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Sensitivity analysis of a complex, proposed geologic waste disposal system using the Fourier Amplitude Sensitivity Test method

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Abstract

The Fourier Amplitude Sensitivity Test (FAST) method has been used to perform a sensitivity analysis of a computer model developed for conducting total system performance assessment of the proposed high-level nuclear waste repository at Yucca Mountain, Nevada, USA. The computer model has a large number of random input parameters with assigned probability density functions, which may or may not be uniform, for representing data uncertainty. The FAST method, which was previously applied to models with parameters represented by the uniform probability distribution function only, has been modified to be applied to models with nonuniform probability distribution functions. Using an example problem with a small input parameter set, several aspects of the FAST method, such as the effects of integer frequency sets and random phase shifts in the functional transformations, and the number of discrete sampling points (equivalent to the number of model executions) on the ranking of the input parameters have been investigated. Because the number of input parameters of the computer model under investigation is too large to be handled by the FAST method, less important input parameters were first screened out using the Morris method. The FAST method was then used to rank the remaining parameters. The validity of the parameter ranking by the FAST method was verified using the conditional complementary cumulative distribution function (CCDF) of the output. The CCDF results revealed that the introduction of random phase shifts into the functional transformations, proposed by previous investigators to disrupt the repetitiveness of search curves, does not necessarily improve the sensitivity analysis results because it destroys the orthogonality of the trigonometric functions, which is required for Fourier analysis.

Keywords: Sensitivity analysis; Fourier amplitude sensitivity test; Performance assessment; Waste management; Nonlinear model; System simulation

1. Introduction

A total-system performance assessment (TPA) code has been developed by the Nuclear Regulatory Commission (NRC) and the Center for Nuclear Waste Regulatory Analyses (CNWRA) as a tool for reviewing the license application for the proposed high-level waste (HLW) repository at Yucca Mountain, Nevada, USA. The TPA code is designed to simulate probable complex behavior of the repository over long time periods (e.g. 10,000 years). Because of the simplifying assumptions to the governing physical processes, the coupling among these processes, the uncertainties in the parameters defining the physical system, and the boundary conditions that prevail over the long time period of interest (TPI), significant uncertainties are introduced in the future state of the repository simulated by the computer model. The TPA code is designed so that conceptual model uncertainties can be analyzed by using alternative conceptual models (not studied in this paper), and the parameter uncertainties can be studied by assigning them appropriate probability distribution functions. Identification of the most influential parameters among a large number of input parameters, which is usually performed by sensitivity analysis, can lead to a better understanding of the physical processes that control the performance of a repository; attention and resources could then be concentrated on investigating further these controlling physical parameters.

Many sensitivity analysis methods exist such as linear regression [1–4], nonparametric schemes [5–7], or one-at-a-time analysis [8,9]. Each method has its advantages and disadvantages. For example, while the linear regression methods are simple and easy to use, they cannot assess nonlinear effects. Nonparametric methods do not require the input parameters to have well-defined statistical descriptions, but when the input parameters have adequate statistical descriptions, the nonparametric methods usually result in less accurate estimates. The one-at-a-time approaches can clearly attribute the change in output to the change in each input parameter, but they may not be able to study the

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interactive effects (mathematically represented by products of two or more parameters) well because they only allow one parameter to change at any time, and the output is essentially a function of a single parameter at the time of change.

In this paper, a global sensitivity analysis method, the Fourier Amplitude Sensitivity Test (FAST) method [10–14], that determines the sensitivity of the output by averaging it over all input parameters, is investigated. The FAST method allows all input parameters to be varied simultaneously so that the interactive effects (i.e. the mutual or reciprocal effects) among input parameters on the output can be adequately studied. The method was first developed by Cukier, Schaibly, and Shuler, et al. [10–14], to investigate the sensitivity of the solutions of large sets of coupled nonlinear equations to uncertainties in the input parameters. Rather than investigating each individual input parameter separately, the FAST method varies all input parameters simultaneously to conduct the sensitivity analysis. This is in contrast to a differential analysis (a one-at-a-time analysis approach) where the sensitivity is analyzed near a local point in the input parameter space [9].

