CHAPTER

Risk Analysis in Engineering and Economics

FAILURE CONSEQUENCES AND SEVERITY

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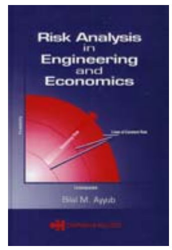
A. J. Clark School of Engineering •Department of Civil and Environmental Engineering



Risk Analysis for Engineering

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CHAPMAN HALL/CRC

Introduction

- Failure consequences are the results of the action or process of failure.
- They are outcomes or effects of failure as a logical result or conclusion.
- A **consequence** can be defined as the results of a failure, e.g., gas cloud, fire, explosion, evacuations, injuries, deaths, public and employee health effects, environment damages, or damage to the facility.

Introduction

- **Failure severity** is the quality, condition, strictness, impact, harshness, gravity, or intensity of failure consequences.
- The amounts of damage that is (or that may be) inflicted by a loss or catastrophe constitute the severities.
- The severity cannot be assessed with certainty, and is desired in *monetary terms*.

Introduction

- The failure of an engineering system could lead to consequences creating a need to assess failure consequences and severities
- The assessment methods can be based on
  1. **Analytical models**, such as microeconomic techniques, and
  2. **Data collection** from sources that include accident reports.

Introduction

- Severity uncertainty has been recognized in the insurance industry and treated using random variable or stochastic-process representations.
- Also, terms such as the maximum possible loss (MPL) and the probable maximum loss (PML) are used.
- They are assessed as the worst loss that could occur based on the worst possible combination of circumstances, and the loss that is likely based on the most likely combination of circumstances, respectively.

Introduction

- Each system failure that can arise has consequences and severities.
- A failure could cause
  - economic damage such as reduced productivity,
  - temporary or permanent loss of production,
  - loss of capital,
  - or bad publicity.

Introduction

- A failure could also result in more serious events such as
  - environmental damage,
  - injury or loss of human life, or
  - public endangerment.
- Consequence and severity estimations are based on either events in past history or on educated guesses including analytical, predictive tools.

Introduction

- Each failure event must have some levels of failure consequence and severity assigned to it in order to calculate the overall risk.
- The failure consequence can be described as a numeric value or a standardized consequence index values.

Analytical Consequence and Severity Assessment

- Cause-Consequence Diagrams (CS)
  - These diagrams were developed for the purpose of assessing and propagating the conditional effects of a failure using a tree representation to sufficient detail levels for assessing severities as losses.
  - The analysis according to CS starts with selecting a *critical event*.
  - Critical events are commonly selected as convenient starting points for the purpose of developing the CS diagrams.

Analytical Consequence and Severity Assessment

- Cause-Consequence Diagrams (CS)
  - For a given critical event, the consequences are traced using logic trees with event chains and branches.
  - The logic works both backward (similar to fault trees) and forward (similar to event trees).
  - The procedure for developing a CS diagram can be based on answering a set of questions at any stage of the analysis.

Analytical Consequence and Severity Assessment

- Cause-Consequence Diagrams (CS)
  - The questions can include, for example, the following:
    - Can this event lead to other failure events?
    - What are the needed conditions for this event to lead to other events?
    - What other components are affected by this event?
    - What other events are caused by this event?
    - What are the associated consequences with the other (subsequent) events?
    - What are the occurrence probabilities of subsequent events or failure probabilities of the components.

Analytical Consequence and Severity Assessment

- **Example 1:** Failure of Structural Components
  - In this example, failure scenarios developed based on the initiating event "buckling of unstiffened side shell panel in a naval-vessel cargo space" are used to demonstrate the process of developing cause-consequence diagrams.

Analytical Consequence and Severity Assessment

- Example 1 (cont'd)
  - These failure scenarios are classified in two groups:
    1. failure scenarios related to the failure of ship systems other than structural failure, and
    2. failure scenarios involving the ship structural system failure.
  - Only failure scenarios associated with this initiating event for its impact on the structural system are considered in this example.

Analytical Consequence and Severity Assessment

- Example 1 (cont'd)
  - Figure 1 shows these failure scenarios , which presents the sequence of events that should be considered for the development of the cause-consequence diagram.
  - The consequences associated with the failure scenarios can be grouped as follows:
    1. *Crew:* possible injuries and deaths as a result of an overall hull girder failure, i.e., hull collapse;
    2. *Cargo:* possible loss of cargo, in case of hull failure;

Analytical Consequence and Severity Assessment

- Example 1 (cont'd)

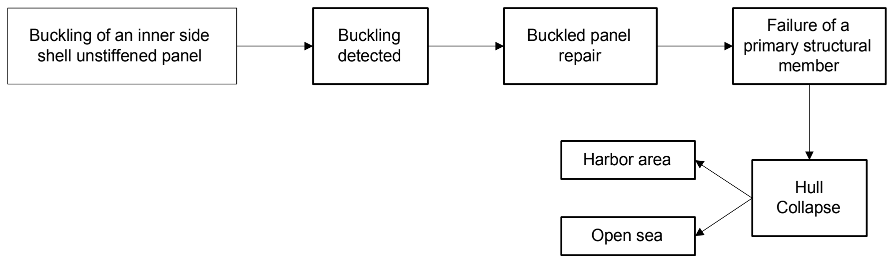

Figure 1. Buckling of an Unstiffened Side Shell Panel and Its Consequences

Analytical Consequence and Severity Assessment

- Example 1 (cont'd)
   3. *Environment:* possible contamination with fuel and lubricant oil, and cargo, in case of hull collapse;
   4. *Non-crew:* none;
   5. *Structure*: extensive hull damage, considering the failure of a primary structural member;
   6. *Ship:* possible loss of ship in case of hull failure;
   7. Cost of inspection, and possible cost of repair, in case of buckling detection

Analytical Consequence and Severity Assessment

- Example 1 (cont'd)
  - The cause-consequence diagram associated with this initiating event is presented in Figure 2.
  - The consequences of the possible failure scenarios associated with the buckling of an inner side shell unstiffened panel, in the cargo space, are presented in Table 1.

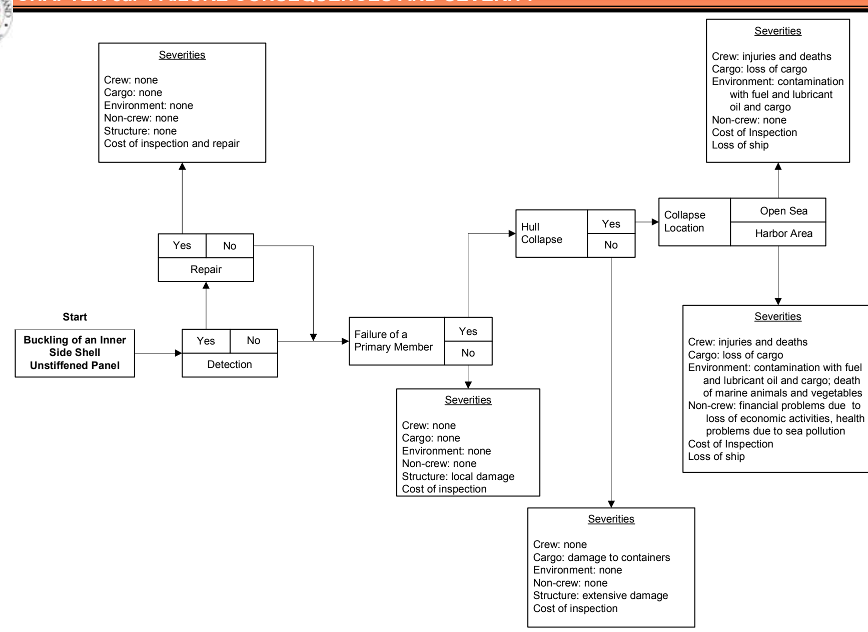

Figure 2. Cause-Consequence Diagram for the Buckling of an Unstiffened Panel

Analytical Consequence and Severity Assessment

Table 1. Structural Consequences Associated with the Buckling of an Unstiffened Panel

