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Methodology for estimating seismic coefficients for performance-based design of earthdams and tall embankments

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ABSTRACT

Following an overview of pertinent literature, this paper presents a new methodology for estimating seismic coefficients for the performance-based design of earth dams and tall embankments. The methodology is based on statistical regression of (decoupled) numerical data for 1084 potential sliding masses, originating from 110 non-linear seismic response analyses of 2D cross sections with height ranging from 20 to 120 m. At first, the methodology estimates the peak value of the seismic coefficient k_{hmax} as a function of: the peak ground acceleration at the free field, the predominant period of the seismic excitation, the non-linear fundamental period of dam vibration, the stiffness of the firm foundation soil or rock layer, as well as the geometrical characteristics and the location (upstream or downstream) of the potentially sliding mass. Then, it proceeds to the estimation of an effective value of the seismic coefficient k_{hE}, as a percentile of k_{hmax}, to be used with a requirement for pseudo-static factor of safety greater or equal to 1.0. The estimation of k_{hE} is based on allowable permanent down-slope deviatoric displacement and a conservative consideration of sliding block analysis.

1. Introduction

It is well known that the assessment of seismic stability of earth structures may be performed via: (a) traditional pseudo-static analyses, (b) a great number of available displacement-based (Newmark or sliding block) methods, and (c) dynamic stress-deformation numerical analyses. Although robust numerical analyses, i.e. method (c), are nowadays quite common, methods (a) and (b) are still the basis of engineering practice in the seismic design of earth dams and tall embankments worldwide, at least in the preliminary design stages.

Pseudo-static analyses have the benefit of accumulated experience, reduced cost and user-friendliness, since they merely require the estimation of a Factor of Safety FS_d against seismic "failure" of the slopes of the earth structure. The described problem is illustrated in Fig. 1, which also depicts significant problem parameters like the peak values of the seismic acceleration at the crest, PGA_{crest}, at the outcropping (bed)rock PGA_{rock} and at the "free-field" of the foundation soil, PGA. The critical measure of the whole analysis is the value of the horizontal inertial force F_h that is applied at the center of gravity of the sliding mass and equals to the weight of the sliding mass W multiplied by a dimensionless seismic coefficient k_h. In general, the value of F_h (and k_h) should reflect the vibration of the sliding mass during the design earthquake, and its rational selection is therefore critical.

Given that the sliding mass is generally not rigid, different locations within this mass do not vibrate in phase and with the same intensity. Therefore, the value of k_h should be related to the resultant (horizontal) acceleration time history of the sliding mass, which, in turn, has been related to the resultant (horizontal) force time history along the shear band delineating the sliding mass within the dam body. This resultant acceleration time history is generally expected to be a function of the characteristics of the dam and the excitation, as well as the geometry of the sliding mass [36], but also to be affected by whether slippage has initiated along the shear band that delineates the sliding mass within the dam body [45].

Overall, there are two types of numerical procedures for estimating resultant acceleration time histories (and displacements) of sliding masses, i.e. "decoupled" procedures where the dynamic response of the dam is calculated separately from possible slippage of any sliding mass within it (e.g. [36,35]) and "coupled" procedures where the dynamic response of the sliding mass (and not the dam) is considered simultaneously to the accumulation of permanent deviatoric displacement (e.g. [33,45]). In all cases, an accurate

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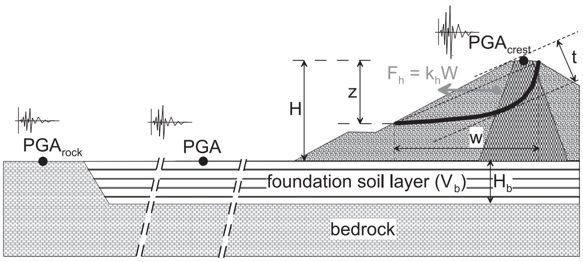

Fig. 1. Definition of critical geometric and geotechnical parameters for seismic slope stability of earth dams and tall embankments.

estimation of the resultant acceleration time history of a flexible sliding mass requires robust dynamic numerical analyses, which are demanding in software, expertise and cost. Thus, in order to avoid such analyses, researchers and practitioners around the world have devised various empirical methods for estimating appropriate values of seismic coefficients to be used in pseudo-static analyses (e.g. [52,17]). Andrianopoulos et al. [5] present a critical evaluation of such empirical methods and show that they generally disregard important problem parameters (e.g. dam characteristics) and may prove unconservative (e.g. for shallow sliding masses).

In any case, the peak value of the resultant acceleration time history is observed only momentarily. Therefore, the design of earthdams using the respective peak value of the seismic coefficient k_{hmax}, along with a requirement for a pseudo-static factor of safety against seismic "failure" $FS_d \geq 1.0$, leads to an overly conservative approach. Hence, common practice dictates the use of an "effective" value of the seismic coefficient k_{hE} (a percentile of k_{hmax}) in combination with the requirement for $FS_d \geq 1.0$, as more representative of the overall intensity of the shaking throughout its duration. This k_{hE}/k_{hmax} ratio in the literature ranges from 0.5 to 0.8, and its value has mostly been selected on the basis of experience and intuition [40]. This simple method of rationalizing the seismic design comes at the expense of generally "small", but unknown permanent down-slope deviatoric displacements. For example, Hynes-Griffin and Franklin [28] suggest that use of $k_{hE}/k_{hmax} = 0.5$ leads to displacements less than 30 cm, a value corroborated by Bozbey and Gundoglu [12] who also showed that for PGA < 0.5 g these displacements are even less than 20 cm.

