SEISMIC ANALYSIS OF TEPUXTEPEC DAM

Ulises Mena Hernández[1] and Nava-Tristán O. E.[1]

[1] *Researcher, Gerencia de Ingeniería Civil, Instituto de investigaciones Eléctricas, Cuernavaca, México.*
Email: umena@iie.org.mx, oenavat@iie.org.mx

ABSTRACT :

In this paper, the results obtained of the seismic analysis to Tepuxtepec's dam are presented. Tepuxtepec dam was constructed in order to fulfill three functions, namely: power generation, flood control and to supply water for the irrigation to 3,680 ha in the region. The dam is located inside the Acambay graben. In spite of the fact that the majority of the earthquakes in Mexico are related directly to the tectonic plate's movement, there are however, less frequent earthquakes that happen inside the continents, which magnitudes could be important. The Acambay graben is located in the central sector of the Mexican Volcanic Belt, which is one of a series of east-west–oriented grabens along the Chapala-Tula fault systems that practically follows the axis of the belt, and are thus interpreted as intra-arch tectonic depressions. The Acambay graben is responsible of earthquakes that occur near the Tepuxtepec's dam. For this reason and considering number of years that Tepuxtepec's dam has been in operation, LyFC (Government company) decided that it was necessary to perform a complete analysis of the structure, in order to determine its present factor of safety, considering current conditions of materials, the seismicity and the operation conditions, to which one the dam is subjected. The results will serve to define the necessary actions that LyFC needs to take, in order to improve the seismic behavior of the dam, since it is expected that dam will continue its operation for yet several years.

KEYWORDS: Dam, safety factor, Acambay graben, seismic analysis, hydrodynamic analysis.

1. INTRODUCTION

Tepuxtepec's dam was constructed in three stages, beginning in 1928 and ending in 1970. As a consequence of this, the dam is formed by several materials, principally of dry masonry and concrete. The dam has a height of 47 m, a crest length and width of 675.0 m and 4.0 m, respectively and a capacity of the reservoirs of 585 hm3. Tepuxtepec's dam was constructed to realize three functions, which are: the avenues control, hydroelectric energy generation and the irrigation of approximately 3,680 hectares in the region of Lerma River. Given the importance that the dam has in the region, it has contemplated that continues working several years more, carrying out the functions for those that it was planned. For this reason, an stability analysis is necessary, taking into account the real material properties, the dam current configuration, and especially its location in the Transmexican Volcanic Belt (figure 1.1), since it is a geologically active zone, owing to the presence of normal faults in the region, that form The Acambay graben or an east-west intra arc tectonic depression in the central sector of Mexico.

In November, 1912, the south side of Acambay graben, known as Pastores fault, moved vertically and released a high seismic energy (M=7), causing an important damages that affected a huge part of this region. This event known as Acambay's earthquake, had an epicenter in a geographical coordinates 19.93 N 99.83 W. In the same place other earthquakes were registered in 1915, 1916, 1947 and two in 1953 by magnitudes among 4.0 4.5. Suter *et al*. (1991) and Aguirre-Díaz *et al*.(1999) published a map showing the Acambay's faults (figure 1), confirming that the dam was constructed inside Acambay graben. In 1979 there were registered three earthquakes (with magnitudes of 4.6, 5.0 and 5.3) in the zone near to the dam (Figueroa, 1970 and NGA, 2007). With this scenario, a detail analysis of seismic hazard was carried out in Tepuxtepec site, in order to obtain the maximum acceleration, which serves to generate seismic record.

