SEISMIC GUIDELINES FOR EARTH AND ROCK FILL DAMS

Ulises Mena Hernández[1], Nava-Tristán O. E.[1], Xiangyue Li Liu[2], Enrique Mena Sandoval[3] and Federico Hach G.[3]

[1] *Researcher, Gerencia de Ingeniería Civil, Instituto de Investigaciones Eléctricas. Cuernavaca, México*
[2] *Researcher, Subcoordinación de Hidráulica Ambiental. Instituto Mexicano de Tecnología del Agua., Cuernavaca, México.*
[3] *Researcher, Gerencia de Estudios de Ingeniería Civil, CFE. México, D.F.*
Email: xiangyue@tlaloc.imta.mx, umena@iie.org.mx, oenavat@iie.org.mx, enrique.mena@cfe.gob.mx

ABSTRACT :

In this paper, seismic recommendations for earth and rock fill dams are presented. These recommendations will be included into the Seismic Design Chapter of the seismic design handbook of CFE. The procedure to calculate the seismic loads and to check the dynamic conditions in this kind of structures are explained. These criteria are adapting to the new concepts of seismic hazard of Mexico developed by The Mexican Electric Research Institute and that they will be available in a short time. In the analysis of the earth and rock fill dams are examining and proposing recommendations for the following aspects: dynamic response, seismic stability, seismic permanent deformation, pos seismic stability, pos seismic permanent deformation and other damages, by means of three analysis a) Simplified analysis, b) Analysis in stages and c) Complete analysis.

The simplified analysis studies several aspects of the seismic behavior of the dams, since the dynamic response, the seismic stability up to the permanent deformation, using simple procedures. The analysis in stages will begin for the static study, continuing by the dynamic response analysis, and checking the changes that the shear resistance of materials could be suffer, due the generation of pore pressure excess by the accumulation of the residual deformation. Finally, the complete analyses will assemble all the described analyses previously that begin since the static conditions up to analyses a time after the culmination of the earthquake. For the importance that these types of structures and considering that 90 % of the dams in Mexico are of earth and rock fill, the recommendations proposed in this document will be fundamental in the seismic design of the dams.

KEYWORDS: Earth, rock fill, dam, seismic analysis

1. INTRODUCTION

Early century XX, earth and rock fill dams built with hydraulic landfill material are the most vulnerable to seismic actions. Nevertheless, in the last fifty years of the century, these types of dams didn't register any damages due to seismic events. The dam's excellent performance obeys to the construction's modern technologies and theoretical and experimental geotechnical advance. On the other hands, seismic damages in earth and rock fill dams were observed when a seismic event reaches a degree greater than VI in a modified Mercalli intensity scale. In general terms, rock dams have a good seismic behavior, thanks to the compaction's modern technologies that increase the shear strength of the construction material. Besides, the earth and rock fill dams high permeability help to improve the shear strength during seismic events, without liquefaction's problems or reduction in the shear strength.

2. GENERALITIES

Sherard (1967) presented a list with a failure's probable causes of earth and rock fill dams induced by seismic loads. These are:

- Dam's failure induced by a foundation failure
- Loss of freeboard induced by differential tectonic movements
- Landslide's failure induced by seismic movements
- Loss of freeboard induced by landslides or soil compaction
- Dam's slides induced by unfavorable condition of foundation's soil
- Piping failure through cracks induced by seismic movements
- Dam's overflow induced by reservoir swell
- Dam's overflow induced by slide or fall of rocks towards the reservoir
- Spillway's failure

This list, elaborated forty years ago, continues being a guide to understand the dam's seismic risk. The main damages in dams caused by seismic events are: longitudinal cracking, transverse cracking, slide, settlements, seepage and concrete's structural damage.

2.1. Seismic selection and loads combination

Service earthquake (or operating base earthquake) is related with the dam's functionality mainly. To this seismic level corresponds seismic loads that could produce important movements in the site of dam, without dam's malfunctioned. Collapsed prevention earthquake (maximum design earthquake) defines the seismic loads which are used in order to design the dams. In this case, the design will allow that dams could suffer an important structural damages or economic large losses, but without catastrophic consequences such as total collapsed or uncontrolled spillage of reservoir.

