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Discussion

Closure to discussion of critical earthquake load inputs for multi-degree-of-freedom inelastic structures

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ABSTRACT

This closure addresses the comments raised by Dr Ashkinadze on the author's paper on modeling critical earthquake load inputs for multi-degree-of-freedom inelastic structures [JSV 325 (2009) 532–544].

The author thanks the discusser for his interest in his paper on modeling critical earthquake loads on inelastic structures. The author's earlier papers on the same subject have addressed all concerns of the discusser [1–17]. A quick review of the literature on critical earthquake load modeling will clarify this fact. While the discusser's conference paper addresses a similar problem to that considered by the author, the two papers have different objectives. The author's paper aims to model robust critical ground motion inputs to important structures, and thus the use of accurate nonlinear time-history analysis and nonlinear optimization is very essential [3]. On the other hand, the discusser's paper tries to use the concept of the critical excitation as a basis for selecting earthquake records to be used in seismic design of structures as specified in seismic codes [18–21]. Accordingly, the use of several approximations in representing the ground motion (the use of a steady-state function and not using optimization) is done. In fact, the two papers handle two different scenarios. The author's paper models critical earthquake loads on inelastic structures when the seismic knowledge is available in terms of past recorded ground motions at the site. This scenario is realistic for many parts of the world where sufficient records are available (note that earthquake recording started 76 years ago and nowadays well established seismic recording networks exist worldwide). The discusser's paper assumes that the earthquake knowledge is given in terms of the response spectra of the site. However, Ref. [22] compares the derived critical excitation obtained from a response spectrum with past records which initially were assumed to be unavailable, thus ignoring important available data from past recorded ground motions. Furthermore, Ref. [22] implies that the discusser is not aware of the existing rich literature on the critical excitation method since 1970 [1–17,23–25]. For instant, Ref. [22] does not cite any paper on the critical excitation method while the work is mainly based on the critical excitation method. Moreover, the present author has already adopted the concept of the critical excitation method in the process of record selection for seismic design of structures before the appearance of the discusser's conference paper [10–13]. Furthermore, the use of the site response spectra in modeling critical earthquake loads has also been studied by the author [4]. The discusser needs a careful review of the literature on the same subject. The detailed response to the numbered points is as follows:

1. Introduction: the critical seismic excitation paradigm

The discusser states that the critical excitation paradigm relies on some of the earthquake parameters, such as, the maximum seismic magnitude expressed in terms of the energy or the peak ground acceleration (PGA). Firstly, it must be

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noted that earthquake ground motions represent transient loads that have finite energy, and thus an explicit constraint on the energy is a must. Moreover, an implicit constraint on the nonstationarity of the ground acceleration is essential. The constraint on the PGA alone is not enough since it does not imply finite energy or transient trend of the ground acceleration. More discussion on this point can be found in Refs. [1–3]. Furthermore, it is not true that the nonlinear time-history analysis of the structure is mostly used for illustration and research purposes. This statement was true 30–40 years ago. Nowadays, modern seismic codes require full time-history analysis for critical facilities, important structures, structures having irregularities in plan or elevation and special structures, such as, base-isolated structures (see Ref. [3] in the discusser's conference paper and Refs. [18–21]). Thus, the time-history analysis is compulsory in certain cases, especially for important structures driven by extreme loads, such as critical earthquakes. Moreover, given the current advances in computers, finite elements software, and seismic design methods (e.g., displacement- and performance-based design), the time-history analysis became a simple regular analysis. In our paper, the nonlinear behavior of the structure is accounted for and all relevant information on the ground motion is also considered. The imposition of a constraint on the critical future earthquake, in terms of the Fourier amplitude or the entropy rate, is not arbitrary. This constraint was indeed introduced by Shinozuka in a deterministic setting [23] and was also proposed by Takewaki within the framework of probabilistic analysis [26]. The author's paper does not exclude the case when the information on the energy and peak ground acceleration is only available. Actually, Table 1 of the paper contains case 1 which treats this situation and case 4 that tackles a different situation when further information on the critical input is available. In fact, case 1 can be used at preliminary design stages or when very limited earthquake information is available while case 4 can be used when more seismic information on the critical future earthquake is available. A careful reading of the author's paper and the literature will clarify these facts.

