Role of Component Sensitivity Analysis in the Risk Assessment of a Large and Complex System

Sitakanta Mohanty, Budhi Sagar, Ron Janetzke, Gordon Wittmeyer, Wesley Patrick

CNWRA, SwRI, 6220 Culebra Road, San Antonio, Texas, 78228, USA

Contact author: Sitakanta Mohanty, smohanty@swri.org, fax: +01 210 522 5155

PSAM 7 / ESREL '04 Abstract

BACKGROUND

Physics-based probabilistic analysis is emerging as an important tool for risk assessments of large and complex systems, because it is generally not possible to observe the behavior of a large and complex system directly. Such system models are designed to embody many physical features of the system, processes, coupling among processes, and uncertainties—often through simplified models—so that risk can be evaluated adequately within a reasonable timeframe. Model sensitivity analyses are then conducted with this system model to identify the aspects of such large and complex systems that contribute most to risk. Model aspects of interest for sensitivity analyses may include different conceptual formulations, associated model parameter ranges, and potential conditions to which a system may be subjected during its service life. Generally, model sensitivity is estimated in terms of a change in model behavior [measurable model output(s)] caused by specified changes in model attributes (e.g., conceptual models, parameters, boundary conditions, excitations, etc.). Because a model, of necessity, is a simpler representation of the actual system and because not all-simplifying assumptions affect the model results the same way, no one particular type of sensitivity analysis appears to provide complete, correct, and consistent interpretation of what drives system performance. For instance, if a system has an extremely high cost associated with its failure, it is not uncommon to formulate conservative models. That is, when a choice is to be made between two assumptions (conceptual models, parameter values, boundary conditions, and excitations), the one that will produce a high (low) value of risk (reliability) is selected. If many such assumptions are incorporated in a model, the results of sensitivity analyses may obscure the true nature of system behavior and may lead to erroneous conclusions.

This paper is motivated by our experience applying sensitivity analysis methods to risk assessment of deep geologic repositories for isolating high-level radioactive waste. As an example of the problem of interoperation mentioned above, consider the role of a fractured rock mass as a barrier component of the repository system. If the flow parameters for a fractured rock mass are conservatively assumed such that fracture flow would dominate, then system performance will be insensitive to transport through the rock mass below the emplaced waste. Consequently, an analyst who is unaware that the assumptions are conservative may erroneously conclude on the basis of parametric sensitivity analysis results that the fractured rock mass is not important from a risk standpoint. Another example is containment of waste. If the model predicts the waste container will last beyond the simulation period of interest, the traditional parametric sensitivity analysis will not indicate the importance of the container to reduction in risk because sensitivity will be zero to all model parameters representing container failure.

In this paper, we describe an analytical approach in which the sensitivity of a complex system to change in an entire subsystem or a component of a complex system is estimated. This approach is based on the nuclear power plant importance analysis concept adapted by Eisenberg and Sagar (2000) for application to radioactive waste repository disposal. This analytical approach has distinct advantages in determining as well as conveying in a simple manner which components contribute most to limiting risk by determining how the system will perform if these components do not perform as represented in the model.

APPROACH

In component sensitivity analysis, the functionality of a component (or a group of components), as represented in a model, is suppressed to a specified level. The relative change in the model performance represents the degree of significance of the component. A system can be disaggregated into components in many ways, however, in this paper, we identify components or subsystems that are physical entities of the system. Because physical entities are easy to visualize, insights into system performance can be readily gained. The suppression of a system-component function is accomplished by modifying the model so that the performance of the component decreases to the specific level. This is achieved via (i) selection of an appropriate alternative conceptual model and (ii) appropriate modifications to model parameters.

RESULTS

The component sensitivity analysis method is applied to a system model developed for estimating the performance of the proposed high-level radioactive waste repository at Yucca Mountain. The metric used for component sensitivity analyses is the relative change in the peak expected dose (the performance measure) as a function of change in the functioning of a component or a set of components. In the example, a suppression level of 100 percent is applied as an end member. Other suppression levels such as 10, 25, 50, 75 percent, etc. can be used. However, one should keep in mind that setting parameters at, for example 25 percent (or 75 percent if the response has an inverse relationship with the parameter), does not necessarily suppress the function of the corresponding component by 25 percent. Although complete suppression of some components is not realistic and any consequence resulting from such an analysis should not be compared to the regulatory standard, the method facilitates the understanding of the system behavior and identification of key system components.

Analyses were conducted by suppressing one component at a time (one-off analysis), by adding one component at a time (one-on-analysis), and by suppressing combinations of components. Preliminary analyses show that the degradation of the engineered systems and transport through the saturated zone are most important to overall performance. From the one-off analysis, the largest decrease in performance comes from suppression of the waste package, followed by unsaturated zone, saturated zone, waste form, drip shield, and invert. Suppression of components also shows some interesting interactions. For example, when the functions of both the drip shield and waste package components are suppressed, the increase in dose exceeds the sum of either component individually, revealing a sensitivity to the drip shield that is otherwise masked in the one-off analysis.

SIGNIFICANCE AND ORIGINALITY

Component sensitivity analysis provides a powerful tool for understanding system behavior and an important addition to the array of other methods (e.g., parametric sensitivity analysis) traditionally used in risk assessment. This tool produces results that a system-analyst can easily communicate to process-level analysts because the performance of a system can be more clearly explained at the component level than parameter by parameter. This paper presents a novel approach presents a comprehensive study of one-off, one-on, and combinations, and cumulative addition component sensitivity analyses. The full paper will compare results from various other methods used in risk assessment to illustrate the advantage of the component sensitivity analysis method. The component sensitivity analysis method should be combined with other sensitivity analysis methods to obtain a more complete picture of system behavior.

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