Lecture 14

Reliability-Based Design

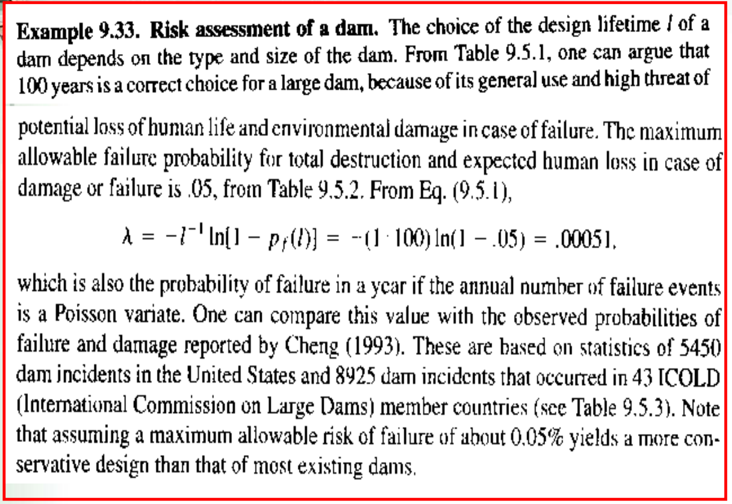
Statistics for
Civil & Environmental Engineers

Reliability-Based Design

- **Maximum of the failure function for $t = l$**

Where l : given lifetime

Example (1-1)



Example 9.33. Risk assessment of a dam. The choice of the design lifetime l of a dam depends on the type and size of the dam. From Table 9.5.1, one can argue that 100 years is a correct choice for a large dam, because of its general use and high threat of potential loss of human life and environmental damage in case of failure. The maximum allowable failure probability for total destruction and expected human loss in case of damage or failure is .05, from Table 9.5.2. From Eq. (9.5.1),

$$\lambda = -l^{-1}\ln[1 - p_f(l)] = -(1/100)\ln(1 - .05) = .00051,$$

which is also the probability of failure in a year if the annual number of failure events is a Poisson variate. One can compare this value with the observed probabilities of failure and damage reported by Cheng (1993). These are based on statistics of 5450 dam incidents in the United States and 8925 dam incidents that occurred in 43 ICOLD (International Commission on Large Dams) member countries (see Table 9.5.3). Note that assuming a maximum allowable risk of failure of about 0.05% yields a more conservative design than that of most existing dams.

Example (1-2)

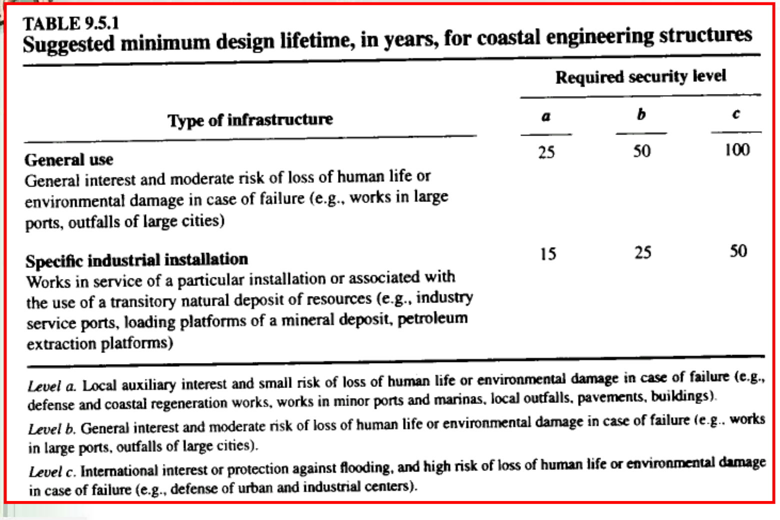


TABLE 9.5.1
Suggested minimum design lifetime, in years, for coastal engineering structures

Type of infrastructure	Required security level *a*	*b*	*c*
General use General interest and moderate risk of loss of human life or environmental damage in case of failure (e.g., works in large ports, outfalls of large cities)	25	50	100
Specific industrial installation Works in service of a particular installation or associated with the use of a transitory natural deposit of resources (e.g., industry service ports, loading platforms of a mineral deposit, petroleum extraction platforms)	15	25	50

Level a. Local auxiliary interest and small risk of loss of human life or environmental damage in case of failure (e.g., defense and coastal regeneration works, works in minor ports and marinas, local outfalls, pavements, buildings).

