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A simplified method for estimating Newmark displacements of mountain reservoirs

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ABSTRACT

In the present article we propose a new simplified method for assessing the seismic performance of large mountain reservoirs. The pseudo-empirical regression model is established on the basis of decoupled dynamic analyses performed on 7 accelerograms applied to 33 structural and geotechnical configurations. We study the influence of embankment geometries and mechanical properties on the prediction of earthquake-induced permanent displacements estimated by Newmark analyses. We also discuss the relevance of our model by carrying out comparisons with existing simplified models and with post-seismic field observations on earth dams. A regression analysis using parameters of interest provides a pseudo-empirical predictive equation to carry out rapid, preliminary assessments of the seismic performance of mountain reservoirs.

1. Introduction

Mountain reservoirs are hydraulic structures generally built in ski resorts. They are designed to store water used for the production of drinking water or artificial snow. These structures are located in mountainous areas, at altitudes between 1200 and 2700 m. They are often installed on steep slopes above facilities which are heavily populated during certain periods of the year. Depending on the geotechnical context, their failure can create torrential flows and, in spite of the low volumes of water stored, have disastrous consequences for public safety.

Mountain reservoirs are unique structures due to their geometry, the type of materials used in their construction, and the level of seismic risk to which they are exposed. Most mountain reservoirs are homogeneous earth dams. Their stability is validated by examining different design situations. These include seismic situations which, in the case of mountain reservoirs, are often critical design factors. Geotechnical investigations are difficult and expensive because the conditions of access to these dams are impeded by the topography of the sites and extreme climatic conditions. Moreover, the financial resources of the owners of such structures are limited, so a sismotectonic study of each site is not conceivable. Therefore there is a strong need for rapid and preliminary methods to evaluate the seismic performance of mountain reservoirs in a context where geotechnical data are scarce and the determination of specific accelerograms for each site is impractical.

The seismic performance assessment of earth dams is usually performed according to the pseudo-static approach [55]. This approach consists in analyzing the stability of a soil mass along a potential failure surface. The soil mass is subjected to horizontal destabilizing inertia forces, expressed in terms of a fraction of the acceleration of gravity (seismic coefficient k). Although some authors have developed a methodology to determine a relevant pseudo-static seismic coefficient from various seismic loading parameters and a target maximum displacement [10,7,42], this approach does not allow the evaluation of post-seismic permanent displacements.

Stress-deformation analyses enable conducting coupled nonlinear dynamic analyses [14,29]. These approaches can simulate all the stages of the life of a structure (construction, impoundment, seismic loading, *etc.*), by taking into account the nonlinearity of constitutive laws, hydro-mechanical coupling, the effect of the loading history, *etc.* The main drawback of these methods stems from the practical difficulty of providing site-specific high density and high-quality data. Indeed, these approaches require extensive geotechnical and sismotectonic investigations. Therefore these methods are generally limited to the analysis of critical projects and are not adapted to the rapid or preliminary assessment of the seismic performance of small earth dams. The objective of permanent-displacement analysis methods is to bridge the gap between the simplistic pseudo-static approach and complex stress-deformation analyses. They are still commonly used to develop seismic assessment approaches applied to the cases of natural slopes

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[50,33,54] and retaining walls [15]. Permanent-displacement analysis methods were formulated on the basis of the sliding block theory proposed by Newmark [40]. According to this theory, the potential sliding soil mass can be treated as a rigid body subjected to the action of seismic forces. Permanent displacements of the mass take place whenever the block acceleration exceeds a critical value called the yield acceleration. In ”decoupled” procedures, the dynamic response of the embankment is computed separately from the sliding mass displacement. In “coupled” procedures, the dynamic response of the sliding mass is calculated simultaneously to its permanent displacement. The main advantage of permanent-displacement analyses is that they require few data and are particularly adapted to parametric studies.

Newmark displacements are calculated following a decoupled procedure in which a rigid-plastic response of the block is assumed. The decoupling hypothesis is known to be conservative, especially when the predominant frequency of the seismic excitation is close to the fundamental period of the dam [36,20]. In contrast, the rigid block assumption is unconservative when the fundamental period of the sliding mass is close to the predominant period of the ground motion [46]. Some authors proposed a correction formula to account for the flexibility of the sliding mass after using rigid block assumptions to calculate the displacements [45]. However, the effect of the stiffness of the sliding block is believed to be of a secondary order relative to the amplification effects occurring in the embankment. Whatever the case, the Newmark displacement does not represent a realistic assessment of the deformation field within the structure. It is an index of the seismic performance of earth dams. If the predicted Newmark displacements are expected to be significant, a more refined method is warranted for further analyses.

To simplify the use of permanent displacement analysis methods, several authors developed empirical relationships on the basis of regression analyses performed on the basis of rigorous Newmark analysis results [38]. They proposed models that predict the Newmark displacement as function of structural parameters (yield acceleration k_y, first fundamental period of the dam T_1), ground motion parameters (peak ground acceleration PGA, earthquake magnitude M, Arias intensity I_a, predominant period of the acceleration spectrum T_m, spectral acceleration at a degraded period $S_a(1.5T_1)$, *etc.)* A summary of commonly referenced methods is provided in Table 1. All these methods were based on simulated Newmark displacement data computed from a large data base of worldwide earthquake records with various magnitudes and sismotectonic contexts. The application of these methods is not straightforward as they necessitate iteration and/or preliminary analyses, such as for the determination of k_{max}.

