used. The two decisive points in the seismic safety assessment of this type of dams can be summarized as: triggering of the sliding for one or multiple blocks along the potential joints and the earthquake-generated stresses and deformations to remain within the acceptable limits (Bureau, 2003). Therefore, the analysis method used in the design should allow to examine the realistic behaviour of the dam under different load conditions.

In this paper, a brief review has been made about the two common methods related to the earthquake design of concrete gravity or roller compacted concrete (RCC) dams, and examples of dams designed with the respective methods have been presented.

2. SEISMIC DESIGN CRITERIA

The first stage in the assessment of the seismic safety for dams is the determination of the seismicity and earthquake parameters at the dam location. The evaluation about the peak ground acceleration (PGA), and site-specific response spectra and acceleration time-history records which may be required according to the design approach, have been excluded from the scope of this paper.

ICOLD (Bulletin – 72, 1989) and USACE (2007) proposes two different earthquake levels to consider in the earthquake design of dams. These are named as the operating basis earthquake, OBE and the maximum design earthquake, MDE (or safety evaluation earthquake, SEE as suggested by ICOLD Bulletin – 72,2010). OBE has been defined as the earthquake with a return period of 144 years by ICOLD (1989), so can be best determined by probabilistic seismic hazard analysis pursuant to the definiton. After an earthquake of this level, the dam, appurtenant structures and equipment need to remain functional and the damage need to be easily repairable. USACE (1995), finds it necessary for the stress levels in the concrete gravity dams to remain within the elastic region in case of OBE.

The MDE (or SEE) defined as the earthquake that generates the maximum ground motion level according to the assumed tectonics, to be used in the design. It can be obtained deterministically by considering the maximum credible earthquake (MCE), or by probabilistic approach with a high return period (such as 2500, 5000, 10000 years, based on the specified tectonics, seismic activity of the region, importance of the dam and risks related to the downstream). After an earthquake of MDE level, reaching of the elastic limits in the dam body and appurtenant structures, and the related damage are considered as acceptable (USACE, 1995). However, a catastrophic failure which may lead to an uncontrolled release of reservoir water or life loss should not occur.

In consequence of the potential damage after an earthquake of MDE level, the post-earthquake stability of the dam and appurtenant structures should be evaluated, also considering the possible changes in the load conditions and material parameters because of the damage; and the necessary controls such as sliding, base pressures should be made for service loads after earthquake and possible aftershocks.

In the dynamic design of the dam, different methods are required to control the performance criteria explained above for different earthquake levels and conditions. A brief information is given about the widely used two of these methods below.

3. DESIGN METHODS

3.1. Seismic Coefficient Method

The seismic coefficient method that considers the inertial forces generated by the seismic ground motion as equivalent static forces with a simplified approach, is still widely used in the sliding and base pressure checks of dams as conventional practice. The system over the potential sliding plane is regarded as a rigid block and the earthquake forces are determined by the product of the seismic coefficient with the structure mass and the hyperbolic water mass moving with the structure as suggested by Westergaard. The seismic coefficient is generally taken as a fraction of the maximum ground acceleration.

The subject method is convenient for a simple assessment of the earthquake forces and the seismic safety of the dam. Here, it is worthy to mention that, there is not an international agreement on the determination of the seismic coefficient, shear strength parameters of the potential sliding plane (e.g. cohesion + friction angle or friction angle only) and the safety factors which should be satisfied; but different criteria are suggested by different agencies. A summary of the suggested measures by different agencies and countries may be found in ICOLD European Club (2004).

In this pseudo-static approach, the dynamic properties of the system composed of dam-water-foundation and also the dynamic characteristics of the seismic ground motion are not taken into account. The significant effects of these mentioned factors have been evaluated and presented by Chopra (1988).

Another disadvantage of this method where the dam body is taken as a rigid block with a seismic coefficient acting as constant along the height of the dam is the incapability of a reliable estimation of the stresses generated within the dam body during the earthquake. As explained previously in Section 2, the stresses should be evaluated in a realistic way in order to check the performance criteria for different earthquake levels, and especially to anticipate the probable damage of dams subjected to high level ground motions. As the use of seismic coefficient method will not be always safe for the dynamic behaviour where the acceleration significantly amplifies with increasing height, this approach is supposed to be convenient in the safety checks like sliding and overturning rather at preliminary design. It is clear that the seismic behaviour of the dam should be evaluated by advanced detailed analyses especially at regions of high seismicity.