2. Comments on the proposed approach and technique

2.1. The limitation on the critical seismic action

The discusser misinterprets the author's paper. The fact is: the critical earthquake load for a linear structure is a resonant acceleration matching the structure's fundamental frequency. All our earlier papers have proved that. For nonlinear structures, the definition of a constant frequency for the structure does not exist. The change in the structural stiffness implies a change in the natural frequencies. On the other hand, the knowledge on the Fourier spectra and on the entropy rate quantified from actual recorded ground motions is not artificial limitation. The discusser needs to read our earlier papers on modeling critical earthquake loads [1–17] to gain more understanding and insight into the nature of these constraints. The discusser states that "if an earthquake is treated as a random process, then past seismic records can be regarded as certain samples for the possible future seismic ground motion". Actually, this is a well known fact and has been implemented by many researchers since 1970 [23–25]. For instant, in the early stage of developing the method of critical excitation, the future critical earthquake was expressed as a weighted summation of past recorded ground accelerations. Since this representation contains mathematical problems (e.g., the series completeness and the orthogonality of the basis functions that prevent convergence of the series when the number of the basis functions increases), we have expressed the ground acceleration as a Fourier series to overcome these problems [7]. In fact, the representation of the ground acceleration proposed by the discusser in his conference paper is not realistic since it does not represent real ground accelerations of transient trend and finite energy. We have also addressed the treatment of the constraints as being random variables in some of our earlier papers [8]. The discusser should read the literature on the critical excitation method including our papers on modeling deterministic and probabilistic critical earthquake loads before making strong comments [7,8].

The author disagrees with the discusser that the way of the constraints on the critical earthquake is unreliable. In fact, all constraints imposed on the future earthquake are realistic and represent important parameters that accurately describe the ground motion characteristics (e.g., PGA, energy, Fourier spectra, etc.). Additionally, our approach represents extension and improvements to the approach proposed by Drenick, Shinozuka and Iyengar 40 years ago [23–25]. In fact, the approach presented in Ref. [22] is not robust due to the unrealistic representation of the ground acceleration and the severe approximations employed.

The author would like to emphasize that the method of critical earthquake excitation is proposed mainly for important structures driven by extreme loads. The extraction of critical earthquake loads based on a response spectrum for the site is not new and has been studied by the author [4]. Moreover, the critical excitation always produces a conservative response, and therefore earlier research was concerned with modeling what is called "subcritical excitation" and with developing further constraints to produce more realistic response of the structure. The discusser is asked again to read the literature on the critical excitation method including our earlier papers (e.g. [7,8]).

2.2. The computational technique

The modeling of critical excitation for linear structures is simpler compared to the case of nonlinear structures. If the nonlinear behavior of the structure is to be included in the analysis, which is necessary in modeling critical earthquake loads since damage of the structure under extreme loads is expected, additional computation is required. This is not a limitation of the method. If one has to carry out accurate nonlinear time-history analysis, there is no way to avoid performing a step-by-step numerical integration. This is not a drawback of the method.

The discusser, again, misinterprets the series representation of the ground motion used by the author. The use of the Fourier series representation in the paper does not aim to simplify the analysis for nonlinear structures. As is well known, the principle of superposition does not hold in this case. This representation overcomes several limitations that are involved in expressing the ground motion as a weighted combination of past recorded ground motions as proposed by Drenick, Shinozuka and others [7,23–25]. In fact, the discusser contradicts himself by rejecting the Fourier series representation while he employs the same representation in his conference paper and ignoring the nonstationarity of the ground acceleration (Eq. (3) of Ref. [22]). A careful reading of the literature on the critical excitation method will clarify the discusser's misunderstanding. Nowadays, the time-history analysis is a simple exercise for the structural engineering students and is provided in most textbooks of structural dynamics. The modeling of the critical ground motion requires more computation than the linear case but, at the same time, it is very essential to account for the nonlinear behavior of the structure since the critical excitations represent extreme loads. Furthermore, the extra computations require a few additional minutes than the linear case which does not represent any serious difficulty.

The discusser again makes inaccurate judgment without any knowledge of the literature on the critical excitation method. It is not true that only bilinear inelastic behavior has been considered by the author. Cubic nonlinearity, elastic–plastic behavior and brittle failure have also been considered by the author [6,9,15]. The discusser points out that the sequential quadratic programming (SQP) imposes severe constraints (termed as limitations in the discussion paper) on the type of the response nonlinearity considered which is again not true. The optimization program does not impose any constraints. The SQP searches for the optimal solution that best satisfies the constraints imposed by the programmer. Again, the discusser makes a strong judgment that our approach does not fit structures that deform plastically which is again not true. The simple fact is, whatever the structural behavior involved, the critical excitation method is capable of modeling the associated critical earthquake load. All to be done is the correct implementation of the structural behavior (i.e., the computation of the structural response). In fact, we have recently studied the modeling of critical seismic loads that produce the largest damage in elastic–plastic structures [10,17]. The discusser must read the literature before making strong comments without enough knowledge on the existing literature.

