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Discussion

Discussion on “Critical earthquake load inputs for multi-degree-of-freedom inelastic structures” by A. Moustafa

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1. Introduction: the “critical seismic excitation” paradigm

Nonlinear time-history analysis using real and synthetic earthquake acceleration records (accelerograms) as input action is the most physically consistent and versatile tool for seismic analysis of structures. However, at present, it is mostly used for illustration and research purposes, not for practical design. High level of uncertainty associated with the earthquake phenomenon undermines credibility of the analysis in a design case, where the goal is to assure survival of the structure under any possible seismic actions on the site—the ones that have occurred in the past and the ones that have not, but may occur in the future. The latter part presents the most difficulties.

The discusser wholly agrees with the author of the discussed paper [1] that “it is essential to develop robust methods for seismic-resistant design of structures”. The “critical seismic excitation” (CSE) paradigm relies only on those few parameters of the earthquake that can be predicted with greater certainty, such as the maximum seismic magnitude expressed in terms of energy input, or the peak ground acceleration (PGA). For all other parameters, such as the spectral content of the earthquake, it abstains from making assumptions that would reduce the response of the structure, because these assumptions may not materialize in a future earthquake. Rather, it assumes that these parameters are at their most unfavourable values for the structural response (within certain limitations); hence the term “critical seismic excitation”. Thus, the CSE paradigm shifts the emphasis from refinement of the parameters of seismic action to avoidance of dangerous dependency on the accuracy of these parameters.

2. Comments on the proposed approach and technique

2.1. The limitations on the critical seismic action

The discussed paper [1] points out that the CSE is necessarily resonant unless some artificial limitations are imposed on the Fourier spectrum. These limitations, as well as the “entropy” limitation used in earlier papers of the same author [2,3], attempt to attain a “rich frequency content” of the model critical earthquake, approaching that of a real earthquake.

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This provision is the main point of objection by the discusser. The goal of avoiding undue criticality of the action, unrealistic in a naturally occurring earthquake, is valid; however, the discusser feels that the way these limitations are introduced is unreliable, based only on the limited number of past earthquakes, and the "entropy" limitation is also not a law of nature but merely a phenomenological observation.

In fact, these provisions reintroduce the a-priori assumptions about "knowledge" of the properties of the future earthquake that have been previously expelled by demanding that the parameters of the seismic action, except for the zoning limitations, shall be at their most critical values. The discusser does not believe there is sufficient information about earthquakes worldwide that allows such generalizations.

The target paper [1] selects the maximum of such parameters as Arias intensity, PGA, PGV (peak ground velocity), PGD (peak ground displacement) and upper and lower limits on the Fourier spectra of the past ground acceleration at a certain site as predefined constraints to attain the CSE. The perils of this approach are not fully realized. If an earthquake is treated as a random process, then the past seismic records can be regarded as certain samples for the possible future seismic ground motion. However, there is no assurance in the paper that this sample is statistically representative. The level of exceedance probability of the CSE in Ref. [1] needs to be further studied and designated.

2.2. *The computational technique*

Another point of contention by the discusser is the extremely obtrusive nature of the algorithm involved. In the earlier papers [2,3], which concerned linear–elastic structures, the problem was pre-solved for the single harmonic in the Fourier spectrum. Thus, there was no need for the stepwise integration of the differential equations of motion, and the problem of finding the CSE reduced to a one-pass optimization.

When the author now considers nonlinear systems, it requires different mathematical techniques. Since the principle of superposition is not applicable to nonlinear systems, the Fourier decomposition of the sought critical action is of little benefit for such systems. The increment of the input acceleration Δa_g in the differential equations of motion written for one time step:

$$\mathbf{M}\Delta\ddot{\mathbf{r}}+\mathbf{C}\Delta\dot{\mathbf{r}}+\mathbf{K}\Delta\mathbf{r}=-\mathbf{M}\Delta a_g \tag{1}$$

is an independent variable in its own right and does not need to be considered as part of a harmonic. (In Eq. (1), $\mathbf{M}$ is the mass matrix of the system; $\mathbf{C}$ the damping matrix; $\mathbf{K}$ the current stiffness matrix; $\Delta\mathbf{r}$, $\Delta\dot{\mathbf{r}}$ and $\Delta\ddot{\mathbf{r}}$ the vectors of increments of nodal displacements, velocities and accelerations, respectively.)

The maximization of the structural reaction needs to be performed at every step of integration to compute the sought critical action. The author states that it takes thousands of iterations (from 1600 to 16,000) for the optimization process to converge, and on average the CSE contains about 50 harmonics. Also, the incremental solution of the differential equations of motion usually takes thousands of time steps. As a result, the system of equations (Eq. (1)) has to be solved millions (billions?) of times.

The optimization algorithm utilized in Ref. [1] (sequential quadratic optimization) imposes severe limitations on the types of response nonlinearity that can be considered. The only nonlinear deformation diagram implemented so far is bilinear hysteretic diagram with an ascending yielding branch. No descending branches of degrading stiffness, no brittle failure or buckling failures are allowed by this method because it requires that the incremental stiffness matrix of the structure remain positive definite throughout the integration process. Please note that this is not a physical limitation but is imposed strictly by the optimization procedure used.