3.2. Time-history Analyses

Time-history analyses are defined as the most effective method for the assessment of dynamic behaviour of structures, as they allow the solution of equations of motion in small time steps by direct integration (USACE, 2007). In the calculation method where the equilibrium of motion is satisfied at every time step, the earthquake behaviour of the dam may be examined for the whole earthquake duration and accordingly the time variations of the stresses and deformations may be inspected. A more realistic and reliable assessment of the seismic behaviour is allowed as the foundation, reservoir water, dam body and the interactions in between may be modelled and simulated in the subject method. An extensive information about the time-history analyses may be found in USACE (2003).

Another important advantage of the time-history analysis is the solution capability for both linear and nonlinear systems, and accordingly a coherent check of the performance criteria for OBE and MDE. Besides the method gives accurate and reliable results for cases where concrete stresses are below the elastic limits; it is suggested for all dam designs to examine the behaviour beyond linear limits and estimate the potential damage by international standards (FEMA, 2005; USACE, 2007).

Vertical construction joints take place in conventionally vibrated concrete (CVC) or roller compacted concrete (RCC), and horizontal lift joints with smaller tension and shear strength compared to parent concrete are formed during the dam body construction. In a high intensity ground motion, cyclic opening-closing in the vertical joints, and cracks due to tension in the horizontal lift joints, concrete-rock contact or corners with stress concentrations are likely to occur (USACE, 2007). In this regard, most of the deformations will take place on these cracks and crack generation in other parts of the body will be prevented as the tensile stresses will reduce. Therefore, it is expected to have a few major crack surfaces in case of a large magnitude earthquake (Wieland, 2008). For such a case, there are two main approaches in order to investigate the nonlinear seismic behaviour of the dam body. These are referred as the smeared crack and discrete crack approaches.

In the smeared crack approach, the same numerical model with the linear elastic analyses is used and the crack generation and propagation is examined by utilizing a convenient nonlinear material model for concrete that is capable of simulating the crack behaviour. Detailed information and analysis examples about the subject method can be found in references such as El-Aidi (1988), Panel on Earthquake Engineering of Concrete Dams (1990), Yamaguchi et al. (2004) and Mirzabozorg and Kianoush (2008). A large number of parameters are generally required for the advanced material models for concrete in this approach, and difficulties are of concern in the assessment of them. Besides, the accuracy and validity of the solution depends on the factors like the number of elements in the model, the smallness of the load steps, the number of iterations; and the nonlinear modelling of a real inelastic behaviour is not practical even for the fast computers of present day. In this sense, simplified methods, which consider the joints and weak planes that designate the potential yielding and cracking behaviour of the dam body, are suggested (USACE, 2007; Wieland, 2008).

In the discrete approach as a simplified method, joints to simulate the sliding and gap behavior are defined at the construction joints or regions where cracking is expected according to the linear elastic analysis results, and linear behaviour is taken into account for the blocks interconnected to each other via the subject joints. The advantage of this method is that the nonlinear behaviour can be examined by using only the basic parameters for the joints. Potential blocks formed by the determined cracks based on the linear elastic results and experience in similar dams should be taken into consideration. During an earthquake, the displacement of the blocks along these crack surfaces should be evaluated, and the post-earthquake stability should be checked by using residual strength parameters of the crack surface and unfavorable distribution of the uplift pressures along the crack. The calculation details for Pervari Dam, designed with this approach are given in Section 4.

4. DESIGN EXAMPLES

4.1. Cindere Dam

Cindere Dam, construction of which has been started in January 2002 is the first hardfill dam in Turkey. The dam with a 107 m maximum height and 281 m of crest length has been designed using 0.7H:1.0V slopes at both upstream and downstream faces. Special emphasis has been placed on the structural design, stability and choice of the construction materials because of the high seismicity of the dam location on the Büyük Menderes Graben in west side of Turkey. Conventional stability analyses have been utilized for the shape and slope optimization of the dam, and finite element analyses have been conducted to determine the strength requirements. The pseudo-static approach has been adopted in both type of analyses. OBE level with a horizontal design acceleration of a = 0.2 g has been taken into account to designate the body volume and cementitious material content. Moreover the stability of the dam has been checked for MDE using a = 0.3 g. According to the results, the safety factors against sliding have been obtained as 1.39 and 1.05 for OBE and MDE cases respectively, which are satisfactory with respect to DSİ (General Directorate of State Hydraulic Works) criteria.