Level b. General interest and moderate risk of loss of human life or environmental damage in case of failure (e.g., works in large ports, outfalls of large cities).

Level c. International interest or protection against flooding, and high risk of loss of human life or environmental damage in case of failure (e.g., defense of urban and industrial centers).

Example (1-3)

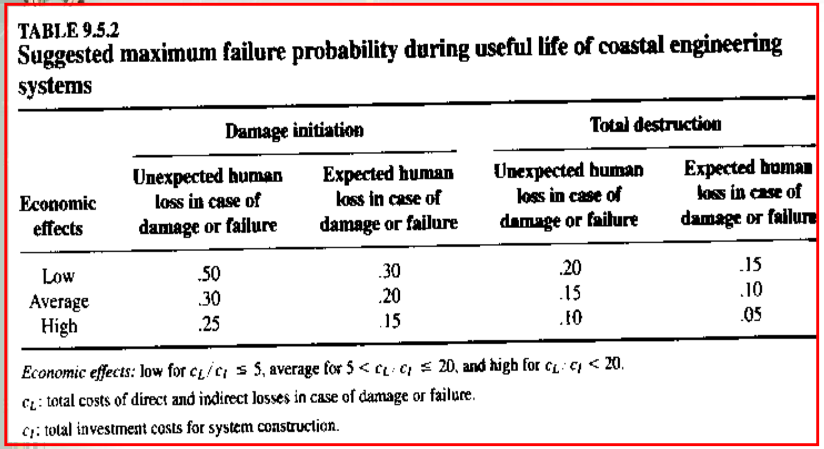


TABLE 9.5.2
Suggested maximum failure probability during useful life of coastal engineering systems

Economic effects	Damage initiation: Unexpected human loss in case of damage or failure	Damage initiation: Expected human loss in case of damage or failure	Total destruction: Unexpected human loss in case of damage or failure	Total destruction: Expected human loss in case of damage or failure
Low	.50	.30	.20	.15
Average	.30	.20	.15	.10
High	.25	.15	.10	.05

Economic effects: low for $c_L/c_I \le 5$, average for $5 < c_L/c_I \le 20$, and high for $c_L/c_I < 20$.

c_L: total costs of direct and indirect losses in case of damage or failure.

c_I: total investment costs for system construction.

Example (1-4)

