

The Role of Risk Analysis in Water Resources Engineering

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Introduction

Uncertainties and the consequent related risks in water resources engineering design and operation are unavoidable. Water resources projects are always subject to a probability of failure in achieving their intended purposes. As an example, a flood control project may not protect an area from extreme floods. A water supply project may not deliver demanded water. This failure may be due to failure of the delivery system or may be due to lack of supply. A water distribution system may not deliver water meeting quality standards even though the source quality does. The rationale in the selection of the design and operation parameters and the design and operation standards are continually questioned. Water resource engineering design and operation procedures do not involve any required assessment and quantification of uncertainties and the resultant evaluation of a risk.

For purposes of this paper risk is defined as the probability of failure. Failure is defined as the event in which the system fails to function with respect to its desired objectives. Reliability is defined as the complement of risk, i.e. the probability of non-failure. Failure can be grouped into either structural failure or performance failure. A good example of this is for water distribution systems. A structural failure such as pipe breakage or pump failure can cause demands to not be met. Also operational aspects of a water distribution system such as the inability to meet demands at required pressure heads is a failure without any structural failure of any component in the system. See Mays (1989) for more details and a survey of methods for water distribution systems.

The objective of this paper is to discuss the role of uncertainty analysis and the resultant quantification of risk for the design and operation of water resources engineering projects.

The Uncertainties

Uncertainty can be defined as the occurrence of events that are beyond our control. The uncertainty of a water resources system is an indeterministic characteristic and

is beyond our rigid controls. In the design and operation of these systems, decisions must be made under various kinds of uncertainty.

The sources of uncertainties in water resources engineering projects are many-fold. We will first discuss the ideas of natural uncertainties, model structure uncertainties, model parameter uncertainties, data uncertainties, and operational uncertainties. Natural uncertainties are associated with the random temporal and spatial fluctuations inherent in natural processes. Model structural uncertainties reflect the inability of a simulation model or design procedure to represent precisely the system's true physical behavior or process. Model parameter uncertainties reflect the variability in the determination of the parameters to be used in the model or design. Data uncertainties include a.) measurement inaccuracy and errors, b.) inadequacy of the data gauging network, and c.) data handling and transcription errors. Operational uncertainties are associated with construction, manufacture, deterioration, maintenance, and other human factors that are not accounted for in the modeling or design procedure.

The four major categories of uncertainties in water resources engineering are; 1.) hydrologic uncertainty; 2.) hydraulic uncertainty; 3.) structural uncertainty; 4.) and economic uncertainty. Each of these uncertainties has various component uncertainties. Hydrologic uncertainty can be classified into three types: inherent, parameter, and model uncertainties. The occurrence of various hydrological events such as stream flow or rainfall events are considered as stochastic processes because of the observable natural, or inherent, randomness. Because of the lack of perfect hydrological information about these processes or events there exist informational uncertainties about the processes. These uncertainties are referred to as the parameter uncertainties and the model uncertainties. The model uncertainty in many cases results from the lack of data and knowledge adequate to select the appropriate probability model or through the use of an oversimplified model such as the rational method for storm sewer design.

Hydraulic uncertainty is the uncertainty in the design of hydraulic structures and in the analysis of the performance

of hydraulic structures. It mainly arises from three basic types: model, construction and material, and operational conditions of flow. The model uncertainty results from the use of a simplified or an idealized hydraulic model to describe flow conditions, which contribute to the uncertainty in determining the design capacity of hydraulic structures. Simplified relationships such as Manning's equation are typically used to model complex flow processes that cannot be adequately described, resulting in model errors.

Structural uncertainty refers to the failure from structural weakness. Physical failures of hydraulic structures can be caused by water saturation and loss of soil stability, erosion or hydraulic soil failures, wave action, hydraulic overloading, structural collapse, material failure, etc. An example is the structural failure of a levee system either in the levee or in the adjacent soil. The structural failure could be caused by water saturation and loss of soil stability. A flood wave can cause increased saturation of the levee through slumping. Levees can also fail because of hydraulic soil failures and wave action.

Economic uncertainty can arise from uncertainties in construction costs, damage costs, projected revenue, operation and maintenance costs, inflation, project life, and other intangible cost and benefit items. Construction, damage, and operation/maintenance costs are all subject to uncertainties because of the fluctuation in the rate of increase of construction materials, labor costs, transportation costs, economic losses, regional differences, and many others. There are also many other economic and social uncertainties that are related to inconvenience losses. An example of this is the failure of a highway crossing caused by flooding resulting in traffic-related losses.

Analysis of Uncertainties

The objective in the analysis of uncertainties is to systematically incorporate the uncertainties into the evaluation of the loading and resistance. The most commonly used method is the first order analysis of uncertainties. These methods are used to determine the statistics of the random variables loading and resistance which are typically defined through the use of deterministic models but have uncertain parameter inputs.

One of the accompanying papers by Professor Tung in this journal briefly describes several methods for the analysis of uncertainties. For the first order methods one can refer to Chow, Maidment and Mays (1988), Mays and

Tung (1992), Yen (1986), and Yen and Tung (1993). Tung (1996) provides an excellent review of the various methods that can be used.