The design stages of dams will begin with the service level and will end with verifying the safety of the structure considering the prevention of collapse level. For both earthquakes' design the maximum ground's acceleration and velocity, and design spectra will define. In case of, step by step analysis methods, acelerogramas synthetic will must be generated using as base the design spectra (at least 3 acelerograms will be generated)

In order to determine the maximum ground's acceleration and velocity of the dam site, the PRODISIS program will be used (CFE, 2008). Later, the design spectra will be constructed using the seismic recommendations included into the Seismic Design Chapter of the seismic design handbook of CFE. The design spectra obtained with the CFE's handbook, correspond to the collapsed prevention level in structures of the B group. This design spectrum is multiplied by the factor of 1.5 of A group, since the dams are considered into this group. In the case of the service level, named operating base earthquake, the collapsed prevention spectra is divided by the factor of 5.5. If dam is instrumented, and some seismic records exist, those records could employ to generate synthetic acelerograms. It's important to define the maximum probable earthquake, based in seismological studies of site, in order to obtain the correct scale of the seismic source. These studies will provide ground records of acceleration, velocity and displacement, as well as, the respond and design spectra. For earth and rock fill dams, a magnitude in Richter's scale and a seismic duration must be provided.

When the dam's foundation is rock, the seismic parameters will be defined at the basal rock level. In opposite case, a soil deposit must be considered and a detailed site responds analysis must be carry out. Besides, seismic load capacity, induced deformations, as well as, spatial variation of earthquake must be defined. The seismic parameters can be obtained in two different ways: a) if the analysis includes the soft soil implicitly, the seismic parameters must be defined at the basal rock level; b) When the seismic parameters are defined on surface of soil deposit, a convolution method must be employed in order to obtain the seismic parameters at the basal rock level. If the seismic study is carried out near to the dam, this must be done at the base's level modified by the effects of the foundation deposit.

Two load conditions are defined. The first one is named unusual seismic load, which is the combination of unusual loads and the earthquake of service level. The second one is named extreme seismic load, which is the combination of normal loads and the earthquake of collapsed prevention level. All possible combinations of normal and unusual loads must be considered, taking into account that the loads with less probability to occur at the same time with the earthquake of collapsed prevention level must be eliminated. On the other hand, besides the load conditions mentioned particular nature hazards' analysis of site, related on the induced seismicity, reservoir's slide and failure, active faults in the mouthpiece, tsunami or seismic swell.

The reservoir's hydrodynamic effects are considered only in rock fill dam with concrete face, applying the virtual mass model (CFE, 2008). Seismic effects are not considered in stress seepage or subpressure. The dynamic effects of sediments are considered in big dams with an important height of sediments.

When the dam's length is less than three times of its height (built dams in wide mouthpieces), dams can be analyzed bi-dimensionally, taking into account a unitary length. Tri dimensional effects are important in dams with concrete's face, indistinctly of the mouthpiece form. The tri-dimensional analysis is necessary in arc's dams or buttress dam.

2.2. Dams classification in seismic analysis

Based on the seismic analysis and design, dams are classified in four groups. With loss potential of shear strength, associated potential damage, according the height and the site's seismicity (CFE, 2008).

The materials without loss of shear strength are those, which during cyclical loads and a saturation's state, undergo a small reduction of shear strength, generation of excess of pore pressure or accumulation of residual deformations. Clay and rock materials are typical of this group. As saturated clays have low permeability, not permit the dissipation of excess of pore pressure, generating by dynamic loads, nevertheless, its undrained static strength is kept intact. On the other hand, gross granular materials have a high permeability, so excess of pore pressure is not accumulated during seismic loads and the drain strength is maintained in effective stress' terms. In this type of material, the cyclical deformations are small.

Materials with loss of strength undergo cyclical deformations with excess of pore pressure or significant residual deformations until large deformations. Strength to dynamic shear reduces itself in an appreciable way, under static conditions. The majority of saturated soils are into this group. However, saturated uniform sand unconsolidated, its strength can be diminished and exist only the undrained residual strength under large deformations. These materials are referred like materials with loss of flow strength and could be gravel or with certain content of fines.