Failure Scenario[1]	**Severities**						
Definition	Crew	Cargo	Environment	Non-crew	Structural System	Inspection and Repair	Rating
YYUUU	None	None	None	None	None	Cost of inspection and repair	1
YNYYO NUYYO	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo	None	Loss of ship	Cost of inspection	5
YNYYH NUYYH	Injuries and deaths	Loss of cargo	Contamination with oil (fuel and lubricant) and cargo, death of marine animals and plants	Financial problems due to loss of economic activities, health problems due to sea pollution	Loss of ship	Cost of inspection	5
YNYNU NUYNU	None	Damage to containers	None	None	Extensive damage	Cost of inspection	3
YNNUU NUNUU	None	None	None	None	Local damage		2

Analytical Consequence and Severity Assessment

- Example 1 (cont'd)
  - The following is an explanation of the five-character scenarios defined in Table 1:

_ XXXX = the first character corresponds to the detection of the buckling;
X _ XXX = the second character corresponds to the repair of the buckled panel;
XX _ XX = the third character corresponds to the failure of a primary structural member;
XXX _ X = the fourth character corresponds to the hull collapse; and
XXXX _ = the fifth character corresponds to the geographical location of the hull failure,

Analytical Consequence and Severity Assessment

- Functional Modeling
  - Assessing the impact of the failure of a system on other systems can be a difficult task.
  - For example, the impact of structural damage on other system can be assessed using a special logic based fuzzy sets, pattern recognition and expert systems based on functional modeling.
  - Prediction of the structural response of a ship structural components or systems, as an example, could require the use of nonlinear structural analysis.

Analytical Consequence and Severity Assessment

- Functional Modeling (cont’d)
  - Failure definitions need to be expressed using deformations rather than forces or stresses.
  - Also, the recognition and proper classification of failures based on a structural response within the simulation process need to be performed based on deformation responses.
  - The failure classification is based on matching a deformation or stress field with a record within a knowledge base of response and failure classes.

Analytical Consequence and Severity Assessment

- Functional Modeling (cont'd)
  - In cases of no match, a list of approximate matches is provided, with assessed applicability factors.
  - The user can then be prompted for any changes to the approximate matches and their applicability factors.

Analytical Consequence and Severity Assessment

- **Example 2:** Failure Definition based on Functional Modeling
  - Prediction of the structural response of a complex system, such as a floating marine system, could require the use of nonlinear structural analysis.
  - Failure definitions need to be expressed using deformations, rather than forces or stresses.
  - The process of failure classification and recognition needs to be automated in order to facilitate its use in a simulation algorithm for structural reliability assessment.

Analytical Consequence and Severity Assessment

- Example 2 (cont'd)
  - Figure 3 shows a procedure for an automated failure classification that can be implemented in a simulation algorithm for reliability assessment.
  - The failure classification is based on functional modeling.
  - In cases of no match, a list of approximate matches is provided, with assessed applicability factors.

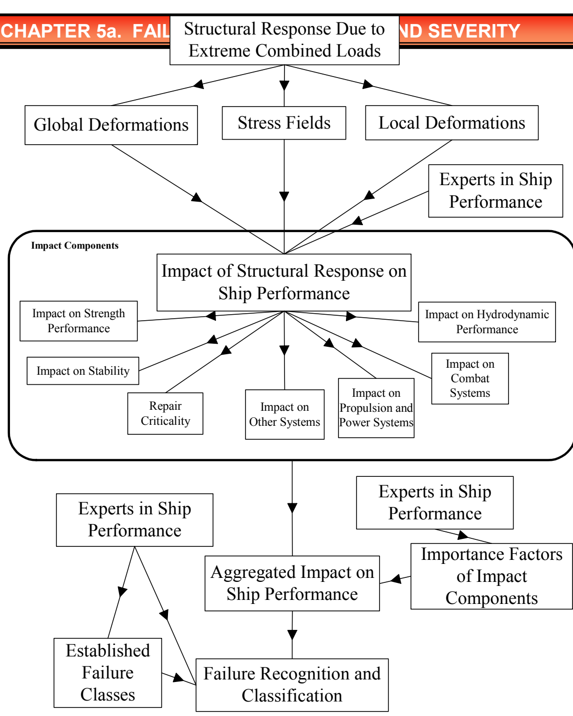

Figure 3. Failure Recognition and Classification Procedure

Analytical Consequence and Severity Assessment

- Example 2 (cont'd)
  - In the case of poor matches, the user can have the option of activating the failure recognition algorithm shown in Figure 4 to establish a new record in the knowledge base.
  - The adaptive or neural nature of this algorithm allows the updating of the knowledge base of responses and failure classes.
  - The failure recognition and classification procedure shown in the figure evaluates the impact of the computed deformation or stress field on several systems of a ship.

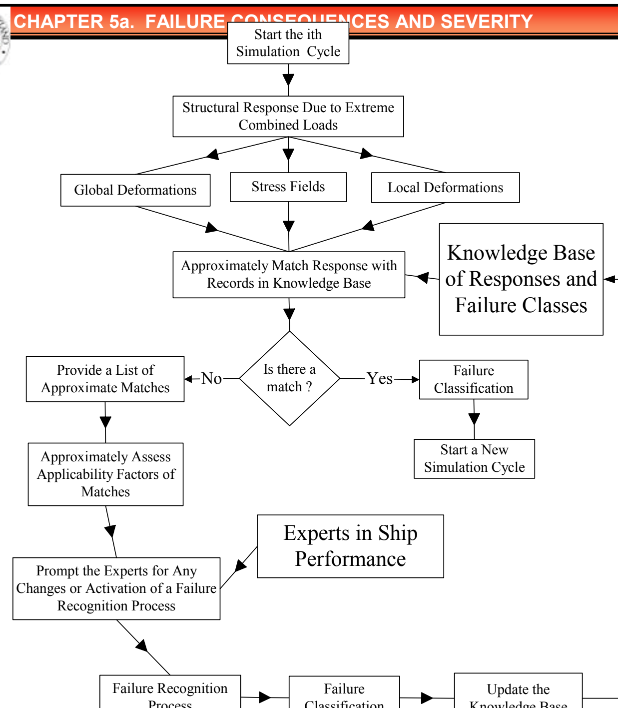

Figure 4. Failure Recognition Algorithm

Analytical Consequence and Severity Assessment

- Example 2 (cont'd)
  - The severity assessment includes evaluating the remaining strength, stability, repair criticality, propulsion and power systems, combat systems, and hydrodynamic performance.
  - A prototype computational methodology for reliability assessment of continuum structures using finite element analysis with instability failure modes can be developed.

