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Single and multi-hazard capacity functions for concrete dams

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ABSTRACT

In the context of performance-based engineering (PBE), it is essential to determine a functional relationship for the response in terms of externally (such as hydraulic or seismic) or internally (such as alkali silica reaction)-imposed stressors. The importance of nonlinear analyses for each of the critical load cases (or stressors) or combinations thereof, as well as the final safety assessment are discussed.

This extensive survey paper reviews an extensive body of literature in multiple disciplines. This article aims to present all relevant methods (specially those not tailored for dams) in a more palpable way to dam engineers. Finally as a result of this extensive study new multi hazard capacity functions are introduced.

1. Introduction

The safety of infrastructure (specifically concrete dams in this paper) is affected by many events. A comprehensive safety evaluation methodology should take into account all potential events. Ultimate decision-making can be based on either the critical event or on the result of all events with their respective contributions. A safety assessment can be performed within the framework of performance-based engineering (PBE); this process begins with a project's initial concepts and extends throughout the life cycle of the structure [1].

The PBE of buildings and infrastructure has been indirectly undertaken since the introduction of strength in concrete structural design in the 1960s [2]. It has included force-based analysis and the design verification of components using:

$$\sum \alpha_i L_i \leq \phi C \tag{1}$$

where α_i is the load factor, L_i the load effects (dead load, live load, etc.), ϕ a capacity reduction factor, and C the component capacity.

In concrete dams, "failure" refers to the uncontrolled release of the reservoir water. This may or may not always be the case, and any other definitions are acceptable for failure depending on the project purpose [3]. The initiating events leading to dam failure include [4]: 1) hydrological events, such as flooding and increased flow through the spillway; 2) static events, such as reservoir water load, ice load and equipment malfunction; 3) material deterioration, such as erosion and alkali-aggregate reaction (AAR) in the concrete; 4) increased seepage, clogging of drains, degradation of the grout curtain; 5) seismic events, such as earthquake load; and 6) other initiators, such as human operating error, fire, landslides into the reservoir, vehicular impact, underwater explosion, sabotage and vandalism.

Considering just the most probable events, i.e. seismic, hydrological and material degradation, the dam capacity should be evaluated in the context of PBE. This concept has already been developed for various events, e.g. performance-based earthquake engineering (PBEE) [5], performance-based fire engineering (PBFE) [6], performance-based hurricane engineering (PBHE) [7], performance-based blast engineering (PBBE) [2], and performance-based wind engineering (PBWE) [8]. One commonality among all these events is to evaluate the capacity of the structure subjected to the specific event using varying amplitudes. Such a step yields the system response at different structural levels (i.e. linear, nonlinear, collapse).

In this paper, the concept of "capacity function" will be introduced for concrete dams and combined with existing structural analysis techniques. Fig. 1 shows the role of the capacity function within the global framework for performance-based assessment of concrete dams.

The general concept and mathematical model will first be presented for the capacity function. Next, various mechanical-, hydraulic- and earthquake-based structural analysis methodologies will be reviewed in detail. Finally, their application to concrete dam engineering will be studied.

2. Capacity functions

2.1. Basic definitions

Let's begin by distinguishing the various terms related to the "capacity" of the structural system.

Capacity curve: In its original definition, this notion refers to a

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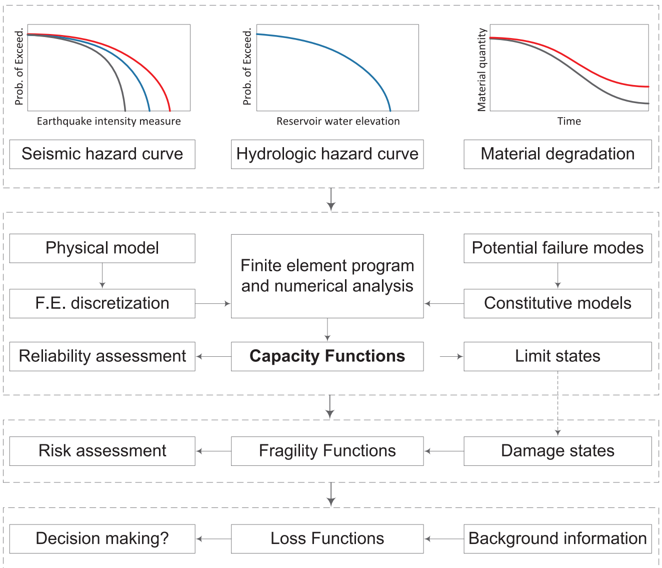

Fig. 1. Global framework for PBE of concrete dams.

nonlinear force-displacement curve [9]; it is determined by statically loading the structure in order to calculate the roof displacement *vs.* base shear. This curve also refers to the *pushover curve* [10]. In the laboratory, the load-displacement curve may be recorded by setting up either load control or displacement control protocols, depending on the availability of facilities. However, using the displacement control test, the post-failure can be captured. The conventional capacity curve may also be plotted in terms of dissipated energy, referred to as the *energy-based capacity curve* [11].

