A simplified procedure for seismic stability analysis of embankments

Une procédure simplifiée pour l'analyse de stabilité sismique de barrages

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ABSTRACT: It is presented a simplified method, which allows the evaluation of free board loss in earth-rockfill dams due to earthquakes. First of all, it is analyzed the response of the maximum middle section using a dynamic modal procedure based on the classic shear beam theory. With the calculated response, it is determined the acceleration maximum variations in the dam and the corresponding seismic coefficient are defined, which are used in the analysis of the conventional stability to determine the pseudostatic safety factor taking into account the seepage forces. The free board loss is finally obtained by an integration of the deformations considering the safety factors for three failure circles. This method is applied to the Adolfo López Mateos (El Humaya) dam.

RÉSUMÉ: Il est présenté une méthode simplifiée, qui permet l'évaluation de perte de conseil libre dans les barrages de terre et roches grâce aux tremblements de terre. Tout d'abord, il est analysé la réponse de la section mileu maximum en utilisant une procédure modal dynamique basée sur la classique théorie de la poutre de cisaillement . Avec la réponse calculée, il est déterminé les variations maximums de l'acceleration dans le barrage et il est défini chaque coefficient sismique, qui après sont utilisés dans l'analyse de stabilité conventionnelle pour déterminer le facteur de sûreté pseudostatic et tenir compte des forces de seepage. La perte de conseil libre est finalement obtenue par une intégration des déformations, qui considèr les facteurs de sûreté pour trois cercles de faille. Cette méthode est appliquée dans le barrage Adolfo López Mateos (El Humaya).

1 ANALYSIS OF THE SEISMIC RESPONSE

To evaluate the seismic stability of dams with the simplified method, first of all it is analyzed the seismic response of the maximum middle section (or the critical section) using a dynamic modal procedure based on the classic shear beam theory, proposed by Makdisi & Seed (1978). They consider the non-linear effects induced by the maximum probable earthquake, using an equivalent linear approximation, which consists in an iterative procedure to ensure that the dynamic properties used in the analysis are compatible with the computed strain levels generated by the seismic excitation. The approximation of the procedure that predicts the embankment's response is acceptable, as it has been verified through the comparisons with more complete analytical solutions, such as the finite elements method and with historic cases (Gazetas 1987). From the calculated seismic response it is determined the variations of the maximum accelerations inside the curtain and it is defined the respective seismic coefficients, which are used in the calculus of the seismic stability.

2 CALCULUS OF THE SEISMIC STABILITY CONSIDERING SEEPAGE FORCES

For the seismic stability analysis of the dam, it is used the pseudostatic method. Herein, it is supposed a circular failure surface ABC, as it is shown in Figure 1. ABC is an arch from a circle with center in O.

Taking into account a section of a unit length perpendicular to the plane of the drawing, the forces acting in the failure surface are the following:

Weight of the soil's slice limited by the slope and the circle's arch, W. Inertia force of the slice's weight, K_hW, which takes into account the effect of the earthquake acting upon the slice. The K_h is an average of the horizontal seismic coefficient acting in the slice $K_h=Sa_{ave}/g$; where Sa_{ave} is the spectral ordinate for the slope analysis as defined in Figure 3, and the resistance force per unit area, S, which is the soil resistance acting along the failure surface, ABC.

The safety factor, without considering the seepage force, F_s, is calculated as:

$$F_S = \frac{S(\mathrm{arc}(ABC))R}{WL_1 + K_h WL_2} \tag{1}$$

Where: R = circle's radius; S = resistance force along arc ABC

Now, when the seepage forces are considered, F_F, as shown in Figure 2, they can be computed as:

$$F_F = \gamma_W iA \tag{2}$$

Where γ_W = Unit weight of water; i = Hydraulic gradient; A = Cross-sectional area of the dam below the seepage line and the circle of failure.

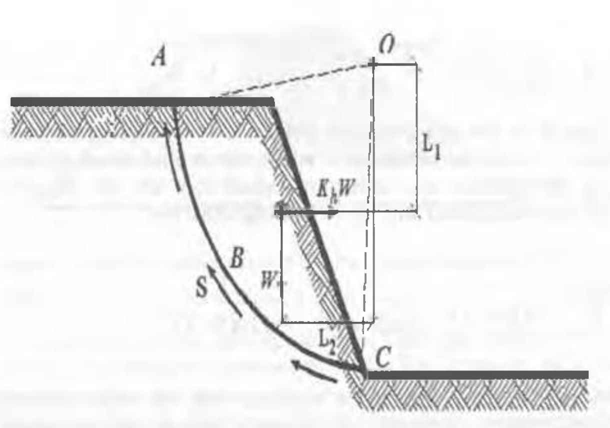

Figure 1. Pseudostatic stability analysis without considering seepage forces

The seepage force, F_F, is assumed to act in the center of the soil mass beneath the upper flow line and the failure circle (Fig. 2).