The most important advantage of the symmetrical slope used in hardfill type dams is to provide the body to be subject to compressive stresses in all load cases. In this regard, the cyclic shear stresses induced by the earthquake forces can be resisted by friction forces generated under compression, eliminating the requirement for a high target strength or an extensive improvement of the lift joints with bedding mortar. Moreover, the large dam base allows the dam to be constructed on relatively weak rock foundations. The design method has been found as satisfactory, considering the dam type, dimensions and obtained results; a more rigorous seismic design has not been deemed as necessary. The required compressive strength has been determined as 6 MPa to satisfy the stress and durability criteria for the most unfavorable conditions; in this regard the target strength has been designated as 8 MPa that allowed a significant economy and speed in the construction. Details about the seismic design of Cindere Dam can be found in Gürdil (2004).

4.2. Pervari Dam

The seismic behaviour of Pervari Dam with a maximum height of 180 m designed as RCC type, located in Siirt Province of Turkey has been examined by performing finite difference analyses utilizing the FLAC computer program. In this paper, only the time-history analyses are presented; the static and pseudo-static calculations used in cooperation for the design are excluded from the scope.

The dam geometry has been designed as having a 0.6H:1.0V slope in the lower portion of the upstream and 0.75H:1.0V slope in the downstream face, to provide the sufficient base area according to the stability analyses. The maximum section of the dam body is shown in Figure 4.1. The maximum reservoir level is 5 m below the crest, and the silt level in the upstream face has been assumed as 125 m from the base. The finite difference grid constructed to investigate the earthquake behaviour of the dam is given in Figure 4.2. In the model where plane-strain elements are used, the foundation rock has been extended down to a depth of 40 m, and the reservoir water and silt have been included in the numerical model by plane elements. The left and right sides of the model are extended to reasonable distances and free-field boundaries are utilized to minimize the effect of these boundaries on the dynamic behaviour of the system.

