RELIABILITY OF OPERATION OF WATER RESOURCES SYSTEMS

Lucien Duckstein
Ecole Nationale du Génie Rural, des Eaux et des Forêts/Laboratoire de Gestion du Risque en Sciences de l'Eau, Paris, France

Keywords: Bayes risk, bridge pier design, consequence function, design by reliability, exceedence probability, foundation failure, levels of design, sample uncertainty, supply failure, structural failure

Contents

Summary

The concept of reliability of a water resources system is examined from the point of view of hydrologic design, within a model-based system framework. Four levels of design are distinguished and illustrated. Level I is the classical method of design by exceedence probability; level II consists in design by Gaussian probability of failure (or its complement, the reliability); level III is design by actual probability of failure; level IV requires the minimization of a consequence or loss function, whose estimation may require the decision maker to quantify social values. If this quantification is not feasible, level III design by reliability is recommended.

Two examples illustrate the concepts. First the design of a bridge pier is presented under both randomness of flood occurrence and parameter uncertainty, because of the short record of extreme events. Second, the design of a foundation that is to withstand corrosive ground water is described to demonstrate the interrelationship between the design decision or action and the mode of failure.

1. Introduction

This article is a follow-up of Article "Water Resources Systems Analysis", where a system framework was provided to evaluate risk and reliability-related criteria (performance indices PI, figures of merit FM), among other usual measures of water resources systems performance such as cost/benefit. In order to specify how the concept of reliability enters into systems operation, the main approaches to water resources system design will be briefly presented and then two examples will be given.

2. Levels of Water Resources System Design

2.1 The Four Levels of Design

The estimation of reliability procedure can be formulated in terms of the general systems approach presented in Article "Water Resources Systems Analysis". Depending on the performance index that has been selected, one can distinguish a number of different design approaches. Four different performance indices are used, which define different design levels, where the understanding is that the higher the level, the more data are required for its application:

- Level I uses the exceedence probability PE as performance index.
- Level II uses probability of failure PF as performance index, but assumes all probability densities to be Gaussian (or to be convertible to Gaussian distributions).
- Level III uses the probability of failure PF as performance index, where all probability distributions have their true shape.
- Level IV uses the generalized risk RI as performance index, with special cases included.

Plate and Duckstein have extended the design methods to the use of reliability RE as performance index. This index RE relates the failure or exceedence probabilities to the life expectancy of the structure and should include uncertainties.

2.2 The Classical Approach (Level I)

Level I constitutes the classical approach to water resources systems design and is based on the exceedence probability, PE. Consider the example of flood levee design: in this level I approach, the levee height is the height required to accommodate a design discharge Z, which has a preassigned recurrence interval of T years, such as the $T = 100$ year flood. To this height, a freeboard is added, which allows not only to account for design uncertainties due to the flood itself, but also for changes in the levee height caused by other than flood-related causes. Because this design requires only that the exceedence probability of the flood stages of the extreme floods be known, it is the design at the lowest design level, level I. The probability of failure in itself is not flexible enough as a design criterion for the general case. According to the usual definitions, it is based on a year as the time unit. Hydraulic structures or water resources systems should be designed not for 1 year, but for their life expectancy: a probability of failure of once in 10 years on average, has a different meaning for the safety of a dam which has to last for 100 years, as for a coffer dam with a life of about 2 years. This fact leads in a natural way to the concept of reliability as a design criterion.

2.3 Reliability-based Procedure (Levels II and III)

In the general system framework, the reliability RE is considered as a performance index PI to evaluate the performance of a water resources system. In this section (levels II and III), reliability is considered directly with a focus on the design and operation of structures as the figure of merit (FM) for the design; it is the criterion which rates the performance of the system, as well as the value of the performance. We shall not consider more than one load, i.e., the generalized load vector $\boldsymbol{L}$ reduces to a one-dimensional random variable. Similarly, only one resistance is considered, so that the generalized resistance vector $\boldsymbol{R}$ also reduces to a one-dimensional random variable. The reliability is calculated as the ratio of the average number nf of failures to the number n of events that may cause failures. From Article "Water Resources Systems Analysis", the reliability FM is obtained as n = infinity, i.e., for the ensemble of system experiments or simulation runs. Henceforth, RE is understood to be an FM unless noted otherwise.

On the other hand, for a continuous load function $L(t)$, the reliability must be expressed as the probability of the first time that the structure, say a flood levee or a supply reservoir, fails, i.e., the probability of reaching the condition $\boldsymbol{L} \geq \boldsymbol{R}$ over time. This time has a distribution function $F_t(t)$ where t is the time from the beginning of service of the structure to first failure.

The reliability $RE(T)$ of the structure at any time t is defined through the probability density function $f(t) = dF(t)/dt$ as:

$$RE(t) = 1 - f(t). \tag{1}$$

In reliability theory, it is useful to distinguish between $f(t)$, which is a function that varies with time, and $B(t)$, the hazard function or hazard rate, also called the failure rate, which is defined as the conditional probability density for the failure event to occur in the time interval $(t,t + \Delta t)$ if it did not occur before time t.