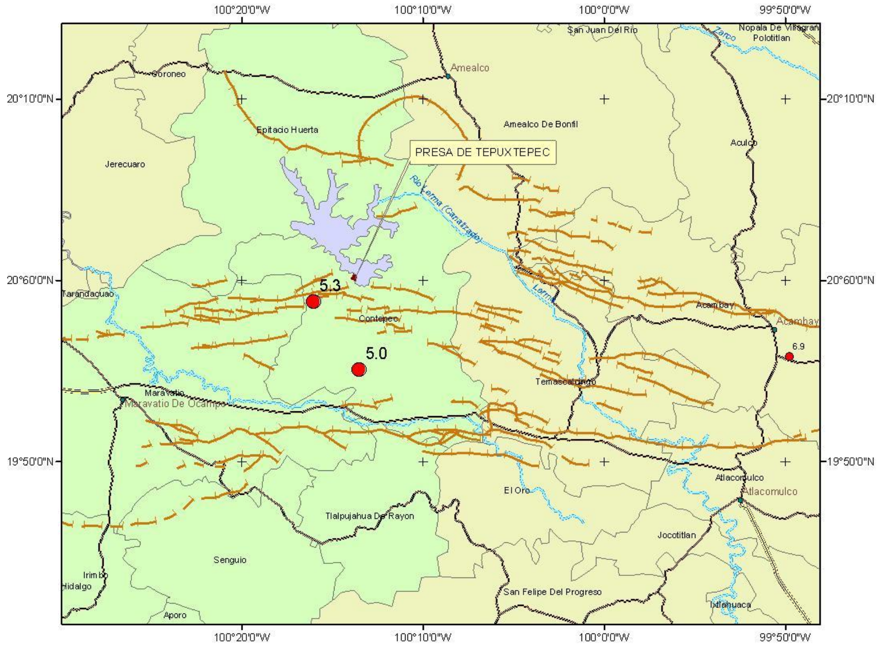


Figure 1.1. Tepuxtepec´s dam location.

In order to carry out the dam's stability analysis, several field investigations were done to obtain current characteristics. Besides, in the dam analysis was considered several hydrological conditions, different load cases (static and seismic analysis), as well as uplift pressures along the dam-foundation interface. The field investigations were: a) Topographic survey, including a reservoir bathymetric survey, b) Geotechnical investigations (including water chemical analysis and geological local study) and finally, c) A numerical analysis of the dam’s most critical sections.

2. GEOTECHNICAL INVESTIGATION

The geotechnical investigations are probably the most important activity in the stability analysis, since it is necessary to know the materials mechanical properties of the dam and the area of foundation, and its distribution inside the structures. For this reason a geotechnical exploration were planned in order to obtain samples and to determine the material mechanical properties (Figure 2.1). The geotechnical explorations server to characterize, as realistic as possible, the dam - foundation structures.

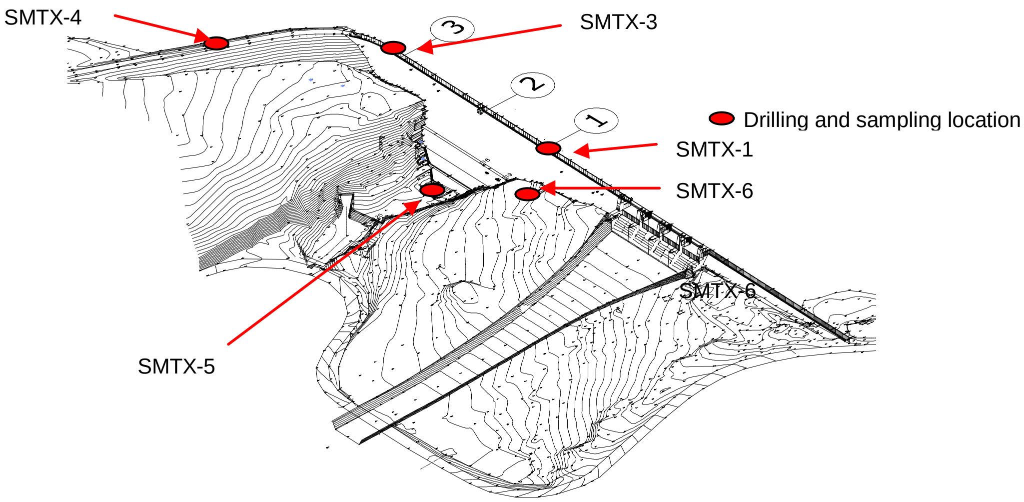


Figure 2.1. Tepuxtepec´s dam borehole location.