Analytical Consequence and Severity Assessment

- Example 2 (cont'd)
  - A crude simulation procedure can be applied to compare the response with a specified failure definition, and failures can then be counted.
  - By repeating the simulation procedure several times, the failure probability according the specified failure definition is estimated as the failure fraction of simulation repetitions.
  - Alternatively, conditional expectation can be used to estimate the failure probability in each simulation cycle.

Real Property Damage

- Monetary terms is used in the assessment of real property damage as a result of failure
- This can be accomplished utilizing microeconomic models.
- The structure and workings of such models depend on hazard and properties being investigated.

Real Property Damage

- The primary concepts that can be used for assessing property damage are presented in this section using water flooding as a hazard and residential structures and vehicles as the property.
- Two formulations are provided based on
  1. Microeconomic modeling, and
  2. Expert-opinion elicitation.

Real Property Damage

- The failure severity in terms of property loss can be assessed as the current replacement value less depreciation to obtain the ***actual cash value*** of a property.
- Sometimes ***replacement cost*** is used to assess the loss, where replacement cost is defined as the cost of reconstructing the property with like kind and quality.
- A primary difference between the actual cash value and replacement cost value is depreciation.

Real Property Damage

- The replacement cost is needed in both approaches.
- Assessing the content loss of a residential structure can be based on a detailed breakdown of content by structure size, quality, and functions of various spaces in the property.
- The content loss for each room can then be estimated and aggregated for the entire structure.

Real Property Damage

- As for businesses, property loss could include machinery and equipment, furnishings, and raw materials and inventories.
- Computer programs are commercially available to aid in this type of estimation for both residential and commercial structures.
- Some aspects of these estimation methods are illustrated herein.

Real Property Damage

- **Microeconomic Modeling**
  – A Corps of Engineers Floodplain Inventory Tool (CEFIT) was developed in 2001 to organize floodplain inventory data and estimate residential structure and content damage for various depths of flooding on a structure-by-structure basis.
  – CEFIT estimates residential content values by depth by factoring in the typical number of rooms, items generally kept in homes of various quality levels, and the placement of those items relative to the first floor.

Real Property Damage

- **Microeconomic Modeling (cont'd)**
  - CEFIT estimates structure values using residential estimation software called the Residential Estimator (RE), developed and marketed by Marshall and Swift.
  - CEFIT predicts flood damage by assuming that each component or assembly would be cleaned, repaired, replaced, or reset at each given flooding depth.
  - This methodology is depicted in Figure 5 .

Real Property Damage

- **Microeconomic Modeling (cont'd)**

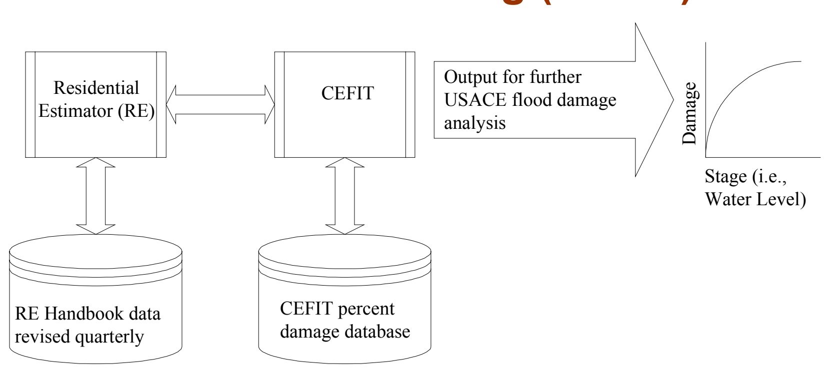

Figure 5. CEFIT Methodology for Computing Flood Stage Relationships

Real Property Damage

- **Microeconomic Modeling (cont'd)**
  - When a component or assembly is replaced, its full-depreciated replacement costs, as estimated from RE, is accrued as part of the flood damage.
  - When a component or assembly is cleaned or repaired, fractions of the replacement cost are accrued.
  - CEFIT uses the Residential Estimator to calculate replacement cost and applies the technique of aggregating lower-level cost information (or component costs) against a listing of quantities or "*bill of quantity*."

Real Property Damage

- **Microeconomic Modeling (cont'd)**
  - Steps in providing key user-defined inputs are given in Figure 6.
  - The library of 960 models covers all combinations of key user-defined parameters (8 styles, 3 building material types, 2 age periods, 5 infrastructure types, and 4 quality types).
  - The user interface of CEFIT permits defining the dwelling type using selections chosen by the user from pull-down menus.

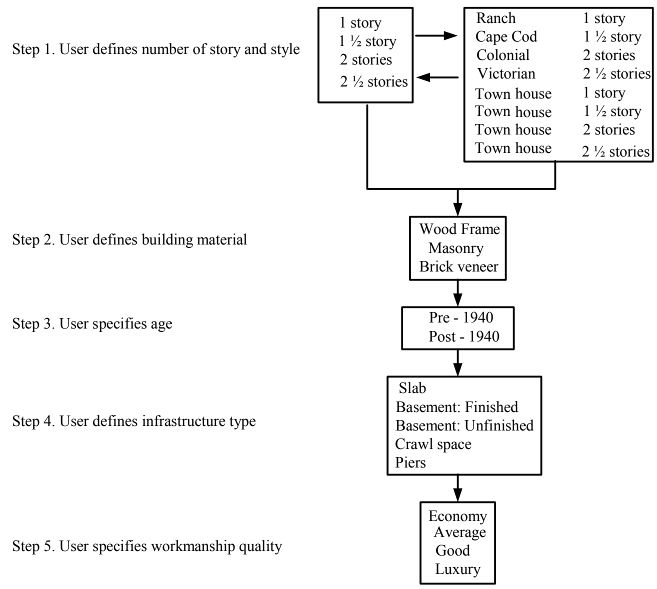

Figure 6. Steps in Providing Key CEFIT User Defined Inputs

Real Property Damage

- **Microeconomic Modeling (cont'd)**
  - User input data includes:
    - house configuration
    - material type
    - infrastructure type
    - Location
    - living area and vertical footage at which water reaches the 1st floor level.
  - CEFIT selects the model that fits the user input from the library of 960 models and defines the number of rooms, their size and location, i.e., story, in the house (which story).

Real Property Damage

- **Microeconomic Modeling (cont'd)**
  – CEFIT selects the level of flood in the model that corresponds to the user input.
  – The model estimates flood damage, that includes building repair and replacement costs, based on extrapolating to the specified total floor area and updating the remove, clean, replace, and reset operations to the systems and components based on the pre-defined flood level.

Real Property Damage

- **Microeconomic Modeling (cont'd)**
  – The pre-defined flood level is accessible for 16 increments of flooding.
  – The flood damage estimate is localized at the price level for any given zip code within the United States.

Real Property Damage

- **Example 3:** Property Loss Due to Flooding I
  - To illustrate the loss estimation used by the Corps of Engineers Floodplain Inventory Tool (CEFIT), a 2000-square-foot home with an effective age of 0 years, located in zip code 22222 (Arlington, VA) was used for illustration purposes.
  - The house has the following characteristics that are needed by CEFIT as an input:

Real Property Damage

- Example 3 (cont'd)
  - Characteristics needed by CEFIT as an input:

Number of Stories	= 1
Foundation Type	= Slab
Construction	= Standard
Style	= Ranch
Quality	= Average
Condition	= Average
Exterior Wall	= Frame, Siding, Wood
Roofing	= Wood Shingle

Real Property Damage

- Example 3 (cont'd)
  - Table 2 show losses for this residence at flood depths from 1 to 10 feet, as calculated by CEFIT.
  - These losses were calculated as a percentage of the Residential Estimator replacement cost of $104,747 in 2001.
  - The results are also shown in Figure 7.