In the design of a flood levee (or another hydraulic structure) the so-called probability of failure $PF(t,\Delta t)$ is customarily used instead of the failure rate $B(t)$. Here $PF(t,\Delta t)$ is a dimensionless quantity that is, the integral from t to $t + \Delta t$ of the failure rate $B(t)$ defined in the time interval $(t,t + \Delta t)$.

The dependency of $PF(t,\Delta t)$ on t here expresses the fact that, in general, PF is non-stationary. The dependency on Δt results from the time scale chosen for defining PF. For example, if Δt (as is customary in structural design) corresponds to one year, then PF = 0.01 means that the failure event occurs once every $[(1/PF)\Delta t]$ = 100 years on the average, where $[(l/PF)\Delta t]$ is called the recurrence interval.

One of the most serious shortcomings of the traditional hydraulic design involving probabilistic components results from equating PF with the exceedence probability PE(Xe) of a design load component L = Xe. Taking reliability as the design criterion, the structure must then be designed so that the actual reliability RE based on the design life TD exceeds a reliability RED, which is given as part of the design information, or from standards:

$$\mathrm{RE(TD)} > \mathrm{RED} \tag{2}$$

In general, both load and resistance are random variables, whose probability can be modified by changing design parameters. The set of all design parameters is combined into a decision vector $\boldsymbol{u}$, which is one of the inputs into the system model. For each choice of design parameters one obtains a particular value of PF. Since the design condition of Eq. (2) can be met for many sets of parameters, it is useful to impose a second condition that optimizes some parameter. For example, one might seek a set of parameters that leads to a minimum cost design. Furthermore, the set of parameters may be subject to constraints $\boldsymbol{u} \leq \boldsymbol{u}_\mathrm{c}$ imposed by external or internal factors. With these conditions in mind, we may formulate the design problem in a slightly different way to read:

$$\text{Find } \boldsymbol{u}^* \text{ subject to } \boldsymbol{u} \leq \boldsymbol{u}_\mathrm{c} \text{ such that } \mathrm{RE(TD)} > \mathrm{RED} \tag{3}$$

Eq. (3) embodies the concept of design by reliability.

The main improvement over previous design concepts based on PE lies in the fact that it corresponds exactly to the failure that the design is supposed to avoid. Since it has been shown that RE bears little relation to PF, design, according to Eq. (3), seems preferable to a design based on PF.

Why is design by Eqs. (2) or (3) more realistic than using a design based on PF only? The reliability is defined over the whole design horizon T, whereas PF(t,Δt) is only a temporal quantity which may vary during the life of the structure.

The concept of calculating the probability of failure PF yields, in spite of the variability of both load and resistance, a single value of PF for the set of experiments. If all the assumptions leading to the calculation of PF were correct, then such a value could be trusted. In actual cases, however, this true value cannot be found because of uncertainties; consequently, PF and thus also RE are random variables, *PF* and *RE*, whose probability density function (pdf) may not be known.

The uncertainty of PF is mainly caused by two effects: the uncertainty in the data and the uncertainty of the models. The data uncertainty is due to measurement errors or to the fact that there is usually insufficient time to collect enough data to get stable estimates of parameters of input pdfs. For example, for the design of a flood levee, we need long series of extreme values, or rainfall data, which are converted into runoff data through conceptual models. The model uncertainty is caused by our not knowing, for example, the true extreme value distribution for our situation or by the fact that we approximate the essentially non-linear rainfall-runoff process by a linear model, such as the unit hydrograph.

The effect of uncertainty can be analyzed by different methods. Second moment analysis has been extensively used. Bayesian analysis, which usually requires a loss function as described in the next section, can also be applied. These methods serve to estimate ranges and perhaps pdfs of PF, but the decision on what is acceptable cannot be made by any such method. Ultimately, the final decision of an acceptable design must come from the engineering judgment of an individual, or from past experience of the profession as codified in standards and regulations.

Because the analysis of uncertainty deals mostly with unknown probability distributions on all variables, one finds that there exists certain arbitrariness in allocating the uncertainty to load or resistance, or to hydrological or hydraulic models. This is exemplified in the freeboard for the flood levee, which includes allowances for many uncertainties. It is therefore suggested to proceed for the calculation of PF as follows: all uncertainties which can be associated with non-hydraulic features (such as, for a levee, settlement, permeability, propensity to erosion) are allocated to the resistance uncertainty, whereas all phenomena which influence hydraulic phenomena (such as roughness changes, waves and wind effects) are parts of the hydraulic uncertainty. In effect, this definition separates resistance and load according to the types of experts: again for a levee, the soil mechanics expert is responsible for the resistance and the hydraulic engineer, for the loads.