Dam's preliminary information indicates that it is formed for three materials mainly: dry masonry, masonry joined with mortar and concrete. In order to obtain the dam's properties of the materials, five tests drilling and sampling were done: three ones on the dam's crest (SMTX-1, SMTX-3 and SMTX-4 with depth of 15.10, 22.15 and 11.50 m, respectively) and two ones on the foundation (SMTX-5 and SMTX-6, with depth of 27.0 and 20.50 m respectively). SMTX-1 and SMTX-3 were carried out in dry masonry section; SMTX-4 was carried out in the graduated materials section. The last two tests were carried out in the downstream foundation's rock section.

Profile soil was determined using the results of the geotechnical exploration and laboratory data. On the other hand, the main section was obtained based on the topographic and bathymetric surveys. The foundation material used in the stability analysis was fractured basalt and healthy basalt (figure 2.2).

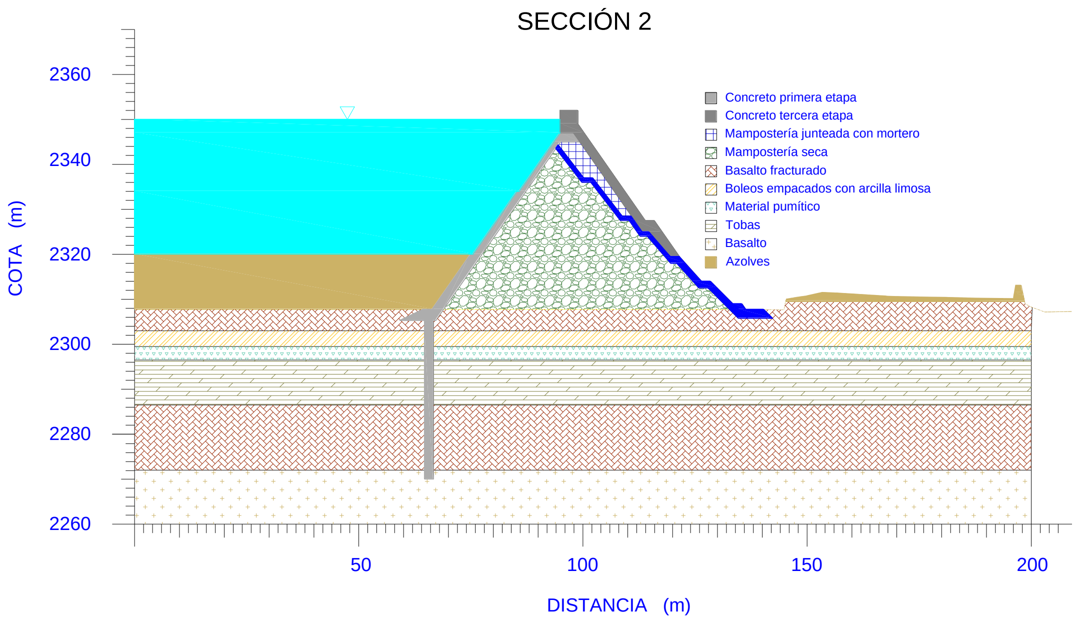


Figure 2.2. Critical dam section.

3. TEPUXTEPEC DAM'S STABILITY ANALYSIS

In order to assessment the safety of the Tepuxtepec dam, based on the geometric characteristics and materials' properties, a limit equilibrium analysis was considered. Dam stability is evaluated in deterministic form, based on a factor of safety (FS) defined as the relation between the resistant forces and the imposed forces. The most critical mechanism of fault that in a stability analysis must review is rotational slip of a soil volume that is considered rigid. This soil moves downwards on a fault surface with semicircular trace. However, in the particular case of the Tepuxtepec dam analysis, a flat fault surface is considered too, since this fault might appear owing to the dam is majority of dry masonry, which could be represented like rock fill (Marsal and Reséndiz, 1975; IMTA, 2001). Pore pressure used in analysis is obtained, considering a steady flow, not confine, in two dimensions. The seismic forces are considered by means of equivalent horizontal forces equal to a fraction (seismic coefficient) of the weight of soil volume that can move.