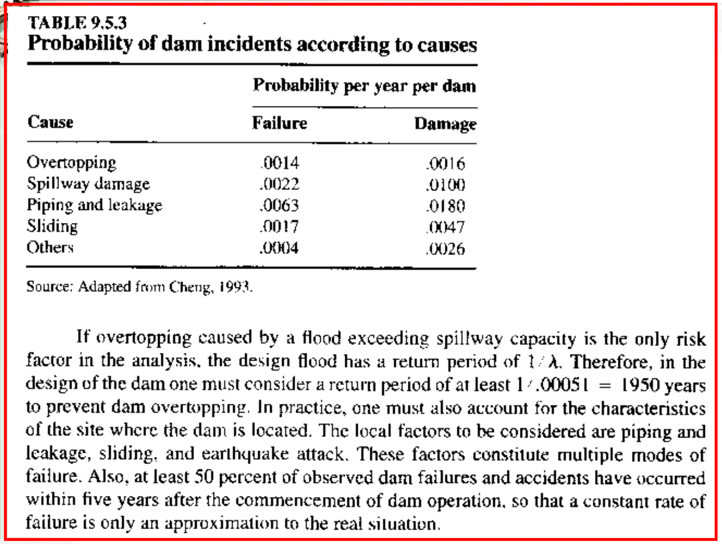


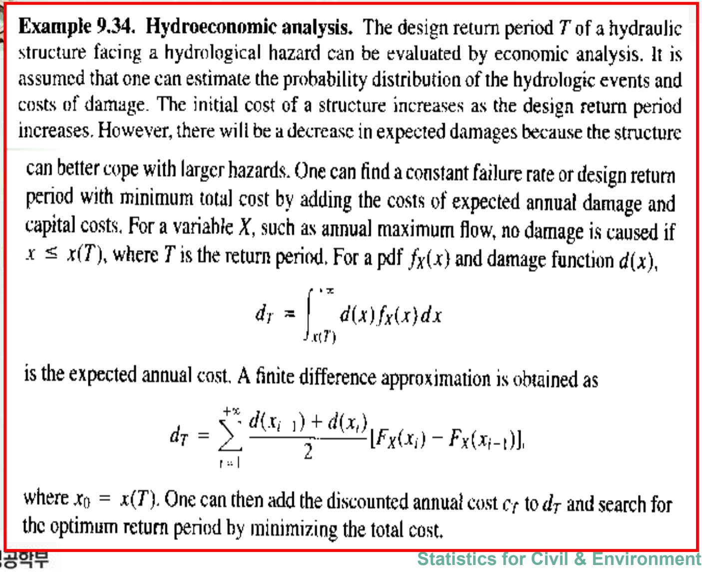
TABLE 9.5.3
Probability of dam incidents according to causes

Cause	Probability per year per dam: Failure	Probability per year per dam: Damage
Overtopping	.0014	.0016
Spillway damage	.0022	.0100
Piping and leakage	.0063	.0180
Sliding	.0017	.0047
Others	.0004	.0026

Source: Adapted from Cheng, 1993.

If overtopping caused by a flood exceeding spillway capacity is the only risk factor in the analysis, the design flood has a return period of $1/\lambda$. Therefore, in the design of the dam one must consider a return period of at least $1/.00051 = 1950$ years to prevent dam overtopping. In practice, one must also account for the characteristics of the site where the dam is located. The local factors to be considered are piping and leakage, sliding, and earthquake attack. These factors constitute multiple modes of failure. Also, at least 50 percent of observed dam failures and accidents have occurred within five years after the commencement of dam operation, so that a constant rate of failure is only an approximation to the real situation.

Example (2-1)



Example 9.34. Hydroeconomic analysis. The design return period T of a hydraulic structure facing a hydrological hazard can be evaluated by economic analysis. It is assumed that one can estimate the probability distribution of the hydrologic events and costs of damage. The initial cost of a structure increases as the design return period increases. However, there will be a decrease in expected damages because the structure can better cope with larger hazards. One can find a constant failure rate or design return period with minimum total cost by adding the costs of expected annual damage and capital costs. For a variable X, such as annual maximum flow, no damage is caused if $x \le x(T)$, where T is the return period. For a pdf $f_X(x)$ and damage function $d(x)$,

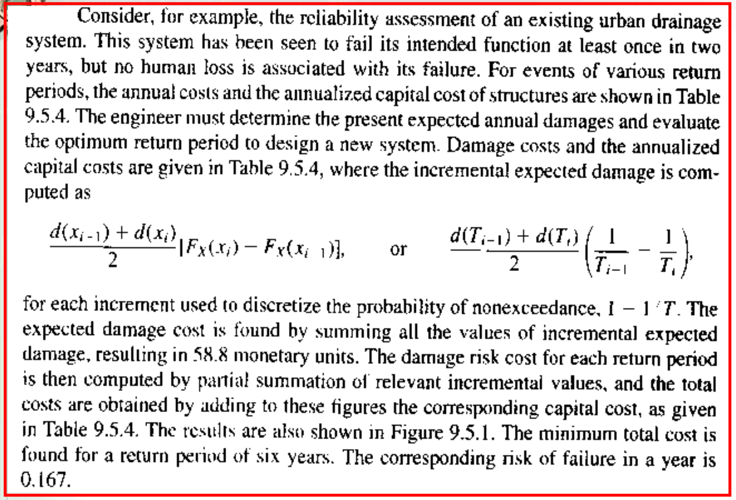
$$d_T = \int_{x(T)}^{+\infty} d(x) f_X(x)\, dx$$