It becomes obvious that permanent downslope deviatoric displacements don't directly govern, but are related to the selection of an "effective" seismic coefficient for the traditional pseudo-static design of earth dams and tall embankments (method (a) above). On the contrary, these permanent displacements play the lead role in modern performance-based design of such structures (method (b) above). In particular, Newmark [37], being the pioneer of this effort, devised the rigid sliding block theory for downslope deviatoric displacement computations based on the estimation of the yield acceleration of the sliding mass $k_y g$ (where g is the acceleration of gravity and k_y the yield seismic coefficient), via trial-and-error pseudo-static analyses for $FS_d = 1$. According to this method, the accumulated downslope deviatoric displacements of the slopes may be obtained by double integration of the relative acceleration, i.e. of the difference between the resultant acceleration time history and the critical acceleration $k_y g$ of the sliding mass.

In Newmark's proposition, the sliding mass was considered rigid and required case-specific time-histories for estimating displacements. To alleviate the latter problem, many research efforts ever since have made parametric use of this basic concept for a large number of seismic recordings attempting to devise user-friendly equations and/or charts for estimating permanent downslope displacements, given different selections of seismic motion measures (e.g. earthquake magnitude M, PGA, peak ground velocity PGV, Arias intensity, predominant T_e excitation period) and the value of the yield seismic coefficient k_y (e.g. [22,46,55,1,16,32,48,12]). Realizing further that the rigid block assumption is potentially too crude for a deep and flexible sliding mass, many researchers went on to estimate the resultant acceleration time-history and the down-slope displacement of this sliding mass, either with "decoupled" (e.g. [36]) or with "coupled" analyses (e.g. [45]). Again, parametric efforts enabled the proposal of empirical equations and/or design charts for estimating permanent down-slope displacements using "decoupled" (e.g. [36,13]), but mostly "coupled" analyses (e.g. [14,44]). The proposed equations and/or design charts appropriately employed seismic intensity measures related to the resultant acceleration time history of the sliding mass (e.g. k_{hmax}), rather than the seismic excitation itself (e.g. PGA) as in rigid sliding block methods. Hence, besides the need for estimating k_y via pseudo-static analyses, some of these displacement-based methods also include procedures for estimating the peak seismic coefficient, k_{hmax}. Again, Andrianopoulos et al. [5] show that existing pertinent procedures disregard important problem parameters (e.g. reservoir impoundment, existence of berms), while, in some cases, they are cumbersome to employ since they are not stand-alone methodologies (e.g. [36] require the estimation of PGA_{crest}).

In conclusion, methods (a) and (b) for the seismic design of earth dams and tall embankments are, in reality, clearly interrelated. Acknowledging this fact, there are efforts in the literature lately to directly relate the appropriate selection of an "effective" seismic coefficient k_{hE} (for use in pseudo-static analyses) to the allowable downslope deviatoric displacement [7,15,58,12]. These efforts definitely reduce the arbitrary nature by which the k_{hE}/k_{max} ratio has been dealt with in the past. However, Biondi et al. [7] and Bozbey and Gundogdu [12] deal with very specific sliding mass geometries (infinite slope, wedge in slope) that cannot cover all potential sliding masses of earthdams and tall embankments. On the other hand, Bray and Travasarou [15] propose an elegant scheme for estimating k_{hE} by considering it equal to k_y and requiring that $FS_d = 1$ for a given level of allowable displacements. To do so they propose an equation that uses an intensity parameter that is not yet well-established in engineering practice (spectral acceleration S_a for an elongated period of the sliding mass) and is related to the seismic excitation and not the dam vibration. Finally, Zania et al. [58] propose a "seismic coefficient spectrum" that yields values of $k_{hE} < k_{hmax}$ as a function of slope displacements. In concept, it is a rational approach, since it incorporates resonance and out-of-phase dam vibration effects, but their results pertain to specific sliding mass geometries and come with significant scatter due to the employed correlation to PGA, rather than PGA_{crest} (the latter is related to dam vibration, but not the former).

This paper falls within this last category of recent research efforts and aims at explicitly introducing performance-based design concepts in the well-established pseudo-static analysis. It also aims at proposing a stand-alone and easy-to-use method for estimating seismic coefficients for any potential sliding mass geometry. The method takes into account the allowable downslope displacements, and all important dam-foundation-excitation parameters, thus remedying the insufficiencies of existing methodologies. To do so, it first proposes a methodology for independent estimation of the peak seismic coefficient k_{hmax} (Section 3) and then proceeds to the estimation of its "effective" value k_{hE} based on allowable downslope displacements and a conservative consideration of sliding block analysis (Section 4). These tasks are enabled by a statistical regression of numerical results originating from a large number of two dimensional (2D) non-linear "decoupled" seismic response analyses of earthdams of parametric nature (Section 2). Section 5 presents a verification of the proposed methodology on the basis of case histories from the