In reality, if the system deforms significantly in the plastic range, as is typical when a CSE is used, there is generally good agreement between the outcomes computed by refined nonlinear deformation diagrams and the ones corresponding to the simplified nonlinear relationships (even a rigid plastic one; see Ref. [4]). However, this only applies to structures that deform essentially plastically (i.e. beam members governed by flexure). There are many types of structures that do not fit in this class, such as shear walls, wall-beams, slender columns, concentrically braced frames, keyed joints of wall panels, etc. Their behaviour is governed by shear, brittle failures, degrading and non-stationary response, or buckling. The method proposed in Ref. [1], at this stage, is not suitable for the analysis of these types of structures.

3. Alternative approaches and conceptual analysis of the CSE method

An alternative proposal, which can potentially overcome most of the noted problems, is the method of "absolute accelerogram" and "reduced absolute accelerogram", proposed by the discusser [5]. It is beyond the scope of this Discussion to describe this alternative method in detail; rather, only the differences in the approach are highlighted.

To properly formulate the concept of CSE, it is necessary to clarify what is actually known about the seismic properties of a particular site. The two key parameters of a CSE are the peak ground acceleration and the response spectrum.

The PGA is the only parameter known about a site with relative certainty. In the old code paradigm adopted in most countries until 2000 [6], seismic sites were zoned on the basis of the PGA. (In the more recent codes [7,8], the basis for the zoning was changed to "spectral response acceleration" (SRA), which depends on both the zonal seismicity and the period of the structure.) In many areas where insufficient records of strong ground motions existed to quantify the zonal PGA, the latter was evaluated from historical depictions of the extent of damage caused by ancient earthquakes.

The spectral content of a "design basis" earthquake is substantially less determinate. For practical purposes, it is established as a consensus of leading experts in the field, reflected in standard response spectra. The code developers are responsible for the selection and scaling of model accelerograms that are used to generate these spectra, to ensure that the probability to exceed the coded response is less than a certain acceptable margin. In essence, the assignment of the allowable limit of risk is not a technical question but rather a political one in the particular jurisdiction. After the PGA, this stipulated safety margin is the second given quantity for any design model of seismic action.

The alternative methods proposed by the discusser [5] follow this logic. The "absolute accelerogram" is the loading time history most unfavourable for a given structure with the ordinates of the input accelerogram not exceeding the zoned PGA. As shown in Ref. [5], it is a stepwise-periodic resonant loading that can be formulated in a time-history analysis without the need for explicit optimization. Thus, the double nested loop in the CSE generation algorithm [1] (iterations for optimization inside the cycle by the integration time steps) is avoided.

An advantage of this approach is that it does not impose any limitations on the types of nonlinearity considered, as opposed to the highly constrained methods of Ref. [1]. In Ref. [5], the construction of the model accelerogram has been illustrated for four types of deformation diagrams: (i) linear–elastic, (ii) elastic–plastic with hardening and hysteresis, (iii) nonlinear–elastic, and (iv) elastic–brittle with degrading stiffness.

The reduction of the CSE to correspond with the code-stipulated margins of safety in Ref. [5] is ascertained by "reduced absolute accelerograms". The key input required for this procedure is the target response reduction ratio. The proposed method utilizes coded standard response spectra to determine the ratio by which to reduce the reaction from the full resonance case, embodied by the action of the absolute accelerogram. The corresponding "reduced-critical" accelerogram is then constructed by frequency modulation from the absolute accelerogram.

Comparing this methodology with that proposed in Ref. [1], it is seen that the conditions imposed to reduce the tendency of the optimized accelerogram to approach resonance are similar in nature. However, the method of reduced absolute accelerograms refers directly to the design codes and standardized response spectra, while the method proposed in Ref. [1] attempts to "reverse-engineer" these provisions in terms of Fourier spectrum or entropy limitations. In the latter case, there is no guarantee or formal demonstration that this procedure has been performed correctly, used the same set of accelerograms that was used when developing the standard spectrum, etc.

4. Conclusions

- The concept of CSE proposed by the author of the discussed paper [1] is agreed to be a promising approach, overcoming the uncertainty in defining histories of ground motion representative of future earthquakes on the considered site.
- The primary aspiration in Ref. [1] is the reality of the shape of the critical seismic input. Although existing seismic zoning only provides a single quantity of PGA or SRA, it is proposed to extract non-stationary/transient trends, entropy and spectral characteristics from records of real past earthquakes and consider them in formulating the CSE.

  The discusser disagrees with this approach. Although it is tempting to construct the critical seismic action such that it simulates a real earthquake, there is simply not enough seismic data available to support confidently assigning the numerous parameters required for such modelling. (How much is "enough" is a question that can be resolved by standard methods of formal hypotheses validation in statistics and system dynamics [9].) In essence, proposal [1] conflicts with the declared "critical" nature of the constructed seismic record. It is worth reminding that the entire CSE paradigm was developed as a reaction to the inherent uncertainties of the "design basis earthquake" formulation.
- More comparisons should be made between the structural response to the model accelerogram proposed and the response to design real or artificial accelerograms. In the discussed paper, there are no direct comparisons of the structural response to the CSE vs. real accelerograms after the latter ones have been decomposed to extract their spectral parameters.
- Another matter of concern is the extreme computational complexity of the proposed method, which is not suited for the general case of structural nonlinear response.
- The discusser proposes an alternative approach to the problem [5] that removes most of the complexities encountered in Ref. [1] by rescinding the requirement that the critical seismic input shall be realistic-looking and carry basic spectral characteristics of real accelerograms. This requirement, in the discusser's opinion, is not essential for the purpose of the CSE analysis. Rather, the design should be based on real earthquake records, while the structural response to the model "critical" accelerogram should be used as the basis for selection and scaling of the input accelerograms so that the probability of exceedance of the incurred structural reaction is kept below the stipulated limit.

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