3.1. Stability analysis methods

As mentioned, a limit equilibrium analysis was carried out. This method is widely used in a professional practice. Three different procedures based on this method were used in order to compare the results: Ordinary (Fellenius), modified Bishop and Spencer (Duncan, 1996; Abramson, 2002; USACE, 2004 and Krahn, 2004).

3.1.1 Ordinary Method

It's a simple method, since the normal and shear forces are neglected inside elements. For this reason, the bending moment must be fulfilled. This method used equation 1:

$$FS = \frac{\sum_{i=1}^{n} \{c \cdot L + N \cdot \tan\phi\}_i}{\sum_{i=1}^{n} A_1 - \sum_{i=1}^{n} A_2 + \sum_{i=1}^{n} A_3} \tag{3.1}$$

3.1.2 Bishop Method

In spite of it's a simple method, the results obtained are similar that ones obtained with rigorous methods. Equation 2 is used in this method:

$$FS = \frac{\sum_{i=1}^{n} \{c \cdot L + N \cdot \tan\phi)_i}{\sum_{i=1}^{n} A_1 - \sum_{i=1}^{n} A_2 + \sum_{i=1}^{n} A_3} \tag{3.2}$$

3.1.3 Spencer Method

It's a particular case of a general method or GLE (General Limit Equilibrium). This method is considered rigorous, since satisfied forces and bending.

3.2. Seismic analysis (Pseudo static method)

In order to carry out the seismic analysis, ten synthetic accelerograms were generated using the seismic horizontal coefficient. In pseudo statics analysis is not common using the vertical one (Kramer, 1996). The seismic horizontal coefficient usually used for this type of analysis is the half of the maximum acceleration, a_0 (Hynes-Griffin and Franklin, 1984). However, because of the geological conditions of dam's site, a_0 will considered. In agreement to Handbook of seismic design of CFE (1993), the design spectrum recommended for Tepuxtepec's dam is shown in figure 3.1.

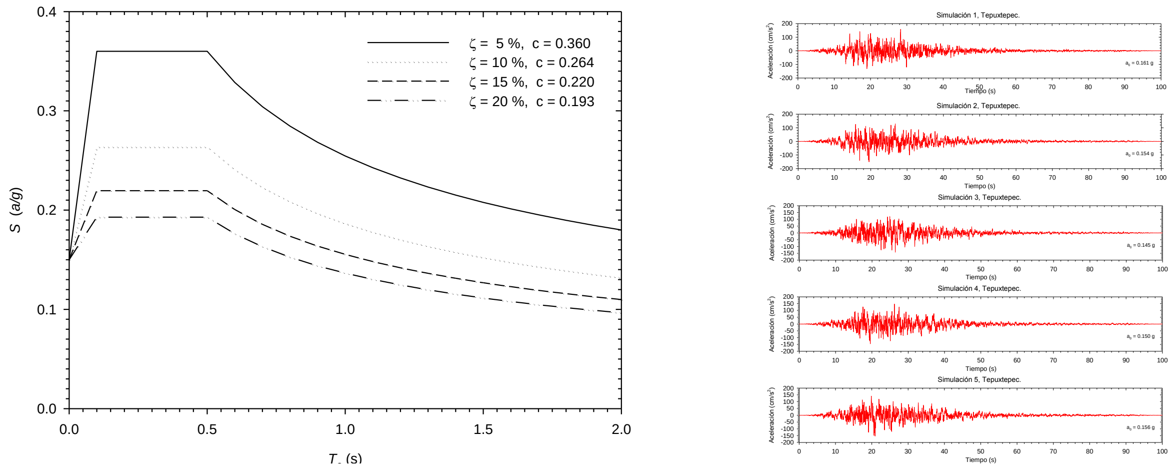


Figure 3.1. Spectrum design of Tepuxtepec dam and synthetic acelerograms.