-
-
-

Bibliography

Ayyub B. M. and Chao R. J. (1997). Uncertainty modelling in civil engineering with structural and reliability applications. 3-28 *Uncertainty Modelling and Analysis in Civil Engineering* (ed. B. M. Ayyub), Boca Raton. FL: CRC Press LLC. [Reliability analysis in structural engineering]

Bernier J. (1987). Elements of Bayesian analysis of uncertainty in hydrological reliability and risk models. *Engineering Reliability and Risk in Water Resources*, 45-57 (eds. L. Duckstein and E. J. Plate), NATO ASI Series, Dordrecht: M. Nijhoff. [Analysis of uncertainty in hydrologic risk modeling]

Bernier J. (1998). Information, modèles, risques et hydrologie statistique. *Methodes Statistiques et Approches Bayésiennes en Hydrologie* (eds. E. Parent, P. Hubert, B. Bobee and J. Miquel), pp. 23–38. Paris: UNESCO Press. [Further development of the previous study]

Bogardi I. and Duckstein L. (1978). Design under stochastic groundwater fluctuation. *ASCE Journal of the Hydraulics Division* **HY1**, 59–74. [Reliability analysis of an underground structure exposed to agressive water]

Bogardi L., Duckstein L. and Szidarovsky F. (1987). Reliability estimation of underground water control systems under natural and sample uncertainty. 270-289, *Engineering Reliability and Risk in Water*

Resources (eds. L. Duckstein and E. J. Plate), NATO ASI Series, Dordrecht: M. Nijhoff. [About bauxite mining under the water table]

Chow V. T. (ed.) (1964). *Handbook of Applied Hydrology*. 641 pp., New York: McGraw Hill. [Classical manual in hydrology]

Davis D. and Dvoranchik W. (1971). Evaluation of the worth of additional data. *Water Resources Bulletin* **7**(4), 700–707 [Extensive Baysian analysis of the failure of a bridge pier]

Davis D. R., Kisiel C. and Duckstein L. (1972) Bayesian decision theory applied to Design in hydrology. *Water Resources Research*. **8**(1), 33–41. [Further analysis of the example in the previous paper].

Dhillon B. S. and Singh V. (1981). *Engineering Reliability: New Techniques and Applications*. 412 pp., New York: John Wiley. [Classic text on the subject].

Duckstein L. (1998). Bayes and fuzzy logic modelling of engineering risk under dynamic change. *Méthodes Statistiques et Approches Bayésiennes en Hydrologie*. (eds. E. Parent, P. Hubert, B. Bobee, J. Miquel), pp. 451–464. Paris: UNESCO Press. [Comparison of statistical Bayesian and fuzzy logic analysis]

Duckstein L. and Bogardi I. (1981). Application of reliability theory to hydraulic engineering design. *ASCE Journal of the Hydraulics Division* **107**, 799–815. [Design of a flood levee on the Tisza river].

Laursen, M. (1970). Bridge design considering scour and risk. *Transportation Engineering Journal* TE2(May), 149–164. [Design of highway bridges and culverts]

Plate E. J. (1984). Reliability Analysis of Dam Safety. *Frontiers in Hydrology* (eds. W. H. C. Maxwell and L. R. Beard), pp. 288–304. Littleton, CO: Water Resources Publications. [Pioneering analysis of dam reliability]

Plate E. J. and Duckstein L. (1987). Reliability in Hydraulic Design. *Engineering Reliability and Risk in Water Resources* 253-268, (eds. L. Duckstein and E. J. Plate), NATO ASI series, Dordrecht: M. Nijhoff. [Further analysis of the previous example]

Szidarovszky F., Duckstein L. and Bogardi I. (1976). Levee system reliability along a confluence reach. *ASCE Journam of the Engineering Mechanics Division* **101**(EM5), 659–622. [Reliability of a levee exposed to backwater phenomena]

Vogel R. M. (1987). Reliability indices for use in the design of water supply reservoir. *Engineering Reliability and Risk in Water Resources* 279-293 (eds. L. Duckstein and E. J. Plate), NATO ASI Series, Dordrecht: M. Nijhoff. [Reservoir yield analysis]

Von Thun L. (1987). Use of risk-based analysis in making decisions on dam safety. *Engineering Reliability and Risk in Water Resources* 182-199 (eds. L. Duckstein and E. J. Plate), NATO ASI Series, Dordrecht: M. Nijhoff. [Economic, social, and human costs of dam failure]

Yen Ben. (1987). Reliability of hydraulic structures possessing random loading and resistance. *Engineering Reliability and Risk in Water Resources* 205-221 (eds. L. Duckstein and E. J. Plate), NATO ASI Series, Dordrecht: M. Nijhoff. [More general case of reliability analysis]

Yevjevich V. (1972): *Probability and Statistics in Hydrology*, 402 pp. Littleton, CO: Water Resources Publications [One of the first texts on the subject]

Biographical Sketch

Lucien Duckstein was a professor of Systems and Industrial Engineering and also of Hydrology and Water Resources at the University of Arizona Tucson ,USA,from 1962 to 1997.

He has then become a professor emeritus at the same institution and has since returned to his native city, Paris, France, as a professor at ENGREF (French Institute of Agronomy, Water Resources and Forestry). His research areas cover multiobjective analysis, decision theory, statistical and Bayesian decision theory, fuzzy logic with applications to hydrology and water resources.