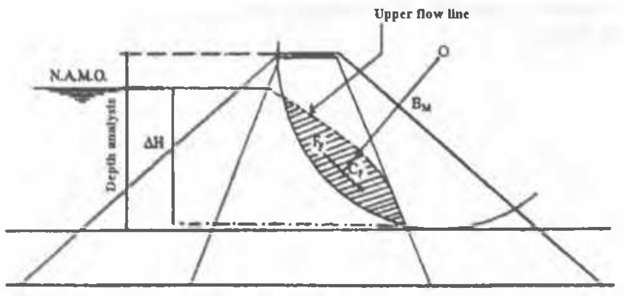

Figure 2. Pseudostatic stability analysis considering seepage forces, F_F.

As shown in Figure 2, $F_F * B_M$, gives the acting moment that is produced by the seepage force. Therefore, the safety factor, taking into account the seepage forces, F_{SF}, is given by:

$$F_{SF} = \frac{S(arc(ABC))R}{WL_1 + K_h WL_2 + F_F B_M} \tag{3}$$

If the safety factor F_{SF} is equal or higher than one, the failure surface is stable. As an idealization, the dam is considered as a structure made of a homogeneous material with frictional behavior. In other words, $\tau = \sigma \tan\phi$. To assign to each failure circle a seismic coefficient ($K_h = Sa_{ave}/g$), it is considered a linear variation between the maximum acceleration in the dam's base, (Sa_1), and the maximum acceleration at the crest (Sa_2). Sa_{ave} is given by the average between (Sa_2) and the acceleration (Sa_y), as it is shown in Figure 3. This average acceleration (Sa_{ave}) is applied in the slice mass center constituted by the circle's arch, the slope and the dam's crest (Fig. 3).

3 CALCULUS OF FREE BOARD LOSS

Reséndiz & Romo (1972) proposed a simplified procedure for the calculus of permanent deformations in embankments under their own weight. Lately, this method has been extended to the case of a seismic load in that is taken into account the local deformations an are considered in the calculus of the free board loss by the dynamic action of an earthquake. The following equation to calculate the dam's crest settlement was derived supposing that both the embankment volume and its crest's width remain constant during the deformation process.

$$\frac{L}{H^2} = \frac{1}{(B+b)}\left[\left\{\frac{\delta_{max}}{H}\right\}_u + \left\{\frac{\delta_{max}}{H}\right\}_d\right] \tag{4}$$

Where H = the embankment's height, B = embankment's base width, b = embankment's crest width, the subindex u and d express downstream and upstream respectively and the (δ_{max}/H) values are calculated with the following equation:

$$\frac{\delta_{max}}{H} = \frac{1}{93(F-1)} - \frac{1}{535(F-1)^2} + \frac{1}{9310(F-1)^3} \tag{5}$$

Where F is the safety factor obtained with the finite element method, which is related with the safety factors calculated with the pseudostatic method F_{SF}. The integration procedure to calculate the free board loss of the dam is as follows: The embankment is divided in horizontal slices. In most of the cases, it is enough with three or four divisions (Fig. 4).

The pseudostatic safety factor (F_{SF}) is calculated for the failure surfaces tangents to each horizontal plane selected. With these conventional safety factors (F_{SF}) and the dam's slope the actual safety factor, F; is obtained through the relation shown in Figure 5. With this safety factor corrected and Equation 5 it is estimated δ_{max}/H for each failure surface. The δ_{max} values are calculated considering the correspondent height, the distance between the embankment's crest and the respective horizontal plane (Fig. 4).

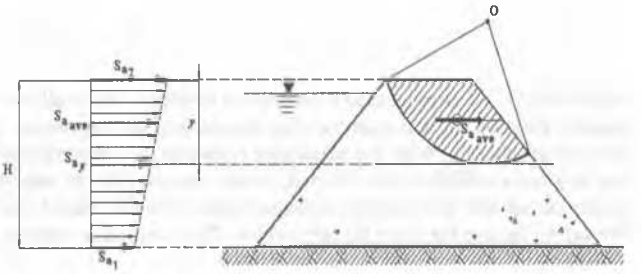

Figure 3. Determination of the seismic average acceleration Sa_{ave}.

