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Combination rule for critical structural response in soft soil

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ABSTRACT

This work studies the problem of combining the seismic effects on structures caused by the simultaneous action of two horizontal orthogonal components of ground motion. In accordance with the random vibrations theory, several analytical expressions were developed to combine the two horizontal orthogonal seismic effects in order to estimate the elastic bi-directional peak response. The main hypothesis made in the development of these expressions was that the Fourier amplitude spectrum for the two orthogonal components of ground motion could be represented by a Dirac's delta. This hypothesis is supported by the observed characteristics of ground motions of earthquakes recorded in soft soils. Through the fully bi-directional elastic "step-by-step" analysis of different structural models, the accuracy of the proposed method was verified, in contrast with different combination rules. The exposed procedure explicitly considers the angle of the earthquake incidence and the type of response in terms of the direction of its components (orthogonal or collinear).

1. Introduction

During earthquakes, the structures are subjected to a rather complex ground motion field. However, in practice, it is common to analyze them only under the action of two horizontal orthogonal components of ground motion. In some cases (regions near the earthquake epicenter, for example), a third orthogonal component acting vertically is also included.

When structural analysis is conducted by means of spectral techniques, most codes recommend independently analyzing the structure in two orthogonal directions to obtain the unidirectional peak responses of interest. The main problem is determining the method of combining the unidirectional peak responses, $R_{x\ max}$ and $R_{y\ max}$, in order to estimate the maximum bidirectional response $R_{xy\ max}$ (Fig. 1).

Design codes specify different procedures to estimate the maximum bidirectional peak response by combining the unidirectional peak responses calculated by spectral methods. The procedures most frequently used are the α *combination rules*. In these methods, the bidirectional peak response is estimated by combining the effects of 100% of the unidirectional peak response caused by the action of the earthquake acting in one direction and α times the unidirectional peak response caused by the earthquake acting in the orthogonal direction.

A value of α = 30% was proposed by Rosenblueth and Contreras [1], and presently, several codes and recommendations have adopted this value [2–7]. Newmark [8] proposed a value of α = 40%, which has been adopted for other design codes or specifications [9,10]. Some codes specify a third rule as an option, which estimates the bidirectional peak response as the square root of the sum of the squared unidirectional peak responses (the *SRSS* rule) [2,9].

Menun and Der Kiureghian [11], based on work by Smeby and Der Kiureghian [12], proposed a modal combination rule for elastic systems denoted as *CQC*3. This rule explicitly takes into account the correlation between the modal responses, as well as the correlation between the horizontal components of the ground motion. In addition, the *CQC*3 rule provides an equation to calculate the response as a function of the earthquake incident angle and a formula for evaluating the critical angle, which is defined as the incident angle that produces the largest response value [13].

An explicit formula for calculating this critical response, which does not require the explicit evaluation of the critical angle in the original *CQC*3 rule, has been developed by Lopez et al. [14]. This explicit formula depends on the ratio between the spectral shapes, the ratio between the response components and the correlation coefficient between the components of the response caused by the action of the orthogonal ground motion components. For the purposes of this paper, this simplified formula is going to be

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referenced as the *CQC*3 rule, which is given by the following simplified expression:

$$r_{cr} = r_x \left((1+\hat{k}^2)\left(\frac{1+\beta_{CQC}^2}{2}\right) + \left(1-\hat{k}^2\right)\sqrt{\left(\frac{1-\beta_{CQC}^2}{2}\right)^2 + \left(\frac{\mu_{xy}}{r_x r_y}\right)^2 \beta_{CQC}^2} \right)^{\frac{1}{2}} \quad (1)$$

where $\hat{k}$ is the ratio between the response spectra considered to be acting along the x and y axes, $\beta_{CQC} = r_y/r_x$, r_x and r_y are the unidirectional peak responses in x and y directions, respectively, and μ_{xy} is a cross-term of the modal responses that contributes to r_x and r_y, which is evaluated as:

$$\mu_{xy} = \sum_i \sum_j \rho_{ij} r_{xi} r_{yj} \quad (2)$$

ρ_{ij} is the modal correlation coefficient between the i and j modes.