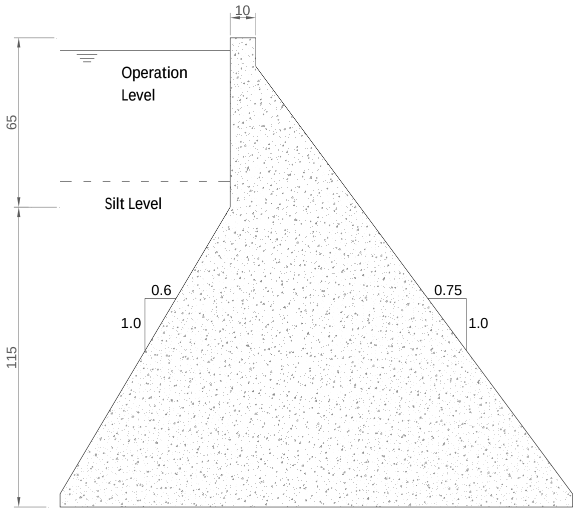

Figure 4.1. Typical Cross-Section of the Dam

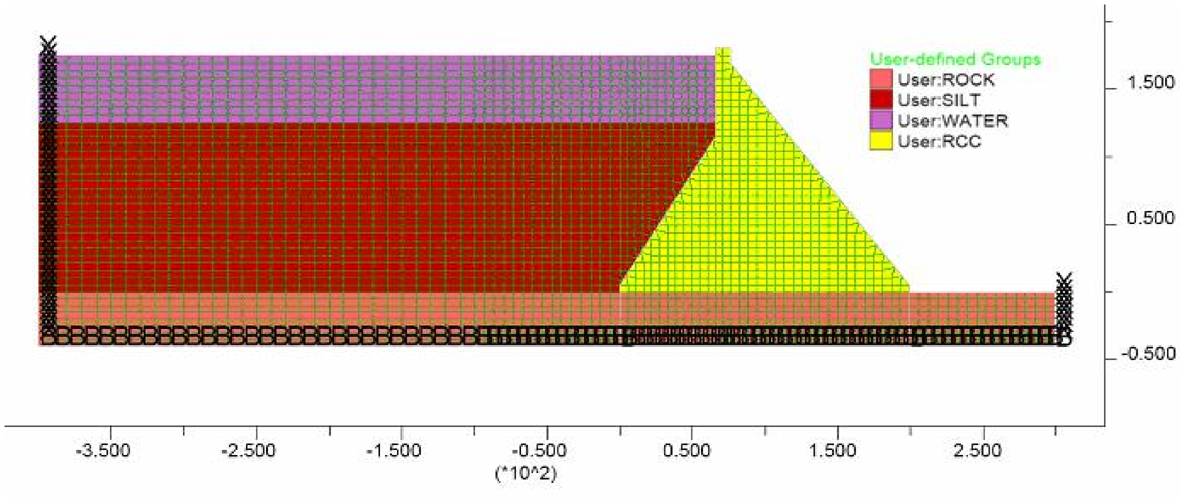

Figure 4.2. Finite Difference Grid

According to the geological and geotechnical evaluation on the foundation rock, the elasticity modulus has been estimated as E_r = 12 GPa and the shear strength of the rock has been appraised to be greater than the shear strength of the lift joints in the dam body. In this regard, the foundation rock has been modelled as a linear elastic material and the stress and stability checks have been performed for the dam body with smaller strength. The target compressive strength of the RCC has been determined as 16 MPa by preliminary analyses. The tensile strengths in the principal direction for the dam body and vertical direction for the lift joints have been determined as given below with regard to USACE (2000) criteria, provided that formation of cold joints will be prevented by application of bedding mortar where necessary. The tensile strength has been increased 50% for dynamic load case.

$$\sigma_{tv} = 0.05\ \sigma_c = 0.80 \text{ MPa} \tag{4.1}$$

$$\sigma_{tv\text{-}dyna} = 1.5\ \sigma_{tv} = 1.2 \text{ MPa} \tag{4.2}$$

$$\sigma_{tp} = 0.09\ \sigma_c = 1.45 \text{ MPa} \tag{4.3}$$

$$\sigma_{tp\text{-}dyna} = 1.5\ \sigma_{tp} = 2.15 \text{ Mpa} \tag{4.4}$$

In the above formulas, σ_{tv} and $\sigma_{tv\text{-}dyna}$ show the static and dynamic tensile strengths in vertical, σ_{tp} and $\sigma_{tp\text{-}dyna}$ indicate the static and dynamic tensile strengths in principal direction. The cohesion and friction angle of the lift joints have been assumed as c = 0.80 MPa and ϕ = 42 degrees whereas the elasticity modulus of RCC has been taken as E = 20 GPa. It is deemed for the target strengths of the construction materials to be used in RCC dam body to adapt to “design values + 1 standard deviation”.

The reservoir water play an important role in the dynamic behaviour of the concrete gravity dams. To take into account this effect in the dynamic calculations, the reservoir water are modelled in different ways such as nodal masses by Westergaard approach, continuum elements (plane or three dimensional) or acoustic elements. Scheluen at al. (2010) have shown that consistent results with the measurements can be obtained by modelling the water with either continuum or acoustic elements. In this study, the reservoir water is included in the numerical model by plane-strain elements with very small shear stiffness as seen in Figure 4.2, and the effect of the reservoir on the dynamic response has been aimed to be simulated in a realistic way.

The peak ground accelerations (PGA) corresponding to operating basis earthquake (OBE) and maximum design earthquake (MDE) have been determined as 0.11 g and 0.38 g respectively by the seismic hazard study (Martin, 2010). The suggested earthquake records and the scale factors to be used in the time-history analyses are summarized in Table 4.1. The original (unscaled) earthquake records are shown in Figure 4.3.

