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Discussion

Comment on J.U. Klügel's: Problems in the application of the SSHAC probability method for assessing earthquake hazards at Swiss nuclear power plants, in Engineering Geology, vol. 78, pp. 285–307

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1. Introduction

The Senior Seismic Hazard Analysis Committee's (SSHAC, 1997) guidance for performing probabilistic seismic hazard analysis (PSHA) has been used to evaluate earthquake hazards at Swiss nuclear power plants (Klügel, 2005). Klügel (2005) found many inconsistencies and deficiencies in the SSHAC guidance and concluded "the results can not be explained by the available information on seismic activity and ground motion recordings in Switzerland." In other words, the results (hazard estimates) can not be physically compared to the geological and seismological observations. Also, Klügel also found that "the better the experts tried to discover and to quantify uncertainties following the SSHAC guidance, the more diffuse the resulting distribution will be." All these observations raise questions about the SSHAC guidance.

The SSHAC guidance was developed by a seven-member committee to address the large differences in PSHA results by different practitioners. The most important conclusion reached by the committee is "that differences in PSHA results are due to procedural rather than technical differences" (SSHAC, 1997). In other words, "many of the major potential pitfalls in executing a PSHA are procedural rather than technical in character" (SSHAC, 1997). The SSHAC guidance only deals with procedural problems in executing a successful PSHA, but not technical problems with PSHA itself. The technical problems may be one of the main reasons for the large differences, however. Thus, it would be beneficial to review the basics of PSHA and its drawbacks.

2. Basics of PSHA

PSHA was originally derived from engineering seismic risk analysis in comparison with the analogous flood and wind problems (Cornell, 1968). It was extended to incorporate ground-motion uncertainty directly (Cornell, 1971) and became a standard method in seismic hazard assessment (McGuire, 1976, 1995; Frankel et al., 1996, 2002). Using McGuire's (1995) formula, annual probability of exceedance (γ) of a ground motion (y) can be expressed as

$$\gamma(y)=\sum_i \nu_i \iiint f_{\mathrm{M}}(m) f_{\mathrm{R}}(r) f_{\varepsilon}(\varepsilon) P[Y>y|m,r,\varepsilon]\mathrm{d}m\mathrm{d}r\mathrm{d}\varepsilon, \tag{1}$$

where ν_i is the activity rate for seismic source i; $f_{\mathrm{M}}(m)$, $f_{\mathrm{R}}(r)$, and $f_{\varepsilon}(\varepsilon)$ are earthquake magnitude, source-to-site distance, and ground motion density functions, respec-

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tively; ε is the standard deviation (logarithmic); and $P[Y>y|m,r,\varepsilon]$ is the probability that Y exceeds y for a given m and r. As shown in Eq. (1), PSHA is really a mathematical aggregation or function of earthquake occurrences $[f_M(m)]$ and probabilities of source location $[f_R(r)]$ and ground-motion exceedance $[f_\varepsilon(\varepsilon)P[Y>y|m,r,\varepsilon]]$. This can be clearly seen through a situation where all seismic sources are considered to be characteristic. For characteristic source, we have

$$f_M(m) = \begin{cases} 1, \text{if } m = M_C \\ 0, \text{if } m \neq M_C \end{cases}, \tag{2}$$

$$f_R(r) = \begin{cases} 1, \text{if } r = R_C \\ 0, \text{if } r \neq R_C \end{cases}, \tag{3}$$

and

$$f_\varepsilon(\varepsilon) = \begin{cases} 1, \text{if } \varepsilon = \varepsilon_C \\ 0, \text{if } \varepsilon \neq \varepsilon_C \end{cases}, \tag{4}$$

where M_C is magnitude of the characteristic earthquake, R_C is the shortest distance between the site and source, and ε_C is the ground-motion uncertainty for M_C at the distance R_C. Therefore, for characteristic sources, Eq. (1) becomes

$$\gamma(y) = \sum_i \frac{1}{T_i} P_i(Y>y|\varepsilon_C), \tag{5}$$

where T_i is the average recurrence interval of the characteristic earthquake for source i. In current practice, the inverse of the annual probabilities of exceedance ($1/\gamma$), called return period (T_P), are more often used. Eq. (5) can also be written as

$$T_P(y) = \frac{1}{\sum_i \frac{1}{T_i} P_i(Y>y|\varepsilon_C)} \tag{6}$$

These are the basics of PSHA. Because of its aggregated nature, PSHA inherits several obvious drawbacks:

