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The John A. Blume Earthquake Engineering Center

Department of Civil Engineering
Stanford University

PRIORITIZATION OF BRIDGES FOR SEISMIC RETOFITTING

by
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and
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Vulnerability assessment includes evaluation of the seismic hazard at the bridge site, classification of existing bridges into bridge classes and fragility analysis. Vulnerability is expressed as a function of seismicity in order to capture the direct effect of ground motion on damage. New bridge classes are defined based on the proposition that bridges with similar structural characteristics will experience similar damage under a given seismic loading. An expert system is developed to classify bridges into bridge classes. The need for the development of fragility curves for each bridge class is emphasized.

Importance assessment considers the attributes that relate the consequences of failure of a bridge to the public safety and socio-economic well-being of a community. The importance of a bridge is conceived to be closely related to its function within the transportation network system. Network analysis is used to evaluate the emergency response factor that assesses the impact of disruption of the available routes or the time delays due to destroyed components after an earthquake. A value model is developed to properly determine the multi-attribute importance criterion that depends on the decision maker and his or her objectives. The developed value model is also used to integrate the vulnerability and importance criteria.

A detailed review and critique of the existing prioritization methodologies is included. The developed methodology is illustrated by an example application conducted for the Palo Alto, California area.

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CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Bridges are critical components in transportation systems. Damage to bridges from earthquakes can be particularly disruptive since repair time can be lengthy and rerouting of traffic can be difficult. The potential deficiency in existing bridges, and the need to mitigate seismic hazard for these structures has become more evident during the recent earthquakes. For example, the 1971 San Fernando Earthquake caused substantial damage to then recent bridge construction and exposed a number of deficiencies in bridge design specifications in force at that time. This has led to modifications in bridge design specifications and to research programs to develop specific seismic design guidelines for bridges. Bridges designed to pre-1971 design specified force levels by Caltrans or AASHTO performed very poorly during the 1987 Whittier Narrows and 1989 Loma Prieta Earthquakes. In spite of the few bridges that have collapsed or had severe damage, the majority of bridges performed well in the most recent 1994 Northridge Earthquake demonstrating the improvements in seismic design and retrofitting schemes for bridges within the last two decades.

The vulnerability of bridges as evidenced in recent earthquakes emphasizes the importance of mitigating the possible risk and consequences of seismic damage of existing bridges. As a first step towards the mitigation of bridge failures, it is necessary to assess the *vulnerability*, i.e., the damage potential of existing bridges subjected to future earthquakes, and the *importance*, i.e., the socio-economic impact of the failure to a community. Retrofitting of existing bridges is one approach for mitigating seismic risk. The method presented in this report focuses on seismic retrofitting as a means of mitigating seismic hazard. Alternatives of seismic hazard mitigation for bridges include: (a) complete replacement of old bridges with new ones that are designed to current seismic criteria; and (b) closure of the bridge to traffic. Usually, retrofitting is the selected alternative unless the bridge is assessed to be deficient also under regular loading conditions such as daily traffic.

Seismic retrofitting and upgrading to current design codes of all bridges that are in need of repair is difficult and extremely costly. Furthermore, a detailed seismic risk evaluation of every bridge in a large highway network for the purposes of seismic vulnerability assessment is very time consuming. Thus, retrofitting and upgrading decisions under limited resources require that the ensemble of existing bridges be ranked in the order of decreasing vulnerability and importance. Prioritization methods contemplating these issues need to be developed to identify and rank the bridges that are in need of retrofitting.

1.2 OBJECTIVE AND SCOPE

The objective of this research is to develop a prioritization method that identifies the high risk bridges for seismic retrofitting purposes. The developed prioritization method is to be used for the formulation and implementation of a retrofitting program that optimally reduces the risk of seismic damage to bridges under limited resources.

The intent of this research is to develop a general methodology that can be applied to any state within the country. In order to demonstrate the methodology, bridge data from California will be used. Due to differences in seismic activity of the region, bridge design standards or the bridge inventory, the details of the methodology might need to be adjusted for states other than California. However, the main framework of the methodology is applicable to any region.

The resulting ranking is intended to be at the screening level. Since the analytical models that are used at any stage of the prioritization scheme are not detailed, a more extensive analysis will be necessary for the bridges that are identified as candidates for seismic retrofitting.

The methodology developed under this project considers seismic forces as the primary hazard to bridges. The overall methodology is independent of the source of hazard and can be used for prioritization purposes for hazards such as extreme wind forces, ship collision or floods. The implementation of other hazards requires that the specific hazard be modeled and the hazard damage relationships be described.

Although the highway bridges are the focus of the presented method, railway bridges, other critical structures or components of any lifeline system can be considered for prioritization purposes with small adjustments for vulnerability assessment.

1.3 ORGANIZATION OF THE REPORT

This report presents the methodology for prioritization of bridges for seismic retrofitting. Chapter 2 gives a detailed review of existing prioritization methods and identifies the limitations in these methods. Examples of ranking using some of these methods are illustrated. Chapter 3 introduces the conceptual approach, centering on vulnerability and importance as the main criteria. The components of both vulnerability and importance are defined and the tools that are necessary in analyses are identified. The relationship between vulnerability and importance and their different components are outlined.

Chapters 4 and 5 discuss the vulnerability criterion and the methods for vulnerability assessment. In Chapter 4 classification of bridges for vulnerability assessment and new bridge class definitions are described. Data manipulation techniques are briefly presented and the outline of the developed expert system - **ESCOB** - is given. Chapter 5 summarizes the steps of the vulnerability assessment which includes seismic hazard analysis at the bridge site and fragility analysis. Tools that are used in each of the stages are also discussed in that chapter.

Chapter 6 presents the importance assessment particularly for emergency response purposes. Lifeline network analysis conducted for the transportation system's connectivity is explained. The multi-attribute utility theory is discussed in relation to the developed utility functions for the importance attributes.

An application of the developed method is presented in Chapter 7. The Palo Alto, California area is used for the application. Chapter 8 gives a summary of the work presented in this report and makes recommendations for future work.

CHAPTER 2

REVIEW OF THE CURRENT APPROACHES

In order to insure the availability of a transportation system immediately after an earthquake and for long term economic recovery, many states in the United States are currently in the process of prioritizing bridges in their states. The two most widely used systems for bridge prioritization utilized in this country are those developed by the California Department of Transportation (Caltrans) (Maroney, 1990; Maroney and Gates, 1990) and the Applied Technology Council (ATC-6-2, 1983). Two other systems have been developed in recent years: the methodology used by the Illinois Department of Transportation (Woodward Clyde Consultants, 1991) and the methodology that is used by the Washington State Department of Transportation (Babaei and Hawkins, 1991; 1993). In the following subsections each of these methodologies is briefly reviewed.

2.1 CALTRANS APPROACH

2.1.1 Objectives of the Caltrans Approach

Caltrans has followed the philosophy to first retrofit those structures which are of greatest risk and are most vital for the functionality of the transportation system. The ultimate goal in their approach is to insure that all of the bridges in the state of California are capable of surviving the maximum credible earthquake. The approach is developed under the premise that some structural damage is inevitable but collapse must be prevented by proper retrofitting. In the case of lifeline structures, the structure should be made to withstand the maximum level earthquake with only minor damage and should remain in service following the event. The main goal of this prioritization approach is to identify the structures most susceptible to collapse during a large earthquake (Sheng and Gilbert, 1991).

The prioritization scheme utilized by Caltrans is based on a *level one* risk analysis procedure. Level one risk analysis offers a procedure to consistently apply expert knowledge gained from past earthquakes and bridge characteristics. This analysis replaces the massive data supported by statistical distributions by judgment and can be applied quickly to a decision making process. The level one analysis used can be summarized as follows (Roberts, 1991):

1) Identify major faults with high event probabilities (priority one faults),

2) Develop attenuation relationships at faults identified at step 1,
3) Define the minimum ground acceleration capable of causing severe damage to bridge structure,
4) Identify all the bridges within high risk zones defined by the attenuation model of step 2 and the critical acceleration boundary of step 3,
5) Prioritize the bridges at risk by summing weighted bridge structural and transportational characteristic scores.

The last step constitutes the process used to prioritize the bridges within the high risk zones to establish the order of bridges to be investigated for retrofitting.

2.1.2 Attributes of the Risk Algorithm

The attributes used in the risk algorithm are as follows:

- bedrock acceleration,
- soil conditions,
- number and type of hinges,
- column design (single or multiple bents),
- height,
- skew,
- length of the bridge,
- abutment type,
- year of construction (relates to confinement details of column),
- traffic exposure (average daily traffic),
- facilities crossed,
- route type (major and minor), and
- detour length.

2.1.3 Risk Analysis Algorithm

The risk analysis algorithm calculates a weighted risk number ranging between 0 and 1. Numbers close to 0 reflect relatively low levels of risk and numbers close to 1 reflect relatively high levels of risk, i.e., high risk due to structural characteristics or high cost of loss due to transportation characteristics. The risk number is defined as the summation of the product of the assigned weight and preweight score of each attribute given as follows:

$$\textit{Risk Number} = \sum_{i=1}^{n} [(weight_i) * (preweight_i)] \tag{2.1}$$

The preweight score of each attribute i, is assigned a value between 0 and 1 with increasing risk level. In general, preweight scores are developed using engineering judgment considering available data, its form, and engineering/mechanical relationships between the particular characteristics and typical structural or transportation system responses. Scores for skew, height, traffic exposure and detour attributes are obtained through the following preweight equations:

$$Preweight_{(skew)} = \frac{1.0}{(90)^2} (x) \tag{2.2}$$

where x = Skew in degrees. Any skew over 90 degrees receives a preweight score of 1.0.

$$Preweight_{(height)} = 1.0 - \frac{1.0}{(30)^3} \times (30 - x)^3 \tag{2.3}$$

where x = Column height in feet. Any column height over 30 feet receives a preweight score of 1.0.

$$Preweight_{(traffic\ exposure)} = 1.0 - \frac{1.0}{(2 \times 10^8)^2} (x - 2 \times 10^8)^2 \tag{2.4}$$

where x = (*average daily traffic* * *length*). The average daily traffic is measured in vehicles/day and the length is measured in feet. Any x value over ($2x10^8$) receives a preweight score of 1.0.

$$Preweight_{(detour)} = \frac{1.0}{100} x \tag{2.5}$$

where x = Detour length in miles.

2.1.4 Long Term Risk Algorithm

A long term risk algorithm for bridges is also considered by the Caltrans Seismic Advisory Board. However, this model is currently in a conceptual form. In this model the risk number is defined as the multiplication of the weighted factors for the main three categories listed below:

- *Seismicity (load factor)* - considers the level of ground motion at each bridge site. The ground motion level is a function of the source, the distance and the soil conditions along the wave path in an event (Maroney, 1991). Maximum credible peak bedrock acceleration levels are used as ground motion levels.

- *Importance (social factor)* - reflects the transportation characteristics which determine the value of what is at risk in a large earthquake.

- *Vulnerability (structural factor)* - reflects the seismic performance of a structure.

The macro-components are functions of other attributes defined as micro-components. Table 2.1 lists the macro- and micro-components. Each micro-component is assigned a preweight component score x_{ij} based on the site and structure characteristics. Each of the micro-components for a given macro-component are multiplied by a weighting factor $weight_{ij}$. This weighting factor expresses the relative importance of each micro-component to the others for the given macro-component. The load factor is modified by the probable occurrence coefficient associated with the threatening fault to get the unweighted factor. The sum of the product of x_{ij} and $weight_{ij}$ gives the unweighted factor. Then the weighted factor is calculated as a product of the unweighted factor and a global load weight, $global\ weight_j$. The global load weight is used to express the relative importance of each of the macro-components. The expression for risk is given below:

$$Risk = \prod_{j=1}^{3} \{[\sum_{i=1}^{n} (x_{ij} \times weight_{ij})] \times (global\ weight_j)\} \qquad (2.6)$$

where n = Number of attributes.

Macro-components	Micro-components
Load Factor	Magnitude, acceleration Duration (long, intermediate, short) Soil at site (high risk, not high risk)
Structural Factor	Number of hinges Year of construction Number of columns per bent Outrigger, etc.
Social Factor	On lifeline Multi-level Average daily traffic Route type Miles to detour, etc.

Table 2.1 Macro- and Micro-Components of the Risk Factor

2.2 ATC APPROACH

2.2.1 Objectives of the ATC Approach

The provisions ATC-6-2 apply only to bridges with the following characteristics:

- conventional steel and concrete,
- girder and box girder construction,
- with spans not exceeding 500 ft.

Suspension bridges, cable-stayed bridges, arch type and movable bridges are *not* covered by these provisions.

The first major step of the seismic retrofitting process in ATC-6-2 provisions is preliminary screening. The preliminary screening process is followed by a quantitative evaluation of seismic capacity and overall effectiveness of retrofit measures and the identification of retrofit measures and design requirements for increasing the seismic resistance of existing bridges. Preliminary screening identifies and rates the bridges according to their need for seismic retrofitting. Bridges high on the list are recommended for further investigations to determine the benefits of retrofitting. However, as the final decision for retrofitting depends on political, social and economic factors as well as engineering issues, high priority bridges may not necessarily be retrofitted whereas bridges with a lower priority may need to be retrofitted immediately.

2.2.2 Seismic Rating System

The *Seismic Rating System* is used as a basis in selecting bridges for more detailed quantitative evaluation. This rating system considers only the technical aspects of the problem and does not include administrative, economic or political considerations.

Bridges are classified according to Seismic Performance Categories (SPC). SPC's as given in Table 2.2, are based on the acceleration coefficient and the importance classification (Table 2.3) of the bridge. Further screening of bridges that fall in SPC-C and SPC-D is compulsory whereas it is optional for bridges in SPC-B and not necessary for those in SPC-A.

Acceleration Coefficient (A)	Importance Classification I	Importance Classification II
$A \leq 0.09$	A	A
$0.09 \leq A \leq 0.19$	B	B
$0.19 \leq A \leq 0.29$	C	C
$0.29 \leq A$	D	C

Table 2.2 Seismic Performance Category (SPC) (from ATC-6-2)

Importance Classification (IC)	Types of Bridges
I	Essential Bridges; those that must continue functioning after an earthquake. These bridges are essential based on Social/Survival and Security/Defense requirements.
II	All other bridges

Table 2.3 Importance Classification (from ATC-6-1)

The three major variables considered in seismic retrofitting are:

- the vulnerability of the structural system,
- seismicity of the bridge site, and
- the importance of the bridge.

The proposed Seismic Rating System addresses each of these variables separately by requiring that vulnerability, seismicity and importance ratings be calculated for each bridge. These individual ratings are combined to arrive at an overall seismic rating as follows:

$$\textbf{\textit{Seismic Rating}} = \sum_i [(\textbf{\textit{Rating}}_i \times \textbf{\textit{weight}}_i)] \tag{2.7}$$

where i = Variable that represents vulnerability, seismicity and importance.

($Rating_i$) ranges between 0 and 10. The higher the seismic rating score, the greater the need for the bridge to be evaluated for seismic retrofitting.

Vulnerability Rating: It has been observed from the past earthquakes that the most vulnerable bridge components to damage are the bearings; columns, piers and footings; abutments; and foundations when susceptible to liquefaction. Among these, the bearings can be most economically retrofitted. For this reason the vulnerability rating to be used in the seismic rating system is determined by examining the bearings separately from the remainder of the structure. The vulnerability rating for the remainder of the structure is determined as the maximum of the vulnerability ratings for any of the components; columns, piers, footings and abutments, and the vulnerability rating for ground liquefaction. Table 2.4 gives the elements of the vulnerability ratings for each of these components. Separate vulnerability ratings between 0 and 10 are assigned for both bearings and the remainder of the structure. The overall vulnerability rating of the bridge is taken as the larger of the two vulnerability ratings. The detailed vulnerability ratings for each component is given in (ATC-6-2, 1983).

Seismicity Rating: Seismicity Rating is taken as 25 times A where A is the acceleration taken from the Acceleration Coefficients Maps (ATC-3, 1978) which reflect the level of expected seismic activity in the United States.

Importance Rating: Importance Rating is based on the Importance Classification, IC, of the bridge given in Table 2.3. The relative importance of bridges within each importance classification are assigned by considering the following attributes:

- the average daily traffic on or under the bridge,
- length and width of the bridge,
- detour length, function of bridge following a major earthquake, i.e., being on a lifeline network in a short term emergency case and involvement of other lifeline utilities.

The importance rating varies from 0 to 10, depending on the relative importance of the structure within each of the Importance Classifications as shown in Table 2.5.

Components	**Factors Affecting Vulnerability Rating**
Bearings	support skewness bearing type support length
Columns, piers, footings	shear and flexural capacity as a function of effective column length, column bent type, reinforcement percentage transverse and longitudinal reinforcement skewness
Abutments	settlement of the fill at the abutment skewness type of abutment
Foundations (liquefaction)	soil conditions magnitude of the acceleration coefficient discontinuity of the superstructure skewness redundancy

Table 2.4 Factors Affecting the Vulnerability Rating for the Most Vulnerable Bridge Components

Importance Classification (IC)	Importance Rating (IR)
I	6-10 points
II	0-5 points

Table 2.5 Importance Rating (from ATC-6-2)

2.3 ILLINOIS DEPARTMENT OF TRANSPORTATION (IDOT) APPROACH

2.3.1 Objectives of the IDOT Approach

The objective of the Illinois Department of Transportation (IDOT) method is to rank bridges on the basis of their seismic risk. The bridges that are candidates for a detailed seismic evaluation and potential retrofitting are ranked higher. IDOT uses a risk-based method to efficiently screen a large number of bridges in a given transportation network. Risk is expressed as the product of two components:

- *the probability of failure of a bridge*, obtained by combining the probability of occurrence of different levels of ground motion and the probability of failure for each of these levels, and

- *consequences of such a failure*, evaluated by developing a multi-attribute value function which is calibrated using acceptable tradeoffs among different measures of impacts of failure. These tradeoffs are assessed by formally eliciting value judgments of decision makers and/or their representatives.

The output of the method is a priority score for each bridge. Bridges are ranked in descending order of their priority score. Bridges above a certain priority score are then selected for more detailed evaluation.

2.3.2 Two Stage Approach

A two stage approach is adapted to achieve an evaluation of bridges that would be sufficiently detailed to provide useful results, in a reasonable amount of time. The first one is a screening stage providing a preliminary ranked list of all bridges. A more detailed evaluation is performed in stage two.

Structural rating procedure of prioritizing bridges for retrofitting used in this approach investigates those features and components of bridges which have contributed to bridge failures in the past earthquakes. Many of the concepts are subjective.

2.3.2.1 Screening Stage

This stage of the analysis uses readily available information, such as seismicity catalogs, statewide soil maps and the National Bridge Inventory System (NBIS), to rapidly evaluate priorities of individual bridges in a given highway system. Seismic risk is defined as the expected consequences of the failure of a bridge caused by a seismic event as given in equation (2.8).

$$\textbf{\textit{Risk}} = \textbf{\textit{Probability of Failure}} * \textbf{\textit{Consequences of Failure}} \tag{2.8}$$

A separate risk equation is used for bridge ranking as follows:

$$\textbf{\textit{Bridge Score}} = \textbf{\textit{Bridge Vulnerability Factor}} * \textbf{\textit{Importance Factor}} \tag{2.9}$$

The relative risks for the bridges are examined and bridges with relatively high risk are identified to be analyzed in the next stage. The NBIS database for Illinois used for this stage did not have sufficient structural information for all the bridges. For this reason, all the bridges are assumed to have equal vulnerability with a Structural Rating of 100 resulting in a ranking due to only importance factor.

<u>2.3.2.1.a) Evaluation of Probability of Failure:</u> The evaluation of probability of failure due to seismic loading involves the following steps:

1) *Probabilistic characterization of seismic hazard.* This step includes the identification of seismic sources, characterization of seismic sources, characterization of ground motion attenuation and calculation of seismic hazard as the four basic elements of a probabilistic model. Probability of exceedance (seismic hazard) curves for the state of Illinois are developed in this step.

2) *Probabilistic evaluation of structural failure*. The structure failure depends on:

- the level of ground motion to which the structure is subjected; and
- the structural vulnerability of the bridge.

This approach requires the development of *fragility curves*. Fragility curves provide the relationship between ground motion levels and probability of structural failure or damage of a bridge. These relationships depend on the structural vulnerability of different bridges. In their method, structural details that are vulnerable to seismic loading hence require particular attention in vulnerability assessment include bearings and column details, and overall structural system. Structural vulnerability is assessed in terms of Structural Rating on a scale of 0 to 100 where 0 corresponds to no structural vulnerability and 100 corresponds to the highest structural vulnerability.

3) *Probabilistic evaluation of ground failure*. The ground failures included in the evaluation are liquefaction, slope failure and fault rupture. However, fault rupture is excluded from the application to the state of Illinois since sucn an event has never been experienced in the history of the state. The primary ground failure is considered to be liquefaction. Fragility curves for liquefaction potential are developed in this step.

4) *Synthesis of information*. In this step the information from the first three steps is combined to obtain a risk index for each individual bridge. The following equation is used to compute the risk index that is defined as the probability of failure:

$$P[overall\ failure] = P[structural\ failure] + P[ground\ failure] - P[structural\ and\ ground\ failure] \tag{2.10}$$

Structural failure and ground failure are assumed to be conditionally independent for a given level of ground motion. Thus the joint probability of structural and ground failure is obtained as follows:

$$P[structural\ and\ ground\ failure] = \sum_i P[structural\ failure \mid a_i] * P[ground\ failure \mid a_i] * P[a_i] \tag{2.11}$$

Equation (2.11) is used in the evaluation of the probability of overall bridge failure defined by equation (2.10).

A *Structural Vulnerability Factor* (SVF) is defined as the product of structural fragility and ground motion hazard for each bridge. A *Ground Vulnerability Factor* (GVF) is developed as a function of liquefaction potential, soil amplification and expected bedrock acceleration at site. This factor is obtained as a product of liquefaction fragility and seismic hazard. *Bridge Vulnerability Factor* (BVF) is defined as the combination of the SVF and GVF.

2.3.2.1.b) Evaluation of Consequences of Failure: Measurable value functions are used in determining multi-dimensional consequences of failures as they provide a consistent and rational procedure to evaluate impacts of multiple and diverse factors on a common scale. A value function is developed over multiple measures of impacts termed attributes. Thus, an attribute is a measure of the impact on a given factor. The value function is commonly scaled from 0 to 1 with the higher numbers indicating greater consequences of failure.

The process of developing a multi-attribute function can be summarized as follows:

1) *Define relative attributes.* The attributes defined for evaluating bridge priorities are given as follows:

- Number of vehicles directly impacted,
- Emergency route classification,
- Defense route classification,
- Vehicle-miles of detour and
- Classification of utilities.

Since the repair cost can not be estimated without more detailed evaluation, cost of repairing the bridge is not included. In addition, repair cost estimation is out of their analysis scope where the objective is to assess priority ranking based only on risk potential.

2) *Determine the general preference of structure.* A value function that can be used to calculate an index of the overall consequences of failure is developed. The value function expressed in terms of the attributes is given below:

$$v[x_1, x_2, \ldots, x_n] = \sum_{i=1}^{n} k_i v_i(x_i) \qquad (2.12)$$

where v_i = Single-attribute measurable value function scaled from 0 to 1,

k_i = Scaling constant each scaled from 0 to 1 and

x_i = Attribute i.

3) *Assess single-attribute value functions.* Single-attribute value functions are assessed by expert opinion surveys. A single-attribute value function assigns a relative impact values to different levels of the attribute x_i. For continuous attributes linear and exponential functions are the common forms of the single-attribute value functions. For discrete attributes, the impact values of different levels of the attribute may be assessed directly. Interviews with five representatives of IDOT are conducted to develop the specific functions and levels for each of the selected attributes.

4) *Evaluate scaling constants.* The scaling constants in the multi-attribute value function indicate the relative importance of the different attributes in assessing the overall impact value. The necessary scaling functions are calculated using value tradeoffs between pairs of attributes. These tradeoffs are assessed by the five representatives of IDOT.

5) *Checking for consistency and reiterating.* The consistency of the value model is assessed by examining the consequence values calculated for bridges with different attributes.

2.3.2.2 Detailed Evaluation Stage

The second stage of the analysis requires the collection of additional data such as structural details, data from the boring logs for the bridge site and utilities on the bridge. By processing additional information in combination with the available data, a better assessment of the probability of failure and consequences of such a failure for ranking purposes will be achieved. The additional information for different ratings in the second stage include the following:

- Geometry, stiffness and mass for *Bridge Geometry Rating*,
- Bridge geometry, superstructure continuity, bearings, seat widths and configurations for *Superstructure Rating*,
- Bridge geometry, intermediate support type and configuration, column details for *Substructure Rating.*

A spreadsheet-based computer program is developed which recalculates the bridge scores and reranks the bridges. The procedures used in stage one to prioritize bridges is repeated in stage two. However, in stage two additional information is used for the refinement of the information about soil at bridge site and structural vulnerability. Therefore, the BVF is refined based on more detailed information in stage two. As all the structures have been conservatively assigned a Structural Rating of 100, it is expected that the detailed information will result in a lower ranking for a given bridge rather than a higher ranking. Stage two is designed to be executed by the IDOT District Offices.

2.4 WASHINGTON STATE DEPARTMENT OF TRANSPORTATION (WSDOT) APPROACH

2.4.1 Objectives of the WSDOT Approach

The Washington State Department of Transportation (WSDOT) provides a procedure with cost estimates for a seismic risk reduction program for state highway bridges in Washington.

