CHAPTER

5b

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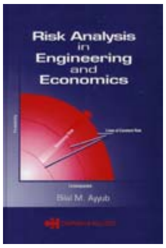
Risk Analysis in Engineering and Economics

FAILURE CONSEQUENCES AND SEVERITY

• A. J. Clark School of Engineering •Department of Civil and Environmental Engineering



Risk Analysis for Engineering
Department of Civil and Environmental Engineering
University of Maryland, College Park

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure
  - Introduction
    - Dam failure can have various consequences, some of which can be significant including loss of life.
    - Each system failure that can arise has consequences.
    - Flood plains, population at risk, dam breach inundation, and fatality rates are discussed herein.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Flood Plains
    - A floodplain is defined by the American Geological Institute as the portion of a river valley adjacent to the river channel which is built of sediments during the present regimen of the stream and which is covered with water when the river overflows its banks at flood stages.
    - The floodplain is a level area near the river channel.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Flood Plains (cont'd)
    - The *floodplain* is an integral and necessary component of the river system.
    - If a climate change or land use change occurs, then the existing floodplain may be abandoned and new floodplain construction begins.
    - *Sediment* is deposited when the stream flow overtops the banks; this occurs approximately every 1.5 to 2 years in stable streams.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Flood Plains (cont'd)
    - The floodplain extends to the valley walls.
    - In engineering, floodplains are often defined by the water surface elevation for a design flood, such as the 100- or 200-year flood.
    - Changes in the natural floodplain development are caused by changes in sediment loads or water discharge.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Flood Plains (cont'd)
    - Increases in both the sediment and water discharge are often caused by land use changes, typically urbanization.
    - Other causes include changes to the channel itself, such as straightening or relocating.
    - Climatic changes can cause the current floodplain to be abandoned; however, this is seldom a concern for engineering as the time scale is geologic rather than engineering.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics
    - The number of people at risk in the event of capacity exceedence or other uncontrolled release depends on the population within the inundation area and the conditions of release.
    - A variety of scenarios are defined by the planning team to represent a range of modes of failure, given overtopping and other potential conditions of breaching.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - For each scenario, specific characteristics of the release are defined, and quantitative characteristics of downstream effects are estimated for economic cost and loss of life.
    - Probabilities are associated with each scenario based on reliability analyses, and the resulting probability-consequence combinations used as the basis for risk assessment.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - A quantitative expression for estimating loss of life (LOL) in dam failures, based on statistical analysis of empirical data related to severe flooding can be expressed as:

$$LOL=\frac{PAR}{1+13.277(PAR^{0.44})\exp\{0.750(WT)-3.790(Force)+2.223(WT)(Force)\}} \quad (1)$$

LOL = potential loss of life
PAR = population at risk
WT = warning time in hours, Force = forcefulness of flood water (1 for high force, 0 for low force).

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - The PAR is defined as the number of people within three hours travel time of the flood wave, and includes not just those exposed to "treacherous flood waters," but all risk of "getting their feet wet."
    - The empirical equation is statistically valid only for PAR's less than 100,000.
    - An example calculation is shown in Figure 14.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)

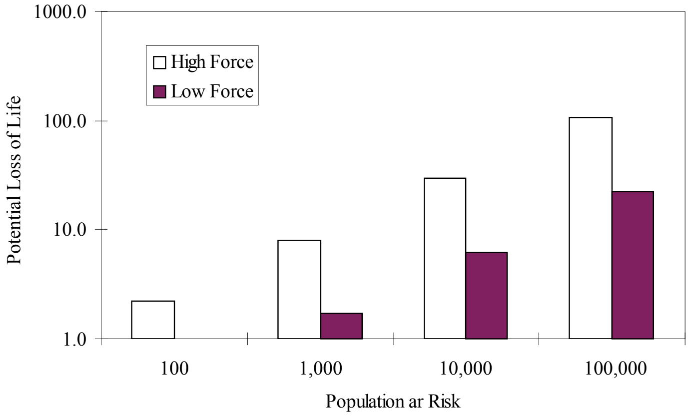


Figure 14. Example Calculation of Potential Loss of Life for a Warning Time of One Hour