1. The physical meaning of the ground motion is not clear or is even lost. This was one of the conclusions reached by the Aki Committee, which noted that "the aggregated results of PSHA are not always easily related to the inputs" (NRC, 1988). In other words, "the concept of a 'design earthquake' is lost; i.e., there is no single event (specified, in simplest terms, by a magnitude and distance) that represents the earthquake threat at, for example, the 10,000-year ground-motion level" (McGuire, 1995). Wang and others (2003, 2005), Wang and Ormsbee (2005), and Wang (2005) also demonstrated that it is difficult to explain the physical meaning of the ground motion derived from PSHA for a single or three characteristic sources.
2. The statistical meaning of the ground motion is also not clear or lost. As shown in Eqs. (1) and (5), the annual probability of exceedance is the sum (aggregated) of products of the recurrence interval and the probability of ground motion being exceeded. The annual probability of exceedance (or return period) does not mean that that ground motion will occur at least once at that annual rate (or in that period); rather, it means that it has certain probabilities of being exceeded if all the considered earthquakes occur at the corresponding recurrence rate (or recurrence intervals). Unfortunately, the ground motion with a particular return period has been communicated as that ground motion will occur in the return period. For example, the ground motion with a 2500-year return period has been said to be equivalent to the ground motion that will occur at least once in 2500 years (Frankel, 2004, 2005). This fundamentally changes the statistical characteristics of PSHA: probability of occurrence. This can be clearly seen in a single characteristic earthquake with a 500-year recurrence interval (Frankel, 2004; Wang et al., 2005). According to Eq. (6), the ground motion with a 2500-year return period does not mean that it will occur at least once in 2500 years; rather, it means that it has a 20% probability of being exceeded if the characteristic earthquake occurs. Similarly, at a site with three characteristic sources, the ground motion with a particular return period does not mean that it will occur in that period; rather, it means that there are certain probabilities of it being exceeded if each of the three earthquakes occurs (Wang and Ormsbee, 2005; Wang, 2005). The statistical characteristics of ground motion are lost in PSHA.
3. PSHA provides not one, two, or three choices, but infinite choices for the users and decision-makers. Even though PSHA involves a very complicated process, such as level IV of the SSHAC guidance, the end results are simple, hazard curves, which give a range of annual probability of exceedance (or return period) versus a range of ground-motion values. All points on the curves would be equally valid choices for the users and decision-makers. Having so many choices makes it difficult for the users and policy-makers to scientifically choose one. Furthermore, although there are only a few hundreds years of instrumental and historical records and a few thousand years of geologic records on earthquakes, PSHA can be used to derive ground motions generated by "earthquakes" that have much longer

return periods. For example, earthquake records are available from about 2200 years ago in Switzerland, so PSHA derives the ground motions that have a 10,000-year return period (Klügel, 2005). For the proposed nuclear waste repository at Yucca Mountain, Nev., PSHA derives the ground motions having a 1-million-year return period (annual probability of exceedance of 10^{-6}) or longer (Reiter, 2004).

3. Discussion

Although they were not addressed in the SSHAC guidance, the technical problems of PSHA are obvious: (1) unclear physical basis; (2) obscure uncertainty; and (3) difficulty in determining a correct choice. These intrinsic drawbacks of PSHA can be easily used to explain the many inconsistencies and deficiencies that Klügel (2005) found in the execution of a comprehensive PSHA in Switzerland. For example, Klügel (2005) found it difficult to compare the PSHA results with the historical observations. The PSHA results should not be compared with the historical observations because the former are not physical, but the latter are physical. This was echoed by Frankel (2003), who pointed out that "it is not correct to compare the intensity observations from 1811–1812 with the probabilistic hazard maps that also include the hazard from earthquakes closer to St. Louis."

Implementing the SSHAC guidance could lead earth-scientists from knowing something (i.e., earthquake magnitude, occurrence, and probability of ground-motion distribution) to knowing nothing, without consideration of the intrinsic drawbacks of PSHA. Moreover, selection of a hazard (ground motion with an annual probability of exceedance or return period) is arbitrary and it is difficult to determine if it is safe enough or not. Ground motion with an annual probability of exceedance of 10^{-4} has been selected as the Safe Shutdown Earthquake (SSE) ground motion for nuclear facilities in the United States. Is this ground motion safe enough? It may not be a concern if the ground motion is indeed safe enough, even though there may be some economic implications. It could be a great concern if the ground motion is not safe, however.

Hence, these drawbacks need to be addressed and investigated in executing PSHA.

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