The objectives of developing and evaluating retrofit techniques are:

- Minimize risk of bridge collapse,
- Prioritize projects to minimize risk of life loss,
- Interstate/essential lifeline bridges are to remain in service,
- Accept moderate damage,
- Address both structure and superstructure seismic retrofit needs for each bridge concurrently.

For these purposes the review of the bridge plans is necessary but no detailed structural or geotechnical information is required.

The following types of the existing bridges are excluded from this study:

- bridges located in the lowest seismic risk zone (ground acceleration coefficient less than 0.1g),
- bridges built after 1983,
- single span bridges,
- railroad and pedestrian bridges,
- timber bridges.

2.4.2 Prioritization Criteria

Bridges are first prioritized by the degree of structural deficiencies. The priority groups are listed in Table 2.6. Table 2.6 also shows the three categories for special groups. The substructure deficiencies as referred in this table can be identified as follows:

- Inadequate confinement reinforcement for main longitudinal reinforcing steel in concrete columns,
- Inadequate splice length of main longitudinal column reinforcing to footing dowels,
- Absence of reinforcement in the tops of footings, and
- Inadequate footing support capacity.

Bridges are grouped into five main priority groups with different types of deficiencies. Then each group of bridges are ranked in themselves according to the importance criteria. The factors used in the structural vulnerability and importance criteria are summarized in Table 2.7.

Priority Group	Type of Deficiencies
1	Bridges with in-span hinges.
2	Bridges simply supported at piers.
3	Bridges with single column piers not included in 1 or 2 above.
4	Bridges with 3 or more types of substructure deficiencies.
5	Bridges with 1 or 2 types of substructure deficiencies.
S*	Bridges that require further structural analysis to assess whether seismic retrofit is warranted. These are essentially large or unusual type structures. Double-deck bridges are included in this category.
R*	Bridges that have been retrofitted previously for superstructure deficiencies.
P*	Bridges already programmed or planned for retrofitting.
*: special groups	

Table 2.6 Structural Groups for Bridges
(from Babaei and Hawkins, 1993)

Importance Factors	Structural Details
	Structure Type
Traffic Volume	Bearings
Detour Length	Type of Restraint
Emergency Route Designation	Pier Type
Bridge Length	Column Type and Details
Utilities Carried on the Bridge	Column-to-Footing Anchorage Details
Remaining Service Life of the Bridge	Footing Type
	Abutment Type

Table 2.7 Main Attributes Used in Prioritization

The mathematical representation of the model is given in equation (2.13) (Babaei and Hawkins, 1991):

$$I = C \times V \tag{2.13}$$

where I = Priority Index (0-100), I increases as priority increases.

C = Factor representing criticality of the:

- route carried by the bridge,
- utility lines carried by the bridge,
- route crossed by the bridge,
- detour for the route carried by the bridge,
- average daily traffic (ADT) of the route carried by the bridge,
- ADT of the route crossed by the bridge,
- bridge structure as a threat to public safety.

V = Factor representing vulnerability of the bridge to seismic failure. V increases as the vulnerability of the bridge increases according to the following equation:

$$V = 9.85\,[(a \times K) \times SV]^{0.41} \tag{2.14}$$

where a = Velocity-related peak ground acceleration coefficient (10 percent probability of being exceeded in 50 years),

K = Factor adjusting a to the remaining service period of the bridge (Table 2.8),

SV = Factor representing the seismic structural vulnerability. SV increases as the seismic structural vulnerability increases. SV is zero for bridges that meet current seismic design criteria. It is affected by the superstructure, substructure, foundation and soil conditions. The use of ATC-6-2 approach summarized in Section 2.2 is suggested for determining SV.

The factors C and V are quantified such that I is about the same for a low criticality/high vulnerability bridge and a high criticality/low vulnerability bridge, i.e., criticality and vulnerability have the same weight in the priority model.

K	Remaining Life (year)
1	>40
0.91	30-40
0.80	20-30
0.67	10-20
0.50	<10

Table 2.8 K Factor for Different Remaining Life Time for a Bridge (from Babaei and Hawkins, 1993)

2.5 OTHER APPROACHES

A summary and comparison of the approaches that are reviewed in Sections 2.1 to 2.4 is given in the paper by Buckle (1991). In addition, a methodology which uses importance, seismicity and vulnerability factors to calculate a priority index for each bridge is proposed in that paper. A *rank* is defined as the sum of these factors each multiplied by a weighting factor. The *seismicity factor* is calculated as a function of:

- the acceleration coefficient based on a 10 percent probability of exceedance in 50 years and
- the site coefficient to scale the acceleration coefficient for local site effects.

A *vulnerability factor* is calculated using ATC-6-2 guidelines by determining the bridge's ability to resist earthquake forces and to tolerate large relative movements. The vulnerability factor also includes the seismic design criteria in effect at the time the bridge was designed, its age and state of repair.

An *importance factor* is calculated as a function of:

- route types carried and crossed,
- detour lengths for the routes carried and crossed,
- existence of utility lines,
- average daily traffic and
- ratio of replacement cost to retrofit cost.

A significant aspect of the proposed procedure is that it places greater emphasis on the importance of the bridge and on possible soil amplification effects than either the Caltrans or ATC approaches. The importance criterion also includes a "worth" parameter as the ratio of replacement cost to retrofit cost. The effect of worth on the overall assessment of importance is adjustable through user defined scaling numbers. The second aspect of the procedure is the use of a site coefficient to scale the acceleration coefficient A. Four soil types are recommended ranging from competent rock to landfill, to include a factor for structures on particularly hazardous sites.

A geographic information systems (GIS)-based regional risk analysis program is described in the paper by Kim et al. (1992). The purpose of the paper is to interactively study the vulnerability of bridges in a regional highway system. It considers three major components:

- A *GIS* environment to display geographic data, to handle inquiries and to display the results of a query.

- A *risk model* for bridges that can predict the level of damage due to a particular intensity of ground motion at a bridge site. The model uses data from damaged or failed bridges during an earthquake and considers only ground shaking. Some bridge attributes are defined as components of the risk model which predicts a rank of seismic vulnerability of bridges and compares it to the actual one.

- A *ground motion attenuation model* to predict the intensity of ground motion at a particular bridge.

The attributes used in the study are as follows:

- degree of damage,
- intensity of peak ground acceleration,
- year of design specification under which the bridge was constructed or modified,
- type of superstructure,
- shape of superstructure,
- material of superstructure,
- internal hinges,
- type of pier,
- type of foundation,
- height of pier,
- material of substructure,
- irregularity in geometry or stiffness,
- site conditions,
- effect of scouring, and
- seat length.

The developed model represents the damage probability for the entire collection of bridges that are actually subjected to damaging earthquakes. This is a different approach than any of the methods reviewed in the previous sections. The method also evaluates the potential contribution of each parameter to the level of damage for each bridge in the database used. By this means, important attributes for prioritization are identified.

Erie County in Western New York State is used as the study region for application purposes. Information for identification and characterization of bridges in Erie County is obtained from New York State Department of Transportation (NYSDOT). Seventy four bridges that have been damaged in the past earthquakes are included in the study.

In their paper, Kim et al. (1992) place particular emphasis on the use of Geographic Information Systems to rapidly analyze the spatial impacts of natural hazards. The use of a GIS-based approach provides a platform to integrate the wide variety of information needed to evaluate the impact of earthquakes or other natural hazards on a regional network of primary and secondary bridges. It also serves as a valuable tool for risk analysis of bridges in a regional transportation system. The method is presented in Kim (1993) in a more detailed and comprehensive form.

Another approach that proposes a method to determine a retrofit scheme is considered by Cherng et al. (1992). The retrofit scheme considers retrofit priority and amount of upgrading. The objective is to maximize the net retrofit benefit for a given budget and target network reliability in addition to the bridge criticality to community and its vulnerability to seismic hazard. The use of retrofit criterion, instead of the concept of priority index distinguishes this approach from the other approaches. Consideration of the uncertainties in the seismic environment as well as the transportation systems is a new concept introduced by this paper. The method also considers the uncertainties in seismicity and transportation environment. The retrofit criterion considers the following:

- consequence of failure for the component, including sum of costs for reconstruction, casualty and loss of function,
- loss due to network failure,
- retrofit cost for a component increased from *before-retrofit* strength coefficient to *after-retrofit* strength coefficient.

Component reliability is defined as a function of peak ground acceleration (PGA), design acceleration and a strength coefficient (SI) that ranges from 0 to 1. SI is used to reflect the damage accumulation. The network reliability is defined as the probability of connectivity among certain cities under seismic hazard. A computationally efficient method with polynomial complexity is used to evaluate the network reliability. A hypothetical highway transportation network of nine bridges is used to illustrate the proposed method.

A preliminary method to improve the Caltrans prioritization was proposed by Kiremidjian, (1992b). The method considers a prioritization scheme that uses all the data compiled by Caltrans. In this method, an index that depends on the primary criteria $\{S_1,...,S_k\}$ is proposed. The primary criteria are deemed to have direct impact on the performance and potential losses of a bridge. Each criterion, depends on a set of attributes $\{x_{1i},...,x_{mi}\}$ that can be subdivided into sub-attributes if necessary. For each criterion and attribute, weights $\{w_1,...,w_k\}$ are assigned to show their relative importance. Then, based on multi-attribute decision theory a value function $v(x_{ji},)$ between 0 and 1, is defined. The overall index is computed by multiplying the value functions with the weight of the attributes as expressed in equation (2.15).

$$I = \sum_{all\ S_i} w(S_i) \sum_{j=1}^{m_i} w(x_{ji}) v(x_{ji}) \qquad (2.15)$$

where S_i = Primary criterion,
$w(x_{ji})$ = Weight for attribute j of primary criterion S_i,
$v(x_{ji})$ = Value function for attribute j of primary criterion S_i.

Pezeshk et al. (1993), discuss a prioritization method that has been developed for the seismic vulnerability evaluation of bridges in Memphis and Shelby County area, Tennessee. In this method, the seismic rating of a bridge is defined as a function of the following criteria:

- importance of the bridge as a vital transportation link,
- structural characteristics,
- foundation and site characteristics and
- seismicity of the site.

A score is assigned to each area and summed up for the final ranking. The index score of each criterion was determined on the basis of its relation to the effect of seismic damage due to a moderately strong earthquake. The scoring indices for the bridges are mostly adopted from the ATC approach.

2.6 LIMITATIONS OF EXISTING APPROACHES

Based on the review of the existing approaches presented in previous sections several problems have been found in the computation of the overall ranking based on these approaches. These problems are discussed in the following sections recognizing that these approaches represented the state of the art at the time of their implementation. In addition, more comprehensive approaches such as the one presented in this report require considerable amount of additional information on bridge characteristics and vulnerability performance, which would have made it difficult to implement at that time.

2.6.1 Improper Combination of Ratings Related to Vulnerability and Importance of a Bridge

a) Computation of ranking by addition: The overall ranking is obtained by the addition of bridge attribute scores in the Caltrans and the ATC approaches. However, addition methods are particularly insensitive to relative risks. The insensitivity is most notable for bridges with moderate need of retrofitting. Likewise, the final ranking based on the addition method depends strongly on the weighting factors. The following examples illustrate these shortcomings:

Example 1: Assume that the overall ranking is defined as the addition of three main criteria; seismicity, vulnerability and importance. For each of these criteria, qualitative values can be assessed to give a relative rating in themselves. A possible assignment for the qualitative value is high, moderate and low for each criteria. In this example study, a representative scaling for these levels is given as 3, 2 and 1 respectively. Assigning the same scaling numbers for each criteria, the weighting factor is assumed to be the same. For any of the two criteria a 3x3 matrix is formulated as in Figure 2.1. The rows and the columns of the matrix represent the different levels of each criteria and have the respective scaling values. Each number in the matrix is the addition of the scaling value of the row and the column it belongs to. For example, in Figure 2.1 the element on the second row third column represents the combination of moderate vulnerability and high seismicity. Hence the number is 5 (= 2+3).

SEISMICITY

VULNERABILITY		L	M	H
	L	2	3	4
	M	3	4	5
	H	4	5	6

Low (L) = 1
Moderate(M) = 2
High (H) = 3

Figure 2.1 3x3 Scaling Matrix for Vulnerability and Seismicity

Combination of the three criteria forms a cube as shown in Figure 2.2. The x, y and z axes are defined as vulnerability, importance and seismicity, respectively. Each face is divided into 9 to represent the 3x3 scaling matrix. Therefore, there are 27 different boxes. Figure 2.3 shows the box numbering. In Figure 2.4, the resulting scaling numbers for each box are given. Each box represents one combination of three criteria with a given level. For example, box number 3 represents high vulnerability, low seismicity and low importance. Each box has the scaling numbers for the level of the criterion it represents. In box number 3 for example, 6 is for the combination of high vulnerability and high seismicity (3+3); 4 at the top is for the combination of high vulnerability and low importance (3+1); and 4 on the side is for the combination of high seismicity and low importance (3+1). The addition of the three numbers on three faces of each box gives the overall ranking number for that box. This does not exactly correspond to the method of summing up three weighted criteria as each criterion is referred to twice. However, this is acceptable as the assigned numbers are relative numbers. Dividing the overall ranking number by two would give the same relative ranking. The resulting numbers given in Figure 2.4 show that the combinations including high level attributes give high overall ranking values. Similarly, the

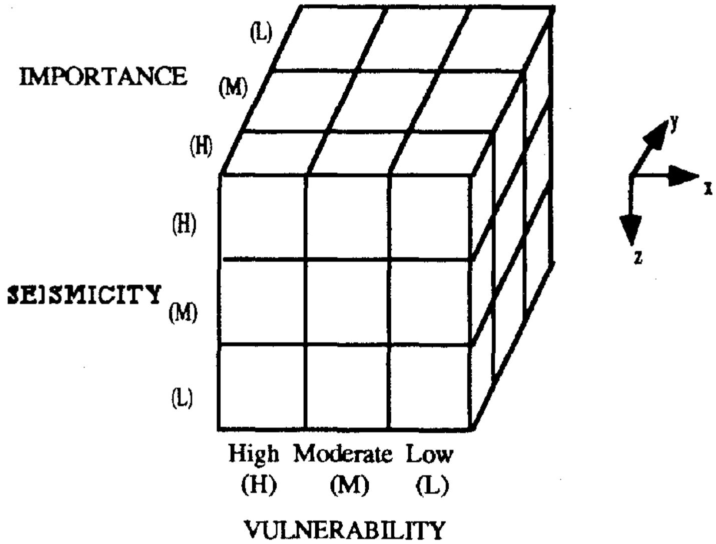


Figure 2.2 Representation of the Ranking Criteria

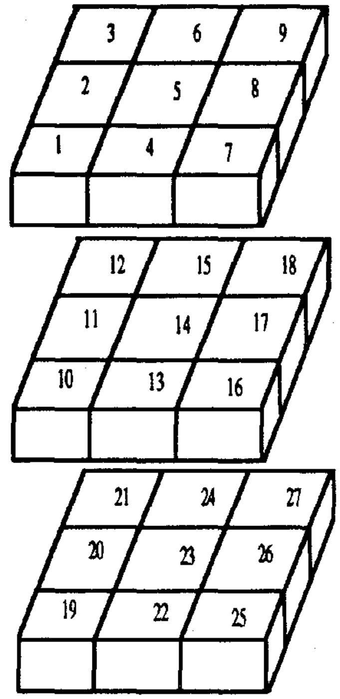


Figure 2.3 Box Numbering

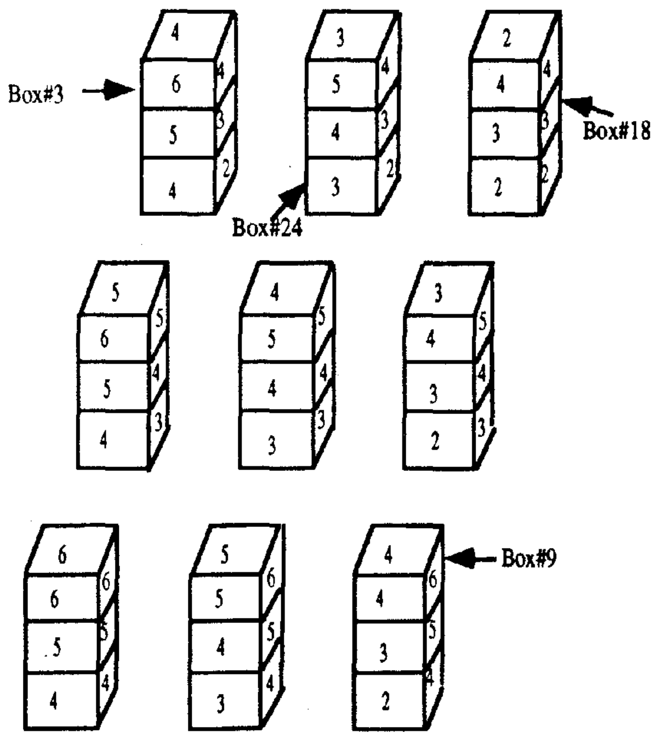


Figure 2.4 Combinations of the Criteria with Equal Weights

High: 3
Moderate: 2 for all three criteria.
Low: 1

The combination uses additive method.

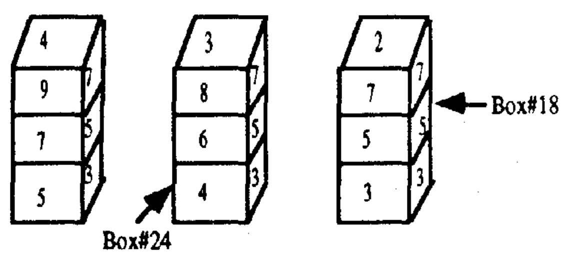


Figure 2.5 Combinations of the Criteria with Unequal Weights

combinations of low level attributes give low level overall ranking values. On the other hand, the overall ranking numbers considering the combination of moderate levels does not result in easily classified overall ranking values. In order to decide which box in the cube belongs to moderate, high or low level, threshold values are necessary. For example, in Figure 2.4 the overall risk number for *low seismicity, low importance* and *moderate vulnerability* (box no. 24; 3+3+2=12) is the same as *moderate seismicity, low importance* and *low vulnerability* (box no. 18; 3+2+3=12). Thus, it would be ambiguous to rank bridges in class 18 higher than those in class 24. These type of results raise the question of "*which of the two categories represent a higher ranking for seismic retrofitting?*". This example illustrates the insensitivity of the addition method for intermediate values.

The results presented in Figure 2.4 are based on equal weight assignment where the effect of seismicity cannot be stressed. Figure 2.5 shows the results when the weighting factors are changed such that seismicity is weighed twice as much as vulnerability and importance. The results reflect the effect of higher seismicity weight. For example, the *low seismicity, low importance and moderate vulnerability* combination has a slightly lower value than the *moderate seismicity, low importance and low vulnerability* (Box number 24 vs. 18). The comparison of the results from Figure 2.4 and 2.5 raises the following concerns :

- *How should the weights be assigned?*
- *What are the threshold values between high, moderate and low levels of ranking?*

Example 2: Forty five bridges with complete information (from the Caltrans database) are chosen randomly and ranked by using the Caltrans approach. The preweight factors are calculated as described in the Caltrans approach and the weight factors specified by the approach are directly utilized. The peak ground acceleration is calculated using the seismic hazard software program STASHA (Kiremidjian et. al., 1994) that considers the effect of all sources within a given radius. The calculated peak ground acceleration has 10 percent probability of exceedance in 50 years. Some of the attributes considered in the approach such as soil type at site and number of hinges are not available in the database. Thus, it is assumed that all bridge sites have low risk soil type and continuous spans, i.e. no hinges. The final ranking is affected by each of these assumptions. The obtained ranking is not an absolute ranking. In fact, this example is performed to show some shortcomings of the approach and not to give a final ranking for the selected bridges. The ranking of bridges are shown in Table 2.9. A sample calculation of the ranking number for two bridges is illustrated in Table 2.10. The bridge attributes and the respective preweight and weight values are listed. The preweight values are calculated using the approach reviewed in Section 2.1.3

BRIDGE NO.	ROUTE TYPE	FACILITY CROSSED	LENGTH (ft)	YEAR BUILT	SKEW	ADT	DETOUR LENGTH	HEIGHT (ft)	COLUMNS PER BENT	ABUTMENT TYPE	LATITUDE	LONGITUDE	PGA (g)	Example 2 Ranking1	Example 3 Ranking 2
34 0045	101	ST RTE 101	133	50	0	260000	2	15	2	monolithic	37.444	122.244	0.752	1	2
28 0127G	24	ST RTE 24	267	60	30	15500	2	25	1	monolithic	37.537	122.042	0.399	2	1
28 0123	80	IS 80	131	60	45	157600	0	15	2	monolithic	37.547	122.19	0.551	3	3
28 0114	80	IS 80	200	60	17	157600	1	15	2	monolithic	37.541	122.186	0.553	4	4
35 0250L	280	STATE ROUTE 280	199	73	20	45000	7	35	2	monolithic	37.281	122.175	0.749	5	10
33 0373L	680	ST RTE 680	158	65	12	53000	5	15	2	monolithic	37.423	121.555	0.451	6	5
33 0373R	680	ST RTE 680	158	65	12	53000	5	15	2	monolithic	37.423	121.555	0.451	7	6
33 0429L	680	ST RTE 680	147	71	4	49450	4	15	0	monolithic	37.305	121.559	0.706	8	11
33 0429R	680	ST RTE 680	147	71	4	49450	4	15	0	monolithic	37.305	121.559	0.706	9	12
33 0026L	580	ST RTE 580	299	69	26	45750	3	35	2	monolithic	37.431	121.419	0.254	10	7
33 0356R	680	ST RTE 680	166	65	12	53000	5	15	2	monolithic	37.426	121.557	0.345	11	9
23 0142R	680	ST RTE 680	310	61	13	23000	6	25	2	monolithic	38.126	122.082	0.287	12	8
33 0026R	580	ST RTE 580	184	69	20	45750	3	15	2	monolithic	37.431	121.419	0.254	13	13
29 0071L	99	ST RTE 99	205	56	23	22200	4	25	2	monolithic	37.516	121.13	0.182	14	14
29 0071R	99	ST RTE 99	205	56	23	22200	2	25	2	monolithic	37.516	121.13	0.182	15	15
34 0089	280	ST RTE 101	180	64	1	147700	2	0	0	monolithic	37.443	122.252	0.752	16	16
35 0250R	280	STATE ROUTE 280	201	73	20	45000	0	25	2	monolithic	37.281	122.175	0.749	17	18
35 0231R	280	STATE ROUTE 280	178	69	44	45400	8	0	0	monolithic	37.268	122.162	0.577	18	17
22 0151	16	CNTY RD 18	218	73	13	3200	3	15	1	monolithic	38.433	121.48	0.076	19	19
14C0034	0V800	BUTTS CYN RD	61	69	0	500	46	15	0	monolithic	38.435	122.307	0.249	20	20
29 0218L	5	ST RTE 5	118	71	13	30950	0	0	0	monolithic	37.529	121.166	0.272	21	22
29 0224R	5	IS 5	139	71	6	30950	0	0	0	monolithic	37.556	121.176	0.182	22	24
18C0065	0F066	PLEASANT GROVE RD	97	60	45	700	8	15	0	monolithic	38.487	121.288	0.077	23	21
19C0006	0F069	SIERRA COLLEGE BLV	32	64	20	2600	4	15	0	monolithic	38.478	121.123	0.138	24	23
23C0071	0J128	LOPES ROAD	22	15	0	1200	4	15	0	non-monolithic	38.12	122.084	0.287	25	25
29 0209L	5	IS 5	134	75	13	19400	1	15	0	monolithic	38.036	121.223	0.084	26	34
29 0209R	5	IS 5	134	75	13	19400	1	15	0	monolithic	38.036	121.223	0.084	27	35
29 0248L	5	IS 5	96	79	16	18900	1	15	0	monolithic	38.148	121.264	0.083	28	33
22 0173R	5	IS 5	122	73	31	10000	4	0	0	monolithic	38.411	121.45	0.077	29	30
18C0063	0F066	PLEASANT GROVE RD	47	22	0	700	4	15	0	monolithic	38.474	121.292	0.075	30	27
18C0064	0F066	PLEASANT GROVE RD	47	22	0	700	4	15	0	monolithic	38.475	121.292	0.075	31	28
19C0054	0F069	SIERRA COLLEGE BLV	32	64	30	2400	6	0	0	monolithic	38.454	121.133	0.075	32	26
19C0063	0V501	FIDDYMENT RD	62	76	0	725	14	15	2	monolithic	38.478	121.211	0.077	33	31
23C0079	0J127	CORDELIA RD	101	88	12	1900	2	15	0	monolithic	38.128	122.078	0.287	34	37
28 0237	4	STA RTE 4	38	77	6	15600	2	0	0	monolithic	37.597	121.421	0.22	35	39
29 0224L	5	IS 5	136	71	12	30950	0	0	0	monolithic	37.556	121.176	0.182	36	40
23C0078	0J149	MANCAS CORNER RD	23	61	30	1101	10	0	0	non-monolithic	38.172	122.07	0.257	37	29
22 0173L	5	IS 5	122	73	31	10000	3	0	0	monolithic	38.411	121.45	0.077	38	44
23C0076	0J131	SUISUN VALLEY RD	86	9	0	2889	8	0	0	non-monolithic	38.162	122.068	0.256	39	32
19C0033	0F088	DARLING AVE (RSVL)	130	50	0	4070	1	15	0	monolithic	38.442	121.172	0.096	40	42
18C0062	0F066	PLEASANT GROVE RD	44	88	0	1000	8	15	0	monolithic	38.458	121.292	0.075	41	41
18C0061	0F091	RIEGO RD	127	82	0	1100	8	15	0	monolithic	38.45	121.296	0.069	42	43
19C0055	0V500	KING RD	34	70	26	1200	10	0	0	monolithic	38.495	121.105	0.075	43	38
19C0088	0F011	SUNRISE BLVD	41	70	0	15289	2	0	0	non-monolithic	38.44	121.163	0.18	44	36
20C0186	0E338	MELITA RD	87	15	0	500	1	0	0	monolithic	38.274	122.384	0.437	45	45