Real Property Damage

Table 2. Losses as a Function of Water Depth

Water Level (ft)	Damage $	Percent of Total Replacement Cost
1	$24,406	23
2	$33,624	32
3	$42,004	40
4	$49,336	47
5	$55,725	53
6	$61,382	59
7	$66,200	63
8	$70,390	67
9	$73,847	71
10	$76,675	73

Real Property Damage

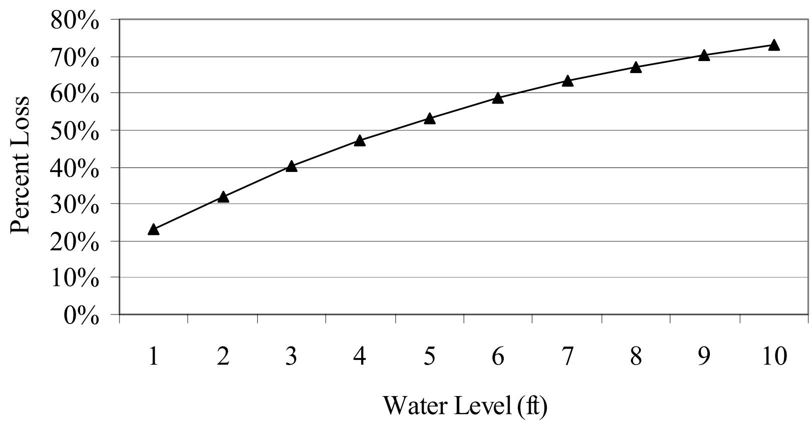

Figure 7. Loss to a Residential Structure Due to Flooding

Real Property Damage

- **Expert Opinions**
  - Expert-opinion elicitation can be used to assess property damage as a result of water flooding.
  - Expert-opinion elicitation can be defined as a heuristic process of gathering informing and data or answering questions on issues or problems of concern.
  - Here we provide an example illustrating the use of this method for assessing property loss is provided.

Real Property Damage

- **Example 4:** Property Loss Due to Flooding II
  - Expert-opinion elicitation is used herein to develop
    - Structural and content depth-damage relationships for single-family one-story homes without basements.
    - Residential content-to-structure value ratios.
    - Vehicle depth-damage relationships in the Feather River Basin of California.

Real Property Damage

- Example 4 (cont'd)
  - These damage functions consider exterior building material such as brick, brick veneer, wood frame, and metal siding.
  - The resulting consequences can be used in risk studies, and in performing risk-based decision making.
  - The expert elicitation was performed during a face-to-face meeting of members of an expert panel that is developed specifically for the issues under consideration.

Real Property Damage

- Example 4 (cont'd)
  - The meeting of the expert panel was conducted after communicating to the experts in advance to the meeting background information, objectives, list of issues, and anticipated outcomes from the meeting.
  - Detailed background for this example on the following items are provided in the textbook:
    - Levee Failure and Consequent Flooding
    - Flood Characteristics

Real Property Damage

- Example 4 (cont'd)
    - Building Characteristics
    - Vehicle Characteristics
    - Structural Depth-Damage Relationships
    - Content Depth-Damage Relationships
    - Content-to-Structure Value Ratios
    - Vehicle Depth-Damage Relationships

Real Property Damage

- Example 4 (cont'd)

Table 3. Summary of Supportive Reasoning and Assumptions by Experts for Structure Value

Houses Types 1 and 2	Houses Type 3
Median house size of 1400 SF Wood frame homes Median house value of $90,000 with land Median land value of $20,000 Median price without land is about $50 per square foot Median house age of 8 years Type 2 has HVAC and sewer lines below finished floor Percentages are of depreciated replacement value of houses Flood without flow velocity Several days of flood duration Flood water is not contaminated, but has sediment without large debris No septic field damages Allow for cleanup cost	Median size of 24 ft by 60 ft (1200 SF) Wood frame homes Median house value of $30,000 without land Median house age of 8 years Finished floor is 3 ft above ground level 8 ft ceiling height HVAC and sewer lines below finished floor Percentages are of depreciated replacement value of houses Flood without flow velocity Several days of flood duration Flood water is not contaminated, but has sediment without large debris No septic field damages Allow for cleanup cost

	Initial Estimate: % Damage by Expert							Aggregated Opinions				
Depth	1	2	3	4	5	6	7	Min	25%	50%	75%	Max
-1.0	4.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	4.0
-0.5	4.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	5.0
0.0	5.0	0.0	10.0	5.0	0.0	10.0	0.0	0.0	0.0	5.0	7.5	10.0
0.5	10.0	40.0	12.0	7.0	10.0	13.0	45.0	7.0	10.0	12.0	26.5	45.0
1.0	15.0	40.0	25.0	9.0	20.0	15.0	55.0	9.0	15.0	20.0	32.5	55.0
1.5	20.0	40.0	28.0	11.0	30.0	20.0	55.0	11.0	20.0	28.0	35.0	55.0
2.0	30.0	40.0	35.0	13.0	30.0	20.0	60.0	13.0	25.0	30.0	37.5	60.0
3.0	40.0	40.0	35.0	15.0	40.0	30.0	60.0	15.0	32.5	40.0	40.0	60.0
4.0	48.0	40.0	40.0	25.0	70.0	50.0	65.0	25.0	40.0	48.0	57.5	70.0
5.0	53.0	65.0	40.0	40.0	70.0	85.0	70.0	40.0	46.5	65.0	70.0	85.0
6.0	65.0	65.0	45.0	50.0	70.0	85.0	75.0	45.0	57.5	65.0	72.5	85.0
7.0	68.0	70.0	75.0	70.0	80.0	90.0	75.0	68.0	70.0	75.0	77.5	90.0
8.0	70.0	75.0	80.0	90.0	80.0	90.0	75.0	70.0	75.0	80.0	85.0	90.0
9.0	73.0	85.0	95.0	100.0	95.0	90.0	75.0	73.0	80.0	90.0	95.0	100.0
10.0	80.0	85.0	100.0	100.0	100.0	100.0	80.0	80.0	82.5	100.0	100.0	100.0
11.0	83.0	85.0	100.0	100.0	100.0	100.0	80.0	80.0	84.0	100.0	100.0	100.0
12.0	85.0	85.0	100.0	100.0	100.0	100.0	80.0	80.0	85.0	100.0	100.0	100.0