3.3. Hydrodynamics forces

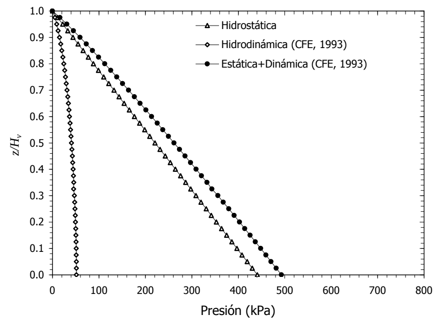
Bathymetric survey identified that sediments upstream have 13 m of high. This sediment generates an important hydrodynamic force on the dam. This force was assessed using the methods recommended in the Handbook of seismic design of CFE (1993) and Reséndiz *et al.* (1972). The recommended method estimates the hydrodynamic force on the dam's top, based on a hydrodynamic spectrum and a modal analysis (eq. 3.3).

$$\frac{p}{\gamma_0 \cdot H} = S_h \sqrt{\frac{2}{3}\left[1-3\left(\frac{Y}{H}\right)^2+2\left(\frac{Y}{H}\right)^3\right]} \tag{3.3}$$

INSTITUTO DE INVESTIGACIONES ELECTRICAS	CÁLCULO DE LA PRESIÓN HIDRODINÁMICA (CFE, 1993) EN LA CORTINA DE LA PRESA TEPUXTEPEC	GERENCIA DE INGENIERIA CIVIL DIVISIÓN DE SISTEMAS MECÁNICOS Proyecto: "Evaluación de ingeniería para determinar la estabilidad de la presa Tepuxtepec" (13168) Sección: 2 Cadenamiento: 0+360

$N =$ 1000	$T_v =$ 0.13 s	Azolves:		$\gamma_{weq} =$	**10.953** **kN/m^3**
$C_a =$ 1400.00 m/s	$T_s =$ 1.15 s	$H_{az} =$ 15.00 m	Calcular	$\gamma_{azeq} =$	**15.872** **kN/m^3**
$H_v =$ 45.00 m	$\rho_w =$ 1000.0 kg/m^3	$\rho_{az} =$ 1427.6 kg/m^3			
$a_{máx} =$ 1.49 m/s^2	$\theta =$ 34.99 º				
$v_{máx} =$ 0.27 m/s	$C_\theta =$ 0.483				
Talud = 0.7 : 1	$T_v/T_s =$ 0.112				