Table 2.9 Ranking for 45 Bridges by the Caltrans Approach

and the weight values for Ranking 1 are taken from Maroney and Gates, (1990). Ranking 1 in Table 2.9 shows the high weighting for ground motion, design specifications and detour length. As equal values are assumed for number of hinges and site soil conditions, the high weighting for these attributes do not affect the final ranking. For example Bridge 28 0237 and Bridge 14C0034 have similar seismicity levels. Bridge 28 0237 carries and crosses interstate highways and has a 2 mile detour length with a higher average daily traffic than Bridge 14C0034. The ranking for these two bridges in Table 2.9 is governed by the detour length, height and the construction year (year built). Bridge 28 0237 has been built in 1977 with the new design specifications and would be less vulnerable than Bridge 14C0034 under a given seismic loading. However, it might constitute a major link on the interstate highway system. For such bridges the damage level should be kept to minimum for operation immediately after an earthquake. Another interesting observation is the

Attributes	Bridge 28 0237		Bridge 14C0034		Weight for Ranking 1	Weight for Ranking 2
	attribute values	*preweight*	*attribute values*	*preweight*		
route type	4	1	0V800	0.2	0.05	0.06
facility crossed	State Rte 4	1	Butts Cyn Rd	0.2	0.06	0.08
year built	77	0	69	1	0.13	0.1
skew	6	0.0044	0	0	0.07	0.05
adt * length(ft)	38*15600	0.006	500*61	3.05E-4	0.08	0.09
detour length	2	0.02	46	0.46	0.05	0.03
columns/bent	0	0	0	0	0.1	0.08
abutment type	monolithic	0	monolithic	0	0.04	0.06
pga (g)	0.22	0.314	0.249	0.356	0.12	0.15
height (ft)	0	0	15	0.875	0.07	0.07
no. of hinges	0	0	0	0	0.11	0.11
soil at site	low risk	0	low risk	0	0.12	0.12
Rank Number 1	0.1278		0.3361			
Rank Order 1	35		20			
Rank Number 2	0.1386		0.3424			
Rank Order 2	39		20			

Table 2.10 Calculation of the Caltrans Ranking Number for Two Sample Bridges for Examples 2 and 3

effect of column height on the ranking. Bridge 28 0237 is a single span bridge, thus having no columns. The column height is assumed as zero for calculation purposes and this assumption leads to a lower ranking. Since single span bridges are omitted from the screening analysis in the Caltrans approach, a column height rating as explained above is not effective for these bridges. The WSDOT approach also excludes single span bridges from the screening level analysis. However, in spite of the fact that, single span bridges are less likely to collapse and be a threat to human life themselves, single span bridges might constitute an important link to a disaster area after an earthquake, hence, need to be considered in ranking. Also, single span bridges might be vulnerable due to their abutment types. This vulnerability of single span bridges requires attention for ranking purposes.

b) Potential inconsistency in assigning weights: The Caltrans, ATC and the WSDOT approaches encounter a potential inconsistency of their weight assignment methods. The assessment of relative weights of different attributes requires a systematic procedure. An assessment for different attributes without considering the effect of other attributes may lead to inconsistencies. The acceptable tradeoffs between competing attributes have to be defined by the decision maker to develop a consistent value model. It is most likely that the attributes used for ranking are coupled by their physical or functional constraints. For example, the traffic volume is related to the detour length. An increase in the detour length will have more socio-economic impact for a bridge with high traffic volume, as the total time loss for the society will increase with an increasing traffic volume. The weights for these two attributes need to be developed in such a way that they show consistency due to the relationship between them. The weight factors in Caltrans, ATC and WSDOT approaches do not follow any procedure that considers the acceptable tradeoffs between competing attributes. However, this topic is included in the IDOT approach. The issue of tradeoffs which considers the existence possibility for two or more variables that need to be considered simultaneously is further discussed and considered in subsequent chapters of this report. In order to show some of the difficulties of weight assignments the following example is developed.

Example 3: The same bridges as in *Example 2*, are ranked using slightly different weighting numbers. The ranking for this case is given in the last column of Table 2.9 under Ranking 2. Table 2.10 lists the different weight values used for this ranking along with the rank numbers and the ranks for the two sample bridges. A comparison of the results show that any slight change in weight assignment might have a notable effect on the results. For example Bridge 14C0034 has a higher detour length than Bridge 28 0237 but carries less traffic. The detour length preweight score is expressed by a linear function in the Caltrans approach. However, the effect of detour length might not be as important as it is expressed by the detour length preweight score when the ADT carried on the structure is considered. For this reason the aforementioned pair-based tradeoff weight assignment should be used. The prioritization method proposed in this report uses the pair-based tradeoff weight criterion. Another drawback of the detour length attribute is the dilemma for the availability of the detour route as it is possible to have other damaged bridges on the detour route recorded in the database. However, the functionality of a bridge as part of a network system has not been considered by any of the approaches reviewed above. Table 2.9 and 2.10 also illustrate the inconsistency in the change of ranking due to different weighting factors. Some bridges receive higher ranking, some receive lower ranking where some others are not affected by the different weight factors. Such an observation alludes to the need for the use of a more robust and consistent method.

c) Computation of ranking by multiplication: In the IDOT and the WSDOT approaches ranking is obtained as the product of the main components vulnerability and importance. A similar argument that is carried out for addition in part (a) above can be adopted for multiplication. A set of figures similar to those for addition is given in Figures 2.6 through 2.8. In this approach, multiplication is used instead of addition at any step of the attribute combination. The extreme values, i.e., high and low ranked bridges are highly emphasized when multiplication is used instead of addition. This emphasis may distort the ranking procedure. The error or uncertainty inherent in each factor is also amplified hence increasing the error in the overall index significantly (Buckle, 1991).

d) Consideration of seismicity and vulnerability as independent criteria for ranking: This approach is utilized by Caltrans and ATC. The weighting and rating procedure does not properly analyze dependencies among factors affecting the probability of failure. In both, Caltrans and ATC approaches, seismicity and vulnerability are treated separately. In the ATC provisions, these parameters are considered by the use of Seismic Performance Categories (Table 2.2). Similarly, the addition of vulnerability and seismicity ratings is an indication of independent treatment of these two criteria. However, the vulnerability of a structure is directly related to the type and level of ground motion. For example, when the structural vulnerability of a bridge is represented by a fragility curve, the damage level is represented for a given ground motion level. Also the fragility curve is different for each type of ground motion such as ground shaking or liquefaction. Thus the interrelationship between seismicity and vulnerability needs to be considered in the overall ranking.

2.6.2 Lack of Consideration of Structural and Material Type

The vulnerability of a bridge is closely related to its material and structural type. For example, a box girder bridge would behave differently than a truss or a suspension bridge; also a steel bridge would respond in a more ductile manner than a concrete bridge under the same seismic

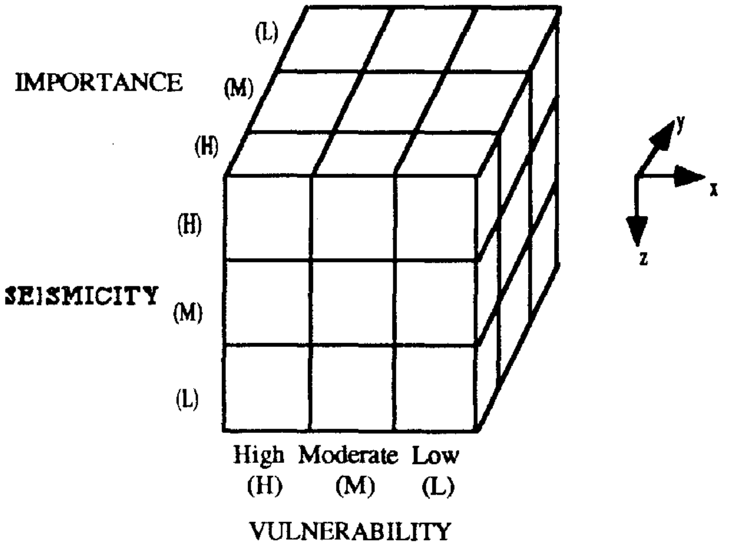


Figure 2.6 Representation of the Ranking Criteria

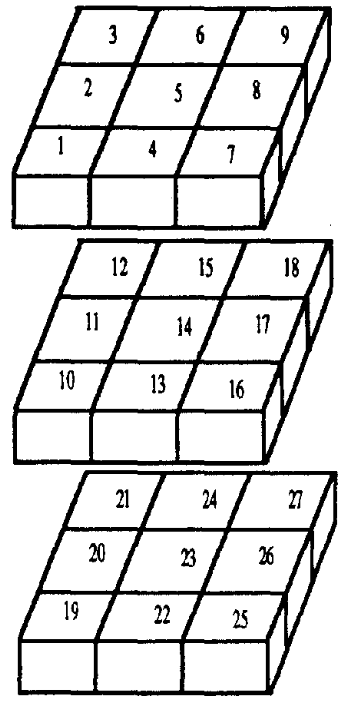


Figure 2.7 Box Numbering

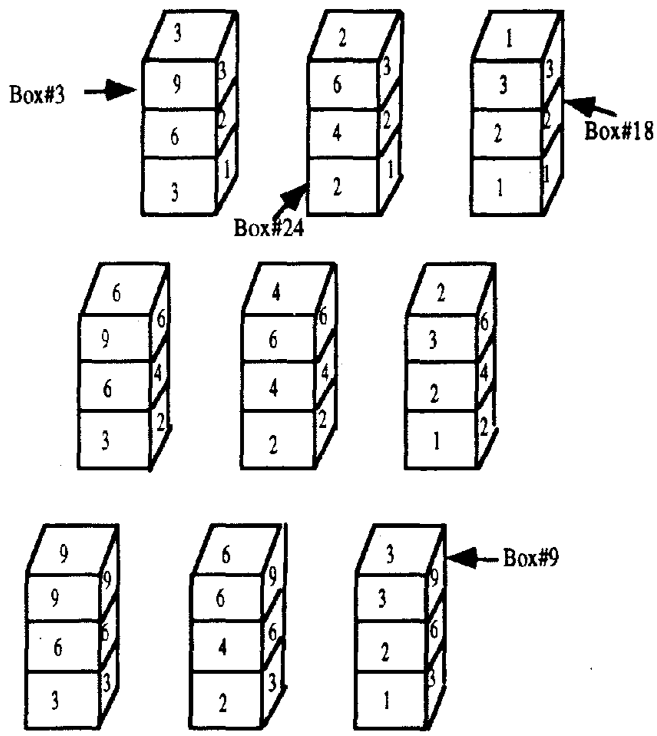


Figure 2.8 Combinations of the Criteria with Equal Weights

High: 3
Moderate: 2 for all three criteria.
Low: 1

The combination uses multiplicative method.

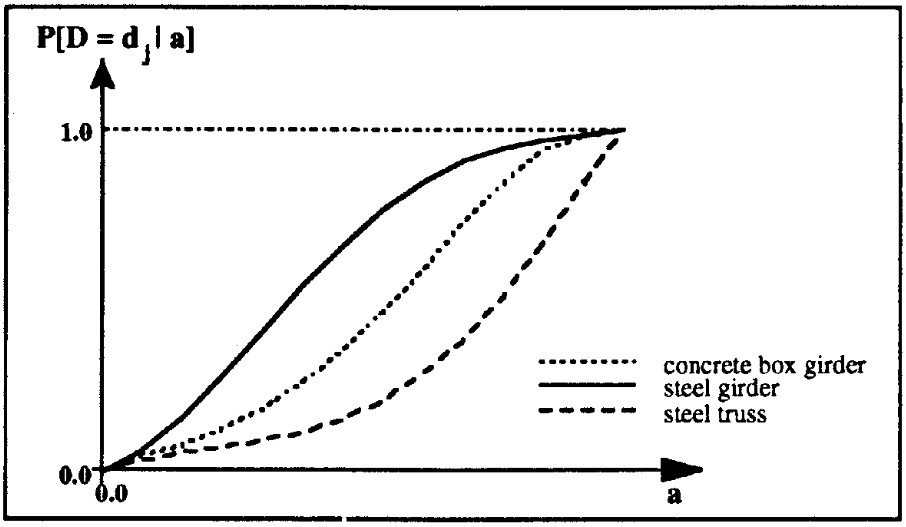


Figure 2.9 Hypothetical Fragility Curves for Different Types of Bridges

loading. For different types of bridges, different fragility curves can be used to reflect this behavior. In Figure 2.9, concrete box girder, steel girder and steel truss bridges are represented by three different fragility curves. The shape and relative values of the fragility curves for three types of bridges are hypothetical. However, the curves illustrate the effect of structural and material type of a bridge on the vulnerability ranking when they are considered as functions of seismicity .

2.6.3 Lack of Procedures for Implementing Incomplete Information

Most of the databases for bridge inventories are incomplete. Some approaches do not consider incomplete data as a potential problem. In fact, bridges with incomplete information have been omitted from ranking process to solve the incomplete information problem. However, the omission of bridges can result in excluding some critical bridges that are in great need of retrofitting. The incomplete information can be either assumed probabilistically from the existing information for other bridges or the effect of that attribute can be computed using other attributes of the same bridge. In Example 2, if the data for site soil and number of hinges were available, the ranking would be different than the one given in Table 2.9. More realistic results may be obtained if the available attribute information is used to infer the values for the missing attributes rather than to assume equal values of attributes for each bridge. In this report an approach is presented for ranking bridges with incomplete information. An expert system -**ESCOB**- is developed to identify missing attributes and to infer the possible values for these attributes based on either statistics from the inventory or expert opinion.

CHAPTER 3

CONCEPTUAL PRIORITIZATION METHOD

A prioritization method has been developed based on ***vulnerability, V*** and ***importance, I***. Contrary to the current Caltrans and ATC approaches, the prioritization method presented in this report considers vulnerability as a function of seismicity. Vulnerability and seismicity are interrelated and the effect of their relationship needs to be considered for prioritization purposes.

Bridges that are of interest for ranking purposes are defined by the set $\{\boldsymbol{B}\} = \{\boldsymbol{B}_1, \boldsymbol{B}_2, \ldots, \boldsymbol{B}_N\}$,

where $\boldsymbol{B}_i$ = bridge i, and
N = total number of bridges.

Let $\{\boldsymbol{R}\} = \{\boldsymbol{R}_1, \boldsymbol{R}_2, \ldots, \boldsymbol{R}_N\}$ be the rank order of the bridges such that:

$$\boldsymbol{R}_1 > \boldsymbol{R}_2 > \ldots > \boldsymbol{R}_N \tag{3.1}$$

where the bridge assigned to $\boldsymbol{R}_1$ is identified as the first candidate for seismic retrofitting.

For each bridge, $\boldsymbol{B}_i$, a set of attributes $\boldsymbol{X} = \{x_1, x_2, \ldots, x_P\}$ and three subsets of attributes, namely $\boldsymbol{Y}$, $\boldsymbol{Y}'$ and $\boldsymbol{W}$ are defined such that:

$$\begin{aligned} \boldsymbol{Y} &= \{y_1, y_2, \ldots, y_{P_1}\} \\ \boldsymbol{Y}' &= \{y'_1, y'_2, \ldots, y'_{P_2}\} \\ \boldsymbol{W} &= \{w_1, w_2, \ldots, w_{P_3}\} \\ \boldsymbol{Y} \cup \boldsymbol{Y}' \cup \boldsymbol{W} &= \boldsymbol{X} \end{aligned} \tag{3.2}$$

where $\boldsymbol{Y}$ = primary structural attributes,
$\boldsymbol{Y}'$ = secondary structural attributes,
$\boldsymbol{W}$ = importance attributes,
P = total number of attributes, and

$$P \le \sum_{i=1}^{3} P_i .$$

The ranking R_i will in general depend on two main criteria, V and I, through a functional relationship described as follows:

$$R_i = f(V_i, I_i) \tag{3.3}$$

where R_i = Ranking of bridge i for seismic retrofitting,
V_i = Vulnerability of bridge i and
I_i = Importance of bridge i.

The flowchart shown in Figure 3.1 illustrates the relationship between the main and sub components of the conceptual prioritization method. For the final ranking, assessment of vulnerability and importance are required.

Vulnerability assessment includes the following:

- seismic hazard analysis at the bridge site,
- classification of bridges based on their structural characteristics and
- fragility analysis.

Thus, vulnerability of a bridge can be expressed by the following equation:

$$V = \beta f[q_r(A)] \tag{3.4}$$

where $\beta = f(Y')$ = Modifier where Y' represents the secondary structural attributes,

$q_r(A) = f(D, A, C_n)$ = Expected value of being in damage state d_r, given seismic hazard at site A, where

D = Damage state assuming values d_r in $D = \{d_1, d_2, \ldots, d_z\}$, z = total number of damage states,

A = Seismic hazard at the bridge site,

$C_n = f(Y)$ = Bridge class n, where Y represents the primary structural attributes, and n is the bridge class identifier.

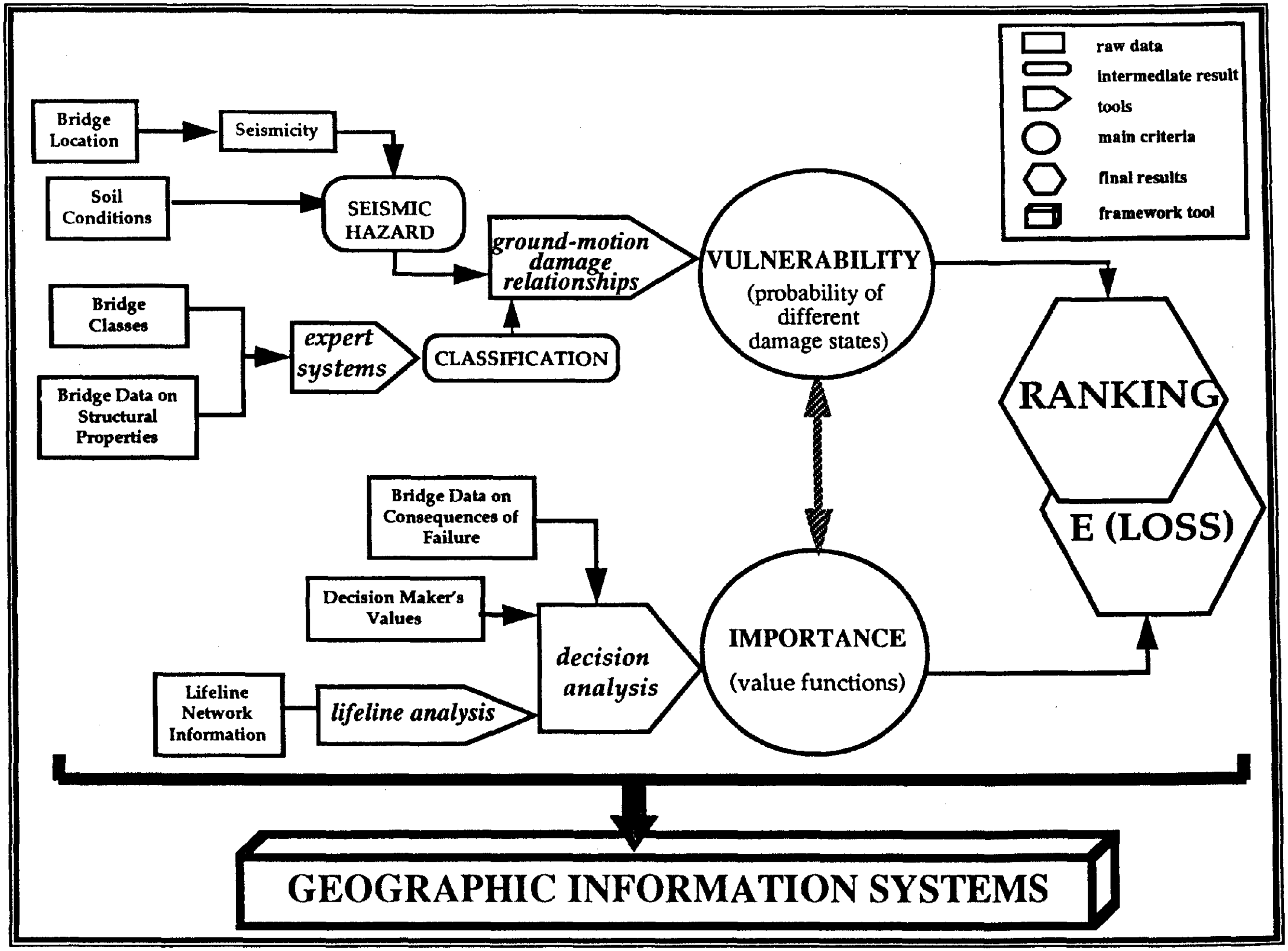


Figure 3.1 Components of Prioritization Method

More specifically equation (3.4) can be written as follows:

$$V = \sum_{D} \int_{A} d_r P[D = d_r | A] \frac{d}{da}[1 - P[A \geq a, (0,t)]] da \tag{3.4.a}$$

where $\frac{d}{da}$ is the derivative with respect to a. The details of obtaining equation (3.4) are discussed in Chapter 5.

The function $f(Y)$ represents the relationship among different elements of Y in defining the bridge classes and is described extensively in Section 4.1. The function $f(Y')$ considers the effect of the modifier β on the ground motion-damage relationships. Modifier β is used to increase or decrease the vulnerability level depending on the elements of the set Y'. The function $f(Y')$ and the modifier β are further explained in Chapter 5.

The seismicity parameter, A is computed in the seismic hazard analysis as a function of local soil conditions at the bridge site and location of the bridge relative to potential seismic hazard sources. For each bridge, the result of the site hazard analysis is obtained as the probability of exceeding various levels of a site parameter over a future time period (Kiremidjian, 1992a), given below :

$$\begin{aligned} P[A \geq a,(0,t)] &= P[\textit{seismic hazard parameter } A \textit{ will exceed level } a \textit{ at least once in time } (0,t)] \\ &= \int_{\varepsilon}\int_{A}\int_{R}\int_{M} \nu_M f_{A/M,R}(a \mid M,R) f_{R/M}(r \mid M) f_M(m) f_\varepsilon(\varepsilon)\, dm\, dr\, da\, d\varepsilon \end{aligned} \tag{3.5}$$

where ν_M = rate of event occurrences for a Poisson sequence of earthquakes,

$f_{A/M,R}(a \mid M,R)$ = probability density function for the site hazard parameter A given the magnitude of the earthquake, M, and the distance from the fault to the site, R,

$f_{R|M}(r \mid M)$ = probability density function for the distance R given the magnitude of the earthquake, M,

$f_M(M)$ = probability density function for the earthquake magnitudes, M,

$f_\varepsilon(\varepsilon)$ = error term for the site hazard parameter, A.

In equation (3.5) A represents either ground shaking or the liquefaction severity. For fault displacement and landslides similar expressions can be used to obtain the probability of exceeding various levels of fault displacement or various sizes of landslides (Kiremidjian, 1992a).

Bridge classes C_n, (n = 1,2,...,10) are defined based on the general structural properties of a bridge. The purpose of defining bridge classes is to generalize the seismic behavior of a given material and structural type of a bridge. The structural properties of the bridge are obtained from available inventories, such as the Department of Transportation Structural Maintenance Inventory.