	Revised Estimate: % Damage by Expert							Aggregated Opinions				
Depth	1	2	3	4	5	6	7	Min	25%	50%	75%	Max
-1.0	1.0	0.0	3.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	2.0	5.0
-0.5	1.0	0.0	5.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	3.0	10.0
0.0	10.0	15.0	10.0	5.0	5.0	15.0	35.0	5.0	7.5	10.0	15.0	35.0
0.5	10.0	40.0	25.0	40.0	20.0	45.0	45.0	10.0	22.5	40.0	42.5	45.0
1.0	25.0	40.0	30.0	40.0	20.0	45.0	45.0	20.0	27.5	40.0	42.5	45.0
1.5	25.0	40.0	40.0	40.0	30.0	45.0	45.0	25.0	35.0	40.0	42.5	45.0
2.0	35.0	40.0	45.0	40.0	30.0	45.0	45.0	30.0	37.5	40.0	45.0	45.0
3.0	40.0	40.0	45.0	40.0	40.0	70.0	45.0	40.0	40.0	40.0	45.0	70.0
4.0	48.0	40.0	55.0	40.0	70.0	80.0	55.0	40.0	44.0	55.0	62.5	80.0
5.0	53.0	65.0	55.0	50.0	70.0	85.0	60.0	50.0	54.0	60.0	67.5	85.0
6.0	65.0	65.0	70.0	60.0	70.0	85.0	65.0	60.0	65.0	65.0	70.0	85.0
7.0	68.0	65.0	75.0	85.0	80.0	95.0	75.0	65.0	71.5	75.0	82.5	95.0
8.0	70.0	65.0	80.0	85.0	85.0	95.0	75.0	65.0	72.5	80.0	85.0	95.0
9.0	73.0	85.0	95.0	85.0	85.0	95.0	75.0	73.0	80.0	85.0	90.0	95.0
10.0	80.0	85.0	100.0	85.0	85.0	95.0	80.0	80.0	82.5	85.0	90.0	100.0
11.0	83.0	85.0	100.0	85.0	85.0	95.0	80.0	80.0	84.0	85.0	90.0	100.0
12.0	85.0	85.0	100.0	85.0	85.0	95.0	80.0	80.0	85.0	85.0	90.0	100.0
Confidence	High	High	High	High	High	High	High					

Table 4. Percent Damage to a Residential Structure Type 1: One-Story Without Basement on Slab

Real Property Damage

- Example 4 (cont'd)

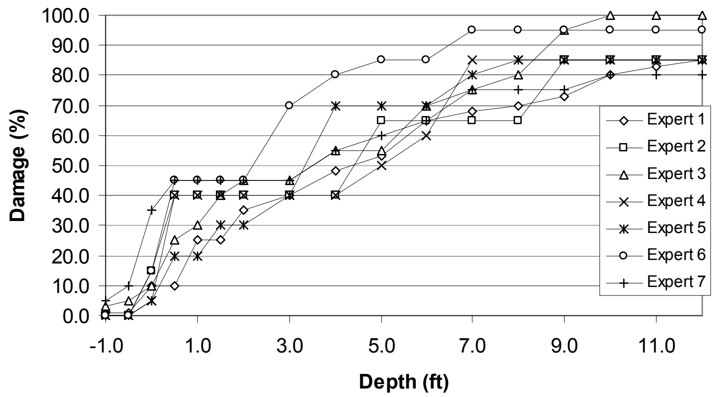

Figure 8a. Percent Damage to a Type 1 Residential Structure (One-Story on Slab without basement)

Real Property Damage

- Example 4 (cont'd)

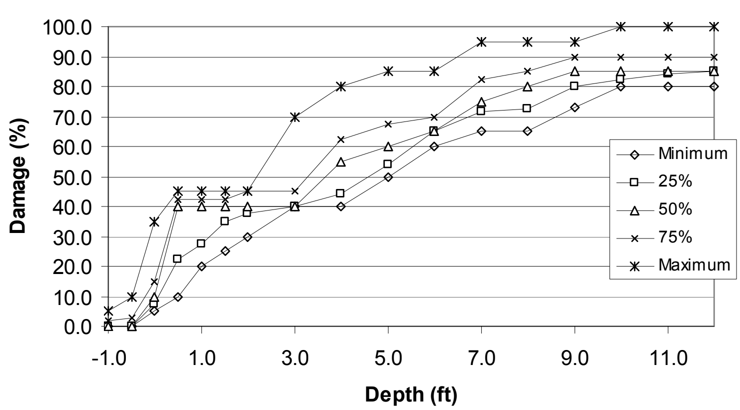

Figure 8b. Aggregated (as Percentiles) Percent Damage to a Type 1 Residential Structure (One-Story on Slab without Basement)

Real Property Damage

- Example 4 (cont'd)

Table 5. Summary of Supportive Reasoning and Assumptions by Experts for Content Value

Houses Types 1, 2 and 3
As a guide, the insurance industry uses 70% ratio for the content to structure value Median house value of $90,000 with land Median land value of $20,000 Garage or shed contents are included Median content age of 8 years Percentages are of depreciated replacement value of contents Flood without flow velocity Several days of flood duration Flood water is not contaminated, but has sediment without large debris Allow for cleanup cost Insufficient time to remove (i.e. protect) contents

	Initial Estimate: % Damage by Expert							Aggregated Opinions				
Depth	1	2	3	4	5	6	7	Min	25%	50%	75%	Max
-1.0	0.5	0.0	3.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	1.8	10.0
-0.5	0.5	0.0	5.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	2.8	20.0
0.0	2.0	30.0	15.0	0.0	0.0	40.0	5.0	0.0	1.0	5.0	22.5	40.0
0.5	2.0	40.0	35.0	20.0	50.0	40.0	10.0	2.0	15.0	35.0	40.0	50.0
1.0	15.0	50.0	35.0	40.0	50.0	40.0	20.0	15.0	27.5	40.0	45.0	50.0
1.5	27.0	60.0	40.0	50.0	60.0	40.0	20.0	20.0	33.5	40.0	55.0	60.0
2.0	35.0	70.0	40.0	60.0	70.0	60.0	40.0	35.0	40.0	60.0	65.0	70.0
3.0	47.0	80.0	70.0	70.0	80.0	80.0	40.0	40.0	58.5	70.0	80.0	80.0
4.0	55.0	80.0	70.0	80.0	80.0	90.0	60.0	55.0	65.0	80.0	80.0	90.0
5.0	80.0	80.0	70.0	90.0	90.0	90.0	60.0	60.0	75.0	80.0	90.0	90.0
6.0	90.0	80.0	70.0	100.0	100.0	90.0	85.0	70.0	82.5	90.0	95.0	100.0
7.0	90.0	80.0	75.0	100.0	100.0	95.0	95.0	75.0	85.0	95.0	97.5	100.0
8.0	90.0	85.0	85.0	100.0	100.0	100.0	100.0	85.0	87.5	100.0	100.0	100.0
9.0	90.0	85.0	90.0	100.0	100.0	100.0	100.0	85.0	90.0	100.0	100.0	100.0
10.0	90.0	85.0	90.0	100.0	100.0	100.0	100.0	85.0	90.0	100.0	100.0	100.0
11.0	90.0	85.0	90.0	100.0	100.0	100.0	100.0	85.0	90.0	100.0	100.0	100.0
12.0	90.0	90.0	90.0	100.0	100.0	100.0	100.0	90.0	90.0	100.0	100.0	100.0

Table 6. Percent Damage to Contents of Residential Structure Types 1 and 2: One-Story on Slab or on Piers and Beams