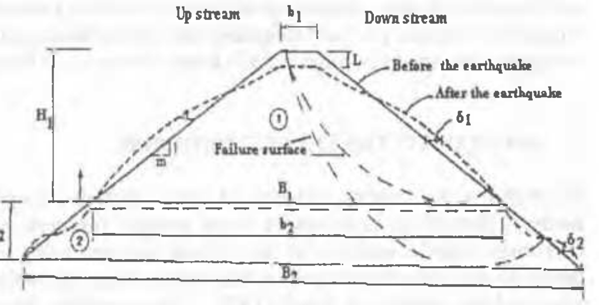

Figure 4. Dam's differential settlements

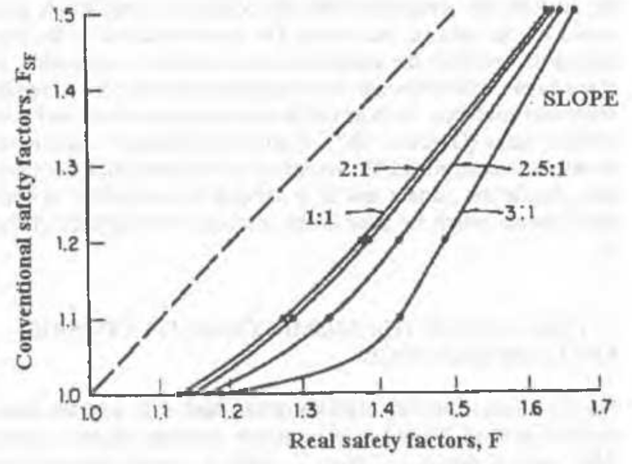

Figure 5. Relationship between F and F_{SF}.

The free board loss, L, is calculated adding each horizontal slice's effects as follows:

$$L = \sum_{i=1}^{n} L_i \tag{6}$$

where:

$$L_i = \frac{H_i}{B_i + b_i}\left\{\left[\delta^i_{max}\right]_u + \left[\delta^i_{max}\right]_d\right\} \quad (7)$$

and i = number of horizontal slices consider in the analysis. In Figure 4, $i = 2$.

4 APLICATION TO AN ACTUAL CASE

In this section the simplified method is applied to Adolfo López Mateos (El Humaya) dam.

4.1 *Dam's characteristics*

The dam is made of graduated materials, with a central, narrow, symmetric and impermeable core, protected with materials compound by gravel filters, sand and rocks, gravel and sand backing; and for erosion and surge protection gravel and boulder. The maximum height is 105.5 m, the crest length is 765 m, and the crest width is 10 m.

4.2 *Dam's mechanical properties*

The ϕ values, needed for the stability analysis were estimated using values obtained for Aguamilpa Dam, (Romo 1991).

4.3 *Dam's dynamic properties*

Since the dynamic properties of the soil depend importantly on the state of the dam static stress before the action of an earthquake, it is necessary as first step to evaluate the static stresses. Due to the poor information of the material's elastic properties that are part of the dam, it was considered sufficient enough for this study to estimate the static stresses in the different materials of the dam using a solution proposed by Goodman & Brown (1963). The dam was considered as a homogeneous structure, for that's sake, it was taken a weighted average of the material's volumetric weight that are part of the dam. Accordingly, it is necessary to calculate the dynamic properties of an equivalent homogeneous section. For this, it was considered as a representative stress of the homogeneous section that determined at a depth of 0.75H from the crest, where H is the height of the dam. To estimate the dynamic shear modulus for small deformations, (G_{max}), several semi-empirical correlations proposed for the clayey materials were applied (Seed & Idriss 1970, Hardin & Drnevich 1972; Romo 1995). For the filter material, two correlations were used, these proposed by Hardin & Drnevich (1972) and Seed & Idriss (1970). For the case of permeable material (gravels and boulders) it was used the equation proposed by Seed & Idriss (1970), but with a K_{2max} value of 100 (Romo & Villarraga 1989). From the results of different correlations, maximum and minimum estimations were obtained for the dam's average shear modulus. This average value was obtained with a weighted average of the shear modulus of each of the materials that are part of the dam. In this way, an equivalent homogeneous section was defined. The weighted average values of the shear modulus (G_{max}), for the most critical case (NAMO up stream and dry down stream) were 240,542 kN/m^2 and 430,683 kN/m^2. NAMO, stands for the maximum water level of operation of the dam. To take into account the shear modulus and damping ratio dependency with the shear strain, the variation curves (maximum, average and minimum) proposed by Seed & Idriss (1970), were used.

4.4 *Input motion at the base*

The acceleration response spectra applied at the dam's foundation are shown in Figure 6. That were obtained using the program PSM (Seismic Risk in Mexico), and correspond for a return period of 100 years.