Table 1
Summary of commonly referenced rigid sliding block models.

Model	Functional form
Sarma [48]*	$\log[\frac{4U}{Ck_{max}gT_m^2}] = 0.85 - 3.91\frac{k_y}{k_{max}}$
Hynes-Griffin and Franklin [25]**	$\log[U(cm)] = -0.116\left(\frac{k_y}{k_{max}}\right)^4 - 0.702\left(\frac{k_y}{k_{max}}\right)^3 - 1.733\left(\frac{k_y}{k_{max}}\right)^2 - 2.854\left(\frac{k_y}{k_{max}}\right) - 0.287$
Makdisi and Seed [37]	$\frac{U}{k_{max}gT_0} = f\left(\frac{k_y}{k_{max}}\right)$ [chart-based mehod]
Yegian et al. [60]	$\log\left[\frac{U}{N_{eq}k_{max}gT_m^2}\right] = 0.22 - 10.12\left(\frac{k_y}{k_{max}}\right) + 16.38\left(\frac{k_y}{k_{max}}\right)^2 - 11.48\left(\frac{k_y}{k_{max}}\right)^3$
Jibson [27]	$\log[U(cm)] = 0.215 + \log[(1 - k_y/k_{max})^{2.341}(k_y/k_{max})^{-1.438}]$
Bray and Travasarou [9]	$\log[U(cm)] = -0.22 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(k_{max}) + 3.04\ln(k_{max}) - 0.244(\ln(k_{max}))^2 + 0.278(M-7)$

* Funtional form presented by Cai and Bathurst [12].
** Funtional form presented by Meehan and Vahedifard [38].

The estimation of k_{max} has to account for amplification effects related to dams's height. The estimation of k_{max} can be deduced from charts giving k_{max} as a function of PGA, T_1 and the ratio z/H representing the maximum depth of the sliding surface (measured from the crest) and the dam's height H [2,37]. However, it has been shown that the uncertainty on the value of the peak acceleration at the crest is of the same order of magnitude as the peak ground acceleration itself [11]. The reduction of uncertainties on the peak acceleration at the crest would require the implementation of advanced dynamic analyses and considerable computational efforts that conflict with the aim of simplified methods [8]. The procedures used for the determination of k_{max} constitute the main limitation of existing simplified methods.

Therefore there is a strong need to develop more effective and simple equations that do not integrate the parameter k_{max} and which are adapted to small earth dams ($H \leq 20\ m$). Considering that the *in situ* measurements published in the literature [53] have demonstrated that the normalization of the yield coefficient k_y by the peak ground acceleration PGA is efficient, we attempt to find a relationship in the following form:

$$\ln U^* = \mathscr{F}\left(\frac{k_y g}{PGA}, p_1, p_2, ...p_n\right) \tag{1}$$

where U^* is a non-dimensionalized displacement and p_i are scalar parameters of the model accessible without any additional computational effort.

In this paper, our objective is to rationalize the impact of seismic loading parameters and structure characteristics on permanent displacement estimates by employing rigorous Newmark analyses. The influence of the geometrical and geotechnical characteristics on the seismic response of the dams can be studied by conducting a parametric analysis. On the basis of 231 numerical simulations, we propose a simplified model for estimating the Newmark displacements as a function of various geotechnical and seismological parameters and discuss its predictive capacity on the basis of a comparison with existing methods and *in situ* measurements published in the literature.

2. Methodology and input data

2.1. Mountain reservoirs characteristics

Generally installed in flat areas, mountain reservoirs are built by excavation and fill and founded on bedrock. In the Alps, they consist of moraines and shales and, to a lesser extent, silts or materials obtained from crushing quartzite, gneiss and limestone. The embankment is then rendered impervious by the installation of a geomembrane. The storage volume of these mountain reservoirs varies from ten thousand to several hundred thousand cubic meters.

The typical geometry of mountain reservoirs is characterized by a trapezoidal cross-section, a crest 4 m in width, a height varying from 10 to 20 m, and a slope ranging from $\tan\beta = 1/2$ to $\tan\beta = 1/3$. The geotechnical parameters commonly encountered in such hydraulic structures are [43]: a moist unit weight around 20 kN/m^3, an effective cohesion c' between 0 and 10 kPa, an internal friction angle ϕ' between 25°and 35°for a maximum shear modulus G_{max} ranging between 180 and 500 MPa.

The simulations were performed considering a constant value of moist unit weight $\gamma_h = 20$ kN/m^3 and for three values of maximum shear modulus $G_{max} = 180, 300, 500$ MPa. The values of H are small enough to consider that the effect of the mean effective stress on G_{max} is of second order as regards to its the range of variation. Therefore, G_{max} is assumed to be independent from the mean effective stress. The combinations of the other parameters defining the situations are presented in Table 2.

Not every combination of parameters was considered in this study. The combinations of parameters were chosen in order to study the

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