	Revised Estimate: % Damage by Expert							Aggregated Opinions				
Depth	1	2	3	4	5	6	7	Min	25%	50%	75%	Max
-1.0	2.0	0.0	3.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0	3.0
-0.5	2.0	0.0	5.0	5.0	0.0	5.0	0.0	0.0	0.0	2.0	5.0	5.0
0.0	15.0	20.0	15.0	10.0	10.0	30.0	5.0	5.0	10.0	15.0	17.5	30.0
0.5	20.0	30.0	35.0	20.0	30.0	40.0	20.0	20.0	20.0	30.0	32.5	40.0
1.0	25.0	50.0	35.0	40.0	45.0	40.0	20.0	20.0	30.0	40.0	42.5	50.0
1.5	25.0	60.0	40.0	50.0	60.0	40.0	30.0	25.0	35.0	40.0	55.0	60.0
2.0	30.0	70.0	40.0	60.0	70.0	60.0	40.0	30.0	40.0	60.0	65.0	70.0
3.0	40.0	80.0	70.0	70.0	75.0	80.0	40.0	40.0	55.0	70.0	77.5	80.0
4.0	50.0	80.0	70.0	80.0	80.0	90.0	60.0	50.0	65.0	80.0	80.0	90.0
5.0	50.0	80.0	70.0	90.0	90.0	90.0	60.0	50.0	65.0	80.0	90.0	90.0
6.0	85.0	80.0	70.0	95.0	90.0	90.0	70.0	70.0	75.0	85.0	90.0	95.0
7.0	90.0	80.0	75.0	95.0	90.0	95.0	100.0	75.0	85.0	90.0	95.0	100.0
8.0	90.0	85.0	85.0	95.0	90.0	95.0	100.0	85.0	87.5	90.0	95.0	100.0
9.0	90.0	85.0	90.0	95.0	90.0	95.0	100.0	85.0	90.0	90.0	95.0	100.0
10.0	90.0	85.0	90.0	95.0	90.0	95.0	100.0	85.0	90.0	90.0	95.0	100.0
11.0	90.0	85.0	90.0	95.0	90.0	95.0	100.0	85.0	90.0	90.0	95.0	100.0
12.0	90.0	85.0	90.0	95.0	90.0	95.0	100.0	85.0	90.0	90.0	95.0	100.0
Confidence	high	high	high	high	high	high	high					

Real Property Damage

- Example 4 (cont'd)

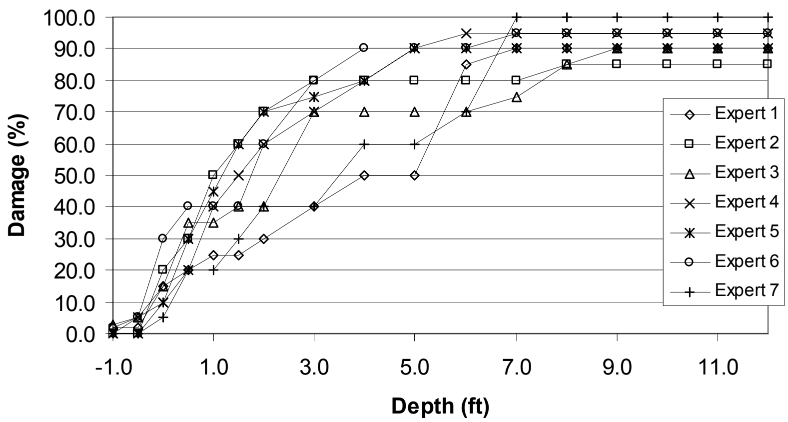

Figure 9a. Percent Damage to Contents of Type 1 and 2 Residential Structures (One-Story on Slab or One Story on Piers and Beams)

Real Property Damage

- Example 4 (cont'd)

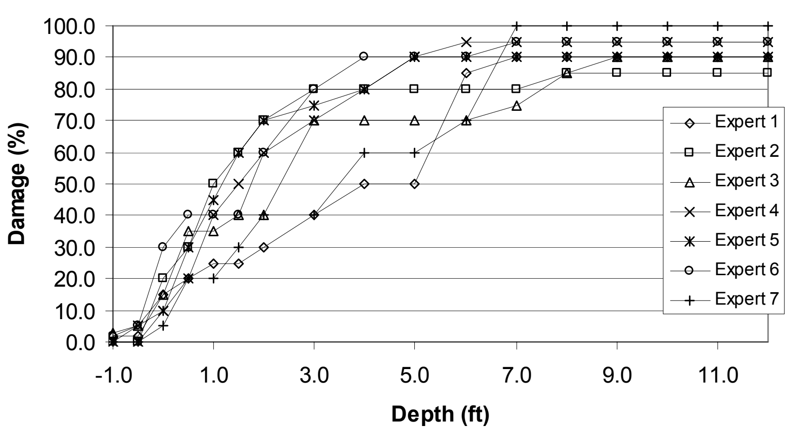

Figure 9b. Aggregated (as Percentiles) Percent Damage to Contents of Type 1 and 2 Residential Structures (One-Story on Slab or One Story on Piers and Beams)

Real Property Damage

- Example 4 (cont'd)

Table 7. Summary of Supportive Reasoning and Assumptions by Experts for Content to Structure Value Ratio

Houses Types 1, 2 and 3
As a guide, the insurance industry uses 70% ratio for the content to structure value Median house value of $90,000 with land Median land value of $20,000 Garage or shed contents are included Median content age of 8 years Use depreciated replacement value of structure and contents Insufficient time to remove (i.e. protect) contents

Table 8. Value of Residential Structures, Contents and Their Ratios (CSVR) for Types 1 and 2 Houses (One-Story on Slab or One-Story on Piers and Beams

	Initial Estimate: % Damage by Expert							Aggregated Opinions				
Issue	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Min**	**25%**	**50%**	**75%**	**Max**
Median Structure (K$)												
Low	70.0	70.0	65.0	50.0	60.0	50.0	40.0	40.0	50.0	60.0	67.5	70.0
Best	90.0	110.0	106.0	70.0	70.0	60.0	70.0	60.0	70.0	70.0	98.0	110.0
High	110.0	250.0	175.0	90.0	80.0	80.0	90.0	80.0	85.0	90.0	142.5	250.0
Median Content (K$)												
Low	35.0	49.0	35.0	25.0	35.0	15.0	10.0	10.0	20.0	35.0	35.0	49.0
Best	50.0	77.0	41.0	50.0	40.0	20.0	20.0	20.0	30.0	41.0	50.0	77.0
High	65.0	175.0	70.0	80.0	45.0	25.0	25.0	25.0	35.0	65.0	75.0	175.0
CSVR												
Low	0.50	0.70	0.54	0.50	0.58	0.30	0.25	0.25	0.40	0.58	0.52	0.70
Best	0.56	0.70	0.39	0.71	0.57	0.33	0.29	0.33	0.43	0.59	0.51	0.70
High	0.59	0.70	0.40	0.89	0.56	0.31	0.28	0.31	0.41	0.72	0.53	0.70