In case of associated potential damage of dams, negative consequences that can to produce the dam failure of zones downstream must be considered. These consequences could be life loss or material damages. The associated potential damage of dams is the result of failure risk studies.

2.3. Design criteria

Seismic behavior of dams in passed earthquakes indicates that seismic events are not the principal cause of failure, since dams present a good behavior during earthquakes. However, there are not exit dams damage records of induced by intense earthquakes.

Unfortunately, not all aspects related with the dam's seismic security can be evaluated, using analytic procedures. In this case, Seed (1979) suggested some consideration in order to carry out the design

- Provide an enough dimension of freeboard in order to reduce settlements, swell actions and movements caused by slide.
- Design wide zones of transition, using materials that are not susceptible to cracks.

- Use vertical drains near the middle of dam.
- Provide of wide zones of drain in order to permit possible flow through cracks.
- Design wide zones of waterproof interior, using plastic materials that are not susceptible to cracks.
- Employ a good graduated filter in upstream of core in order to block cracks.
- Design structural details on dam's crest, in order to prevent erosion when overflow occurs.
- Extend the waterproof core until the slopes.
- Locate material's banks of core, which have not a high saturation degree.
- Stabilize the reservoir's slope in order to prevent slides.
- Design spatial details in foundation, if exist a probable of failure movement.

2.4. Selection of analysis' method

Nowadays, several procedures of assessment are used in order to carry out seismic analysis, however, the complex methods are not always provided the best result, since, this kind of methods, required more seismic data and more materials' properties. Especially, in earth and rock fill dams, the refined methods of analyses must feed with information that is obtained of soil's experimental tests. Therefore, the analysis' method selection must achieve a balance between the requirements, scopes and analysis complexity levels.

2.5. Assessment of freeboard

One of the most devastating effects that generate an earthquake is the loss of freeboard, since; this can derive in a sudden evacuation of the reservoir, which might bring catastrophic consequences to the zone downstream. This effect is particularly significant in earth and rock fill dams, due to the fact that they have small strength to the erosion and scour.

On the other hand, swell induced by earthquakes has been studied a little bit, and in general it's not taking into account, or it takes in approximate way.

3. SIMPLIFIED ANALYSIS OF EARTH AND ROCK FILL DAMS

In general terms, simplified analysis' criteria and procedures are conservatives when the studies cases comply wit the established conditions. If dams comply the security criteria, of conformity with the simplified methods established in this paper, or if a refined methods are used. In opposite case, if dams not comply with the security criteria, applying the simplified methods, could be comply if refined methods are carried out.

3.1. Dynamic response

When dam's slopes have values among 3:1 and 4:1, the induced movements by earthquakes in transversal section are essentially horizontal, or the dams mechanical actions are shear type and rocking effects are not important. This type of behavior is similar to shear column, so a shear beam's model could be applied. This model is adopted in simplified analysis when dam is exclusively horizontal. For a certain height, such movement is uniform and both slopes are not influence in the dam response. If the mentioned hypotheses are no valid, bi and tri dimensional analysis are necessary.

The simplified calculation's procedures of earth and rock fill dams response are similar in uniform sections and procedures are done in an iterative way until to obtaining the maximum acceleration on the crest (CFE, 2008). It relation with the ground maximum acceleration defines the amplification of dam's dynamic response. In order to carry out the analysis is necessary to know the dam's height, the average volumetric weight, the initial or maximum shear modulus, curves of degradation and damping and the response spectra for different damping's levels.

3.2 Seismic stability

One of the most notable characteristics of rock materials are that strength law of shear stops being linear, like in clays and sands. This peculiarity forces that laboratory tests are interpreted with nonlinear criteria and that the stability studies should establish with base in enveloped of nonlinear strength. Several studies consider the Mohr-Coulomb enveloped (*eg.* Duncan y Chang, 1970; Marsal, 1972; Mello, 1977; Charles y Watts, 1980; Jiang *et al.*, 2003).