The FAST method was modified and used by Saltelli and his colleagues on many computer models [15–19]. Although Saltelli et al. [16] have since advocated the use of this method, applications so far appear to have been limited to computer models that have a small parameter set (~10 parameters), and all parameters are assumed to have a uniform distribution function [13,19]. Many real-world computer models, especially the models that conduct performance assessment of a HLW repository, have a far greater number of input parameters and more diverse distribution types for the input parameters.

In this paper, the FAST method, together with the Morris method [9], is used to conduct a sensitivity analysis on a computer model with a large number of sampled parameters (~250) characterized by diverse probability distribution functions. In Section 2, the major functions and components of the NRC/CNWRA computer model (the TPA code) that will be used to evaluate the performance of the proposed geologic HLW repository at Yucca Mountain (YM) are briefly described to give the reader a general idea of the computer model to be analyzed. In Section 3, a short description of the FAST method is presented, In the FAST method, a functional transformation is applied to each model input parameter. To the best of the authors' knowledge, the functional transformations have been presented in the literature only for uniform distribution [13,19]. Also in Section 3, a general functional transformation applicable to uniform and other probability distribution functions is derived. In Section 4, the FAST method is applied to an example problem with a small parameter set for which the importance of each parameter to the output of the example problem is known a priori. This enables us to investigate the effectiveness of the FAST method via its major components: (i) functional transformations applied to either uniform or other distribution functions, (ii) the integer frequency sets characterizing the search paths in the parameter space, (iii) random phase shift introduced in the functional transformations to disrupt the repetitiveness of the search curve, and (iv) number of discrete sampling points used in the FAST method. Application of the FAST method to the TPA computer code to rank model parameters is covered in Section 5 after screening less important parameters. Section 6 presents the results of sensitivity analysis. Verification of these results is presented in Section 7. A summary and conclusions are presented in Section 8.

2. The computer model

The computer model used in this study was developed by the NRC and CNWRA to guide the review of a potential license application for the proposed HLW repository at YM. The TPA computer code [20–22] considers uncertainties and spatial variability of system attributes, model parameters, and future system states (i.e. scenario classes). To capture the effects of uncertainties in system characteristics and future system states, the TPA code operates in a probabilistic manner (i.e. input parameters are sampled from assigned probability distributions). The TPA code estimates radiation doses from released radionuclides during specified time periods (e.g. regulatory compliance TPI) at designated receptor locations (e.g. 20 km downgradient of YM). Only a brief discussion of the processes in the code is presented in the paper. For a complete description of the methods and assumptions, refer to Mohanty and McCartin [22].

The TPA code simulates physical and chemical processes of the repository system. Calculations of the most likely scenarios include the degradation of waste packages (WPs), in which HLWs are disposed in an underground repository, and the release of radionuclides when the water precipitating on top of the mountain finds its way into the failed WPs and transports the radionuclides through a partially water-saturated geologic medium to the water table and, subsequently, to a designated receptor group. The calculation involves several steps including the computation of (i) time-varying precipitation resulting from postulated climate changes, water percolation from the land surface to the subsurface, and subsequently into the emplacement drifts and onto WPs; (ii) the chemical and physical processes (e.g., temperature, humidity, pH, chloride concentration, and carbonate concentration) affecting engineered barrier degradation, including the WPs and radionuclide releases; (iii) corrosion phenomena for determining a WP lifetime; (iv) the number of containers affected by seismicity-induced rock falls; (v) the radionuclide release rate from the EBS to the groundwater pathway as a function of time; (vi) flow and transport of radionuclides through the unsaturated zone; (vii) flow and transport of radionuclides through the saturated zone; and (viii) dose to a specified receptor from groundwater radioactivity concentrations