	Revised Estimate: % Damage by Expert							Aggregated Opinions				
Issue	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Min**	**25%**	**50%**	**75%**	**Max**
Median Structure (K$)												
Low	70.0	70.0	77.0	50.0	60.0	50.0	50.0	50.0	50.0	60.0	70.0	77.0
Best	90.0	80.0	82.0	70.0	70.0	60.0	70.0	60.0	70.0	70.0	81.0	90.0
High	110.0	90.0	94.0	90.0	80.0	75.0	90.0	75.0	85.0	90.0	92.0	110.0
Median Content (K$)												
Low	35.0	49.0	40.0	25.0	35.0	15.0	10.0	10.0	20.0	35.0	37.5	49.0
Best	50.0	50.0	42.0	50.0	40.0	20.0	20.0	20.0	30.0	42.0	50.0	50.0
High	65.0	51.0	50.0	80.0	45.0	25.0	30.0	25.0	37.5	50.0	58.0	80.0
CSVR												
Low	0.50	0.70	0.52	0.50	0.58	0.30	0.20	0.20	0.40	0.50	0.55	0.70
Best	0.56	0.63	0.51	0.71	0.57	0.33	0.29	0.29	0.42	0.56	0.60	0.71
High	0.59	0.57	0.53	0.89	0.56	0.33	0.33	0.33	0.43	0.56	0.58	0.89
Confidence	High	High	Medium	High	High	High	High					

Real Property Damage

- Example 4 (cont'd)

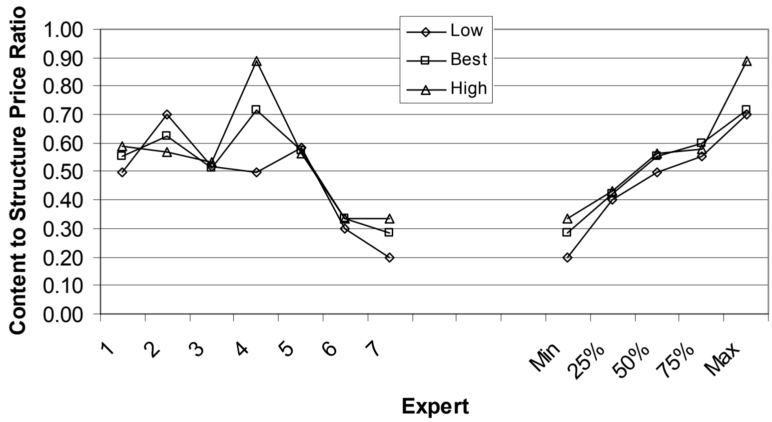

Figure 10. Content-to-Structure Value Ratios (CSVRs) for Types 1 and 2 Houses (One-Story on Slab or One-Story on Piers and Beams)

Real Property Damage

- Example 4 (cont'd)

Table 9. Summary of Supportive Reasoning and Assumptions by Experts for Vehicle Damage

Vehicles Types 1 and 2
Median vehicle age of 5 years Percentages are of depreciated replacement value of vehicles Flood without flow velocity Several days of flood duration Flood water is not contaminated, but has sediment without large debris Allow for cleanup cost

Table 10. Percent Damage to a Type 1 Vehicle (Sedans)

Depth	Initial Estimate: % Damage by Expert 1	2	3	4	5	6	7	Aggregated Opinions Min	25%	50%	75%	Max
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	5.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	5.0
1.0	20.0	0.0	30.0	10.0	25.0	5.0	10.0	0.0	7.5	10.0	22.5	30.0
1.5	25.0	0.0	50.0	15.0	25.0	15.0	50.0	0.0	15.0	25.0	37.5	50.0
2.0	35.0	30.0	80.0	20.0	30.0	20.0	60.0	20.0	25.0	30.0	47.5	80.0
2.5	50.0	35.0	100.0	40.0	70.0	40.0	70.0	35.0	40.0	50.0	70.0	100.0
3.0	60.0	40.0	100.0	50.0	70.0	60.0	90.0	40.0	55.0	60.0	80.0	100.0
4.0	100.0	40.0	100.0	100.0	80.0	80.0	100.0	40.0	80.0	100.0	100.0	100.0
5.0	100.0	50.0	100.0	100.0	95.0	80.0	100.0	50.0	87.5	100.0	100.0	100.0

Depth	Revised Estimate: % Damage by Expert 1	2	3	4	5	6	7	Aggregated Opinions Min	25%	50%	75%	Max
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	10.0	0.0	5.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	3.5	10.0
1.0	25.0	10.0	20.0	20.0	20.0	10.0	20.0	10.0	15.0	20.0	20.0	25.0
1.5	35.0	30.0	50.0	25.0	25.0	40.0	30.0	25.0	27.5	30.0	37.5	50.0
2.0	40.0	40.0	80.0	30.0	30.0	50.0	50.0	30.0	35.0	40.0	50.0	80.0
2.5	50.0	50.0	100.0	40.0	60.0	60.0	70.0	40.0	50.0	60.0	65.0	100.0
3.0	60.0	100.0	100.0	50.0	70.0	80.0	80.0	50.0	65.0	80.0	90.0	100.0
4.0	100.0	100.0	100.0	100.0	100.0	80.0	100.0	80.0	100.0	100.0	100.0	100.0
5.0	100.0	100.0	100.0	100.0	100.0	80.0	100.0	80.0	100.0	100.0	100.0	100.0
Confidence	High	High	High	High	High	Mediur	High					

Real Property Damage

- Example 4 (cont'd)

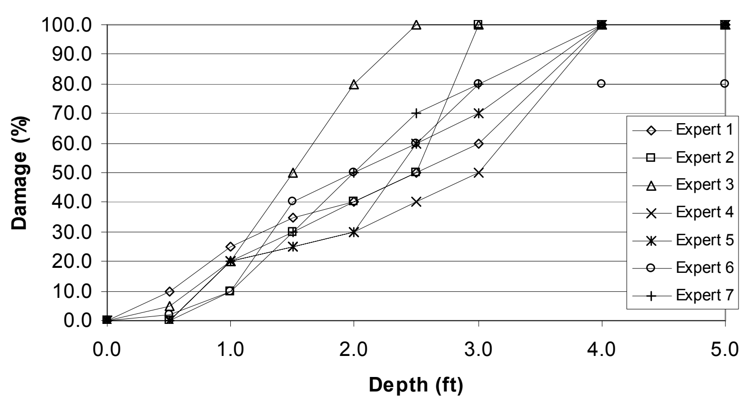

Figure 11a. Percent Damage to a Type 1 Vehicle (Sedans)

Real Property Damage

- Example 4 (cont'd)

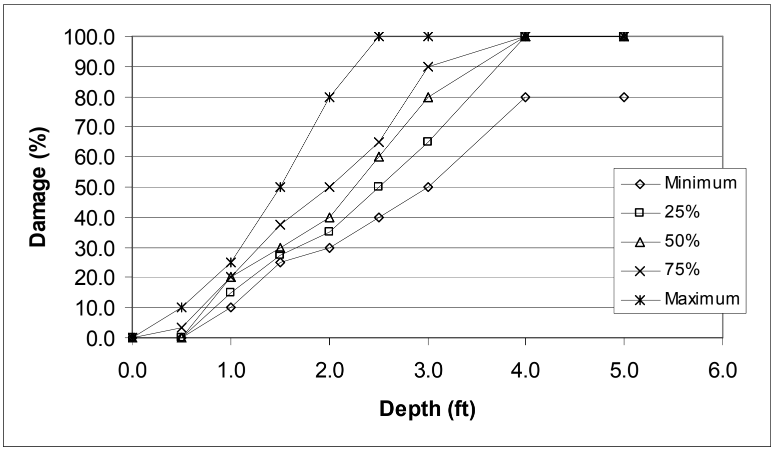

Figure 11b. Aggregated Percent Damage to a Type 1 Vehicle (Sedans)

Loss of Human Life

- Failures sometimes lead to human life loss
- Designing systems often requires tradeoff analyses to maximize benefits to society including reducing human life loss likelihood.
- The value of life (VOL) enters in these analyses often in an implicit manner.
- The value-of-life can be viewed as a statistical value, not necessarily values associated with identified lives

Loss of Human Life

- Benefit-cost analyses require assessing health consequences of exposure or accidents expressed in units that can be compared with other damages and with the cost of potential safety enhancements for reducing human life loss likelihood.
- These analyses imply assigning a monetary value to human injuries and fatalities requiring societal judgments about the statistical value of life (SVOL).