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Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - For an example dam, the following values are assumed: PAR = 100,000, WT = 1 hours, and Force = 0 and 1.
    - The resulting values for LOL are 0.3 and 5 persons for Force = 0 and 1, respectively.
    - The warning time (WT) in the above equation depends on the existing warning system.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - This is the time in hours before the arrival of flooding by which the "first individuals for each PAR are being warned to evacuate" according to the USBR in 1989.
    - As a lower bound, warning time is sometimes taken as just the flood travel time (i.e., no warning is issued prior to loss of containment).
    - This is thought appropriate for events such as earthquake induced failures, but conservative for hydrologically caused failures

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Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - The affect of warning time on loss of life also depends on the warning procedure (e.g., telephone chain calls vs. siren) and on the evacuation plan.
    - Neither of these factors enters the above equation.
    - The forcefulness of floodwaters (Force) in the above equation is treated as a dichotomous variable with value one for high force and zero for low force.
    - "**High force**" means waters that are swift and very deep, typical of narrow valleys.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Demographics (cont'd)
    - "**Low force**" means waters that are slow and shallow, typical of broad plains.
    - For cases in which the population resides in both topographies, the PAR is subdivided.
    - The PAR does not need to be divided into no more than two subgroups, because non-linearity in the above equation causes over estimation of loss of life as the PAR is subdivided.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Simulating Dam Breach Inundation
    - Simulation of a breach requires flow over the dam, flow through the breach, and flow down the dam face.
    - The flow over the dam is typically modeled as weir flow.
    - The breach shape is assumed in all models, either as a regular geometric shape or a most efficient breach channel shape where the hydraulic radius of the breach channel is maximized similar to stable channel design.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Simulating Dam Breach Inundation
    - The initial breach grows by collapse of the breach slopes, due to gravity and hydrodynamic forces, and erosion of the soil, typically modeled using sediment transport equations which have been developed for alluvial river channels.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Dam Failure and Flood Fatalities
    - Since the 12th century, approximately 2000 dams have failed, although most of these failures were not major dams.
    - About 200 reservoirs in the world failed in the 20th century, and more than 8000 people died in these reservoir failures.
    - The reasons behind these numbers of failure and fatality should be used to improve the safety of dams.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Dam Failure and Flood Fatalities
    - Table 11 shows calculated failure rates for dams based on failure.
    - An estimated failure rate for dams based on this table is 10^{-4}, without an indication of fatality rates for the associated failures.
    - The rate is given as the number of failures per dam per year (per dam-year).
    - Consequences of notable failure dams in U.S. for the period 1963 to 1983 are given in Table 12.

Loss of Human Life

Table 11. Referenced Dam Failure Rates

Area	Failures	Total Dams	Period, years	Rate $(\text{dam-year})^{-1}$
U.S.	33	1764	41	4.5×10^{-4}
	12	3100	14	2.8×10^{-4}
	74	4974	23	6.5×10^{-4}
	1	(dam-year = 4500)		2.2×10^{-4}
World	125	7500	40	4.2×10^{-4}
	9	7833	6	1.9×10^{-4}
Japan	1046	276,971	16	2.4×10^{-4}
Spain	150	1620	145	6.6×10^{-4}
Britain	20	2000	150	0.7×10^{-4}

Loss of Human Life

Table 12. Dam Failure Consequences from Notable U. S. Dam Failures, from 1963 to 1983

Name & Location of Dam	Failure Date	Fatalities	Property Damages
Mohegan Park, Conn.	Mar. 1963	6	$3 million
Little Deer Creek, Utah	June 1963	1	Summer cabins damaged.
Baldwin Hills, CA	Dec. 1963	5	41 houses destroyed. 986 houses damaged. 100 apartment buildings damaged.
Swift, Montana	June 1964	19	Unknown
Lower Two Medicine, Mont.	June 1968	9	Unknown
Lee Lake, Mass.	Mar. 1968	2	6 houses destroyed. 20 houses damaged. One manufacturing plant damaged or destroyed.