Load-Resistance

The load for a system can be defined as an external stress to the system and the resistance can be defined as the capacity of the system to overcome the external load. Load and resistance are terms that have been used in structural engineering but definitely have a place in the types of risk analysis that need to be performed for water resources engineering projects. In water resources engineering these terms have a much more general meaning as illustrated in Table 1.

If we use the variable R for resistance and the variable L for load, then we can define a failure as when the load exceeds the resistance and the consequent risk as the probability of the loading exceeding the resistance, $P(L > R)$. A simple example of this would be the failure of a dam due to overtopping. The risk would be the probability that the water surface elevation in a reservoir exceeds the elevation of the top of the dam. In this case the resistance is the elevation of the top of the dam and the loading is the maximum elevation of the water surface of a flood wave entering the reservoir.

Because many uncertain variables define both the resistance and loading, they are both considered as random variables. A simple example would be to use the rational equation, $Q = CiA$, to define the design discharge (loading) for a storm sewer. The loading, $L = Q$, is a function of three uncertain variables: the runoff coefficient C , the rain fall intensity i , and the drainage area A . Because none of these three variables can be determined with complete certainty they are considered as random variables. So in this case the loading is a random variable consisting of three random variables. If the resistance is defined through the use of Manning's equation then the resistance is a function of Manning's roughness factor, the pipe diameter, and the slope (friction slope). The two main contributors to uncertainty in this equation would be the friction slope and the roughness factor so that they are considered as random variables. The resistance is then also a random variable which is a function of the two random variables.

It is interesting to note that in the storm sewer example both the loading and the resistance are defined by deterministic equations, the rational equation and Manning's equation. Both are considered to have

uncertain design parameters that result in the resistance and loading being uncertain, and consequently are considered as random variables. In the storm sewer example as in many types of hydraulic structures, the loading uncertainty is actually the hydrologic uncertainty and the resistance uncertainty is the hydraulic uncertainty.

Composite Risk

The above discussion about the hydrologic and hydraulic uncertainties being the resistance and loading uncertainties leads to the idea of a composite risk. The probability of failure defined previously as the risk, $P(L>R)$, is actually a composite risk. If only the hydrologic uncertainty, in particular the inherent hydrologic uncertainty, were considered then this would not be a composite risk. In the conventional design processes of water resources engineering projects only the inherent hydrologic uncertainties have been considered. Essentially a large return period is selected and artificially considered as the safety factor without any regard to systematically accounting for the various uncertainties that actually exist.

What is being proposed herein, and in many other places in the literature, is to systematically account for the uncertainties through the development of the composite risk-safety factor relationships. What has been briefly described above considers the hydrologic and hydraulic uncertainties in the composite risk evaluation. What is needed is to consider all four of the categories of uncertainties: hydrologic, hydraulic, structural, and economic in the evaluation of the composite risk.

Safety Factor

The safety factor is defined as the ratio of the resistance to loading, R/L . Because the safety factor, $SF=R/L$, is the ratio of two random variables, it is also a random variable. The risk can be written as $P(SF<1)$ and the reliability can be written as $P(SF>1)$. Using the storm sewer example above, both the resistance and the loading were considered as random variables because they are both functions of random variables. Consequently because the resistance and the loading for the storm sewer design are random variables, the safety factor for storm sewer design would also be a random variable.

Risk Assessment

Risk assessment requires several phases or steps which can vary for different types of water resources engineering projects. These steps include:

- Step 1: Risk or hazard identification.
- Step 2: Assessment of loads and resistance.
- Step 3: Perform analysis of uncertainties.
- Step 4: Quantify the composite risk.
- Step 5: Develop the composite risk-safety factor relationships.

A Model for Risk-Based Design

The risk-based design of water resources projects promises to be, potentially, the most significant application of uncertainty and risk analysis. The risk-based design of water resources projects integrates the procedures of economics, uncertainty analysis, and risk analysis in design practice. Such procedures can consider the tradeoffs among risk, economics, and other performance measures in hydraulic structure design. When risk-based design is embedded into an optimization framework, the combined procedure is called optimal risk-based design. The optimal risk-based design approach is the ultimate model for design, analysis and operation of water resources engineering projects that we need to strive for in the future.

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Table 1. Examples of Load and Resistance for Water Resources Projects (adapted from Duckstein et al., 1987)

Type of Problem	Load	Resistance
Bridge pier	Scouring	Pier pile depth
Flood levee Dam	Flood stage Flood duration Flood exposure Wind	Levee height Hydraulic and soil resistance to botling sliding, erosion
Water supply	Requirements or demand	Supply capacity
Flood volume control	Flood volume	Reservoir flood storage
Max. flood stage control	Incoming flood stage	Cresting capacity
Underground excavation	Piezometric pressure	Permeability of walls
Water quality (Streams, lakes)	Nutrients, sediments, pollutant loading	Cleaning capacity, low flow augmentation
Waste management	Hazards (chemical, radioactive)	Physical, individual, collective
Recreation	Number of visitor-days	Carrying capacity of facility