On the other hand, pseudo static studies are accepted widely where the seismic load is supposed as a ratio of gravity force. The above mentioned studies can use in the stages of preliminary design, particularly when the seismic coefficients are established correctly for study's region. This kind of studies also serves for final designs in dams with low potential hazard, The analyses of pseudo static stability are useful when the critical seismic coefficients can be calculated. With this coefficients can be determinate permanent deformations of slopes, by means of the procedure of Newmark's double temporary integration (Newmark, 1965).

3.3 Seismic permanent deformation

Several simplified analysis' methods have been proposed in order to estimate dams permanent seismic deformation, among these are: calculation of slides block movements as the proposed one for Newmark (1965), Idriss and Seed (1967), or the calculation of the crest‘s settlements. Both estimations are useful since it is possible to establish tolerance criteria for slides and settlements. It is necessary to consider that lateral slides can be 2 to 4 times the settlements (Ishihara *et al.*, 1990).

4. DETAIL ANALYSIS OF EARTH AND ROCK FILL DAMS

During the period among 1930 and 1970, in the design practice, the seismic effects were considered, only incorporating a simply lateral static force in the stability analysis, representing the induced inertia by an earthquake. This lateral force was a fraction (5 to 10 %) of the vertical force induced by the own weight of the dam. Due to the fact that earthquakes have been registered with acceleration greater than 0.3 g, substantially major that the acceleration level considered in the traditional analysis (0.05 to 0.1 g), the analysis methods were considered to redesign. In this respect, San Fernando's dam contributed in the improvement of seismic analysis methods, from the sixties and seventies (Seed *et al.*, 1975).

4.1. Static analysis

For purposes of the analysis of dynamic response, the static study will have to determine, as minimum: 1) Components of principal stress before the earthquake in order to define the dynamic initial stiffness of the dam; 2) the flood's surface in order to include the seepage's forces in the stability analysis and 3) the distribution of shear stress that serves to evaluate the potential of resistance's loss. The static analysis procedure also will be useful to carry out the studies of pos seismic permanent deformation.

4.2 Dynamic response

The seismic excitation in the dam's site has three direction, two horizontal ones and vertical one. The horizontal excitation appear in transversal and parallel direction to the dam's axis. As slope stability is the most important aspect in the evaluation of the earth and rock fill dam's seismic behavior, the horizontal transverse excitation has the major incident in the evaluation, for this reason, the effects associated with the vertical component and the horizontal parallel can be eliminated in the preliminary analysis. Therefore, a bi dimensional analysis of transversal section is considered under a horizontal and transverse excitation.

Though the excitation in the parallel direction of dam's axis is not important for the evaluation of the earth and rock fill dam's stability, the geometry's variation in the above mentioned direction must not be ignored. The limitation of the mouthpiece diminishes the vibration's natural periods and increases the magnitude of dynamic response and consistently the seismic forces. On the other hand, the flexibility of the rocky masses of the mouthpiece permits a reduction of the dynamic amplification. These three-dimensional effects must be considered in the rock fill dams constructed in closed mouthpieces or dams with concrete face, for any geometry of the mouthpiece.

4.3. Initiation of strength loss

To estimate the safety factors against the liquefaction, the coefficient method of cyclical stress is the most used (CSR). Based on standard penetration tests, the method has been checked and calibrated by a lot of field's experiences and continues getting improved constant (Finn, 1996).

4.4 Seismic stability

To establish the safety factors and accelerations of the excitation the Hynes-Griffin and Franklin (1984) criteria are adopted. In the literature could be found other criteria (Duncan and Wright, 2005).

4.5. Seismic permanent deformation

Newmark's method (1965) considers the earthquake characteristics in the permanent deformation, which include the intensity, duration and frequencies' content. Traditionally the method considers the slippage body as rigid, where the acceleration is uniform in the mass. Recent studies have considered the effect of the flexibility of the mass (Kramer and Smith, 1999).

The critical accelerations are an indicator of the slope's performance (Abramson *et al*., 2002) if they are compared with the maximum ground accelerations, when the first ones come closer or even they exceed the second ones, the slopes tend to experience seismic damages.