Loss of Human Life

Table 12. (cont'd) Dam Failure Consequences from Notable U. S. Dam Failures, from 1963 to 1983

Name & Location of Dam	Failure Date	Fatalities	Property Damages
Buffalo Creek, WV	Feb. 1972	125	546 houses destroyed. 538 houses damaged.
Lake "O" Hills, Ark.	Apr. 1972	1	Unknown
Canyon Lake, SD	June 1972	33	Unable to assess damage because dam failure accompanied damage caused by natural flooding
Bear Wallow, NC	Feb. 1976	4	1 house destroyed.
Teton, Idaho	June 1976	11	771 houses destroyed. 19 houses damaged.
Laurel Run, PA	July 1977	39	6 houses destroyed. 19 houses damaged.
Sandy Run and 5 others, PA	July 1977	5	Unknown

Loss of Human Life

Table 12. (cont’d) Dam Failure Consequences from Notable U. S. Dam Failures, from 1963 to 1983

Name & Location of Dam	Failure Date	Fatalities	Property Damages
Kelly Barnes, GA	Nov. 1977	39	9 houses. 18 house trailers and college buildings destroyed; 6 houses, 5 college buildings damaged.
Swimming Pool, NY	1979	4	Unknown
About 20 dams in Conn.	June 1982	0	Unknown
Lawn Lake, CO	July 1982	3	18 bridges destroyed. 117 businesses and 108 houses damaged. Campgrounds, fisheries, power plant damaged.
DMAD, Utah	June 1983	1	Unknown

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont’d)
  - Dam Failure and Flood Fatalities (cont’d)
    - NID data comprising records on 75,187 dams existing in 1995-1996, was analyzed to compute a dam’s age in 1997 and record its structural type and purpose.
    - Total dam years and a incident rate were calculated from the following:

$$\mathit{Total\ Dam\ Years} = \sum(\mathit{NID\ age\ computed\ values}) + \sum(\mathit{age\ values\ from\ incident\ file}) \qquad (2)$$

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Dam Failure and Flood Fatalities (cont'd)

$$Incident\ rate = \frac{Total\ number\ of\ incidents\ occurring}{Total\ dam\ years} \qquad (3)$$

    - The number of incidents at which fatalities occurred and the total number of fatalities for these incidents was also recorded for the purpose of calculating the number of fatalities per incident and used to compute a fatality rate as follows:

$$Fatality\ rate = \frac{Number\ fatalities}{Number\ incidents\ with\ fatalities}(Incident\ rate) \qquad (4)$$

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Dam Failure and Flood Fatalities (cont'd)
    - A dam incident with no loss of life was recorded as a fatality number of zero.
    - Where the description of the incident appears to be one in which no loss of life would have occurred but this could not be verified, these incidents are recorded as probable zero fatalities and were separately included in the final results.
    - The depth and velocity of the floodwaters can also be included with a proper consideration of the structural type in the path of the floodwaters.

Loss of Human Life

- Human Life Loss Due to Floods Resulting from Dam Failure (cont'd)
  - Dam Failure and Flood Fatalities (cont'd)
    - A flood-fatality model similar to the following model for fatalities from an earthquake can be developed:

$$\log\ N(D) = a(D) + b(D)M \qquad (5)$$

    - where the number of casualties, *N*, is a function of the magnitude, *M*, and the population density, *D*, in the area effected.
    - The parameters a and b are regression parameters that depend on density ranges.

Injuries

- The Abbreviated Injury Scale (AIS) is an anatomical scoring system first introduced in 1969 that since then has been revised and updated against survival so that it now provides a reasonably accurate ranking the severity of injury.
- A recent incarnation of the AIS score is the 1990 revision.

Injuries

- The AIS is monitored by scaling committees such the scaling committee of the Association for the Advancement of Automotive Medicine, and updated as needed.
- Injuries are ranked on a scale of 1 to 6, with 1 being minor, 5 severe, and 6 unsurvivable.

Injuries

- The AIS is not an aritmetic injury scale, in that the difference between AIS level 1 and AIS level 2 is not the same as that between AIS level 4 and AIS level 5 (i.e., it is on an ordinal scale).
- Table 15 shows the relationship between the AIS and a fraction of the WTP value – for example, $3,000,000 based on FAA guidance documents.