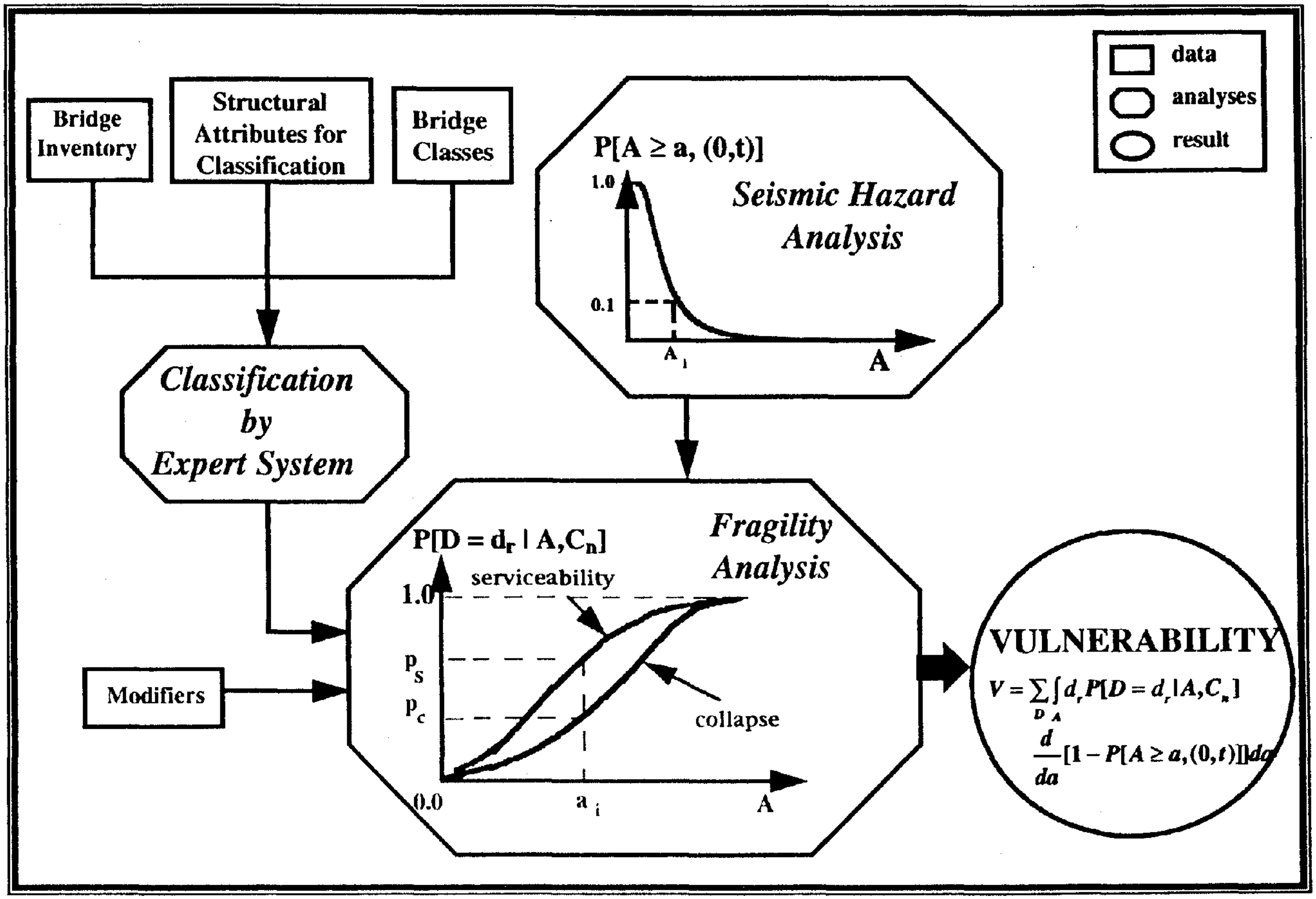
Ground motion-damage relationships are used to compute the probability of being at a given damage level for a specified ground motion level. Most frequently, these relationships are expressed in terms of fragility curves that define the probability of a bridge being in a particular damage state given a ground motion level, $P[D = d_r | A, C_n]$. Ground motion-damage relationships for each of the new bridge classes are needed.

As the existing bridge classes are deemed to be inadequate to distinguish bridges and to represent seismic behavior of bridges adequately, this research defines new bridge classes. In order to achieve a better representation of bridges, the need for new fragility curves for each bridge class is also addressed. However, the developed prioritization method can be used with any of the well-defined bridge class definitions and ground motion-damage relationships.

The steps for the vulnerability assessment for any given bridge can be summarized as follows:

- Obtain the structural information (sets Y and Y') from the inventory,
- Assign the bridge to one or more of the predefined bridge classes, C_n (n = 1,2,...,10) and determine if any modifiers β need to be assigned,
- Obtain information on the location of the bridge and soil condition at the bridge site,
- Perform seismic hazard analysis to compute the seismicity hazard curve, i.e., compute $P[A \geq a, (0,t)]$ as a function of A,
- Select the corresponding ground motion-damage relationship for the bridge class that the bridge is assigned to and find $q_r(A)$ and
- Evaluate the vulnerability parameter V using equation (3.4).

Figure 3.2 illustrates the steps summarized above. For implementation purposes of this methodology it is necessary to have: (i) seismicity assessment, (ii) bridge classification and (iii) damage estimation tools. Seismicity assessment methods and computer methods for site hazard analysis are widely available and can be directly utilized in this methodology. In order to classify existing bridges it is necessary to employ methods that use database management and



$$V = \sum_{D} \int_{A} d_r P[D = d_r | A, C_n] \frac{d}{da}[1 - P[A \geq a, (0,t)]] da$$

Figure 3.2 Steps of Vulnerability Assessment expert system tools. A relational database management system (RDBMS) provides efficient storage and management of large databases. Thus, such a system is used in this research to extract the necessary information from any available inventory. In addition, a knowledge-based expert system (KBES) - **ESCOB** - that combines heuristic information with the available data is developed for the classification of bridges. Applications of RDBMS and KBES are further described in Chapter 4.

The prioritization of bridges for seismic retrofitting requires considering attributes that relate the consequences of failure of a bridge to the public safety and socio-economic well-being of a community. These factors are reflected in the importance criterion, $\boldsymbol{I}$, for bridge prioritization. The bridge importance criterion for bridge i is defined as follows:

$$\boldsymbol{I = f(S, E, G, Q, L, H)} \quad (3.6)$$

where $\boldsymbol{S}$ = Public safety, and

$$\boldsymbol{S = f(\rho_{o/u}, ADT(\rho_{o/u}), D)} \quad (3.6.a)$$

where ρ_o = Route carried on the bridge,
ρ_u = Route carried under the bridge,
$ADT(\rho_{o/u})$ = Average daily traffic for the routes on (ρ_o) and under (ρ_u) the bridge,
$\boldsymbol{D}$ = Damage level of bridge i.

$\boldsymbol{E}$ = Emergency response, and

$$\boldsymbol{E = f(\mu, t_d, c)} \quad (3.6.b)$$

where μ = Critical bridge set member,
t_d = Time delay to reach a destination due to failure of bridge i and
c = Highway network configuration.

$\boldsymbol{G}$ = Long term economic impacts, and

$$\boldsymbol{G = f(ADT(\rho_o), T_c(\rho_o), OD_t, D)} \quad (3.6.c)$$

where $ADT(\rho_e)$ = Average daily traffic for the route carried on the bridge,
$T_c(\rho_o)$ = Traffic capacity of the route carried on the bridge,
OD_s = Origin-destination trip matrices for the highway network system,
D = Damage level of bridge i.

Q = Defense route,

L = Interaction with other lifelines, i.e. other lifelines carried on the bridge,

H = Historical significance.

The steps for importance assessment of any given bridge are shown in Figure 3.3 and can be summarized as follows:

- Obtain a decision maker's values for all importance attributes,
- Develop utility functions and scaling factors for all importance attributes,
- For a given bridge obtain attributes for lifeline network analysis,
- Perform network analysis:
  - » connectivity analysis for emergency response,
  - » serviceability analysis for long term economic recovery,
- Obtain total utility value for importance assessment.

The decision maker's tradeoff values for each of the importance criterion factors need to be obtained through a separate analysis. The results of each analysis are combined by the use of multi-attribute utility theory. A value model is developed to properly assess the multi-attribute importance criterion for a given bridge i as given below:

$$U_{Ii} = \sum_{j \in I} k_j u_{ji} \tag{3.7}$$

where U_{Ii} = Utility value (u-value) of the importance criterion for bridge i,
k_j = Scaling factor for each of the importance criterion factors listed in equation (3.6), and $\sum_{j \in I} k_j = 1$,
u_{ji} = u-value of the importance criterion factor j for bridge i.

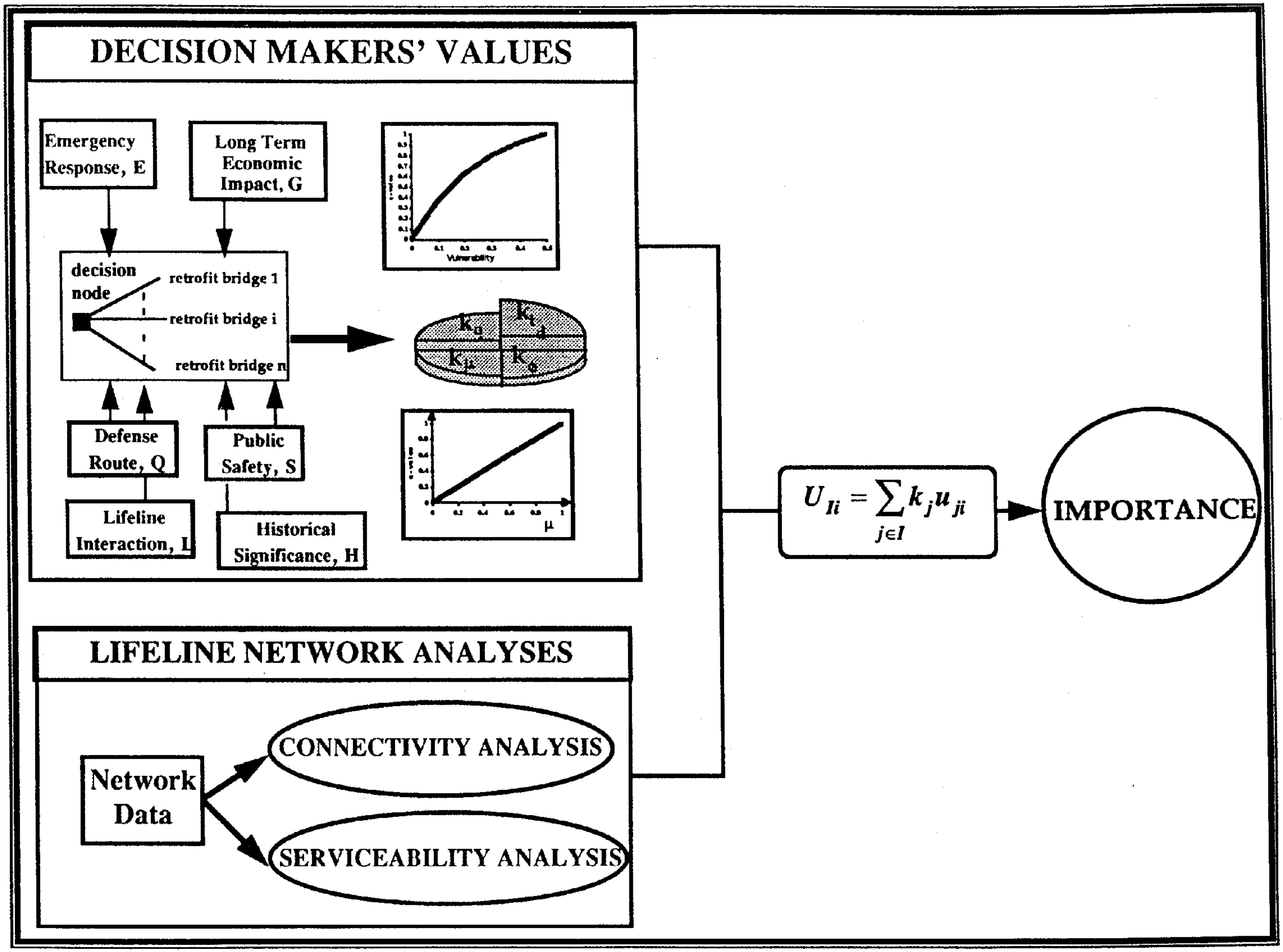


Figure 3.3 Steps of Importance Assessment

For this purpose, utility functions and scaling factors need to be defined for each of the factors listed above. For importance criterion factors ***S, Q, L*** and ***H,*** general utility functions are defined and u_{ji} are calculated for each bridge. The higher the u_{ji}, the more important is the bridge with respect to a given factor ***j***.

For emergency response factor ***E***, the u-value is calculated in two levels. In level one, the u-values corresponding to critical bridge sets are considered and the rank order of these u-values are calculated including u-values for vulnerability. A critical bridge set is mainly defined as the set of bridges that would destroy the connectivity of a disaster area from the available resources locations. However, bridge sets that cause unacceptable time delays for emergency response are also considered critical. In level two, the u-values for bridges within a given critical set are evaluated in order to obtain a unique u-value for each bridge. Connectivity analysis of the transportation network is employed both for level one and level two. The network analysis methods and formulation of u-values for level one and level two are discussed extensively in Chapter 6.

For the importance criterion, ***G***, the economic loss can be defined as a function of the users' time delay. This requires serviceability analysis of the network system solving a dynamic traffic assignment (DTA) problem which includes the capacity and the service level of the bridge in the analysis. Several papers can be found in the literature on DTA problem (Ran et al., 1993, Janson, 1991 and Wie et al., 1990). In order to relate user time to prioritization, one needs to determine the contribution of each bridge or bridge sets to the users' time delay. This further requires to consider the system optimization with different damage states for the bridges where the objective is to minimize the users' time delay. However, development of such a system optimization method is beyond the scope of this project.

The synthesis of the importance and vulnerability criteria is the basis of the ranking methods presented in this research. The final ranking for bridge ***i*** defined as a function of vulnerability and importance in equation (3.3) can further be expressed as follows:

$$\hat{U}_i = k_V U_{Vi} + k_I U_{Ii} \tag{3.8}$$

where $\hat{U}_i$ = u-value for bridge i to be used in obtaining R_i,

k_V = Scaling factor for vulnerability,

k_I = Scaling factor for importance,

U_{Vi} = Utility value for vulnerability (see equation (3.4) for definition of V), and

U_{Ii} = Utility value for importance (see equation (3.7) for definition of I).

Bridges in set $\{B\}$ are then ordered by decreasing values of $\hat{U}_i$.

Equations (3.2) through (3.8) can also be used for ranking bridges due to expected loss. However, in this case damage-dollar loss relations need to be included in the utility functions for vulnerability and importance criteria.

A more detailed discussion of each component of prioritization method is given in the following chapters.

CHAPTER 4

CLASSIFICATION OF BRIDGES

Physical damage due to seismic loading can be related to structural properties of the bridge. Bridge classes can be defined to distinguish bridges with different seismic behavior. Currently, only two bridge classifications are known to the authors. The first one is included in the Earthquake Engineering Facility Classification of ATC-13 (1985) and the latter is included in the Draft Technical Manual of the ongoing project for National Institute of Building Sciences (Risk Management Solutions, 1994 a, b).

The Earthquake Engineering Facility Classification of ATC-13, characterizes structures in terms of their size, structural system and type. This classification reflects the dependence of earthquake induced physical damage on the structural properties. ATC-13 defines only three Earthquake Engineering Facility Classes for bridges. In the NIBS Draft Technical Manual bridges are classified based on their type and seismic design. In addition, an identifier based on the superstructure irregularity, age of bridge and number of spans, is included for the "high risk" bridges. Tables 4.1 and 4.2 list the bridge classes of ATC-13 and NIBS Draft Technical Manual, respectively.

Important Attributes of Bridges in Classification	Facility Number
• Conventional (less than 500 ft spans)	
a) Multiple Simple Spans	24
b) Continuous/Monolithic (includes single-span)	25
• Major (greater than 500 ft spans)	30

Table 4.1 Earthquake Engineering Facility Classification - Bridges (from Table 3.1 in ATC-13)

The Earthquake Engineering Facility Classes are defined so broadly that it is hard to define bridge behavior represented by a specific class. Several experts have stated that they had difficulty in responding to questions related to Facility Class 24, multiple-span bridges or bridges with hinges, because the "damage would be very different for a bridge that is single simple span than for a bridge composed of several simple spans" (ATC-13). The NIBS bridge classification

Name	Description
HBR1	Major Bridge - Seismically Designed
HBR2	Major Bridge - Conventionally Designed
HBR3	Continuous Bridge - Seismically Designed
HBR4	Continuous Bridge - Conventionally Designed
HBR5	Simply-Supported Bridge - Seismically Designed
HBR6	Simply-Supported Bridge - Conventionally Designed

Table 4.2 NIBS Highway Bridge Classification

addresses some of these issues by introducing a "high risk" identifier. For example, high vulnerability of multiple simply-supported bridges is recognized and those bridges are identified as "high risk". However, this classification does not enable one to distinguish between different seismic behavior of bridges with different material and structural types. Another dilemma is encountered with the age attribute of bridges because only bridges designed before 1960 are deemed to be "high risk" in this manual. However, as the application time for the seismic bridge design specifications might change from state to state, use of a single identifier may cause inconsistencies.

As mentioned in ATC-13, a more detailed definition of bridge classes is necessary in order to respond and clarify comments specific to facility classes. A more refined classification will give a better understanding of the behavior of bridges under seismic loading. For this purpose, the existing classes have to be increased in number and detail, i.e., it is essential to formulate new bridge classes. However, it is not possible to consider every characteristics of the bridge structure in the classification. Nor is it practical to specify a large number of bridge classes.

Any existing bridge has its own characteristics due to its structural properties, location and construction. However, bridges with similar structural properties are expected to show the same type of seismic performance under a given seismic loading. Furthermore, it is expected that bridges within the same group will experience similar damage levels under the same seismic loading. Based on these ideas, new bridge classes have been developed to classify bridges with similar structural properties.

In addition, it is necessary to classify existing bridges into predefined bridge classes so that vulnerability of a given bridge can be assessed. For this purpose a classification method that uses a relational database management system (RDBMS) and a knowledge-based expert system (KBES) has been developed. The bridge class definitions and the developed classification method are discussed in the following sections.

4.1 BRIDGE CLASS DEFINITIONS

Primary structural attributes $\boldsymbol{Y}$, are used in defining the bridge classes. Figure 4.1 shows the elements of $\boldsymbol{Y}$ and their hierarchical scheme. The hierarchical order of the selected attributes is important as it might affect the vulnerability rating.

In Figure 4.1, the *material type* Y_1 refers to the material of the substructure which can have the possible values as listed below:

$$Y_1 = \begin{Bmatrix} y_{11} \\ y_{12} \\ y_{13} \\ y_{14} \end{Bmatrix} = \begin{Bmatrix} concrete \\ steel \\ timber \\ masonry \end{Bmatrix} \tag{4.1}$$

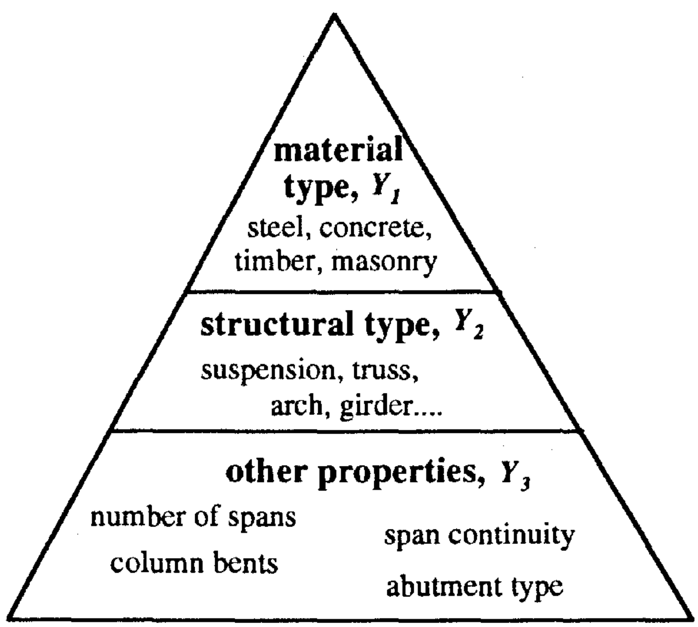


Figure 4.1 Hierarchical Ordering for Primary Structural Attributes

Structural type Y_2 represents the superstructure configuration. Possible values considered in the classification are given below:

$$Y_2 = \begin{Bmatrix} y_{21} \\ y_{22} \\ y_{23} \\ y_{24} \\ y_{25} \end{Bmatrix} = \begin{Bmatrix} \textit{concrete girder} \\ \textit{steel girder} \\ \textit{steel truss} \\ \textit{suspension} \\ \textit{arch} \end{Bmatrix} \tag{4.2}$$

In order to define bridge classes, initially $\overline{Y}$ and δ are defined as follows:

$$[\overline{Y}] = [Y_1] \times [Y_2]^T \tag{4.3}$$

where $\overline{y}_{kr}$ = kth row rth column element of $[\overline{Y}]$, and

$$\delta = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 \end{bmatrix} \tag{4.4}$$

where δ = Indicator matrix for existence of a given combination,

$\delta_{kr} = 1$ $\Rightarrow$ the kth row rth column element of $Y_1 \times Y_2$ matrix is considered in the classification, i.e., bridge construction for this combination exists,

$\delta_{kr} = 0$ $\Rightarrow$ the kth row rth column element of $Y_1 \times Y_2$ matrix is *not* considered in the classification, i.e., bridge construction for this combination does *not* exist.

Then bridge classes C_n, are defined as the combination of material and structural type of bridges such that:

$$(C_n)_{kr} = \delta_{kr} * \overline{y}_{kr} \tag{4.5}$$

where C_n = Bridge class n where n is the bridge class number and $n \in \eta$,

η = Bridge class identifier matrix defined as follows:

for $n = 2k + r - 2 < 6$;

$$\delta_{kr} * (y_{1k} y_{2r}) \in C_n, \qquad n < 6, \; k = 1, 2 \;\; r = 1, 2, 3 \tag{4.6.a}$$

otherwise;

$$\delta_{kr} * (y_{1k} y_{24}) \in C_n, \quad n = 6, \; k = 1,2 \quad r = 4 \tag{4.6.b}$$
$$\delta_{kr} * (y_{1k} y_{25}) \in C_n, \quad n = 7, \; k = 1,2 \quad r = 5 \tag{4.6.c}$$
$$\delta_{kr} * (y_{13} y_{2r}) \in C_n, \quad n = 8, \; k = 3 \quad r = 1,...,4 \tag{4.6.d}$$
$$\delta_{kr} * (y_{14} y_{2r}) \in C_n, \quad n = 9, \; k = 4 \quad r = 1,...,4 \tag{4.6.e}$$

For example, for a concrete substructure (y_{11}), and a concrete girder superstructure (y_{21}), k =1, r = 1, $n = 2k + r - 2 = 1 < 6$ and $\delta_{11} = 1$. Then, $1 * y_{11}y_{21}$ implies bridge class 1 (C_1). As another example consider a timber substructure (y_{13}) and suspension superstructure (y_{24}). In this case, k =3, r = 4 and $n = 2k + r - 2 = 8 > 6$. The combination of k = 3 and r = 4 is only considered for n = 8. However, δ_{34} = 0 implies that this type of bridge construction does not exist and therefore a corresponding bridge class is not included. The indicator matrix for existence of a given super- and substructure combination, δ , is defined based on bridge construction in California. If needed, the bridge class definitions presented herein can be modified for construction practices in other regions.

Bridge Class Identifier, η	**Substructure Material, Y_1**	**Superstructure Material/Type, Y_2**
1	concrete, (y_{11})	concrete girder, (y_{21})
2	concrete, (y_{11})	steel girder, (y_{22})
3	concrete, (y_{11})	steel truss, (y_{23})
4	steel, (y_{12})	steel girder, (y_{22})
5	steel, (y_{12})	steel truss, (y_{23})
6	concrete/steel, (y_{11}/y_{12})	suspension/cable-stayed, (y_{24})
7	concrete/steel/timber/masonry, ($y \in Y_1$)	arch, (y_{25})
8	timber, (y_{13})	any structure type except arch, ($Y_2 \setminus y_{25}$)
9	masonry, (y_{14})	any structure type except arch, ($Y_2 \setminus y_{25}$)
10	concrete/steel/timber/masonry, ($y \in Y_1$)	others, ($y \notin Y_2$)

Table 4.3 Bridge Classes

Table 4.3 lists ten bridge classes defined by equations 4.3 through 4.6. The first nine bridge classes are not all-inclusive. Hence the tenth bridge class is listed for bridges that do not belong to any of the other nine classes. However, based on statistical analysis of bridge data in California, it has been concluded that about 95 percent of the bridges can be assigned to one or more of the first nine bridge classes. Bridges that belong to bridge class ten include movable bridges. Development of a generic fragility curve might not be very efficient for bridges that belong to bridge class ten. The number of such bridges is very small and bridge specific analyses should be performed.

The third level in the hierarchy, $\boldsymbol{Y_3}$, illustrated in Figure 4.1 consists of the following structural attributes:

$$\boldsymbol{Y_3} = \begin{Bmatrix} y_{31} \\ y_{32} \\ y_{33} \\ y_{34} \end{Bmatrix} = \begin{Bmatrix} \textit{number of spans} \\ \textit{abutment type} \\ \textit{span continuity} \\ \textit{piers or bents} \end{Bmatrix} \tag{4.7}$$

In equation (4.7), abutment type also includes bearing type. For example, if the abutment is a seat type, i.e., non-monolithic, then the vulnerability of a bridge with rocker bearings will be different than a bridge with elastomeric padding. Span continuity is defined as a function of joints in the superstructure. For each bridge class $\boldsymbol{C_n}$, four sub-categories are defined. Foremost, each bridge class is divided into two based on y_{31}, as single span bridges and multiple span bridges. Then least and most vulnerable bridge characteristics are defined for both single and multiple span bridges as a function of $\boldsymbol{y} \in (\boldsymbol{Y_3} \setminus y_{31})$, where \ is a negation sign and $\boldsymbol{i} \setminus \boldsymbol{j}$ represents set $\boldsymbol{i}$ not including $\boldsymbol{j}$. A bridge class sub-category is expressed by the notation $\boldsymbol{C_n}^{y_{31}\boldsymbol{h}}$,

where y_{31} = Number of spans; where $y_{31} = s$ for single span bridges and $y_{31} = m$ for multiple span bridges, and

$\boldsymbol{h}$ = Level of vulnerability; where $\boldsymbol{h} = l$ for least vulnerable and $\boldsymbol{h} = m$ for most vulnerable bridge categorization.