3. Alternative approaches and conceptual analysis of the CSE method

In this part, the discusser rejects the critical excitation method introduced by Drenick, Shinozuka and Iyengar and proposes what he calls "absolute accelerogram". It should be emphasized that the absolute accelerogram proposed by the discusser is simply taken from the critical excitation method without giving credit to earlier works done by several researchers on the same subject. The discusser talks about two constraints, namely, the peak ground acceleration and the "design" response spectrum (termed response spectrum in the discussion paper). Again, the discusser contradicts himself by saying that the PGA is the only known parameter about a site and that in most countries until 2000, seismic sites were zoned on the basis of PGA and in recent codes the basis for zoning became the spectral response acceleration. The discusser needs to note two facts: (1) the critical excitation method provides a conservative response, and is thus applicable to important structures and critical facilities, and (2) the PGA is currently of minor importance compared to the earthquake intensity or energy (as stated by the discusser). The rejection of the approach of the critical excitation proposed in several studies during the last 40 years is not acceptable. The finite energy of the earthquake ground motion must be imposed as a constraint. The discusser needs to revise his proposed approach by using robust representation of the ground motion and handling realistic constraints.

4. The proposed approach by the discusser

The discusser suggests that the critical acceleration can be represented as a stepwise periodic function with an upper bound on its absolute value. In this context, it should be emphasized that the basic features observed in real recorded earthquakes must be accounted for. To name a few characteristics that has been ignored in the discusser's approach, the transient trend (earthquake loads always start from rest, reach a strong phase and diminish by the end of the ground shaking) and the finite energy of the ground motion. The total duration of the ground motion is also an important parameter that needs a careful treatment. The discusser's approach avoids these aspects by assuming that the ground acceleration can be represented as a steady-state function (i.e. stationary) that even violates the initial and the end conditions (initial displacement = 0 and final velocity = 0) as well as the finite energy of the ground acceleration. The acceleration duration of the critical input is an important parameter in the dynamic analysis of nonlinear structures. For instant, long-duration earthquakes are capable of driving the structure into its nonlinear range and can produce large damage in the structure. On the other hand, short-duration earthquakes may not produce any significant structural response and/or damage. This simplification is not realistic and questionable since it introduces errors to the optimal solution obtained. The discusser's approach includes also approximations in estimating the response of the structure due to the combination rule adopted for multi-degree-of-freedom structures.

5. Conclusion

The discusser raises questions on the computations involved in the nonlinear time-history analysis and on the Fourier series used in representing the critical future earthquake. The computations involved in our approach is essential and do not constitute any problem given the current advances in computers and computation techniques and the need for accurate analysis of nonlinear structures under extreme loads. The author is surprised with the discusser conclusion that he rejects the author's approach (the discusser has written a single conference paper on the topic in 2010 and is not aware of all research works carried out on the same topic during the last 40 years). Instead, the discusser should read the literature and give credit to previous work based on which he proposes the absolute accelerogram. Additionally, given the 76 years of strong ground motion recording worldwide through well established networks of recording stations, it is not true that there are no enough earthquake records to be used as basis for the critical earthquake. Concerning, the probabilistic modeling of critical earthquake loads, we ask the discusser to read our earlier papers on the same topic [4,8].

The discusser proposes a methodology for extracting critical ground motions when a limited data on the PGA and the design response spectra of the site is available. Conceptually, the author's paper treats the same problem studied by many authors during the last 40 years when the seismic data on past recorded accelerations is available. However, the two approaches treat two different scenarios. As is well known, the response spectrum method does not account for several characteristics of the ground motion, such as, the total duration and encounters approximations when dealing with multi-degree-of-freedom systems (summation of maximum responses that do not occur at the same time instants). In fact, the method of critical earthquake load modeling has been proposed as a counterpart to other methods of earthquake load specifications, namely, for critical facilities and important structures. Such structures are required to survive strong earthquakes and therefore, the use of highly approximate analysis does not provide reliable seismic design.

While the discusser proposes what may constitute a practical approach, however, more rigorous constraints and realistic representation of the future ground motion are needed. Furthermore, his approach does not exclude the nonlinear time history analysis of the structure (the discusser states that his approach is applicable to several nonlinear models which is also true for the author's approach). In short, most of the points raised by the discusser have been already addressed in several papers by the author. In fact, the use of the response spectra in developing critical earthquake load models has been already studied by the author [4]. Furthermore, the literature presented on the record selection by the discusser in Ref. [22] is old and needs to be updated [14]. The use of the notion of the critical earthquake excitation method in selecting earthquake records for seismic design of structures has also been developed by the author [10–14]. The discusser needs to read the literature on the critical excitation method before making strong comments on a well developed subject. Giving credit to previous research work on the same subject is also very essential.

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