The responses, r_x and r_y, are given by

$$r_x = \left(\sum_i \sum_j \rho_{ij} r_{xi} r_{xj}\right)^{1/2}$$
$$r_y = \left(\sum_i \sum_j \rho_{ij} r_{yi} r_{yj}\right)^{1/2} \quad (3)$$

None of the mentioned combination rules (α, *SRSS* and *CQC*3) explicitly take into account the type of response in accordance with the direction of its components (collinear or orthogonal), or the effect of the soil conditions (α and *SRSS*). The importance of distinguishing between collinear or orthogonal responses has been studied and recognized by Reed and Kennedy [15] and Valdés [16]. Heredia-Zavoni and Machicao-Barrionuevo [17] and Valdés [16] demonstrated the relevance of the soil conditions in bidirectional earthquake structural responses. Heredia-Zavoni and Machicao-Barrionuevo [17] examined the effect of orthogonal components of ground motion on the linear response of torsionally stiff and torsionally flexible systems in soft and firm soil conditions. They showed that the bidirectional response is different depending on the dynamic properties of the analyzed model and on the soil conditions. They also examined the percentage combination rules and found that these rules can produce large over- or under-estimations of the design forces. Moreover, Fernández-Dávila et al. [18] studied different building models and demonstrated that the α = 30% and *SRSS* rules underestimate the maximum bidirectional response with errors close to −25%. In the case of bridges, Maleki and Bisadi [19] concluded that for time history analysis none of the combination rules (α = 30% or 40% and *SRSS*) provide conservative results. Recently, Kostinakis et al. [20] demonstrated, using the elastic analysis of several reinforced concrete buildings models subjected to different bi-directional seismic motions, that the percentage combination rule (30% or 40%) leads to unconservative response values, which strongly depend on the user's selection of the reference system. It is clear that there are still some uncertainties in the recommended specifications of the current codes when combining orthogonal seismic effects, which need to be clarified.

On the other hand, it is well known that the amplitude of the seismic waves increase significantly as they pass through upper soft soil layers. This phenomenon, known as site amplification, is one of the most important factors that produces major damage and the collapse of structures during earthquakes [21]. It is crucial to incorporate site conditions in the design of structures, taking into account not only the amplification of the ground acceleration but also the particular frequency content of the signal and the duration of the shaking, which is longer than in firm soils. The characteristics of earthquake ground motion in soft soils are different from those of firm soils, and it is important to study the behavior of structures, while distinguishing between both types of soil. An example of significant site amplifications was observed in the 1985 Mexico City Earthquake (M_s = 8.1) which caused great damage to the structures located on soft soil and killed more than 10,000 people. In this case, the amplification of the ground motion found when comparing nearby records of soft and firm soils was close to five when peak ground accelerations were compared and close to thirteen when peak spectral accelerations were compared. Another example of significant ground motion amplification caused by soft soil conditions was observed during the 1989 Loma Prieta earthquake in California USA. In this case, the amplification of the peak ground acceleration was close to 2.5 [22,23].

All of the existing rules (α, *SRSS* and *CQC*3), including the proposed rule in this paper, are focused on estimating the bidirectional response by considering the elastic behavior of the structures. This type of behavior is in accordance with most of current general design procedures, which are based on an elastic response calculation that is modified using ductility or reduction factors to estimate an inelastic response. To the extent that such a way of estimating the inelastic response of general design

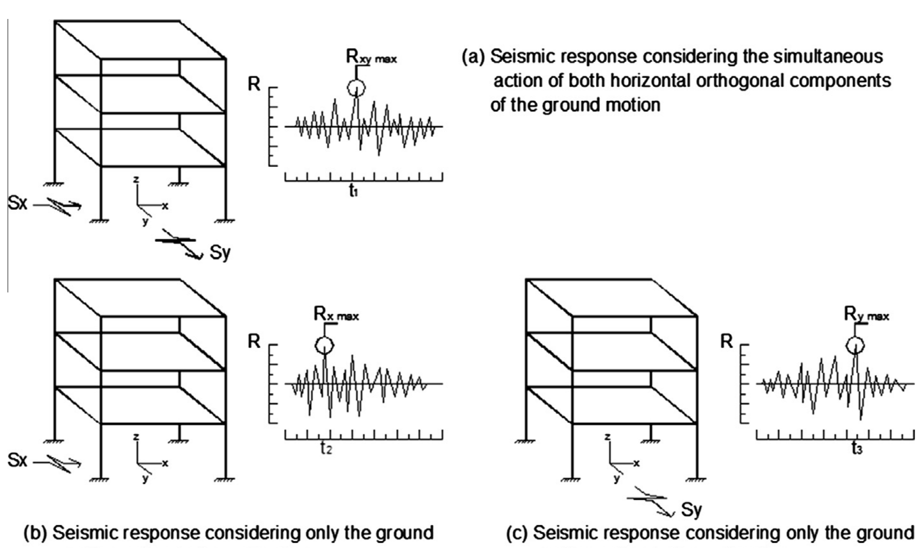

Fig. 1. Unidirectional and bi-directional responses during earthquake loading.