For single span bridges the substructure material type is irrelevant. Hence, single span bridges with the same structural type belong to the same bridge class sub-category regardless of their material type, e.g., $\boldsymbol{C_2}^{sh}$ and $\boldsymbol{C_4}^{sh}$, or $\boldsymbol{C_3}^{sh}$ and $\boldsymbol{C_5}^{sh}$ have the same characteristics. Table 4.4 gives the generic sub-category definitions for a given bridge class, $\boldsymbol{C_n}$. A complete list of the ten bridge classes is given in Appendix A.

Bridge Class C_n (y_{1k}, y_{2r})

$y_{31} = 1$ (single span)

C_n^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_n^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_n^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_n^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Table 4.4 Generic Sub-Category Definitions for Bridge Classes

4.2 CLASSIFICATION OF EXISTING BRIDGES

In order to classify existing bridges, it is necessary to compile, manipulate and analyze all the necessary bridge attributes. Use of a systematic procedure enables a consistent and time efficient ranking process for the large number of bridges that are of interest for ranking purposes. As relational database management systems (RDBMS) in general prove to be a powerful tool in classifying and organizing the available data, in this research such a system is utilized for compilation and manipulation of the bridge data. In addition, a knowledge-based expert system (KBES) -**ESCOB**- that enables to code the expert opinion has been developed to classify a particular bridge into one or more of the ten bridge classes, C_n. **ESCOB** (Expert System for Classification of Bridges) is described in detail in Section 4.2.2. In the remaining of this chapter, data manipulation and inference tools are briefly introduced and **ESCOB** is presented. The difficulties encountered in classification and their suggested solutions are discussed in the next section.

4.2.1 Data Manipulation and Inference Tools

4.2.1.1 Relational Database Management Systems

A database provides a way to organize facts pertaining to the problem in such a way that the solution can be achieved systematically. In theory, it is possible to design a single, massive database to address every detail of a given problem. In most of the database management systems, however, setting up a number of different databases that the full problem uses to pull together the needed information proves to be a better method. A system using this kind of a database is known as the *relational database management system* (RDBMS). The term relational refers to the fact that the component databases are logically related to one other. For example, information on the transportation network and structural characteristics of a bridge can be stored in two separate databases. Figure 4.2 shows an example that illustrates the logical relation provided by the bridge number in the two databases. Using these two databases and a RDBMS, it is easy to create different sets of information as needed. Following are some of the numerous benefits that RDBMS offer (Ullman, 1988):

- easy and efficient data access,
- flexibility in data modeling,
- reduced data storage and redundancy,
- independence of physical storage and logical data design and
- a high level structured query language.

In this study, dBASE 5.0 for Windows has been used as a RDBMS for storage and efficient management of the sizable amount of data in the bridge inventory.

4.2.1.2 Knowledge-based Expert Systems

A computer program that performs a task normally done by an expert or consultant and that uses captured, heuristic knowledge is called a knowledge-based expert system (KBES). (Dym and Levitt, 1991). The progress in the program is controlled by a tightly knit module in which the rules to be tested and applied are determined in advance. In a knowledge-based system, unlike the conventional programming the sequence of rule firing is determined by an inference engine that is contained within the program, and the conditions required to fire any rule(s) may lead to multiple actions or to no action at all. The collection of rules in such a system may incorporate heuristics or rule of thumb that are accumulated by an expert over years of problem solving. This allows the expert system to reason as it performs a task, as well as adapt

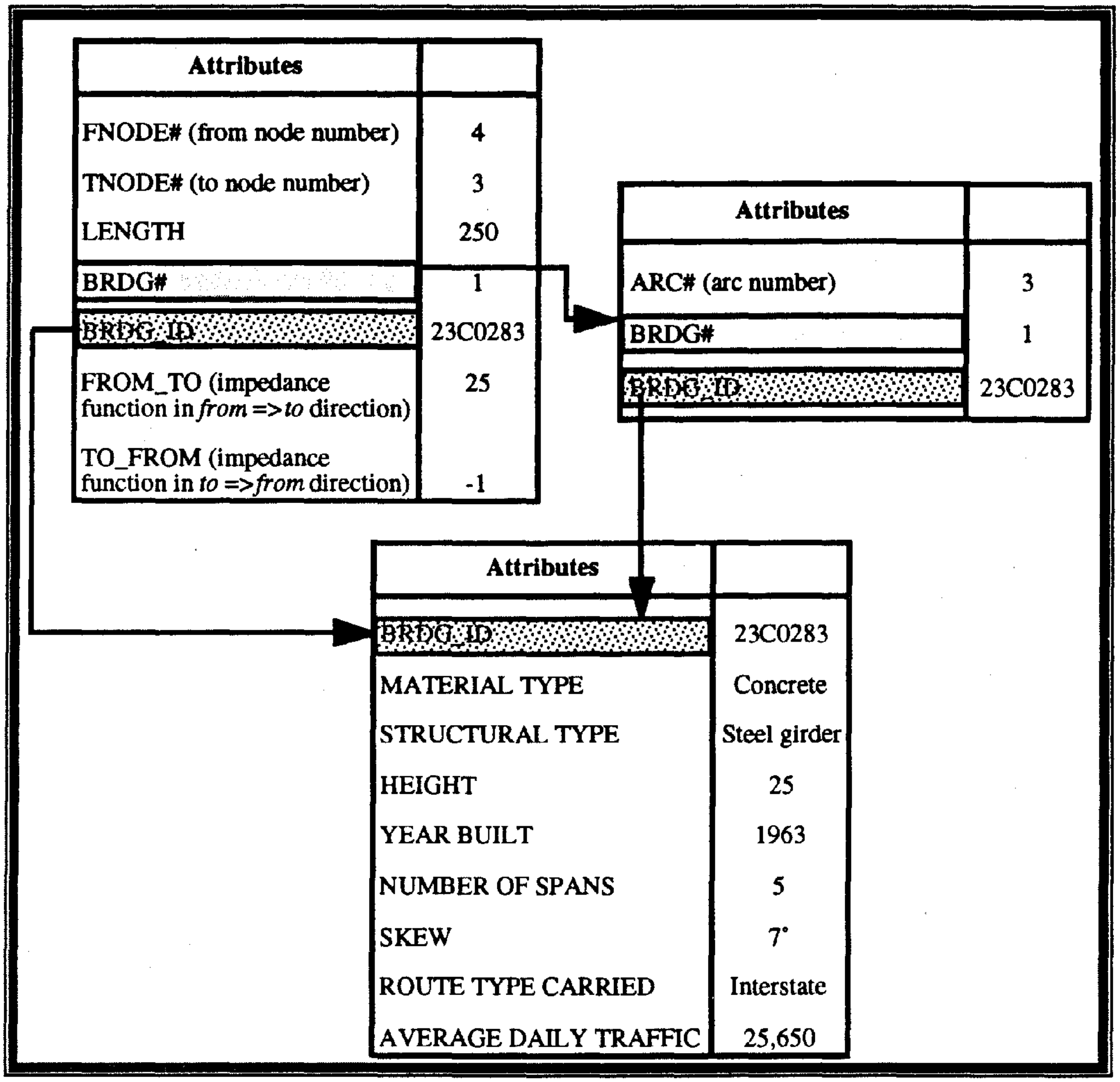


Figure 4.2 A Sample Relational Database

to new data or new situations. The distinctions between conventional algorithmic programming and the knowledge-based programming, and basic architecture of KBES are discussed in Appendix C.

4.2.1.3 Object-Oriented Programming

Object-oriented programming (OOP) is a way of structuring programs so that a particular type of data and the parts of a program that process that type of data are combined (Taylor, 1989). Data and the functions that process them are collectively called *object*. Thus, data and functions to manipulate the data are associated in an object. All the variables that define the object's state are listed in an object definition that describes attributes of a class of object. When a new object of a given class is created, it is said to be instantiated. When a new object is instantiated, memory is allocated to contain the new object's variables, and it inherits specified properties from its upper level class. Objects contain both variables that define their state and a list of functions that manipulate the variables. As new objects inherit variables and functions from prior object definitions, it is easy to define objects that are similar to existing objects. For example, each bridge in the inventory has certain amount of information, such as material type, structural type, length, date of construction and etc. Instead of defining each of these variables for every single bridge in the inventory, one can define these variables for an object such that each bridge inherits the variables and can still store different values. Figure 4.3 shows an example to illustrate the use of object hierarchy. The top level object in Figure 4.3 is called **Bridges. BayAreaBridges** and **PaloAltoBridges** are the two classes of object **Bridges. PaloAltoBridges** has two instances, **PA_brdg1** and **PA_brdg2,** where an instance represents the lowest level of the hierarchy. The variables *name, location, material type* and *number of spans* are defined at the highest level, namely **Bridges** object and inherited by all the lower levels. Specific information is stored at the instance level for each bridge. The inheritance capability makes object-oriented programming an ideal tool for problems where manipulation of large collections of similar entities is required.

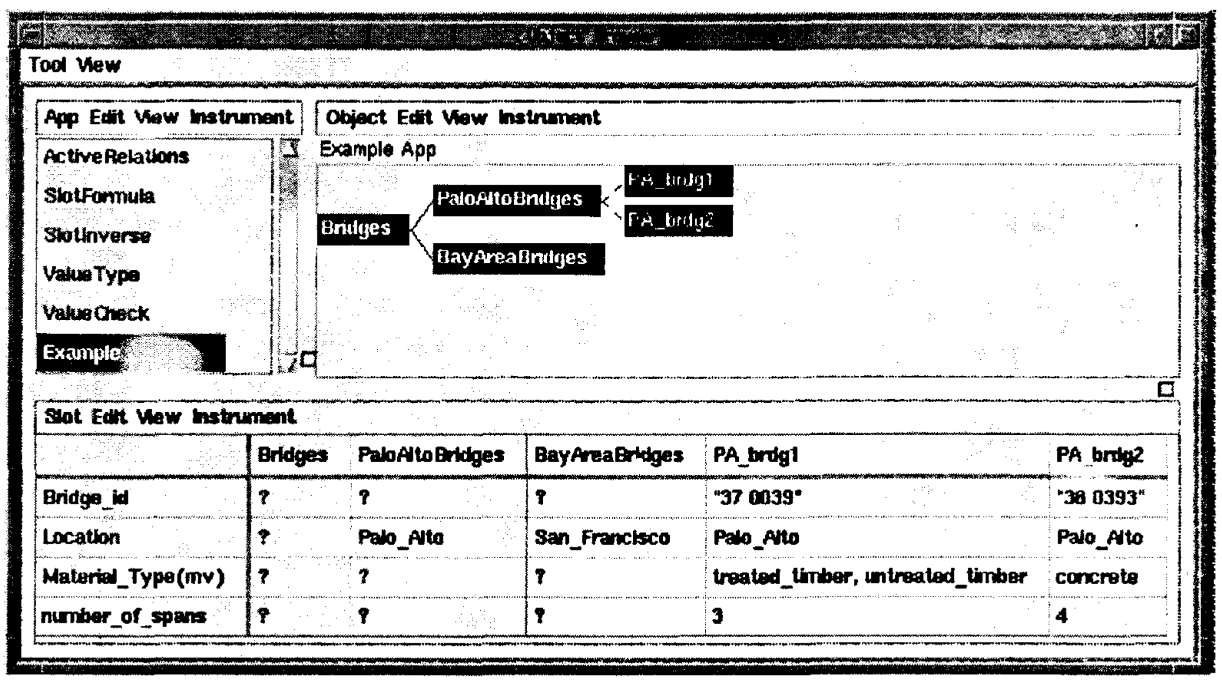


Figure 4.3 An Example of Object Hierarchy

4.2.2 ESCOB: Expert System for Classification of Bridges

4.2.2.1 Description of the KBES

The classification problem has been a prevalent topic since the first KBES applications. Different techniques have been established in solving classification problems of selection, diagnosis, interpretation, evaluation, prediction, and monitoring and control.

The number of bridges that are of interest for ranking purposes is usually large, thus classification of all the bridges becomes a massive task. It would be highly inefficient to classify such a large number of bridges without use of a computer. Conducting the prioritization task by different groups of individuals utilizing a nonsystematic procedure could cause inconsistencies. A KBES application has been deemed to be competent to the problem of classifying existing bridges into bridge classes. Hence, **ESCOB** has been developed to classify bridges into different classes by using attributes related to structural properties of the bridge and the definition of bridge classes. **ESCOB** uses the information of a specific bridge from the available database and classifies the bridge into one of the given bridge classes. Following are some of the advantages of the developed system:

- *Quality:* The results of classification of bridges are more precise (at the level of given definition of bridge classes).

- *Computational efficiency:* It takes shorter time to classify large number of bridges. The developed system is also designed in such a way that different expert opinions and bridge inventories can be used in the classification. This provides a wide range of applications.

- *Consistency:* All the bridges are classified based on the same judgment and heuristics. Thus, the ranking process has become a compatible process regardless of the size of the database.

- *Ability to use expert opinion*: Symbolic programming that is available in a knowledge-based expert system is used to code the expert opinion. In this research, the expert opinion is necessary both for incomplete information about the bridge attributes and classification of a bridge into more than one class. The necessity to match a bridge with several bridge classes and to estimate incomplete information about bridge attributes utilizing the expert opinion favors the use of an expert system to a conventional programming language in classification of existing bridges.

ESCOB utilizes the software ProKappa™ which provides an object-oriented software development environment. Furthermore, the software has a graphical user interface built in X Windows System and runs on a SUN workstation. The user interface(UI) provides capabilities for interaction of the user with the program at any time during the execution of the program.

4.2.2.2 Architecture of ESCOB

The system consists of numerous objects, subclasses and instances that inherit information from their parent objects. Figure 4.4 shows the object hierarchy in the developed system. The system can be divided into four main parts as follows:

i) BRIDGE CLASSES

Bridge classes defined in Table 4.4 are represented by an object called **BridgeClasses** and its subclasses. Primary structural attributes, Y, for each bridge class are stored as the slot values. Bridge classes use the inheritance property of object-oriented programming. For example, the attributes that are common to all bridge classes such as *structural type* or *abutment type* are defined at **BridgeClasses** level. Figure 4.5 shows the object hierarchy defined for the bridge classes. The bridge classes are stored at the instance level which is the lowest level of the hierarchy. Specific information for each bridge class is stored in slots of these instances. Values of the slots for the bridge classes as stored at the instance level are taken from Table 4.4. In Figure 4.5, bridge class sub-categories are denoted by a different notation. The last character of the bridge class name depicts the sub-category where *a* and *b* represent single span least and most vulnerable sub-categories and *c* and *d* represent multiple span least and most vulnerable sub-categories, respectively. For example, BC_1a is the equivalent to C_1^{sl}, (single span least vulnerable sub-category of class 1). Figure 4.6 lists the slots, i.e., attributes of some different level objects. The **BridgeClasses** object is the main module of the system that has many built-in properties. This characteristic of the system leads to a classification based on the new bridge class definitions as presented in this study. Modification of **ESCOB** would be necessary if it were the desire to use another bridge class definition. However, due to the large size of the required control mechanism, the modification of the system proves to be more efficient than designing a system that provides a built-in bridge class definition alteration.

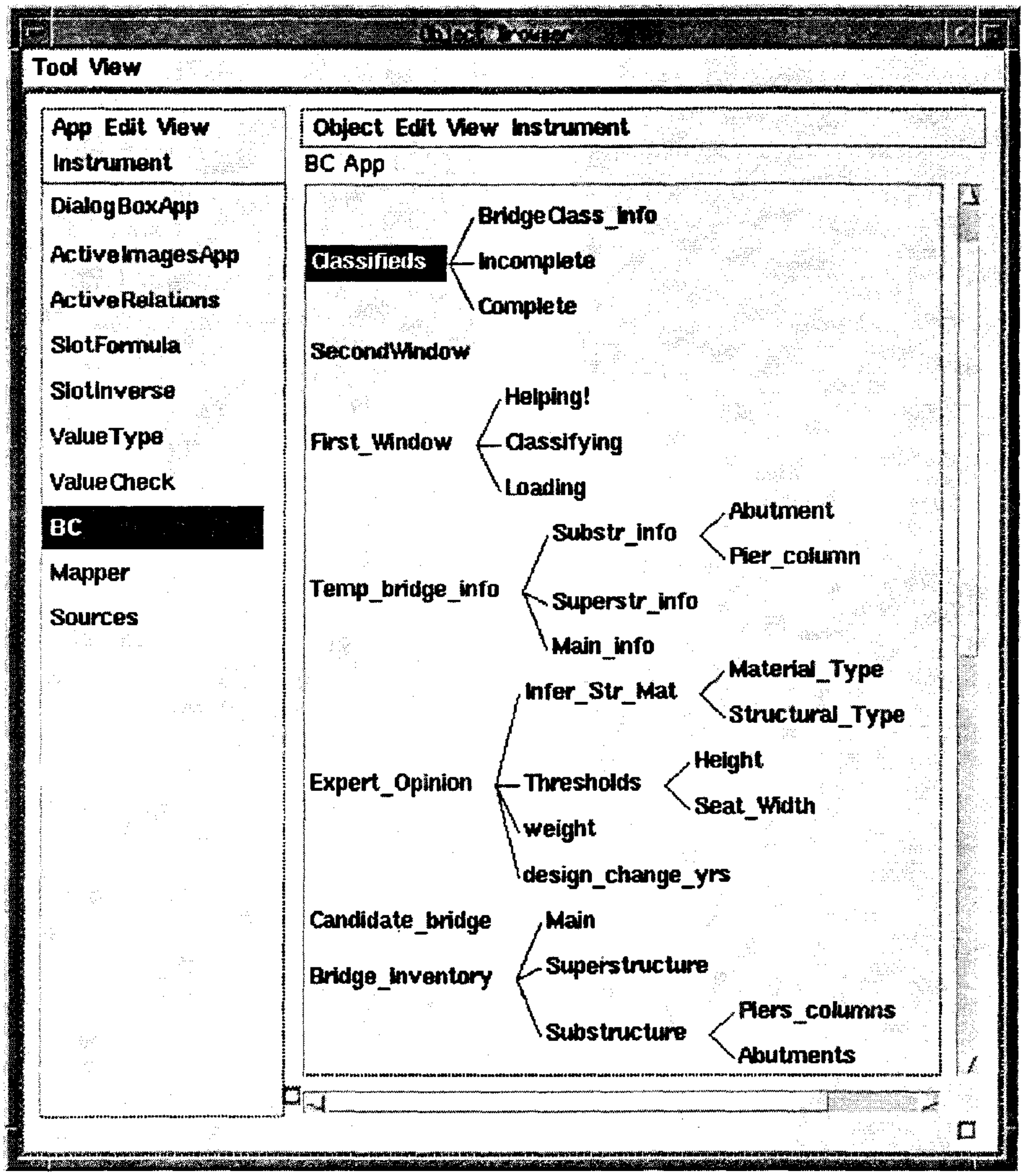


Figure 4.4 Object Hierarchy of ESCOB

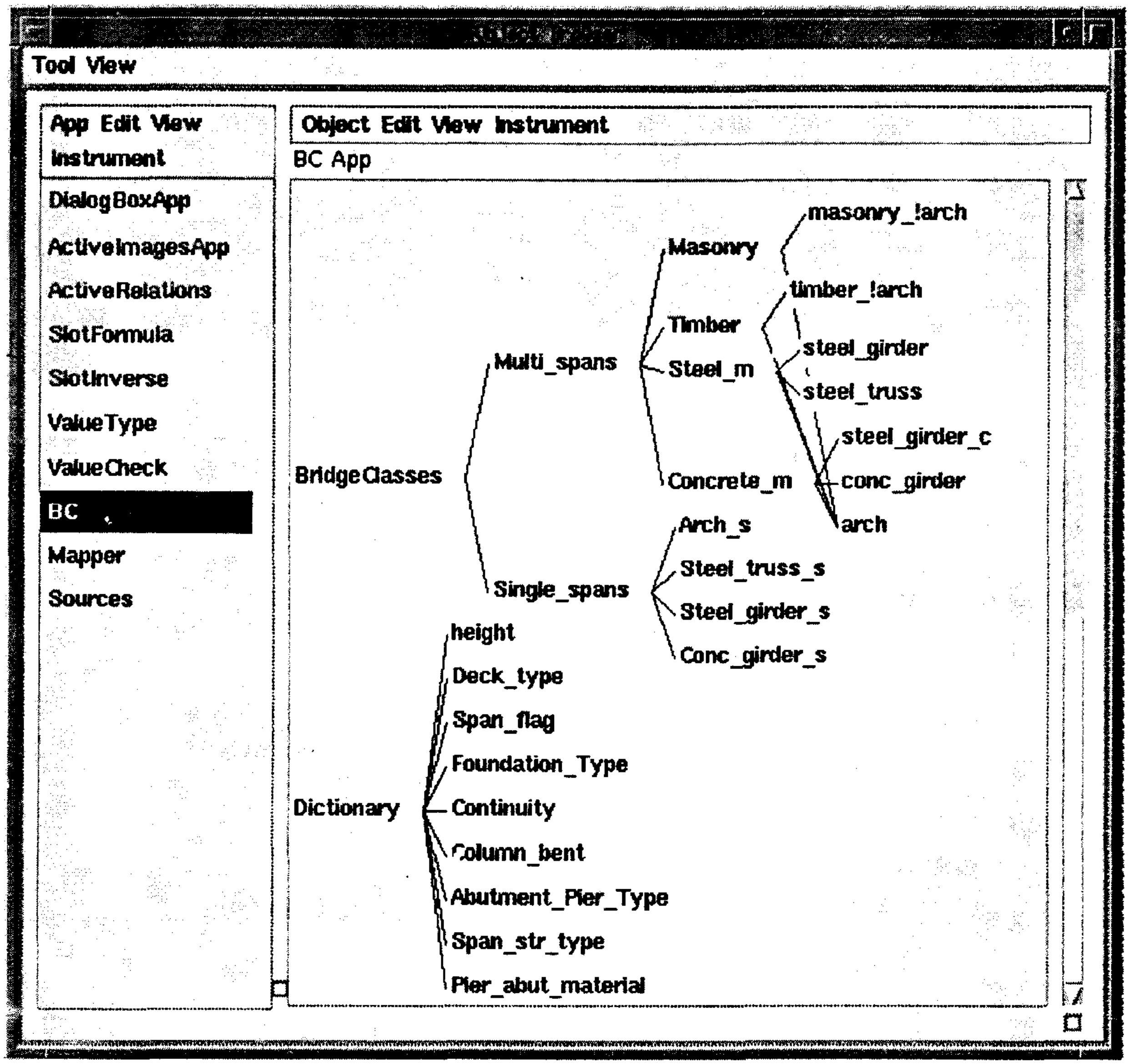


Figure 4.4 Object Hierarchy of ESCOB (continued)