Loss of Human Life

- The difference between the VOL and SVOL
  – The **VOL** is based on analytical methods, such as the willingness-to-pay method.
  – The **SVOL** is based on assessing the implicit value using data, such as premiums paid to workers at risky occupations and for insurance, and statistics using humans as an economic capital.

Loss of Human Life

- Willingness-to-Pay Method
  - The willingness-to-pay (WTP) method results in a statistical quantity based on the WTP of a group of people to reduce the probability of death or injury.
  - The WTP method essentially involves asking a sample of individuals from a population of interest how much they would be willing to pay for an increase in safety, or would require in compensation for an increase in risk of a given type.

Loss of Human Life

- Willingness-to-Pay Method (cont'd)
  - Example:

    if a population of 100,000 persons was willing to pay an average of $50 each to reduce deaths from 4 per 100,000 to 2 per 100,000, the total WTP can be computed as $5 million and the value per statistical life will be $2.5 million since two lives can be saved.
  - The WTP approach yields a substantially higher VOL than does other approaches.

Loss of Human Life

- Willingness-to-Pay Method (cont'd)
  - An individual's willingness-to-pay for safety is estimated, and aggregated over all the affected individuals.
  - Economists appear to favor willingness-to-pay (WTP) because it theoretically reflects a person's real value of safety.
  - This method is also compatible with the notion that, if there were a market for "buying" safety, this approach would yield the price that consumers would be willing to pay.

Loss of Human Life

- Human Capital Method
  - The human capital (HC) method assesses the loss in earnings or earnings not collected through injury or death.
  - The result from this method is age-specific, and many economists consider it to be based on dubious logic because it ignores the individuals desire to live.
  - The WTP method recognizes an individual's desire to live longer.

Loss of Human Life

- Human Capital Method (cont'd)
  - In the case of workers, particularly in jobs with greater risks, a wage-risk approach might make sense.
  - Example:

    two jobs, A and B, are similar except that A has one more job-related death per year for every 10,000 workers than does B. The workers in job A earn $500 more per year than the workers in job B, or $5 million for the 10,000 workers. The value of life of workers in job B who are willing to forgo the money for the lower risk is $5 million.

Loss of Human Life

- Human Capital Method (cont'd)
  - The HC method is based on a national output maximization notion.
  - The cost of an incident that results in fatality, illness or injury, is estimated to be the discounted present value of the loss of a person's future output, i.e., earnings, due to the incident.
  - Allowances typically are made for non-marketed output, e.g., by housewives, and various other costs, such as medical and legal expenses.

Loss of Human Life

- Human Capital Method (cont'd)
  - The HC method offers simplicity and straightforwardness by estimating the discounted present value of future output.
  - On the other hand, the WTP method offers a conceptually compatible and complete economic measure by assessing the premium that people put on pain, grief, and suffering than merely evaluating lost output or income.
  - The WTP method enables analysts to ask those directly affected by a problem what they consider to be the value of safety.

Loss of Human Life

- Human Capital Method (cont'd)
  - In asking such questions, analysts might be faced with the difficulty of ensure that both the scope and content of the questions are understandable.
  - The advantages and disadvantages of each method do not produce a preferred one with an overwhelming preponderance of evidence.
  - Although in recent years, the WTP method has gained popularity among risk analysts and economists.

Loss of Human Life

- Typical Human Life Values
  - Studies on estimating the statistical value of life produced large variations depending on data sources, methodologies used, and assumption made.
  - A recent compilation of the data in 1990 dollars resulted in the following values based on willingness to pay concepts: 0.8, 0.9, 1.4, 1.5, 1.6, 1.6, 2, 2.4, 2.4, 2.6, 2.6, 2.8, 2.9, 3, 4.1, 4.6, 5.2, 6.5, 9.7, and 10.3 in millions of 1990 dollars.

Loss of Human Life

- Typical Human Life Values (cont'd)
  - The median is 2.6 millions.
  - A histogram of the value of life based on these 20 values is shown in Figure 12.
  - Statistical values of life reported in transportation studies were examined and converted to 1990 dollars for cases with sufficient information for this conversion.
  - Costa related to transportation accident reductions yielded SVOL values below 1M in 1990 dollars.

Loss of Human Life

- Typical Human Life Values (cont'd)

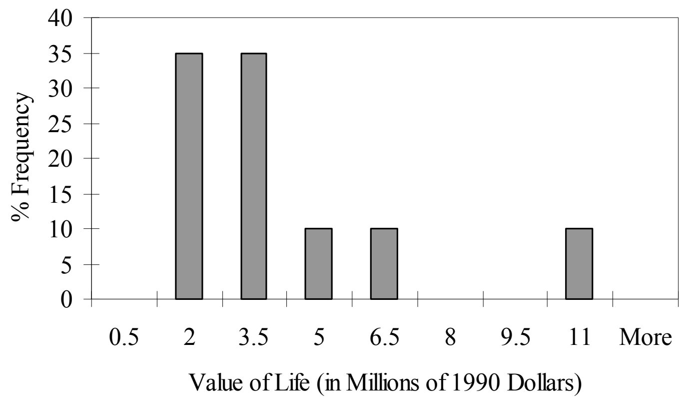

Figure 12. Statistical Value of Life in Wage-Risk Studies Based on the Willingness to Pay Method

Loss of Human Life

- Typical Human Life Values (cont'd)
  - The values ranged from \$50,000 to \$29,000,000, with a median of \$312,000.
  - Transportation studies have used \$1,400,000 (in 1990 dollars).
  - These variation reflect society's acceptance of risk depending on its source.
  - A histogram of the value of life based on these available values is shown in Figure 13.

Loss of Human Life

- Typical Human Life Values (cont'd)

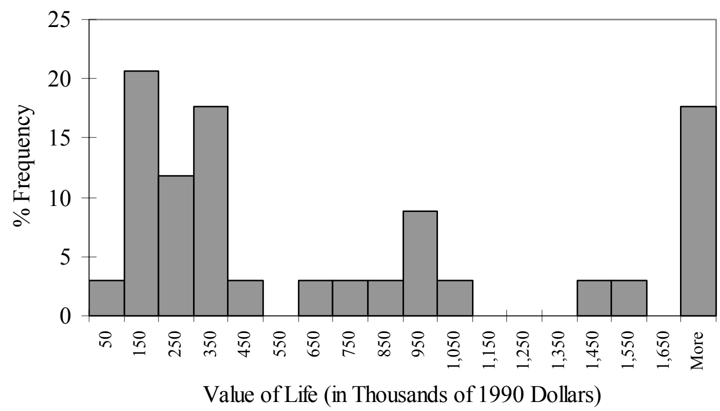

Figure 13. Statistical Value of Life (SVOL)