Injuries

Table 15. The Abbreviated Injury Scale and the Willingness-to-Pay Value (2001 Dollars)

Abbreviated Injury Scale Code	Injury Severity	Definition	Multiplier	Willingness-to-Pay Value
1	Minor	Superficial abrasion or laceration of skin; digit sprain; first-degree burn; head trauma with headache or dizziness (no other neurological signs).	0.2%	$6,000
2	Moderate	Major abrasion or laceration of skin; cerebral concussion (unconscious less than 15 minutes); finger or toe crush/amputation; closed pelvic fracture with or without dislocation.	1.55%	$46,400
3	Serious	Major nerve laceration; multiple rib fracture (but without flail chest); abdominal organ contusion; hand, foot, or arm crush/amputation.	5.75%	$172,500

Injuries

Table 15. (cont’d) The Abbreviated Injury Scale and the Willingness-to-Pay Value (2001 Dollars)

Abbreviated Injury Scale Code	Injury Severity	Definition	Multiplier	Willingness-to-Pay Value
4	Severe	Spleen rupture; leg crush; chest-wall perforation; cerebral concussion with other neurological signs (unconscious less than 24 hours).	18.75%	$562,500
5	Critical	Spinal cord injury (with cord transection); extensive second-or third-degree burns; cerebral concussion with severe neurological signs (unconscious more than 24 hours).	76.25%	$2,287,500
6	Fatal	Injuries which although not fatal within the first 30 days after an accident, ultimately result in death .	100.00	$3,000,000

Injuries

- These percentages reflect the loss of quality and quantity of life resulting from an injury typical of that level.
- In addition to WTP values, the DOT identifies other costs associated with fatalities and injuries related to transportation, including the costs of emergency services, medical care, and legal and court services.

Injuries

- The Office of Aviation Policy and Plans (APO) advises that medical and legal costs be valued on a per-victim basis, as provided in Table 16.
- The values in the table should be added only once to the aggregated sum of the WTP values for injuries suffered by any particular individual.

Injuries

Table 16. Per Victim Medical and Legal Costs Associated with Injuries (2001 Dollars)

Abbreviated Injury Scale Code	Injury Severity	Emergency/ Medical	Legal/Court	Total Direct Cost
1	Minor	$600	$1,900	$2,500
2	Moderate	$4,600	$3,100	$7,100
3	Serious	$16,500	$4,700	$21,200
4	Severe	$72,500	$39,100	$111,600
5	Critical	$219,900	$80,100	$300,000
6	Fatal	$52,600	$80,100	$132,700

Indirect Losses

- Indirect losses sometimes referred to as consequential losses being of a second order in that they are induced by the direct losses.
- They can be classified as time independent and being time dependent losses.
- For example the loss of building has the direct loss of its value, and indirect losses that include loss of use of the building that is time dependent.

Indirect Losses

- Time independent losses, for example, include the loss in value of clothing sets due to loss of other clothing parts.
- Indirect losses also include business interruptions due to shutdown on reduced operations.
- These losses could include depreciation, interest on mortgages and other indebtedness, salaries of personnel, subcontract obligations, maintenance expenses, advertising, and utilities.

Indirect Losses

- The total loss depends also on the period of interruption.
- Some business must continue operation leading to losses due to continued operations that could include operating at higher rates for space, people, and materials.

Indirect Losses

- Indirect losses could also include contingent business interruption due to other contributing properties that are not owned by the loss bearer but is essential for operations, such as an essential supplier of materials.
- Other indirect expenses include leasehold loss as a result of losing a favorable lease terms as a result of loss of leased premises, criminal loss due to dishonesty of employees, and legal liability losses.

Public Health and Ecological Damages

- Assessing health loss to the public requires performing exposure assessment.
- Failure consequences are used to determine how much of each chemical people may be exposed to.
- People must come in contact with the chemicals to be at risk.
- The amount of exposure depends a lot on how much of each chemical is there, who might be exposed, and how they are exposed.

Public Health and Ecological Damages

- The exposure assessment is followed by toxicity assessment to determine which illnesses or other health effects may be caused by exposure to chemicals.
- It will also include determining what dose that can cause harmful health effects.
- Generally, the higher the dose, the more likely a chemical will cause harm.
- These harms need then to be translated into reduced longevity or equivalent life loss.

Public Health and Ecological Damages

- In ecological risk assessment, for example, toxicity, i.e., effects data, and exposure estimates, i.e., environmental concentrations, are evaluated for the likelihood that the intended use of a pesticide will adversely affect terrestrial and aquatic wildlife, plants, and other organisms.
- Data required to conduct an ecological risk assessment may include the following:
  - • Toxicity to wildlife, aquatic organisms, plants, and nontarget insects;
  - • Environmental cahnges;

Public Health and Ecological Damages

  - Estimated environmental concentrations;
  - Where and how the pesticide will be used;
  - What animals and plants will be exposed; and
  - Climatologic, meterologic, and soil information.
- Also, ecological methods may be used for detecting patterns of disease occurrence across space and time and relating the rates of disease frequency to environmental, behavioral, and constitutional factors.