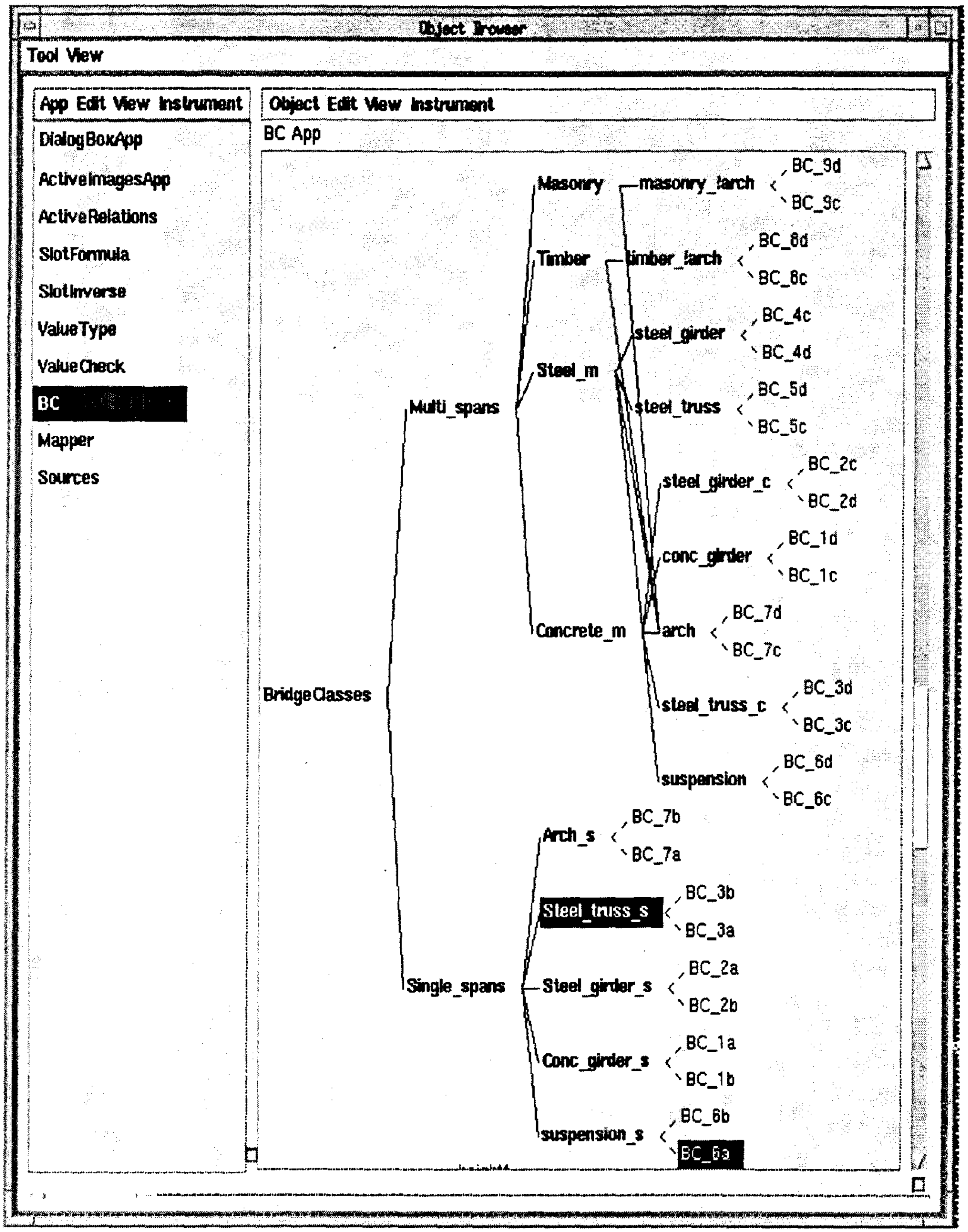


Figure 4.5 Bridge Class Object Hierarchy

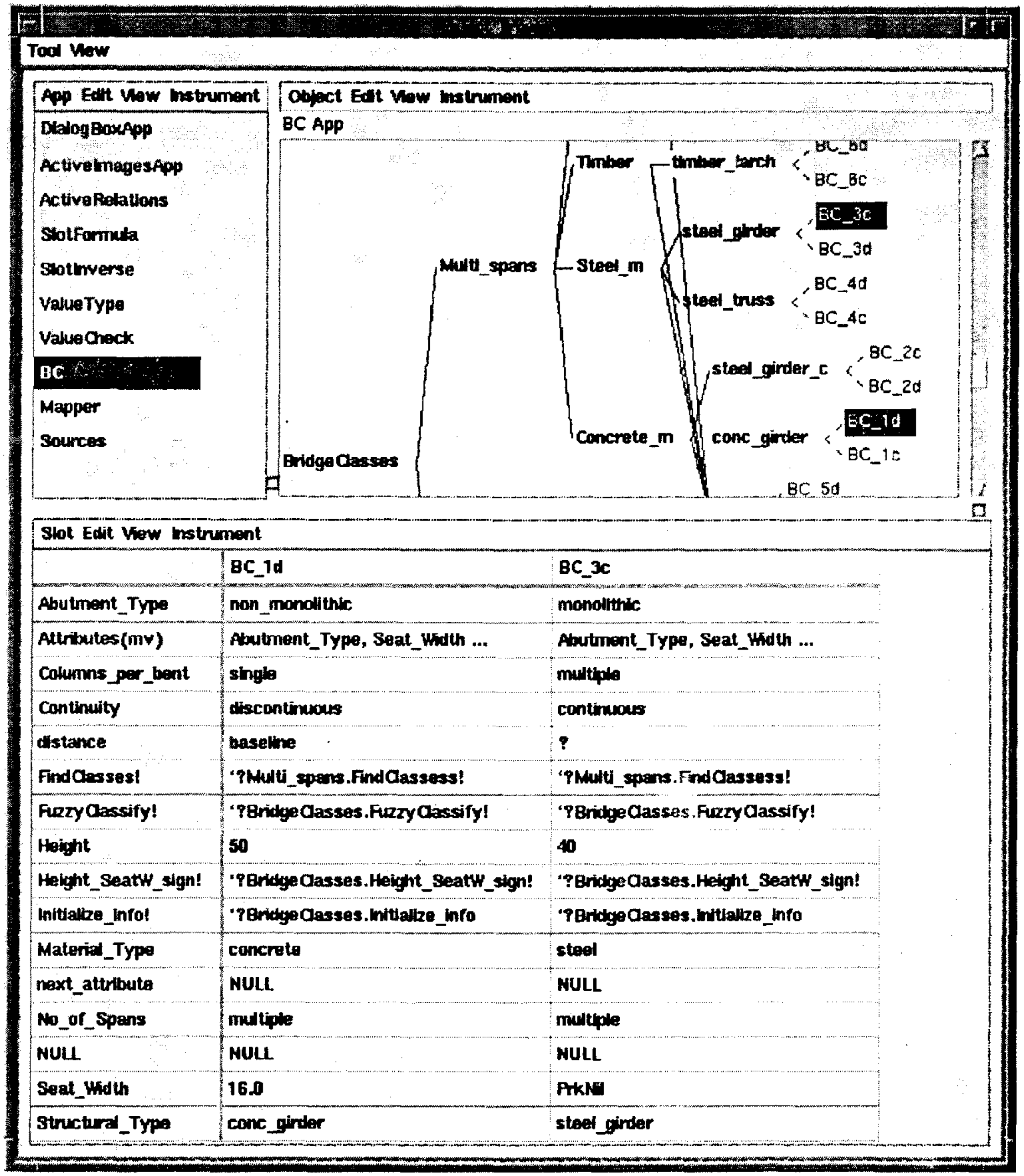


Figure 4.6 Attributes of Bridge Classes in the Object Hierarchy

ii) INPUT

The panel with action buttons as shown in Figure 4.7 provides user interface at the start of the system. The three buttons on the **Start_up_panel** are designed to initiate the data loading and classifying tasks. The **Start_up_help!** button is designed for new users such that it spells out the steps to follow in order to start the system.

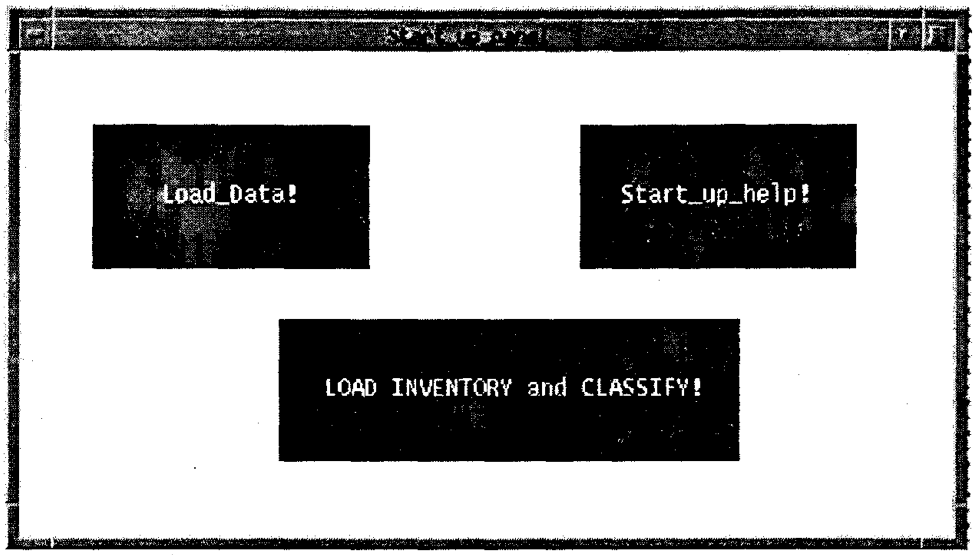


Figure 4.7 User Interface at the Input Level

Following tasks are executed at the input stage:

LOAD_DATA button activates the input tasks of the system which are described in order below.

a) *Initialize and load expert opinion.* Some of the information for the new bridge classes, such as relative importance of attributes within each class, are obtained from expert opinion. The necessary expert opinion and its characteristics will be discussed in Section 4.2.3.1. Such information may vary from location to location or expert to expert. For the purpose of a flexible system, the expert opinion is obtained as input from the user in the form of ASCII text files.

The information on expert opinion is stored in the instances of the top level object **Expert_Opinion**. The instances are created when reading data from the text file into the system. For each new run, the instances are initialized and new information is obtained from the text files.

b) *Initialize and load dictionary.* The bridge class attributes are defined by common terms as given in Table 4.4. For example, if the bridge has more than one span, **No_of_Spans** attribute takes the value of *multiple*, otherwise it takes the value of *single* where *multiple* and *single* are used as the common terms. The purpose of the dictionary is to map the coding of inventory data to that of bridge classes. For example, in an inventory substructure material type can be represented by symbol *C* and in another inventory it might be represented by symbol *B*. Both of these codes should be translated to common term *concrete* for classification purposes. Similar to expert opinion the dictionary is loaded from ASCII text files to make the system flexible. The instances are created for each subclass of the **Dictionary** object. As an example, sample text file and the mapping module for the abutment type attribute are given in Table 4.5 and Figure 4.8 respectively.

Identifier	Inventory Code	Description	Common Term	Scale
Abtyp1	A	Diaphragm	monolithic	0.0
Abtyp2	B	Seat	non-monolithic	1.0
Abtyp3	C	Cantilever	non-monolithic	1.0
Abtyp4	D	Strutted	non-monolithic	1.0

Table 4.5 Sample Dictionary File for Abutment Type

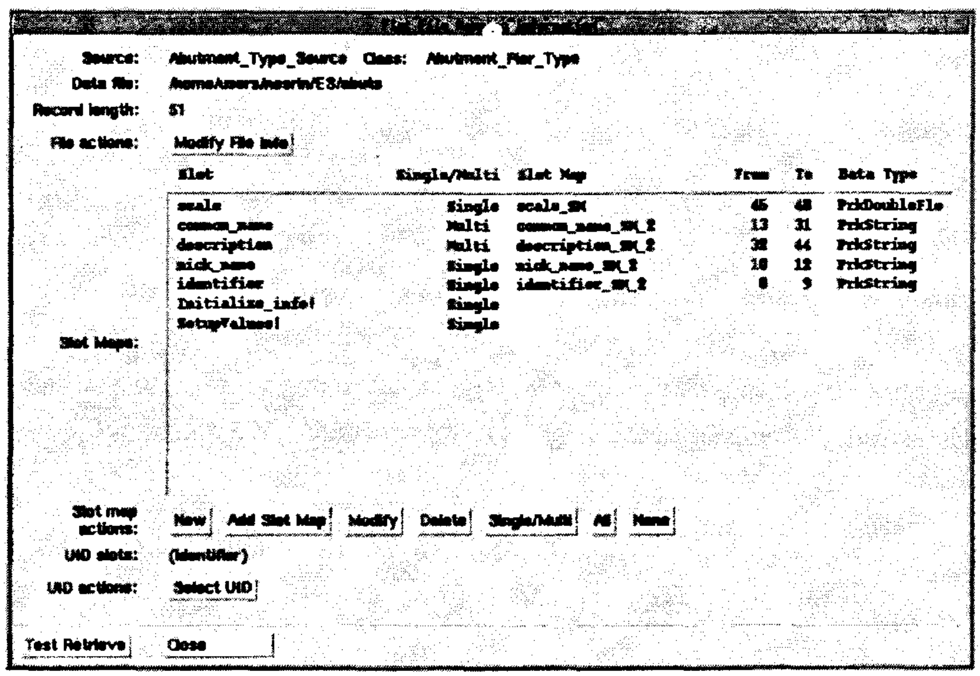


Figure 4.8 Mapping Module for Abutment Type Attribute

After the expert opinion and dictionary information are loaded, the user is informed by a dialogue box (Figure 4.9) that the initial information has been loaded and how to proceed.

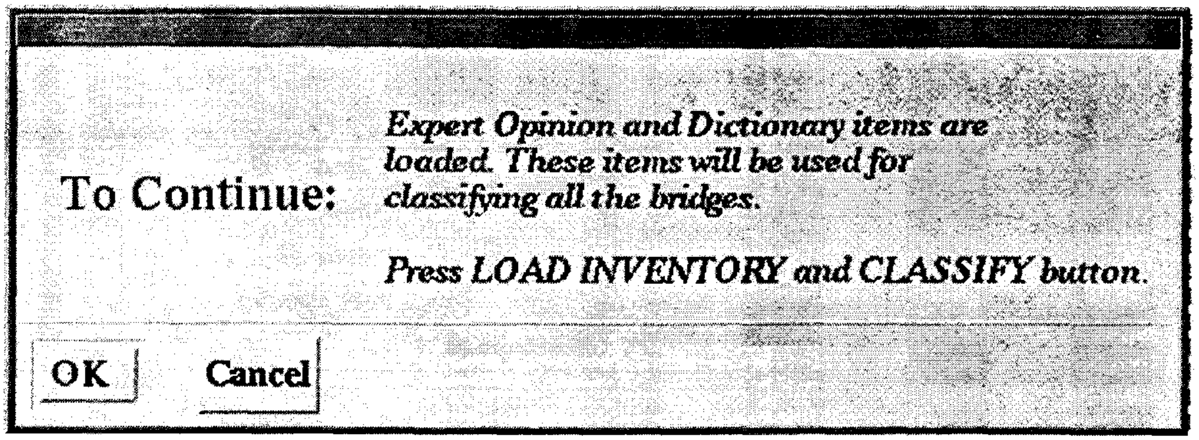


Figure 4.9 User Interface at Classification Level

c) *Initialize and load bridge inventory.* As the next step the bridge inventory is loaded. The bridge inventory is another item that might change. The system is developed in such a way that the bridge inventory mainly follows the database layout of CalTrans. However, this is not much different from FHWA format that some other states might be using. **Bridge_inventory** (see Figure 4.4) is the top level object where bridge information is stored. An instance is instantiated for each item that is loaded from ASCII text files. The attributes that form the slots of subclasses **Main, Superstructure,** and **Substructure** are shown in Figures 4.10 to 4.12.

iii) CLASSIFICATION

a) *Selection of a bridge.* The system selects one of the bridges from the inventory and stores the information in **Temp_bridge_info** object. This top level object functions as an intermediate point between the database and the candidate bridge that is used in classification.

b) *Mapping specific information to common terms.* Once the bridge is selected all the information for that bridge that is stored by specific codes in the inventory is converted to the common terms as will be used in classification. For example, the letter code *C* for material type slot value of **Pier_column** subclass is converted to *concrete* using the information loaded into **Pier_abutment_material** subclass of **Dictionary** object.

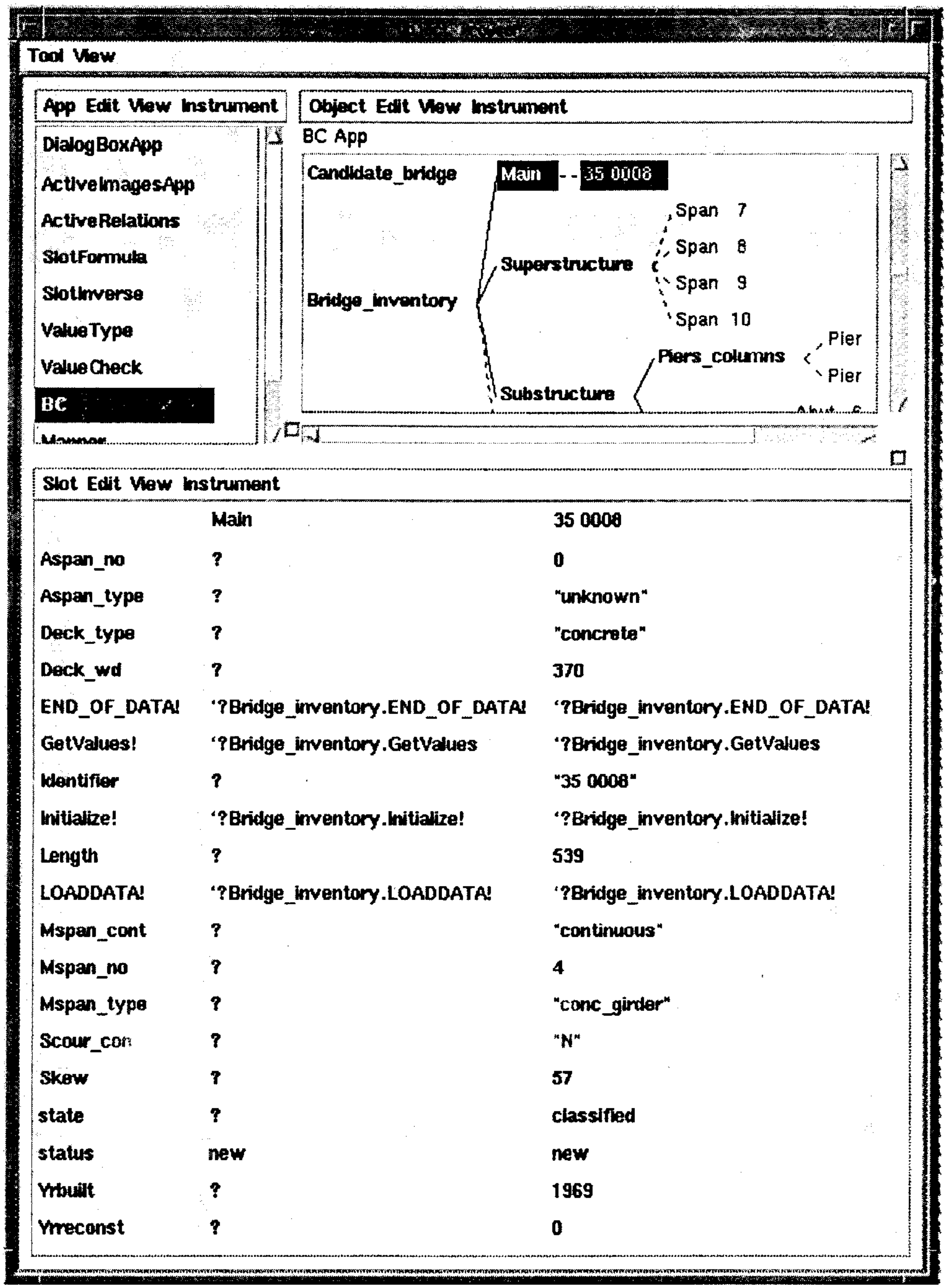


Figure 4.10 Subclass Main and its Slots

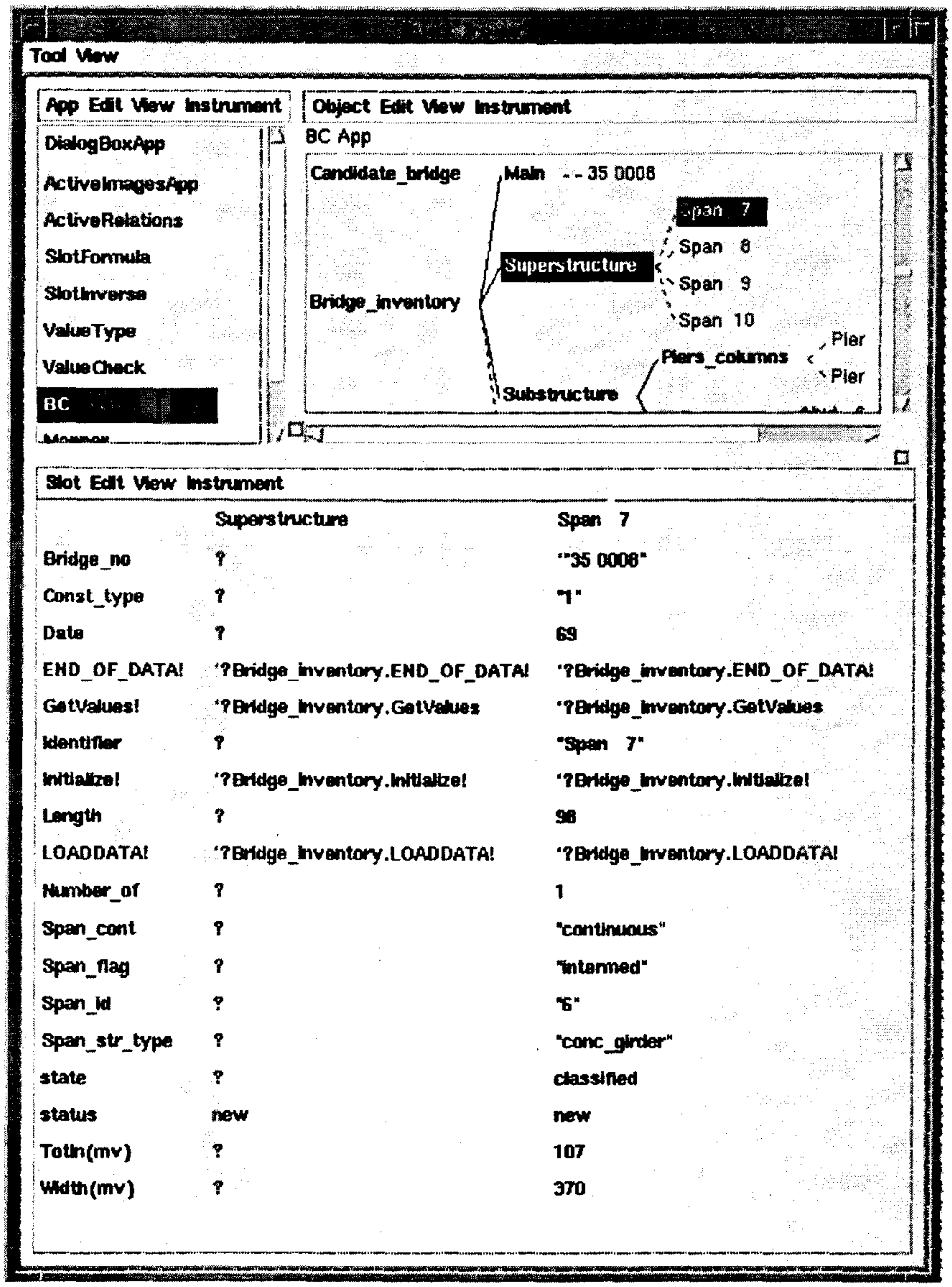


Figure 4.11 Subclass Superstructure and its Slots

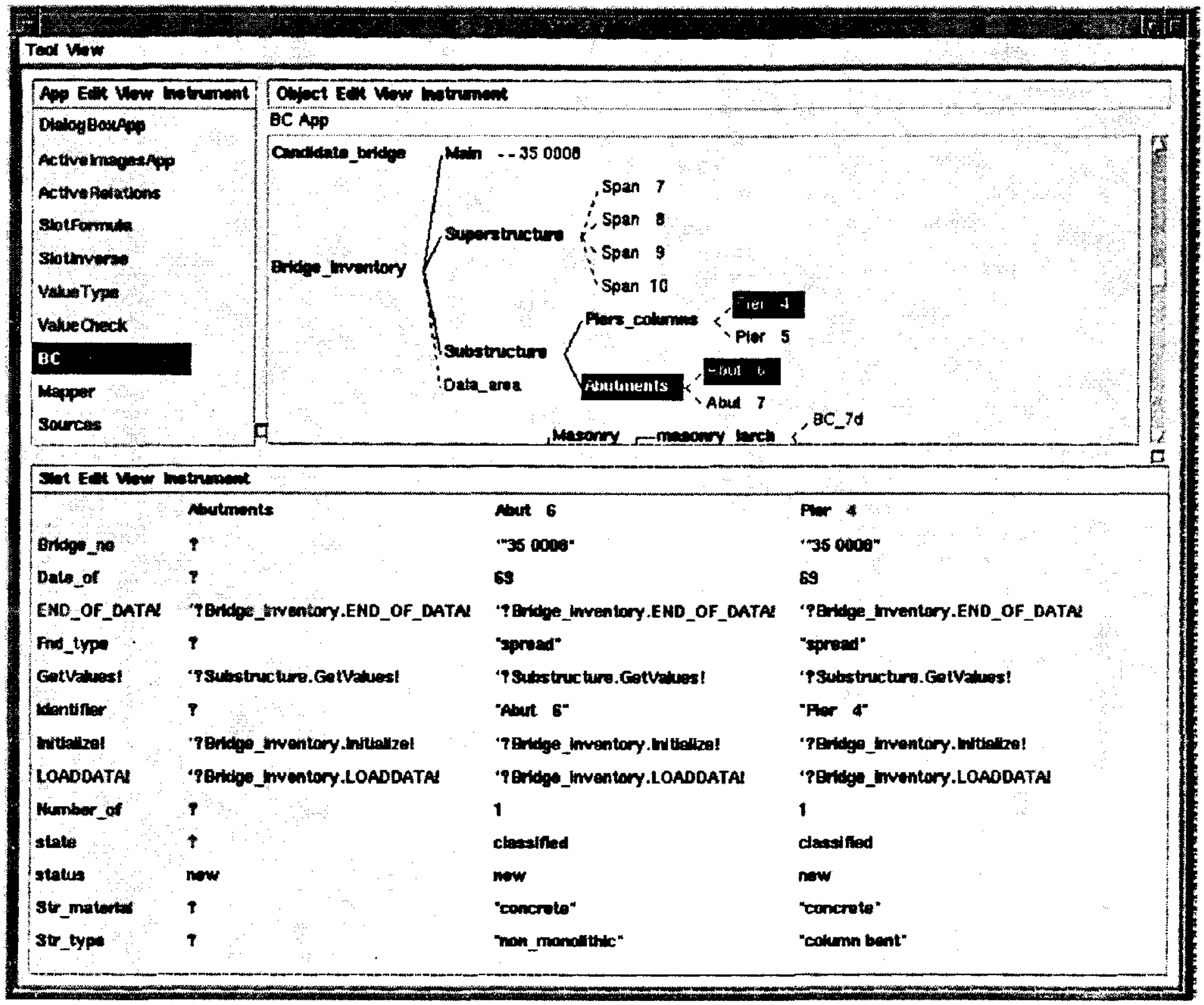


Figure 4.12 Subclass Substructure and its Slots

c) *Gathering the information needed for classification for a given bridge.* The values of the primary attributes which are needed for the classification are stored in slots of the **Candidate_bridge** object. At this stage, the system searches for all the available information in the inventory and in case of incomplete information it uses some heuristics to obtain the necessary information. Manipulation of incomplete information is discussed further in Section 4.2.3.2.

d) *Classification.* The system classifies the bridge that is stored in the **Candidate_bridge** object by using a searching algorithm. It classifies a given bridge into one of the bridge class sub-categories. If the attributes of the bridge yield a unique classification then the bridge is classified into one sub-category. Otherwise, the system classifies the bridge into two most appropriate sub-categories of a bridge class. (see Section 4.2.3.1).

iv) OUTPUT

a) *Conveyance of results.* The bridge class sub-category assigned to a given bridge is recorded in **Candidate_bridge** object. However, for output purposes an object called **Classifieds** is created. Each bridge is stored in the **Incomplete** or **Complete** subclass of the **Classifieds** object depending on the availability of the necessary information at the classification level. In the case of incomplete information, the attributes obtained from heuristic information are stored for explanation purposes.