z/H_v	z (m)	C_{eh}	P_{dinw} (kPa)	P'_{dinw} (kPa)	P_{dinaz} (kPa)	P'_{dinaz} (kPa)	P'_{din} (kPa)	P_{est} (kPa)	$P_{est+din}$ (kPa)
1.000	45.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00
0.975	43.88	0.039	5.255	5.288	7.502	7.549	5.288	11.032	16.32
0.950	42.75	0.067	9.031	9.089	12.893	12.975	9.089	22.065	31.15
0.925	41.63	0.091	12.250	12.328	17.488	17.599	12.328	33.097	45.43
0.900	40.50	0.113	15.106	15.202	21.565	21.702	15.202	44.130	59.33
0.875	39.38	0.132	17.691	17.803	25.256	25.416	17.803	55.162	72.97
0.850	38.25	0.150	20.060	20.188	28.638	28.820	20.188	66.195	86.38
0.825	37.13	0.166	22.249	22.391	31.763	31.965	22.391	77.227	99.62
0.800	36.00	0.181	24.284	24.438	34.668	34.888	24.438	88.260	112.70
0.775	34.88	0.196	26.183	26.349	37.378	37.616	26.349	99.292	125.64
0.750	33.75	0.209	27.960	28.138	39.916	40.169	28.138	110.325	138.46
0.725	32.63	0.221	29.628	29.816	42.297	42.566	29.816	121.357	151.17
0.700	31.50	0.233	31.196	31.394	44.535	44.818	31.394	132.390	163.78
0.675	30.38	0.244	32.672	32.879	46.642	46.938	32.879	143.422	176.30
0.650	29.25	0.254	34.062	34.278	48.626	48.935	34.278	154.455	188.73
0.625	28.13	0.264	35.371	35.596	50.496	50.817	35.596	165.487	201.08
0.600	27.00	0.273	36.606	36.838	52.258	52.590	36.838	176.520	213.36
0.575	25.88	0.282	37.769	38.009	53.919	54.261	38.009	187.552	225.56
0.550	24.75	0.290	38.864	39.111	55.482	55.835	39.111	198.585	237.70
0.525	23.63	0.298	39.895	40.149	56.954	57.316	40.149	209.617	249.77
0.500	22.50	0.305	40.864	41.124	58.338	58.709	41.124	220.650	261.77
0.475	21.38	0.312	41.775	42.040	59.637	60.016	42.040	231.682	273.72
0.450	20.25	0.318	42.628	42.898	60.855	61.242	42.898	242.715	285.61
0.425	19.13	0.324	43.426	43.702	61.994	62.388	43.702	253.747	297.45
0.400	18.00	0.330	44.170	44.451	63.058	63.458	44.451	264.780	309.23
0.375	16.88	0.335	44.863	45.148	64.047	64.454	45.148	275.812	320.96
0.350	15.75	0.340	45.506	45.795	64.964	65.377	45.795	286.845	332.64
0.325	14.63	0.344	46.099	46.392	65.812	66.230	45.499	297.877	343.38
0.300	13.50	0.348	46.645	46.941	66.590	67.014	47.176	308.909	356.09
0.275	12.38	0.352	47.144	47.443	67.302	67.730	47.893	319.942	367.83
0.250	11.25	0.355	47.596	47.899	67.948	68.380	48.543	330.974	379.52
0.225	10.13	0.358	48.003	48.308	68.529	68.965	49.128	342.007	391.13
0.200	9.00	0.361	48.366	48.673	69.047	69.486	49.648	353.039	402.69
0.175	7.87	0.364	48.684	48.994	69.502	69.943	50.106	364.072	414.18
0.150	6.75	0.366	48.959	49.271	69.894	70.339	50.501	375.104	425.61
0.125	5.62	0.367	49.191	49.504	70.226	70.672	50.835	386.137	436.97
0.100	4.50	0.369	49.381	49.695	70.496	70.944	51.107	397.169	448.28
0.075	3.37	0.370	49.528	49.842	70.706	71.155	51.318	408.202	459.52
0.050	2.25	0.371	49.633	49.948	70.855	71.306	51.468	419.234	470.70
0.025	1.12	0.371	49.695	50.011	70.945	71.396	51.559	430.267	481.83
0.000	0.00	0.371	49.716	50.032	70.975	71.426	51.589	441.299	492.89



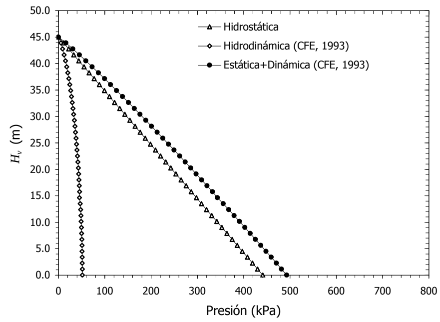


Figure 3.2. Compute of hydrodynamic forces assessment of the main section.

3.4. Stability analysis results

Analysis conditions that were checked in order to know the stability if the dam:

Table 3.1. Factor of safety for the different analysis conditions

No.	Condition	FS	Slope	Notes
1	Steady flow	1.5	Downstream	Spillway level
2	Rapid drawdown	1.2	Upstream	Water intake level
3	Seismic	1.0	Upstream	Spillway level

Rocks parameters used in stability analysis are in term of total stress. Pore pressure is neglected.

Table 3.2. Rock shear strength condition

Condition	Shear strength condition
1. Steady flow	Undrained (simple compression) in terms of total stress
2. Rapid drawdown	
3. Seismic	

3.5. Factor of Safety

The factors of safety (FS) obtained in the stability analysis are shown in table 3.3. The values of FS correspond to the minimal FS obtained for every fault surface. Two type of fault were analyzed: the main body of the dam and in the foundation's area. The rapid drawdown condition only was analyzed in the local fault; because of the sediments don't permit developing to the translation fault.

Table 3.3. FS values for the analysis conditions of the critical section.