Table 4.1. Earthquakes and Scaling Factors Used in the Analyses

Earthquake / Station	Component	PGA (g)	Scale Fac.(MDE)	Scale Fac.(OBE)
Tabas, Iran / Dayhook	LN	0,328	1,0	0,33
L. Prieta/CDMG 58135	NS	0,450	0,70	0,23
Northridge / UCSB LA	EW	0,388	1,0	0,33

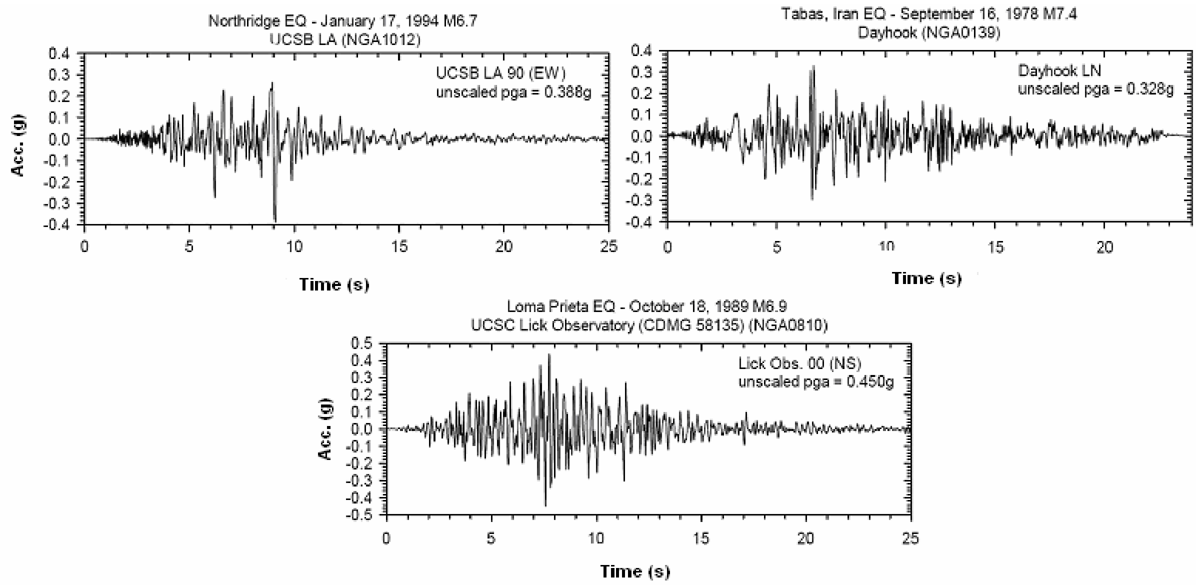

Figure 4.3. Earthquake Records Used (after Martin, 2010)

The abovementioned earthquake records have been applied to the base of the model as acceleration time histories. The damping ratio of the system has been taken as 5% for OBE loading as suggested by USACE (2003). For the MDE load case, the damping ratio has been increased to 7% considering the energy dissipation in the small and large scale cracks due to high level of seismic motion. For the operating basis earthquake, linear elastic material models have been employed in the calculations. The maximum vertical and principal tensile stresses generated during the earthquake are shown in Figure 4.4 for the most critical results obtained in Tabas earthquake loading. It can be seen from the results that the vertical tensile stresses are generated in a small portion of the dam body as below the tensile strength of the lift joints. The tensile stresses in the principal direction exceed the strength at just one local point in the dam base corner. This has been considered as acceptable, as the local high stresses are mainly due to stress concentrations in the numerical model of maximum cross-section, and the subject area is within the improvement zone for concrete strength.