Once all the bridges are classified by using the above procedure, the user is prompted by an information box that the classification has been completed. This box contains two buttons; **EXPORT_TO_FILE** and **SELECT_A_BRIDGE**. Selection of the **EXPORT_TO_FILE** button creates a text file containing the results.

b) *Explanation of results.* **SELECT_A_BRIDGE** button activates the explanation facilities which serve as a guide to the user for outputs. At the output level, the system provides dialogue boxes that describe and explain the attributes or the results. In addition, a complete list of bridges with the respective bridge classes is also available. The user interface (UI) is designed to present information for a specific bridge in which the user has interest.

4.2.3 Difficulties in Classification

Two major difficulties are encountered in the classification of existing bridges:

- Bridges that cannot be assigned into a unique bridge class sub-category,
- Bridges that have incomplete information.

The methods developed to overcome these difficulties are discussed in the following sections.

4.2.3.1 Classification of Bridges into Multiple Sub-categories of a Bridge Class

The bridge classes that are developed are rather general and serve the purpose of capturing the ground motion-damage relationships for some range of a specific attribute. It is not always possible to have an exact match between the attributes of a bridge and that of a bridge class sub-category. Most of the time some attributes of a bridge fulfill the properties of one sub-

Attributes	sub-category *i* (C_2^{ml})	sub-category *j* (C_2^{mm})	bridge *M*
material type, Y_1	concrete	concrete	concrete
structural type, Y_2	steel girder	steel girder	steel girder
no. of spans, (y_{31})	multiple	multiple	5
abutment type, (y_{32})	*monolithic*	non-monolithic	*monolithic*
span continuity, (y_{33})	continuous	*discontinuous*	*discontinuous*
piers or bents, (y_{34})	*multiple*	single	*5*

Table 4.6 Hypothetical Example for Bridge Classification

category, whereas some others satisfy another sub-category's properties. For example consider two bridge class sub-categories and a bridge with the attributes given in Table 4.6.

Bridge *M* has a concrete substructure (y_{11}) and a steel girder superstructure (y_{22}). Thus, it is classified into C_2 using equation (4.6). However, the bridge satisfies some third level attributes of each sub-category as listed in Table 4.6. That is, given that the bridge is in C_2, it can further be classified in sub-category *i* due to number of column bents and abutment type, where *i* represents the multiple span least vulnerable sub-category (C_2^{ml}). Based on span continuity requirement it can be classified in sub-category *j* - multiple span most vulnerable sub-category. In such a situation, it is not possible to directly assign bridge *M* into either sub-category.

In order to classify a bridge into two sub-categories of a given bridge class, a method is developed that uses a well-known pattern recognition concept based on Euler distance measurement. For this method, the attributes that belong to third hierarchy level, Y_3 (see Figure 4.1), are scaled between 0 and 1. The sub-categories (C_n^{sl} and C_n^{sm} for single span bridges or C_n^{ml} and C_n^{mm} for multiple span bridges) are defined as the lower and upper bounds, 0 and 1 respectively. That is, a bridge can be assigned to either C_n^{sl} or C_n^{sm} (similarly to C_n^{ml} or C_n^{mm}) if its attributes match to that of sub-category C_n^{sl} or C_n^{sm} (to C_n^{ml} or C_n^{mm} for the latter case). For simplicity the following notations will be used in the remaining of this report:

$C_n^1 = C_n^{sl}$ = Single span least vulnerable sub-category of bridge class n,

$C_n^2 = C_n^{sm}$ = Single span most vulnerable sub-category of bridge class n,

$C_n^{\,3} = C_n^{\,ml}$ = Multiple span least vulnerable sub-category of bridge class n,
$C_n^{\,4} = C_n^{\,mm}$ = Multiple span most vulnerable sub-category of bridge class n.

Once the sub categories and the attributes of a given bridge i are defined in terms of scaling numbers, the following equations can be used to express the percent amount that a given bridge belongs to a given sub-category.

$$\Delta_{ij} = \sum_k [w_{kj} * (\sigma_{ki} - \sigma_{kj})^2]^{1/2} \tag{4.8}$$

where Δ_{ij} = Distance between bridge i and bridge class n sub-category $C_n^{\,j}$,
w_{kj} = Weight of attribute k for bridge class n sub-category $C_n^{\,j}$,
σ_{ki} = Scaling value of attribute k for bridge i,
σ_{kj} = Scaling value of attribute k for bridge class n sub-category $C_n^{\,j}$, (0 or 1) and
k = 1 or 2 for single span bridges, 3 or 4 for multiple span bridges.

$$\overline{\Delta}_{ij} = \frac{\dfrac{1}{(\Delta_{ij})^2}}{\sum_k \dfrac{1}{(\Delta_{ik})^2}} \tag{4.9}$$

where $\overline{\Delta}_{ij}$ = Normalized distance between bridge i and bridge class n sub-category $C_n^{\,j}$.

<u>Weighting Factors:</u> All the attributes in a bridge class can be assessed as equally important. However, it is also possible to consider relative weighting factors, w_{kj}, for the attributes of each bridge class. The relative weighting factors define the importance rating of the attributes for a bridge class such that their sum is unity. For single span bridges the abutment type is assigned a 100 percent weight since it is the only attribute for single span bridges. These relative weights will be represented by expert opinion. A hypothetical list of weighting factors for any of the bridge classes is given in Table 4.7. For each bridge class different weighting factors might be necessary. A survey that has been prepared to gather expert opinion on weighting factors for each bridge class is given as *Questionnaire 1* in Appendix B.

Scaling Numbers: Information on the *abutment type, piers* or *bents,* and *span continuity* of a bridge are needed for definition of least and most vulnerable bridge characteristics. The level of vulnerability for each attribute is represented by a scale ranging between 0 and 1. 0 is assigned to the least vulnerable behavior and 1 is assigned to the most vulnerable behavior expected from a given attribute. For example, a single column bent can be represented by 1 and a multiple column bent can be represented by 0. Similarly, a monolithic abutment type can be represented by 0 and a non-monolithic abutment type can be represented by 1. Then, it is possible to represent an abutment type by any number between 0 and 1 to reflect that a specific abutment's behavior is neither monolithic nor non-monolithic. The same procedure can also be applied for span continuity. Expert opinion is needed to obtain such scaling values. A survey has been prepared to acquire scaling values from experts. The specific values used in the survey are obtained from Caltrans database for California bridges. The survey is presented as *Questionnaire 2* in Appendix B.

Attributes	Weight for C_n^1	Weight for C_n^2	Weight for C_n^3	Weight for C_n^4
abutment type, (y_{32})	1.0	1.0	0.3	0.2
span continuity, (y_{33})	-	-	0.4	0.5
piers or bents, (y_{34})	-	-	0.3	0.3

Table 4.7 Hypothetical Relative Weight Factors

Hypothetical Case Studies: Some hypothetical examples are presented to classify bridges into two sub-categories. Results are illustrated in Tables 4.8 and 4.9. Table 4.8 lists four different multiple span bridges with scaling numbers assigned to their attributes. These scaling numbers are substituted for the required expert opinion corresponding to the values of the physical attributes. Table 4.9 lists the normalized distance between a bridge and a sub-category of a bridge class as calculated from equations (4.8) and (4.9). Table 4.9 includes two cases: **Case (1)** for equal weighting of attributes and **Case (2)** for relative weight factors. The hypothetical relative weight factors listed in Table 4.7 are used for weighted illustration purposes. In each case, the effect of weighing factors are more notable as the scaling value is further from either end, i.e., 0 or 1. A bridge is represented as a combination of C_n^3 and C_n^4.

Attributes	Bridge i	Bridge j	Bridge k	Bridge n
abutment type, (y_{32})	0.9	0.1	0.7	0.4
span continuity, (y_{33})	1.0	0	1.0	0
piers or bents, (y_{34})	1.0	0	0	1.0

Table 4.8 Sample Bridges with Scaling Numbers

	Bridge i		Bridge j		Bridge k		Bridge n	
Class	*Case 1*	*Case 2*	*Case 1*	*Case 2*	*Case 1*	*Case 2*	*Case 1*	*Case 2*
C_n^3	.996	.997	.015	.009	.578	.647	.460	.395
C_n^4	.004	.003	.985	.991	.422	.354	.540	.605

Table 4.9 Sample Bridges as Classified into Basic Bridge Classes

When classifying a given bridge, the sub-category of a class that a bridge belongs to is represented by the normalized distance values. A bridge that can be uniquely assigned to one sub-category of a bridge class receives a normalized distance value of 1. When the bridge is assigned to more than one sub-category, it receives a normalized distance value for each of the bridge class sub-category such that the sum of the normalized distance values adds up to 1. In the latter case, vulnerability assessment is achieved as follows:

$$V_i = \sum_k V^k * \overline{\Delta}_{ik} \tag{4.10}$$

where V_i = Vulnerability of bridge i,

V^k = Vulnerability of each sub-category C_n^k that the bridge is assigned,

$\overline{\Delta}_{ik}$ and k are as defined in equation (4.9).

4.2.3.2 Incomplete Information

Most of the databases for bridge inventories are incomplete. Some approaches do not consider incomplete data as a potential problem. Bridges with incomplete information are omitted for such a problem in some of the existing prioritization approaches such as the WSDOT approach. However, omitting bridges from ranking would lead to a more biased data and would not give a complete ranking.

The incomplete information for an attribute can be either:

- Inferred from the existing information for other similar bridges, or
- Computed using other attributes of the same bridge based on an expert opinion.

For example consider a bridge that has a suspension superstructure. The substructure material can then be assumed to be steel, based on the statistics obtained from the database for the suspension bridges. If needed, this statistics might be accompanied by a probability value obtained again from the database. Table 4.10 gives a sample statistics of the superstructure type given substructure material type from the Caltrans database for the California bridges.

Material Type	**Super structure Material/ Type**					
	concrete girder	*steel girder*	*steel truss*	*arch*	*masonry*	*others*
concrete	87.4	9.0	1.3	0.8	1.0	0.5
steel	27.3	47.9	8.2	13.7	1.3	1.6
masonry	31.0	22.2	5.5	11.1	16.7	13.5
timber	2.2	5.1	2.6	89.3	0.4	0.4

Table 4.10 Statistics of Superstructure Material/Type based on Substructure Material Type

Seat width is another attribute that can be obtained by expert opinion. Usually, the seat width is not listed in most of the inventories. However, the construction year of the bridge can be used to infer design specifications for the bridge. Then based on expert opinion and design specifications, the seat width can be estimated. Similarly, the construction year can define the type of foundation.

ESCOB can identify the attributes with incomplete information. Then it assigns a value to the unknown attribute utilizing inference schemes and the expert opinion provided. The correctness of the estimated values depend on the provided expert opinion. More knowledge acquisition is necessary to improve the accuracy of estimating incomplete information.

CHAPTER 5

VULNERABILITY ASSESSMENT

Vulnerability is defined as a function of the site hazard and the structural properties of the bridges. The steps of vulnerability assessment have been summarized in Chapter 3 (see Figure 3.2). In this chapter, primary and secondary structural attributes are presented. Then, seismic hazard analysis and ground motion-damage relationships are discussed as part of the conceptual model for the vulnerability assessment.

5.1 STRUCTURAL ATTRIBUTES FOR VULNERABILITY ASSESSMENT

Structural attributes that are used in vulnerability assessment are selected in such a way that no detailed investigation is necessary to utilize them, i.e., the attributes are expected to be easily available from existing inventories. Table 5.1 lists all the structural attributes that are essential for vulnerability assessment. As mentioned in Chapter 3, primary structural attributes, Y, are used to define bridge classes whereas secondary structural attributes, Y', are used as modifiers to increase or decrease the vulnerability level assigned to a bridge. Another attribute listed in Table 5.1 is the *location (latitude-longitude)* of a bridge. This attribute is one of the links between vulnerability and importance assessment as it is used both in evaluating the seismic exposure of the bridge and its location in a network system. Most of the Department of Transportation bridge inventories include all of the attributes listed in Table 5.1. In cases where data are not available, expert opinion can be used to infer necessary data from the available information.

5.2 CONCEPTUAL MODEL FOR VULNERABILITY ASSESSMENT

The objective of the vulnerability assessment is to find $E[D|B_i]$ or $E[L|B_i]$. In simplified notations:

$$E[D|B_i] = E_i[D] = \text{Expected damage for bridge } i, \tag{5.1.a}$$

$$E[L|B_i] = E_i[L] = \text{Expected loss for bridge } i. \tag{5.1.b}$$

The expected damage for a bridge i, at a given site can be calculated as:

$$v_{D_i} = E_i[D] = \iint_{A\,D} d\, f_{D|A}(d|a)\, f_A(a)\, dd\, da \tag{5.2}$$

ATTRIBUTES	DEFINITION
Bridge number	Identification number or the name of a bridge.
Latitude and longitude	Latitude and longitude of the beginning of a bridge(which is defined by a postmile).
Y (Primary Structural Attributes)	**Definition**
MST	Main structure type: - Type according to substructure material (such as steel, concrete, timber) and superstructure type (such as girder, truss, arch, suspension, etc.) - Type according to continuity and substructure properties (such as in-span hinges, deck continuous, etc.)
Total spans	Total number of spans.
Number of hinges	Total number of hinges.
Abutments	Types of abutments.
Column bents / pier wall	Column bents (or pier walls and pier type) within the span length.
Y' (Secondary Structural Attributes)	**Definition**
Column/pier height	Height of column/pier (ft).
Seat width	Seat width for discontinuous spans and abutments.
Skew	Structure skew.
Year built	The year in which the bridge was built-provides information about the age of the bridge and the design specifications used in construction of the bridge.
Year reconstruction	The year of reconstruction includes information on design changes.
Seismic retrofitting	Information about seismic retrofitting history.
Length	Total bridge length (ft).
Width	Bridge deck width (ft).
Type of foundation	Pile foundation or spread foundation.
Crosses water	Existence of water under the bridge.
Condition of bridge	Open or closed.

Table 5.1 Structural Attributes for Vulnerability Assessment

where D = Damage state random variable,

$f_{D|A}(d|a)$ = Probability density function of damage D given the ground motion level A and

$$q_r(A) = \int_{d_i}^{d_j} d_r f_{D|A}(d|a)dd \tag{5.2.a}$$

where $q_r(A)$ = Expected value of being in a damage state d_r given seismic hazard at site, A ,

$f_A(a)$ = Probability density function of the ground motion level.

Figure 5.1 summarizes the notations given in equation (5.2). However, a crude approximation is used very frequently for expressing $q_r(A)$ that is given below:

$$q_r(A) = d_r . P[D = d_r | A] \tag{5.3}$$

Thereafter equation (5.2) can be rewritten as:

$$v_{D_i} = \sum_r \int_A q_r(A) f_A(a) da \tag{5.4}$$

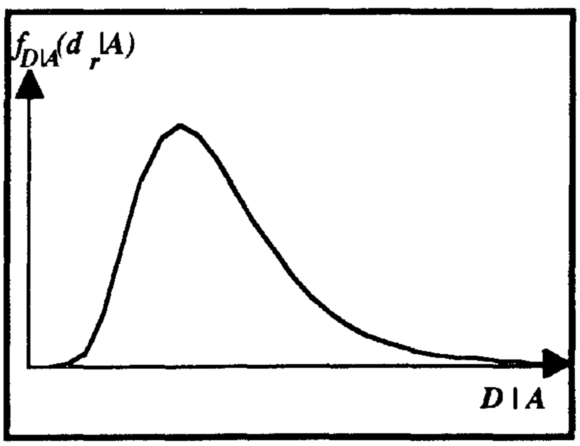


Figure 5.1.a Probability Density Function of Damage D given the ground motion level A

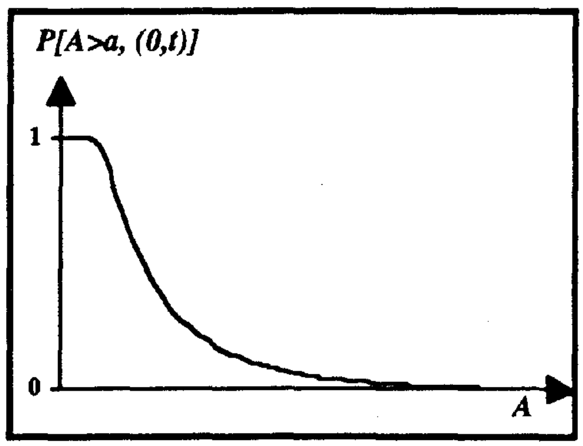


Figure 5.1.b Probability Density Function of Ground Motion Level A

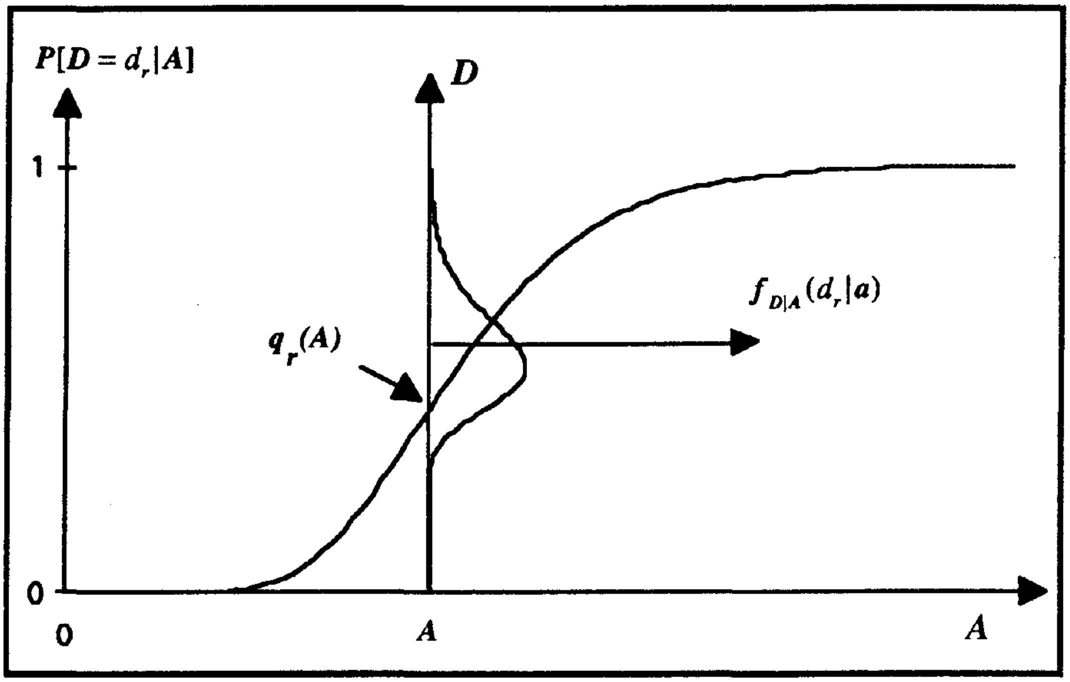


Figure 5.1.c Expected Value of being in Damage State d_r Given Seismic Hazard A , and Probability of being at Damage Level d_r

The mean damage factor for the same bridge, over time t can be evaluated by the following expression (Kiremidjian, 1992a):

$$\nu_{D_i}(t) = -\sum_{r} \int_{A} q_r(A) \left(\frac{G'_A(a)}{1 - G_A(a)} \right) \tag{5.5}$$

where $G_A(a)$ = Seismic hazard over time t with a rate of event occurrences given by λ:

$$\begin{aligned} G_A(a) &= P[A \geq a \text{ at least once in } (0,t)] \\ G_A(a) &= 1 - P[\text{no events with } A \geq a \text{ in } (0,t)] \\ G_A(a) &= 1 - e^{-\lambda t Q_A(a)} \end{aligned} \tag{5.6}$$

where $Q_A(a)$ = complementary cumulative distribution of A and

$G'_A(a) = \dfrac{dG(a)}{da}$ = Derivative of $G_A(a)$ with respect to a.

If the ground motion levels are discretized and the mean damage factor given each ground motion level is known, then equation (5.5) is further simplified as follows:

$$\nu_{D_i}(t)=\sum_{i=1}^{n}\sum_{j=1}^{n}\mu_{D_i|A_j}(d_i\mid a_j)\ ln(\frac{1-G_A(a_{j+1})}{1-G_A(a_j)}) \tag{5.7}$$

where $\mu_{Di|Aj}(d_i|a_j)$ = Expected value of being at the damage level d_i for a given ground motion level a_j.

The discrete damage states are considered in defining equation (5.7). Equation (5.8) is the discretized form of equation (5.2.a).

$$q_r(A)=\sum_r d_r.P[D=d_r|A] \tag{5.8}$$

where $P[D=d_r \mid A]$ = Probability that a bridge is in damage state $D = d_r$ given seismic hazard at site A.

Since equation (5.8) and (5.3) are similar, the final estimation of $\nu_{D_i}(t)$ is not affected by the use of approximation given in equation (5.3). Consequently, in order to evaluate $E_i[D]$, $f_A(a)$ and $q_r(A)$ need to be defined.

5.2.1 Seismic Hazard Analyses

Seismicity is a critical parameter used for the overall ranking computations in seismic retrofitting prioritization methods. In the Caltrans and ATC approaches, seismicity has been considered independently from vulnerability in computation of overall ranking. However, seismic hazard is directly related to vulnerability and their relationship has to be examined.

The seismic load experienced by each bridge depends on the site of the bridge and its proximity to earthquake sources. A seismic hazard analysis is necessary to identify the seismicity at a given bridge site. The seismic hazard experienced at a bridge site depends on the sources of seismicity affecting the region, the effects of the local soil conditions in terms of ground motion amplification, liquefaction potential, landslide potential, and ground displacement due to surface faulting. The seismic hazard at a specific bridge site can be estimated by either deterministic or probabilistic approaches. Deterministic approaches are based on a *scenario earthquake*. The scenario earthquake may be the maximum credible event for the fault nearest to the bridge site, or it may correspond to the maximum probable event on that fault. Ground motion at the site is calculated based on the scenario earthquake. As an example, a magnitude

8.25 event on the San Andreas fault and magnitude 7.5 events on the Hayward and Calaveras faults can be hypothesized for the seismic hazard analyses of bridges in the San Francisco Peninsula Bay area. The ground motion at any bridge site then will be obtained by the available attenuation relationships.

Probabilistic seismic hazard analyses integrate the contribution of all possible earthquakes that can occur on all known faults surrounding the site and evaluate the probabilities that the ground motion parameters will be exceeded within the specified exposure time. The probabilistic approaches incorporate uncertainties into the final results. The results of a seismic hazard analysis for each bridge site is presented by a seismic hazard curve, which is a plot of annual probability of exceedance or return period versus a specified ground motion parameter, such as peak ground acceleration (pga). With the probabilistic approach various site hazards, i.e., ground shaking and collateral hazards, can be combined.

In this research, seismicity is considered as one of the key attributes in defining vulnerability criterion. For the purpose of seismic hazard assessment at each bridge site, the level of ground motion will be calculated. The main ground motion is considered to be ground shaking as it is the most widespread and potentially important hazard to a transportation system. Several ground shaking indices can be used in seismic hazard analysis, such as Modified Mercalli Intensity (MMI), peak ground acceleration (pga) or spectral values (spectral acceleration (S_a), spectral velocity (S_v) or spectral displacement (S_d)). The selection of the ground shaking parameter depends on the ground motion parameter of the fragility curves that need to be developed. Various seismic hazard analysis software programs are available. For the purpose of this research, the program STASHA (Kiremidjian et. al., 1994) will be used.

Seismic ground motions can have significant variations along the length of the structure for long bridges. However, it is beyond the scope of a screening level prioritization methodology to capture the full variation along the length of the structure. A possible solution might be to consider the seismic hazard for a particular bridge at more than one point along its length. Then, since the bridge would fail at its weakest link, the bridge can be interpreted as a system in series and the fragility analysis can be based on the results of the highest seismic hazard along the bridge.

As discussed earlier, collateral hazards also play an important role in determining the level of damage that might be experienced by the bridge under a seismic loading. In past earthquakes liquefaction has been one of the major reasons of bridge damage in seismic events.

Available liquefaction, landslide potential, and fault rupture maps can be utilized to consider possible effects of collateral hazards. The effect of collateral hazards will be included in the vulnerability assessment by modifying the fragility curves.