Public Health and Ecological Damages

- The risk assessment process involves multiple steps, beginning with an appraisal of toxicity and exposure and concluding with a characterization of risk.
- Risk characterization defines the likelihood that humans or wildlife will be exposed to hazardous concentrations.
- Thus, risk characterization describes the relationship between exposure and toxicity.

Public Health and Ecological Damages

- The following modeling methods can be used depending on the situation and analysis objectives:

  Source Modeling: Determining the quantity and the nature of a chemical release is the first step in modeling its transport, fate, human health, and ecological impacts.

  Emissions Modeling: These modeling methods can be used to estimate air emissions from point or area sources such as from waste management and wastewater treatment operations.

Public Health and Ecological Damages

Air Dispersion Modeling: For chemicals that are emitted from sources such as industrial facilities or mobile sources, air dispersion modeling determines both the air concentration and the amount of chemical constituent deposited on surfaces at specified locations.

Groundwater and Surface Water Modeling: These modeling methods enable effective and cost-saving management of groundwater resources. They help decision makers to determine the optimal solutions for pollution control at local, regional, and national levels. They use a variety of water quality models and databases for many situations, including point and non-point sources and in-stream kinetics.

Public Health and Ecological Damages

Food Web Modeling: These modeling methods predict biological uptake and accumulation of chemicals in aquatic and terrestrial food webs. They use data and regression methods to estimate chemical concentrations in produce and animal products. The focus herein is on characterizing the variability in tissue concentration estimates associated with dietary preferences and chemical-specific behavior in biological systems.

Public Health and Ecological Damages

Ecological Modeling: Risk assessors use a holistic approach to predict ecological risks associated with chemical releases in terrestrial, freshwater, and wetland habitats, recognizing the importance of characterizing the variability and uncertainty inherent in ecological simulations.

Public Health and Ecological Damages

Stochastic Models: Environmental models often provide deterministic results, although the input data include both uncertainty and variability. The methods herein provide a distribution of risks that reflect variability in the input parameters, and can provide either a quantitative evaluation or a qualitative discussion of the uncertainty. A statistical method based on response surface methodology can also be used to determine the most sensitive input variables in a Monte Carlo analysis.

Public Health and Ecological Damages

Geographic Information Systems (GIS)-Based Modeling: These modeling methods allow scientists to develop complex, interactive, and flexible applications using geospatial data to simulate and predict real-world events. They may be used to (1) predict the amounts and effects of non-point source runoff, (2) evaluate the effects and dangers of pollutants as they travel through the environment, and (3) simulate the effects of environmental policies. Such capabilities provide flexibility to examine what-if scenarios to better understand environmental processes and the effects of environmental policy.

Public Health and Ecological Damages

Lifecycle Modeling: Lifecycle modeling might be necessary to assess ecological risk. For example, lifecycle emissions for the production and combustion of fuels to produce electricity using electrical-energy distribution grids might require modeling virtually many process that consumes fuel or electricity in order to calculate the tradeoffs among alternative energy sources

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Public Health and Ecological Damages

- The Food Safety and Inspection Service (FSIS) of the U. S. Department of Agriculture is relying more heavily on risk assessments as a means of guiding food safety policy decisions.
- The agency has conducted risk assessments for Salmonella enteritidis in eggs and egg products, in ground beef, and, with the Food and Drug Administration (FDA), a risk ranking for Listeria monocytogenes in a variety of foods.

Public Health and Ecological Damages

- Risk assessment was used as a structured process for determining the risks associated with any type of hazard, including biological, chemical, or physical.
- Having the objective of ensuring the public is protected from health risks of unsafe foods, exposure assessment in this case must differentiate between short-term exposure for acute hazards and long-term exposure for chronic hazards.

Public Health and Ecological Damages

- For acute hazards, such as pathogens, data on levels of pathogens causing illness in vulnerable population groups are important.
- For chronic hazards, such as chemicals that may cause cumulative damage, a lifetime averaged exposure is relevant.

Homework Assignment #5

Problems:

5.2

5.5

5.10

5.14

5.17