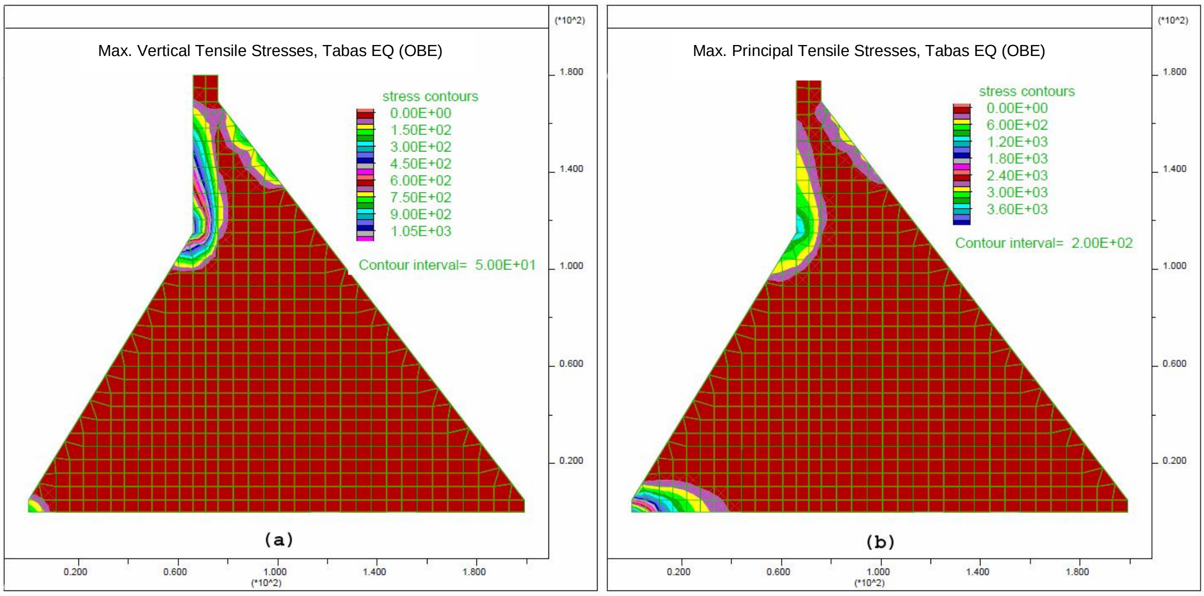

Figure 4.4. Maximum Vertical (a) and Principal (b) Tensile Stresses for Tabas Earthquake (OBE)

The dynamic behaviour of the dam in MDE loading has been primarily examined by considering linear elastic material models; for this purpose Tabas earthquake for that the most critical results are obtained in OBE loading is used. The maximum vertical tensile stress distribution obtained from the analysis is shown in Figure 4.5(a). It can be observed that the tensile strength of the concrete has been significantly exceeded especially at the upstream region of changing slope and the neighbour downstream face. This indicates that the cracks are inevitable in the subject regions in case of a seismic loading of MDE level. To take into account the nonlinear behaviour at the overstressed regions where cracks and joints are expected and to evaluate the permanent deformations, a joint is defined from the upstream face to downstream. The analyses have been repeated with this modification to assess the seismic behaviour by discrete crack approach discussed in Section 3. To be on the safe side, the cohesion and the tensile strength of the joint have been disregarded and only the frictional forces have been taken into account by using the friction angle of 42 degrees. After this analysis, obtained maximum vertical tensile stresses during the earthquake are shown in Figure 4.5(b).

Obtained results indicate that after a major cracking at the subject area, the vertical tensile stresses at the lift joints and the principal tensile stresses at the parent RCC will be smaller than the target tensile strengths. On the other hand, as the permanent displacements after the earthquake, shown in Figure 4.6, are concerned, it has been observed that there can be a permanent displacement of about 0.5 m along the defined joint. After this stage, the post-earthquake safety of the dam body has been investigated by performing a stability analysis. For this purpose, the stability of the block over the defined joint has been checked by pseudo-static approach using OBE loading, conservatively taking a cohesion value of $c = 0$ and full uplift pressure along the joint. It has been observed that the sliding stability of the subject block is satisfied with a safety factor of 1.29, even for an aftershock of OBE level after an MDE event.