is the expected annual cost. A finite difference approximation is obtained as

$$d_T = \sum_{i=1}^{+\infty} \frac{d(x_{i-1}) + d(x_i)}{2} [F_X(x_i) - F_X(x_{i-1})],$$

where $x_0 = x(T)$. One can then add the discounted annual cost c_I to d_T and search for the optimum return period by minimizing the total cost.

Example (2-2)



Consider, for example, the reliability assessment of an existing urban drainage system. This system has been seen to fail its intended function at least once in two years, but no human loss is associated with its failure. For events of various return periods, the annual costs and the annualized capital cost of structures are shown in Table 9.5.4. The engineer must determine the present expected annual damages and evaluate the optimum return period to design a new system. Damage costs and the annualized capital costs are given in Table 9.5.4, where the incremental expected damage is computed as

$$\frac{d(x_{i-1}) + d(x_i)}{2} [F_X(x_i) - F_X(x_{i-1})], \qquad \text{or} \qquad \frac{d(T_{i-1}) + d(T_i)}{2} \left(\frac{1}{T_{i-1}} - \frac{1}{T_i} \right),$$

for each increment used to discretize the probability of nonexceedance, $1 - 1/T$. The expected damage cost is found by summing all the values of incremental expected damage, resulting in 58.8 monetary units. The damage risk cost for each return period is then computed by partial summation of relevant incremental values, and the total costs are obtained by adding to these figures the corresponding capital cost, as given in Table 9.5.4. The results are also shown in Figure 9.5.1. The minimum total cost is found for a return period of six years. The corresponding risk of failure in a year is 0.167.

Example (2-3)

TABLE 9.5.4
Optimal design return period from hydroeconomic analysis for an urban drainage system

Increment	Return period (years)	Annual probability of nonexceedance	Damage (units)	Incremental expected damage (units/year)	Damage risk cost (units/year)	Capital cost (units/year)	Total cost (units/year)
0	1	0.000	0		58.8	0	58.8
1	2	0.500	40	10.0	58.8	0	58.8
2	3	0.667	45	7.1	48.8	8	57.0
3	4	0.750	50	4.0	41.7	11	52.3
4	5	0.800	55	2.6	37.8	13	50.8
5	6	0.833	60	1.9	35.2	15	50.5
6	7	0.857	70	1.5	33.2	18	50.9
7	8	0.875	80	1.3	31.7	20	51.7
8	9	0.889	85	1.1	30.4	22	52.6
9	10	0.900	120	1.1	29.2	25	53.7
10	15	0.933	140	4.3	28.1	36	63.7
11	20	0.950	190	2.8	23.7	50	73.7
12	30	0.967	270	3.8	21.0	70	91.0
13	40	0.975	380	2.7	17.2	90	107.2
14	50	0.980	500	2.2	14.5	110	124.5
15	100	0.990	800	6.5	12.3	210	222.3
16	200	0.995	1500	5.8	5.8	320	325.8

Example (2-4)

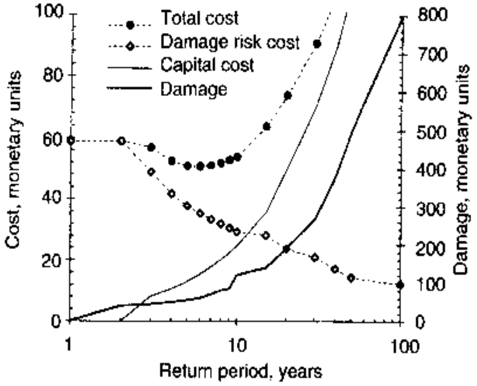


FIGURE 9.5.1
Determination of optimal design return period by economic analysis of an existing urban drainage system.