Capacity diagram: This notion refers to the pseudo-acceleration *vs.* deformation spectrum ordinate [12]; it is computed by dividing both the base shear by the effective modal mass at the fundamental vibration mode and the peak displacement by the mass participation factor. This diagram is also called the *capacity spectrum*.

Capacity function: This notion is defined as the relationship between an external (or internal) parameter affecting the capacity of the structure, also referred to as a "stressor" (S) and "response" (R) of the system at the macro level. As opposed to the conventional capacity curve, the capacity function is a more general concept and can generated by any of the initiators explained in the introduction; moreover, it is not limited to just seismic action.

Stressor: can be 1) an incrementally-increasing monotonic, cyclic or time-dependent load (or displacement, acceleration, pressure); 2) an incrementally-decreasing resistance parameter or degradation in strength properties; and 3) a discrete increasing/decreasing critical parameter in a system leading to failure. In PBEE, S is typically called an intensity measurement (IM) parameter [5]. In the present paper however, S is more generally defined and refers to any quantity whose variation (continuous or discrete) may lead to progressive system failure and its ultimate collapse.

Response: is representative of the system behavior under the varying stressor. It is depicted in either an absolute or relative sense. R may be: 1) a single damage variable (DV), such as drift or energy dissipation; 2) a combination of several DVs in terms of damage index (DI); and 3) any safety monitoring index [13]. In the field of earthquake engineering, R is typically called an engineering demand parameter (EDP) [14].

2.2. Mathematical model

Fig. 2(a) shows a sample capacity function normalized in both axes for the sake of simplicity. Three parts can be detected in this curve: 1) linear, 2) nonlinear, and 3) asymptotic to the horizon. The linear part refers to the elastic behavior of the structure; the nonlinear part refers to an elastic-to-plastic transient (or any other nonlinear model); and the horizontal part represents the system failure/collapse. In addition, Fig. 2(b) shows the derivation of the vertical axis with respect to the horizontal axis $\frac{\partial S}{\partial R}$. In the first part, the slope remains constant, while in the last part it equals zero, and in the transient part the slope decreases either regularly or in an irregular pattern. Three important assumptions/key points are inherent in the ideal capacity functions:

1. Some capacity estimation methods are capable of capturing the post-failure behavior, as will be discussed in Section 3.5. This implies the existence of another part (i.e. a fourth part) in the capacity function, which displays a decreasing nature (linear or nonlinear pattern). However, in the present study, we have only considered the concrete dam behavior up to failure.
2. Depending on the progressive failure methodology (see Section 3) used to derive the capacity function, only one, two or all three parts may be involved. From a mathematical standpoint, the absence of each part is modeled by considering a very small variation for the given part ($R_i \longrightarrow 0$).
3. The capacity function shown in Fig. 2(a) and its subsequent mathematical representation in this section have been idealized (and smoothed). In reality, a single-capacity curve has no uniform trend (especially in the nonlinear phase) mainly due to specific characteristics of the model and analysis. It is common practice however to quantify the epistemic and aleatory uncertainties in using the mean or median curve, which is smoother [15].

The capacity function can be expressed through analytical models. The analytical solution may have the following general form in its simplest expression:

$$\begin{cases} S_1 = a\ .\ R + b & \text{for}\quad 0 \le R < R_e \\ S_2 = f_N(R) & \text{for}\quad R_e \le R < R_u \\ S_3 = c & \text{for}\quad R \ge R_u \end{cases} \tag{2}$$

where a, b and c are constants; f_N is a nonlinear function representing the transition part; R_e and R_u are the limits for the elastic and ultimate responses. The following boundary conditions should also be satisfied when the three parts are connected to form a unified function:

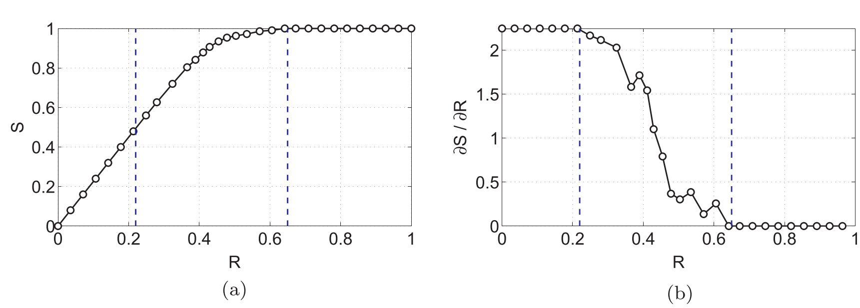

Fig. 2. A sample idealized capacity function (normalized form). (a) Capacity function, (b) Derivative of the capacity function.