SEISMIC ANALYSIS OF TEPUXTEPEC DAM

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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.
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.
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).

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:

\[
FS = \frac{\sum \{c \cdot L + N \cdot \tan \phi\}}{\sum A_1 - \sum A_2 + \sum A_3}
\]  
(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:

\[
FS = \frac{\sum \{c \cdot L + N \cdot \tan \phi\}}{\sum A_1 - \sum A_2 + \sum A_3}
\]  
(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.](image-url)
### 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).

\[
P = S \sqrt{\frac{2}{\gamma_0^2 - H} \left[ 1 - 3 \left( \frac{Y}{H} \right) + 2 \left( \frac{Y}{H} \right)^3 \right]} \]

#### Table 3.1. Factor of safety for the different analysis conditions

<table>
<thead>
<tr>
<th>No.</th>
<th>Condition</th>
<th>FS</th>
<th>Slope</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steady flow</td>
<td>1.5</td>
<td>Downstream</td>
<td>Spillway level</td>
</tr>
<tr>
<td>2</td>
<td>Rapid drawdown</td>
<td>1.2</td>
<td>Upstream</td>
<td>Water intake level</td>
</tr>
<tr>
<td>3</td>
<td>Seismic</td>
<td>1.0</td>
<td>Upstream</td>
<td>Spillway level</td>
</tr>
</tbody>
</table>

Rocks parameters used in stability analysis are in term of total stress. Pore pressure is neglected.
Table 3.2. Rock shear strength condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Shear strength condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Steady flow</td>
<td></td>
</tr>
<tr>
<td>2. Rapid drawdown</td>
<td>Undrained (simple compression) in terms of total stress</td>
</tr>
<tr>
<td>3. Seismic</td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Method</th>
<th>Local Rapid D.</th>
<th>Seismic</th>
<th>Rapid D.</th>
<th>Seismic</th>
<th>Translation Rapid D.</th>
<th>Seismic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Janbu</td>
<td>6.711</td>
<td>5.104</td>
<td>26.664</td>
<td>4.325</td>
<td>2.656</td>
<td></td>
</tr>
<tr>
<td>Spencer</td>
<td>7.145</td>
<td>5.216</td>
<td>27.126</td>
<td>5.026</td>
<td>3.117</td>
<td></td>
</tr>
</tbody>
</table>

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