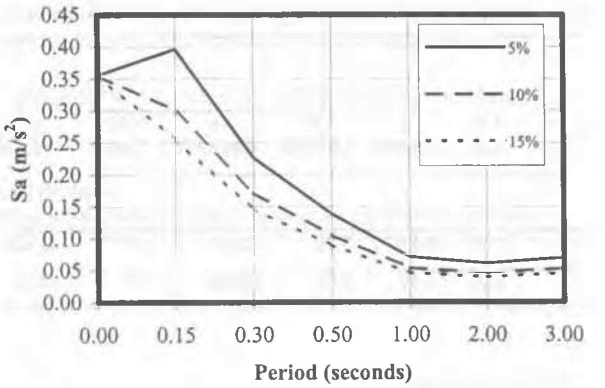

Figure 6. Acceleration spectrum applied to the dam's foundation.

4.5 *Seismic response analysis*

Due to the inherent uncertainties involved in the estimation of the dynamic properties, it was carried out a parametric analysis, which gave two values of G_{max} and three possible variation curves of G/G_{max} and damping ratio with the angular deformation (maximum, average and minimum curves). A response analysis was carried out for 18 different cases, produced by the mentioned combinations, and for each of them was obtained the maximum acceleration at the crest, the angular deformation in the dam, damping ratios and fundamental periods, after compatibility between soil properties and shear strain, were found using the linear equivalent method.

The most critical situation corresponded to the G_{max} = 430,683 kN/m^2 with the combination of maximum variation curve of G/G_{max} and the minimum variation curve of the damping ratio versus angular deformation. The maximum acceleration at the crest of the dam for this case was 0.94 m/s^2. Which means that the input maximum acceleration (0.35 m/s^2) was amplified about 2.7 times.

4.6 *Stability analysis and calculus of the free board loss*

With the acceleration's maximum value at the crest of 0.94 m/s^2 and the maximum acceleration at the base of the dam of 0.356 m/s^2, it is possible to get the seismic coefficient value ($K_h = Sa_{ave}$ /g) required to calculate the pseudostatic safety factor taking into account the seepage force. Once the safety factors, F_{SF}, are known, for three different failure circles (y/H=0.2, 0.7, 1.0) then it is possible to do the crest's settlement integration using Figure 5 and Equations 5-7. Where y, is the distance between the dam's crest and the point where a horizontal line is tangent to the failure circle being considered the uprooted proof of the failure circle (Fig. 7).

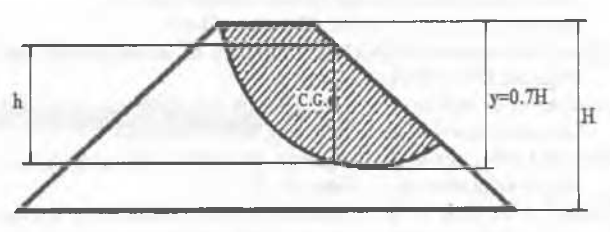

Figure 7. Sketch showing one of the three circles of failure, y/H=0.7.

The results of the free board loss (FBL) are summarized on table 1; the first line corresponds to the FBL obtained using the upper ϕ value and the second line, using the lower value proposed by Romo & Villaraga (1989). This dam is considered stable because the FBL calculated varied between 21.6 and 24.9 cm, which are lower than the design FBL (302 cm).

Table 1. Calculus of the total free board loss of the El Humaya dam

Range values of ϕ	Y/H Top	ϕ (degrees)	Y/H Medium	ϕ (degrees)	Y/H Lower	ϕ (degrees)	SAFETY FACTORS: Pseudostatic method, F_{SF} Y/H Higher	Pseudostatic method, F_{SF} Y/H Medium	Pseudostatic method, F_{SF} Y/H Lower	Finite Element Method, F Y/H Higher	Finite Element Method, F Y/H Médium	Finite Element Method, F Y/H Lower	Total free board loss (cm)
Higher	0.20	47.69	0.70	43.00	1.00	41.62	2.880	2.232	2.066	2.800	2.254	2.114	21.61
Lower	0.20	44.49	0.70	39.80	1.00	38.62	2.576	1.994	1.844	2.544	2.053	1.927	24.97

5 CONCLUSIONS

It is presented a simplified method to evaluate the seismic stability of graduated material's dams considering the seepage forces. The free board loss calculus was calculated from the settlement's integration taking into account three or more failure circles. The method proposed here is useful for preliminary designs or evaluations of existing structures in the presence of seismic events. It allows in a simplified form to determine if a dam fulfills the safety requirements in terms of deformations and safety factors. In case the safety factor is lower than the unit or the settlement of the crest exceeds the free board loss of design, then it is proceeded with detailed studies using techniques that need a greater computational effort like the finite element method. The simplified method was applied to the Presidente Adolfo López Mateos (El Humaya) dam, finding that the dam's crest settlements are below the free board loss of design. So, it is concluded that the dam is stable in the presence of seismic events and there is no need to perform further studies.

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