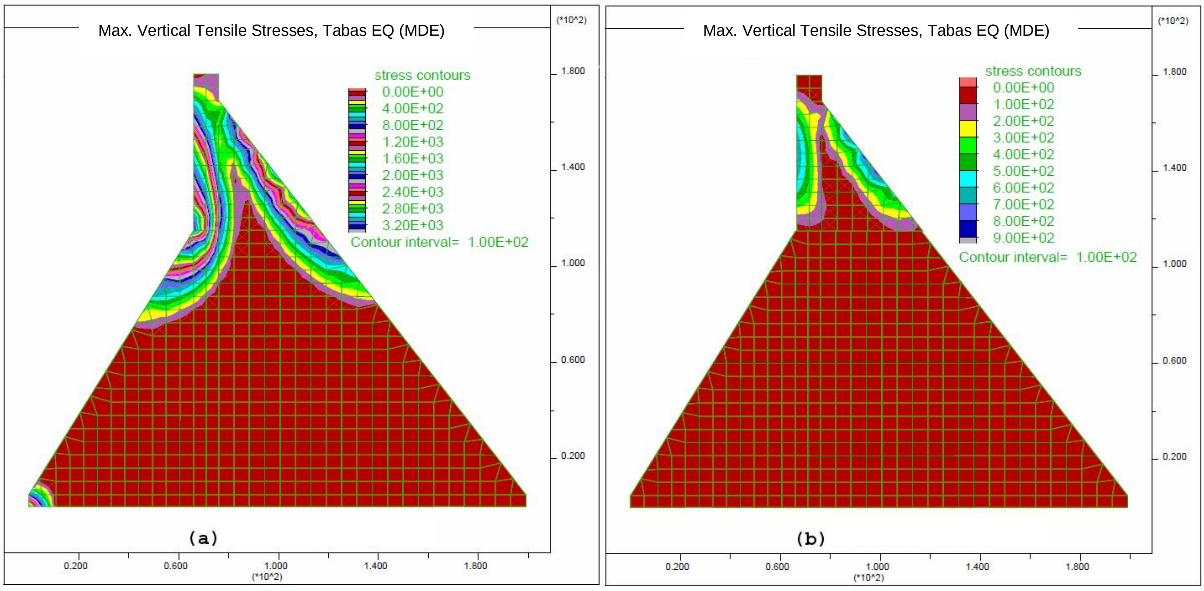

Figure 4.5. Maximum Vertical Tensile Stresses for Linear (a) and Jointed (b) Models after MDE Loading

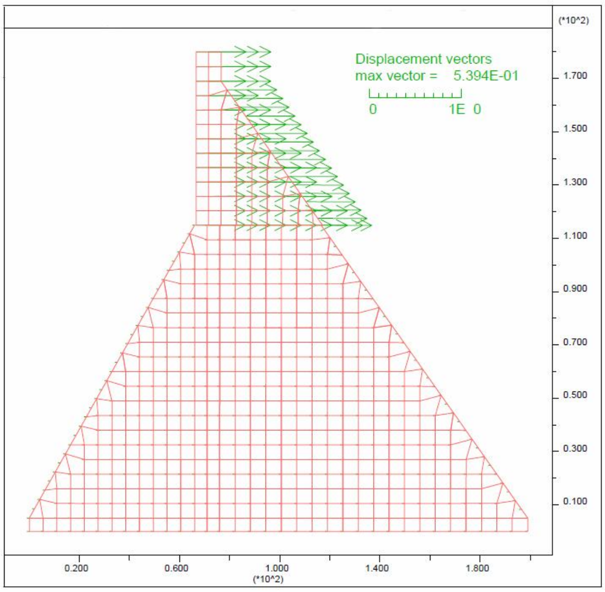

Figure 4.6. Permanent Displacement Vectors after MDE Loading

5. CONCLUSIONS

The seismic ground motions are cyclic and have short durations. In this regard, for the concrete gravity dams of convenient geometry, a full loss of stability is out of concern unless there is a foundation problem.

The pseudo-static approach may be considered as acceptable in the seismic design of dams where the internal stresses are below the linear elastic limits. Consequently, the stresses can be determined by methods of this approach for OBE loading; the minor damage will be easily repairable in case of an earthquake of this level. On the other hand, for MDE loading and especially in high seismic regions, the time-history analysis methods should be preferred for the design, where the tensile stresses in the concrete or lift joints are greater than the strength (FEMA, 2005).

It is not economical to increase the strength requirements because of the stress concentrations at areas where abrupt geometry changes are inevitable. There may be considerable permanent displacements along the assumed cracking surface in case of MDE loading. However, these deformations and the relevant damage may be considered as acceptable where the inelastic behaviour is evaluated in a realistic way by advanced analysis methods, and the stability of the dam or critical blocks are satisfied during and after the earthquake considering the post-earthquake material and load conditions and possible aftershocks.

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