	Local			Translation	
Method	Rapid D.	Seismic	Rapid D.	Rapid D.	Seismic
Janbu	6.711	5.104	26.664	4.325	2.656
Spencer	7.145	5.216	27.126	5.026	3.117

4. CONCLUSIONS

The majority of the older dams were built using methods of seismic analysis and seismic design criteria, which, today, are considered as obsolete or outdated. Therefore, in many cases, it is not known if an old dam complies with the current seismic safety guidelines. The safety of dams and their potential risks to their downstream region, particularly in seismically active areas, are serious concerns for governments, private owners of dams and affected communities. That's why; a stability analysis was carried out to the Tepuxtepec dam.

The FS values obtained for the critical section exceeds the minimal values recommended by seismic guidelines. The highest values were obtained for rapid drawdown (27.126 Spencer method) and minus ones for the dynamic condition (5.104 Janbu method). In translation's fault analysis, the minimal value of factor of safety so much in the static as dynamic condition appears in the stratum of pumice material.

In general, the numerical analysis carried out to the Tepuxtepec dam exceeds for much the minimal FS established, so that, dam does not present stability problems. A valid explanation is in the last reinforcement, the structural analysis was considered high values of acceleration (0.46 and 0.76 g, Esteva, 1969), doing the reinforcement very conservative. The update of seismic hazard indicates that the maximum acceleration for the Tepuxtepec site is 0.15 g

REFERENCES

Abramson, L. W. (2002). Slope stability and stabilization methods. 2nd Edition, John Wiley & Sons Inc. New York.

Aguirre-Díaz, G. J., Urrutia-Fucugauchi, J., Soler-Arechalde, A. M. & Mc Dowell, F. W. (1999). Stratigraphy, K-Ar ages, and magnetostratigraphy of the Acambay graben, central Mexican Volcanic Belt. *Geological Society of America*, USA, Special paper **334**: 1-12.

Comisión Federal De Electricidad, Instituto De Investigaciones Eléctricas (1993). Manual de Diseño de Obras Civiles: Diseño por Sismo. México.

Duncan, J. M. (1996). State of Art: Limit Equilibrium and Finite-Element Analysis of Slopes. *ASCE, Journal of Geotechnical Engineering*, **122:7**: 577-596.

Esteva L., Elorduy, J. y Sandoval J. (1969). Análisis de confiabilidad de la presa Tepuxtepec ante la acción de temblores, Instituto de Ingeniería, UNAM.

Figueroa, J. (1970). Catálogo de sismos ocurridos en la República Mexicana. Instituto de Ingeniería, UNAM.

Hynes-Griffin, M. E. & Franklin, A G. (1984). Rationalizing Seismic Coefficient Method. Miscellaneous Paper **GL** 84-13, USAEWES, Vicksburg, Mississipi.

Instituto Mexicano De Tecnología Del Agua (2001). Geotecnia en Ingeniería de Presas. Primera edición, México.

Krahn, J. (2004). Stability Modeling with SLOPE/W An Enginnering Methodology. GEO-SLOPE/W International, Ltd. Calgary, Canada.

Kramer S. L. (1996). Geotechnical Earthquake Engineering. Prentice Hall, USA.

Marsal, J. R. Y Reséndiz, D. (1975). Presas de tierra y enrocamiento. Limusa, México.

National Geospatial-Intelligence Agency (2007), información obtenida de la página web: http://geoengine.nga.mil/geospatial/SW_TOOLS/NIMAMUSE/webinter/rast_roam.html

Reséndiz D., Rosenblueth, E. y Mendoza E. (1972). Diseño Sísmico de Presas de Tierra y Enrocamiento: Estado del Arte. Instituto de Ingeniería, UNAM.

Suter, M., Aguirre, G. J., Siebe, C., Quintero, O., and Komorowski, J. C. (1991). Volcanism and active faulting in the central part of the Trans-Mexican volcanic belt. In Walawender, M. J., and Hanan, B. B., eds., Geological excursions in southern California and Mexico: San Diego, California, San Diego State University Department of Geological Sciences, 224–243.

USACE (2004), “General Design and Construction Considerations for Earth and Rock Fill Dams”, Engineer manual EM-1110-2-2300.