4.6 Pos seismic stability

For this type of analysis the slope's static stability methods are applied. In general, the slope stability analyses are carried out supposing a certain number of material zones. Nevertheless, for the seismic effects, the modifications in the shear strength of the materials are not uniform in the whole dam's body, for that reason the modified shear strength change considerably of a point to another one. The strength variation must be considered in order to capture the most vulnerable zones of the dam.

4.7 Pos seismic permanent deformation and other seismic damages

The changes in the stress – strain properties of the soils occur for different deformation modes. For plane strain problems, three components must be considered: triaxial, simple shear and of compression. Three families of relations must develop in order to correlate deformation's potential and static and dynamic stress' states, though in the practice it is considered only one of the modes depending on the laboratory tests.

5. COMPLETE ANALYSIS OF EARTH AND ROCK FILL DAMS

The complete analyses or analysis in stages are divided in several evaluations: an initial condition analysis, amplification, stability analysis and evaluation of the permanent deformation. The evaluations use different types of hypothesis and analysis' procedure without trying to carry out a complete history of the dam's behavior. The disadvantage of these analyses is a lot of important factors are not considered in the dam's behavior. In the soils without resistance's loss, the dam's global behavior is sensitive to the geometric configuration, the zoning of material and the mouthpiece. In soils with resistance's loss, during a earthquake, the reasons of the energy dissipation are the hysteretic behavior of the material, elastoplastics flow or change of volume. Due to the complex mechanism of generation, diffusion and dissipation, the pore pressure generated during a earthquake is redistributed not only in the space but in the time scale.

5.1. Elastoplastic model

The rock fill dams with concrete face, graduated materials and with impermeable thin core have been analyzed using the elastoplastic models. Therefore, it is important to check the dam's seismic performance.

A recent report (Alemán, 2006) presented the results of a field survey of several South American dams that possesses a concrete faces and that they have been subject to seismic excitation. The information obtained during this visit showed an excellent seismic performance in this type of dams. In Japan, the Manase' rock dam subjected to severe earthquake was reported. This dam presented settlements and lateral movements. The concrete slab in general has a suitable performance though cracks in joins and in the slab blocks could appear, and consequently an increase of seepage. In the parapet zone, it is where the most notable damages can success.

5.2 Advanced elastoplactic model

The advanced elastoplactic models must include the following aspects:

- Yield and failure surface that can be Von Mises, Tresca, Mohr-Coulomb or Drucker-Prager
- Hardening and softening laws.
- Consistency' condition for hardening by deformation
- Density
- Load and unload criteria
- Anisotropy
- Cyclical movement

According the conventional elastoplastic models, the yield's surface separates the elastic and elastoplastic behavior. The stress' state corresponding to the elastic behavior is into the yield's surface. In this sense, when the stress path is less than the yield's surface, recover deformations are not be presented. However, soils show unrecovered behavior during load, unload and reload. That's because, the conventional elastoplastic model cannot model the accumulation of volumetric deformations or excess of pore pressure. The advanced methods can resolve this disadvantage, since included surface of boundary's plasticity and cinematic yield concepts (Potts y Zdravkovic, 1999).

6. CONCLUSION

In Mexico, the majority of the dams were built of earth and rock fill materials, and considering that Mexico is located in a high seismicity zone, it is necessary to possess with a seismic recommendations for designing new dams and reviewing old dams. For this reason, in this paper, the methods, the procedures and considerations in order to carry out the design and review of earth and rock fill dams under dynamic loads have been described. These recommendations will be included into the Seismic Design Chapter of the seismic design handbook of CFE. These criteria are adapting to the new concepts of seismic hazard of Mexico developed by The Mexican Electric Research Institute and that they will be available in a short time. In the analysis of the earth and rock fill dams are examining and proposing recommendations for the following aspects: dynamic response, seismic stability, seismic permanent deformation, pos seismic stability, pos seismic permanent deformation and other damages, by means of three analysis a) Simplified analysis, b) Analysis in stages and c) Complete analysis.

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