5.2.2 Ground Motion-Damage Relationships

Vulnerability is defined as a function of being in a given damage level at a given ground motion, $q_r(A)$ which can be represented as damage probability matrices (DPMs), as graphs between mean damage ratio and ground motion intensity and as fragility curves (Kiremidjian, 1992). DPMs describe the probability that the structure is in a particular damage state given the level of ground shaking. These damage probability matrices are derived from the probability distribution of damage given the ground shaking intensity level, $f_{D|A}(d|a)$, where A is the ground motion and D is the damage level random variables. D is often assumed to be beta or log normally distributed.

Fragility curves can also be defined as the probability of exceeding a damage level for a given level of ground motion, i.e., $P[D \geq d_r | A] = 1 - F_{D|A}(d_r | A)$. However, in this research, fragility curves are defined as the probability of being at a damage level for a given level of ground motion. The representations of damage probability matrices and the fragility curves are analytically related. The probability density of damage conditional on the ground motion, $f_{D|A}(d|a)$, is the more elementary form of the two.

A generic fragility curve is shown in Figure 5.2 where D is the damage random variable, d_r is the given damage level, and a_i is the given ground motion level. The development of fragility curves is usually time consuming and cumbersome. However, new fragility curves need to be developed for each bridge class in order to achieve a better representation of a bridge's seismic behavior.

DPMs and fragility curves are available for the ATC-13 and the NIBS bridge classes, respectively. The DPMs in ATC-13 have been obtained by fitting a beta probability distribution to damage factors at every ground motion intensity level. These DPMs are obtained from expert opinion. The fragility curves in the NIBS Draft Technical Manual are based on the probabilistic combination of sub-component (such as column, abutment, deck, etc.) damage functions. The relationships among sub-components for different damage states are expressed by fault tree analysis. The information on past earthquake performance of bridges has been used to develop sub-component damage functions (Risk Management Solutions, 1994).

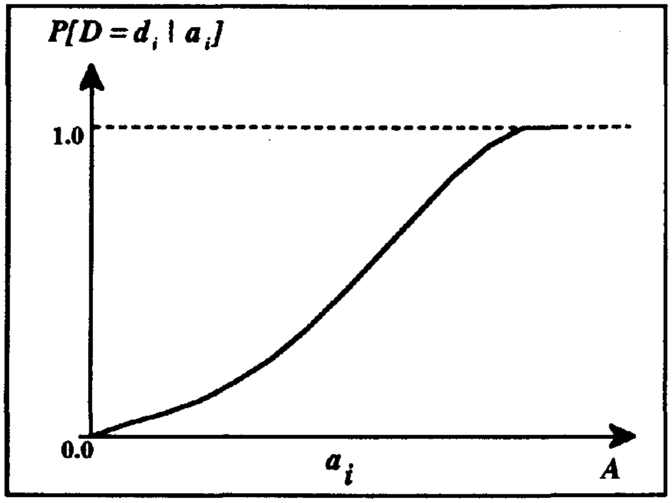


Figure 5.2 A Generic Fragility Curve

Several approaches can be used to develop fragility curves. A simple approach would consider the combination of possible failure modes based on components. The component fragility curves might be obtained empirically as in the NIBS Manual or analytically by calculating limit-states for the components. Then the system reliability based on component reliability can be obtained using reliability methods such as first order reliability methods (FORM) or second order reliability methods (SORM). Another approach considers the identification of limit-states of the system and use of importance sampling for reduced Monte Carlo simulation to calculate system reliability. A third approach is to use response surface method for system reliability analysis. The development of fragility curves is beyond the scope of this project. However, fragility curves for new bridge classes need to be developed and the merit of each approach remains to be assessed.

5.2.2.1 Damage Levels

It is also important to clearly define the level at which vulnerability should be evaluated as the definition of damage level is an important aspect in the overall ranking. Similar to the basic design criteria for the structure, the overall ranking can be based on two damage levels :

- collapse and
- serviceability.

For a given bridge, the fragility curve for collapse damage level is different than the fragility curve for serviceability damage level. A generic representation of fragility curves at these two different damage levels is given in Figure 5.3. At a ground motion level a_i, p_c, and p_s represent the probability of being in collapse and serviceability damage levels, respectively. At different ground motion levels, the probability of being in serviceability damage level can be much higher than that of collapse damage level. Especially for bridges that constitute an important link of a transportation lifeline network, the level of damage should be ensured to be insignificant so that, the bridge is available after an earthquake. Therefore, for such bridges, the fragility curves for serviceability damage level should be considered in prioritization, whereas use of fragility curves for collapse damage level is adequate otherwise. The selected damage level will affect the vulnerability rating directly.

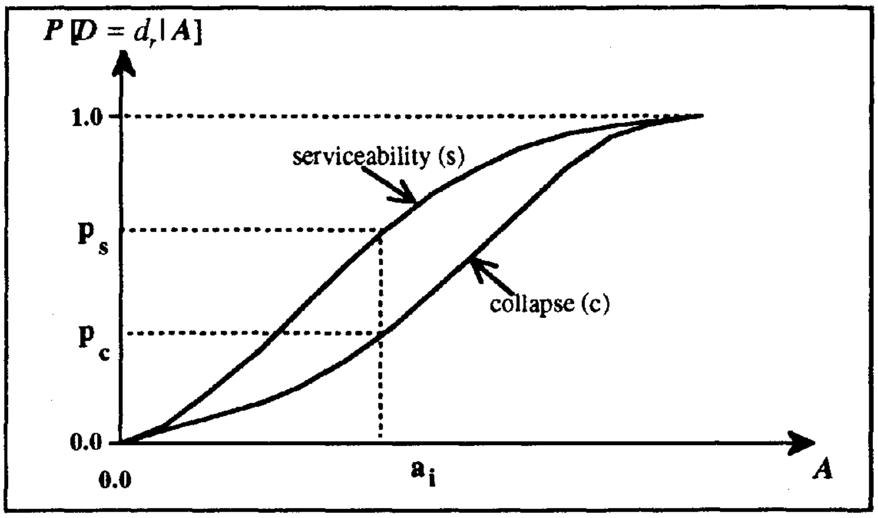


Figure 5.3 Fragility Curves for Two Different Damage States

Each damage level should be related to physical characteristics of a bridge class C_n that is defined as a function of Y_1 and Y_2. Since each bridge class has different substructure material and superstructure type characteristics, different physical damage states need to be defined for each bridge class. For vulnerability assessment, it is possible to define four or five damage states ranging from *no damage* to *total collapse*. A possible range of damage states is shown in Figure 5.4. Then, the relationships between physical damage and functional characteristics of the bridge have to be determined. The physical damage states can be classified under collapse and serviceability damage levels based on the importance factor. That is, for emergency response factor, the collapse damage might include only the *severe damage* and *total collapse* damage states. For the long term economic impact analysis, the physical damage states can be possibly grouped as *closed, limited use*, and *open*. The relation between physical and functional damage states can be defined as a function of the number of accessible lanes.

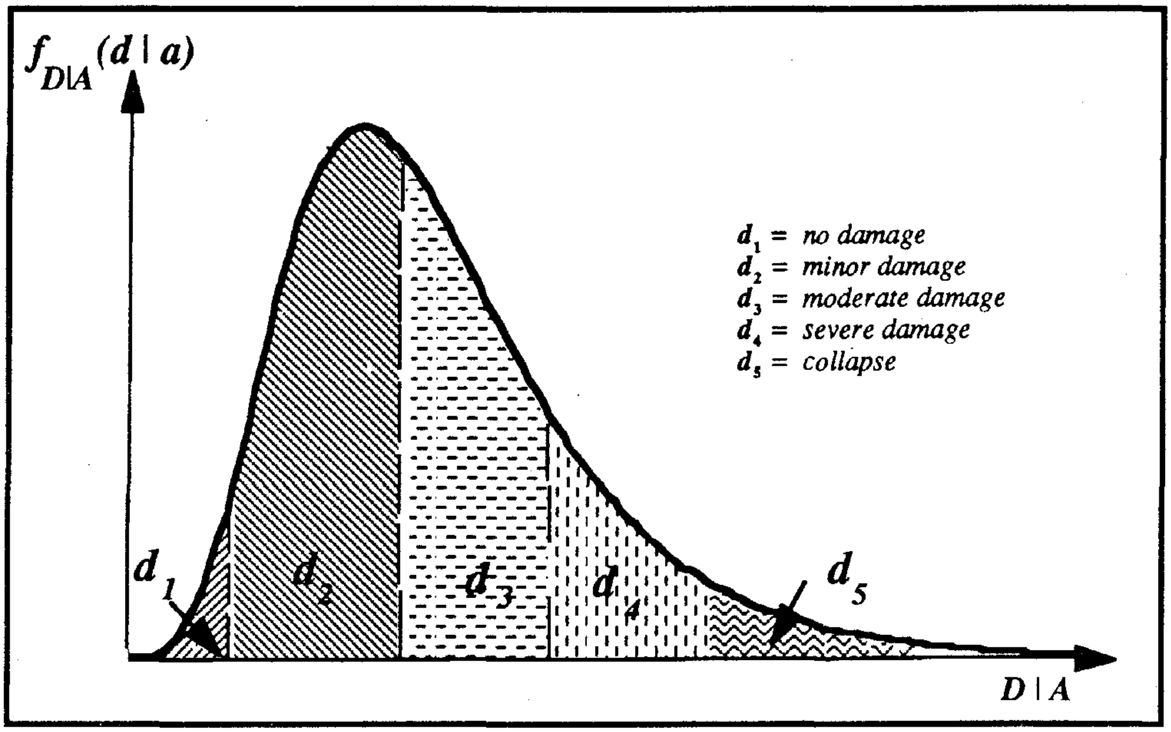


Figure 5.4 Possible Physical Damage States

When bridges are considered as components of a transportation system, the seismic risk analysis of the highway network becomes challenging from a lifeline engineering point of view. It involves multiple components, system performance under various conditions of damage or non-damage to its components, multiple earthquakes that might affect different parts of the system and earthquake effects at multiple locations (McGuire, 1990). The lifeline network analyses become quite complex when different damage states for a bridge are introduced to the system. To avoid complexity in this research, a method is developed that includes network analysis based only on one of the damage states for a given bridge. This damage state is identified by the importance characteristics.

5.2.2.2 Modifiers β for the Fragility Curves

Fragility curves at serviceability and collapse damage levels need to be developed for each bridge class. The bridge classification that has been developed considers the effect of only primary structural attributes, Y. However, other structural characteristics of the bridge that are expressed by the secondary vulnerability attributes Y', would also have an effect on the seismic behavior of the bridge under seismic loading. As mentioned in Chapter 4, it is not practical to consider all possible attributes for bridge classification. Thus, to include the effect of the secondary vulnerability attributes, modifiers β need to be assigned. For example, in a study by Maragakis (1986), it has been shown that as the angle of skewness increases the maximum rotational response increases. The same study also shows that maximum rotation increases whereas maximum displacement decreases as the abutment stiffness increases. Hence, the seismic behavior of the bridge changes. Another example is the effect of seismic retrofitting state of the bridge. The behavior of a bridge that has been seismically retrofitted can significantly improve. Addition of restrainers at joints is an example of such an improvement. The development of the modifiers to the fragility curves will require a detailed investigation which might be achieved by parametric analyses.

CHAPTER 6

IMPORTANCE ASSESSMENT

The prioritization of bridges requires considering importance attributes, $\boldsymbol{W}$, that relate the consequences of failure of a bridge to the public safety and socio-economic well-being of a community. The importance criterion considers these issues and forms one of the main components for the prioritization methodology as depicted in Figure 3.1. Transportation lifeline network analysis and decision analysis are the main tools used to assess the importance criterion. This research focuses on the emergency response factor. Hence, in this chapter network analysis and utility function development are discussed in detail for the emergency response factor.

6.1 IMPORTANCE ATTRIBUTES

In Chapter 3, importance criterion, $\boldsymbol{I}$, is defined as a function of six factors as follows:

$$\boldsymbol{I = f(S, E, G, Q, L, H)} \tag{6.1}$$

where $\boldsymbol{S}$ = Public safety,
$\boldsymbol{E}$ = Emergency response,
$\boldsymbol{G}$ = Long term economic impacts,
$\boldsymbol{Q}$ = Defense route,
$\boldsymbol{L}$ = Interaction with other lifelines, and
$\boldsymbol{H}$ = Historical significance.

$\boldsymbol{S}$ reflects the risk of life loss on/under the structure due to failure of a bridge. $\boldsymbol{E}$, is a measure of identifying the impacts of a failure immediately after the earthquake, especially for rescue operations and fire fighting purposes for which the availability of the transportation system is the main concern. $\boldsymbol{G}$ considers the impact usually for a period of time that starts a few days after the earthquake and extends to anywhere from one to six months depending on the severity of the earthquake. The main concern is the serviceability capacity of the transportation system to meet users' need. The factor, $\boldsymbol{L}$ is related to the interaction of the transportation system with other lifelines and represents the possible economic impact as well as disruption of services to the users due to the loss of utilities carried on the bridge. The $\boldsymbol{Q}$ and $\boldsymbol{H}$ factors are included to reflect different perspectives for the importance of the existing bridges on the transportation network system. The necessary attributes or the assessment of the importance criterion are listed in Table 6.1.

Attributes	Definition
ADT	Average daily traffic (traffic exposure).
Bridge identification	Identification number or the name of the bridge.
Condition of bridge use	Open, closed or posted.
Defense route	Type of routes that are on defense route.
Designation	Designated level of service, e.g., ramp, alternate, toll, etc.
Direction of traffic	One-way or two-way traffic.
Facility crossed (kind)	Type of facility crossed in terms of routes e.g.; interstate, state.
Feature intersected	Type of feature intersected in terms of routes e.g.; interstate, state.
Functional class	Highway types for urban and rural areas.
Historical significance	Historical characteristics of the bridge, e.g., unique for history of engineering, associated with significant events, etc.
Lanes on/under	Highway lanes carried by the structure/under the structure.
Latitude, longitude	Latitude and longitude of the beginning of a bridge (defined by a postmile).
Location in a network	The location of the bridge in a transportation lifeline network, bottleneck point, main connector, etc.
Name (Location)	Description about the area in terms of close main routes.
Origin destination trip survey	Commuter population for a given origin-destination pair.
Other lifelines	Position and relation with other lifeline systems.
Parallel structure designation	Whether separate structures carry the route in opposite directions of travel.
Route	Type of route, e.g.: state, interstate, country route, etc.
Service type	Such as highway, highway and pedestrian, etc.
Traffic capacity	Maximum vehicle of volume assigned to the route.

Table 6.1 Definitions of the Importance Attributes

6.2 CONCEPTUAL MODEL FOR IMPORTANCE ASSESSMENT

The effect of each factor on the importance criterion should be represented by a common measure. It is not possible, however, to use directly monetary values or time loss because the effect of a given attribute is expected to change from one decision maker to another based on their values and risk attitudes. The multi-attribute importance criterion can be evaluated through assessing a utility function $u[v(x)]$, over a given attribute value $v(x)$. The utility associated with each possible consequences of a given attribute is a unitless index that ranges between 0 and 1, and it is a common term defined for all different types of attributes. An alternate approach requires the verifications of assumptions implying a certain form of the utility function instead of value function assessment (Keeney and Raiffa, 1993). In this research, the latter approach is adopted for continuous attributes , S, E, and G by using the simplest form, i.e., additive form, expressed as follows:

$$\hat{u}(W_1, W_2, \ldots, W_T) = \sum_i k_i u(W_i) \tag{6.2}$$

where $\hat{u}(W_1, W_2, \ldots, W_T)$ = Utility function for importance attributes $W = \{w_1, w_2, \ldots, w_{P_3}\}$,

k_i = Scaling factor for attribute i,

$u(W_i)$ = u-value for attribute W_i.

Equation (6.2) is a more general representation of equation (3.7) defined in Chapter 3. For discrete attributes, Q, L and H, the utility function is assessed considering the impact value of the given attribute. Development of the value tradeoff method is discussed in the following section.

6.3 DEVELOPMENT OF A VALUE TRADEOFF METHOD

6.3.1 Value Model

As mentioned earlier, definition of a common term is necessary for importance criterion assessment as a combination of different factors with multi-attributes. A value model that can be defined as a model with qualitative and quantitative relationships can be used to address this need (Keeney, 1992). A value model is developed in a discussion controlled by the questions of a trained analyst and an individual or group whose values are being quantified. The assignment of tradeoffs is done by formally eliciting the value judgments of decision makers and/or their representatives. It is necessary to identify the set of objectives, and the attributes that measure the degree to which these objectives are met. The relationship between different levels of each single attribute is structured by the concepts of attitude toward risk.

In order to facilitate the use of a value model, the attributes should be mainly measurable, operational and understandable. An attribute is (Keeney, 1992):

- *Measurable*, if it is reasonable both to obtain a probability distribution for each alternative over the possible levels of the attribute and to assess the decision maker's preferences for different possible levels of the attribute,

- *Operational*, if it is reasonable to describe the possible consequences with the associated objective and to provide a sound basis for value judgments about the desirability of the various degrees to which the objective might be achieved,

- *Understandable*, if there is no ambiguity in describing the consequences in terms of attributes and no ambiguity in interpreting consequences described in terms of attributes.

It is also important that the set of attributes are (Keeney and Raiffa, 1993):

- *Complete*, so that it covers all the important aspects of the problem,
- *Operational*, so that it can be meaningfully used in the analysis,
- *Decomposable*, so that aspects of the evaluation process can be simplified by breaking it down into parts,
- *Nonredundant*, so that double counting of impacts can be avoided and
- *Minimal*, so that the problem dimension is kept as small as possible.

6.3.2 Utility Functions for Continuous Attributes

Two common single-attribute utility functions are used for the attributes of S, E and G factors. These are:

- *Linear utility function* which has the form of a straight line thus indicating an equal amount of increment in the impact value u_i by each unit change of attribute i.

$$u_i = \alpha_1 + \alpha_2 i \qquad (6.3)$$

• *Exponential utility function* that increases exponentially with attribute levels and has the form given below:

$$u_i = \alpha_1 + \alpha_2 e^{ci} \tag{6.4}$$

In equations (6.3) and (6.4);

u_i = Utility function for attribute i, and
α_1, α_2 and c = Constants.

As discussed earlier, the utility functions need to be evaluated by a decision analyst through iterative meetings with the decision maker. Such an attempt has been included in the Illinois Department of Transportation (IDOT) approach - reviewed in Section 2.3. Similar ideas of multi-attribute utility theory discussed above are employed in their evaluation of importance criterion. In their study, actual utility functions have been developed for the state of Illinois by a decision analyst and a group of ten people as decision makers (Woodward Clyde Consultants, 1991).

The importance factors can be grouped into two, based on the necessary types of analyses to evaluate their contribution to the importance criterion. First group includes S, Q, L and H for which decision maker's values and preferences are reflected by the utility functions developed for each factor. The second group consists of E and G, for which the final utility function has multiple attributes such as critical bridge set member μ or time delay t_d. In order to determine the contribution of these attributes to the importance criterion for a given bridge, first of all a network analysis is conducted and thereafter, utility functions are developed to reflect the decision maker's values and preferences. Emergency response factor, E, has been the focus of this research. The network analysis and decision analysis methods developed for the factor E are discussed in the following sections.

6.4 EMERGENCY RESPONSE FACTOR

The availability of transportation systems immediately after the occurrence of a major earthquake is of primary importance for emergency response purposes. The functionality of such transportation system is to a great extent dependent on the functionality of the bridges within that system. In cases of emergency, roadbeds can still be used with minimal repair. Failure of bridges, however, may completely isolate certain areas in need of emergency services. Thus, bridges can be viewed as the most critical components in a transportation system and their ranking for retrofit prioritization purposes can be achieved by considering their function within the network system.

In general, the objective is to evaluate a utility function u_E, that will represent the consequences of emergency response for a given bridge with certain importance characteristics. Then, the effect of emergency response can be included in the importance assessment. The calculation of u_E for bridge i, u_{Ei}, is performed in two levels. In the following subsections first the attributes of each level are identified and utility functions for each stage are formulated. Then the methods for network analysis as required in each level are discussed.

6.4.1 Utility Functions for Emergency Response Factor Attributes

6.4.1.1 Level One Calculations

In level one, a utility value, U_m' - referred to as the u-value hereafter -, that considers the identification of critical bridge sets and their vulnerability is used. A critical bridge set is defined as any ensemble of bridges that delays accessibility of a disaster area from available resource locations more than a certain time period. The critical bridges are identified by the network analysis. For a set of bridges, j, in critical set m with s bridges, the general form of U_m' can be expressed as follows:

$$U_m' = k_V u_{Vj} + k_\mu u_{\mu j} \qquad (6.5)$$

where m = Set number within a given group,

s = Number of bridges in a critical bridge set, e.g., $s = 1$ for single critical bridge set, $s = 2$ for pairs of critical bridge set, and so on,

j = Set of bridges that belong to critical set m with s bridges,

k_V = Scaling factor for vulnerability at collapse level,

u_{Vj} = u-value for vulnerability at collapse level for set j

k_μ = Scaling factor for critical set members,

$u_{\mu j}$ = u-value for critical set members for set j.

For critical sets with more than one bridge, the u_{Vj} is calculated as the u-value of the product of the V for each bridge, assuming failures of different bridges are independent. In order to obtain $u_{\mu j}$, a bridge from the set j with the maximum μ is selected and its u-value for the critical set member attribute, u_μ, is calculated.

The set $\{\overline{R}\} = \{\overline{R}_1, \overline{R}_2, \ldots, \overline{R}_M\}$ is defined as the rank order of the critical bridge sets where $\overline{R}_1$ corresponds to the highest utility value, U_m', and is assigned rank 1. M is the total number of critical bridge sets.

6.4.1.2 Level Two Calculations

A critical bridge set can include more than one bridge, thus a second level ordering for bridges within a given set is needed. Time delay and the participation factors are the importance attributes considered in level two calculations. The following equation is used to obtain u-values for the second level ordering:

$$\hat{u}_{Ei} = k_{t_d} u_{t_d i} + k_\phi u_{\phi i} \tag{6.6}$$

where i = bridge i and $i \in j$ in equation (6.5),

$\hat{u}_{Ei}$ = u-value for bridge i for emergency response conditions.

k_{t_d} = scaling factor for time delay to reach a given destination,

$u_{t_d i}$ = u-value for time delay to reach a destination due to unavailability of bridge i,

k_ϕ = scaling factor for participation to connectivity,

$u_{\phi i}$ = u-value for bridge i for participation to connectivity,

The u-value for emergency response factor used in the calculation of the importance u-value, U_i (see equations (3.7) and (6.2)) is defined as u_{E_i}. u_{E_i} is obtained by normalizing $U_m{}'$ using $\hat{u}_{E_i}$ for each rank order r, $r = 1,.., M$, and for each bridge in a bridge set with rank $\overline{R}_r$. That is, a line is fit to points $U_m{}'(\overline{R}_r)$ and $U_m{}'(\overline{R}_{r-1})$ in order to rank the bridges within a critical set with rank order r (equation 6.7). By this means the final ranking of each bridge is dominated by level one calculations, i.e., by $U_m{}'$.

$$u_{Ei} = \alpha\left(U_m{}'(\overline{R}_{r-1}) + \Delta U_m{}' * \hat{u}_{Ei}\right) \tag{6.7}$$

where s = number of bridges in a given critical bridge set,

α = normalization factor given by the following expression:

$$\alpha = \frac{1}{U_m{}'(\overline{R}_1)} \tag{6.7.a}$$

$$\Delta U_m{}^s = U_m{}^s(\overline{R}_r) - U_m{}^s(\overline{R}_{r-1}) \tag{6.7.b}$$

where $U_m{}'(\overline{R}_r)$ = u-value for the m^{th} set of s bridge set that is assigned to rank order r.

For $s > 2$, in order to obtain the $\hat{u}_{Ei}$, the steps outlined below should be followed:

For $r = 1$ to s -1;

(1) Obtain the combinations of bridges $\binom{s}{s-r}$,

(2) If $s - r = 1$, then stop; otherwise go to (3),

(3) Apply equation (6.7) using $\hat{u}_{Ei}$ for the combination of the bridges obtained above. The i term in $\hat{u}_{Ei}$ now refers to the combination of $(s - r)$ bridges. $\hat{u}_{Ei}$ for the combination is obtained similarly as u-values were for equation (6.5).

The calculation of the highest value of u_{E_i} is ensured by the first term in equation (6.7). If a bridge has already been assigned a u_{E_i}, then no other u_{E_i} is assigned to the same bridge.

In equations (6.5) through (6.7) the u-value of bridge i for emergency response factor, u_{E_i} is calculated. This is necessary to obtain a u-value for the importance criterion which includes many other factors (see equation 3.6). However, the interest might be in ranking bridges only for emergency response. In this case, u_{E_i} as obtained through (6.7) will give the importance u-value, U_{Ii}, and the final ranking will be obtained by equation (3.8) repeated below as equation (6.7.c) for convenience:

$$\hat{U}_i = k_V U_{Vi} + k_I U_{Ii} \tag{6.7.c}$$

If there are bridges that are not considered in the ranking, then they are grouped and ranked in a separate set. This set is ranked lower than the initial ranking set and is defined as a function of u_{Vi}, since $u_{t_d i}$ and $u_{\phi i}$ are both zero in this case.

6.4.1.3 Development of Hypothetical Utility Functions

Hypothetical utility functions are developed for attributes V, μ, t_d and ϕ. Exponential utility functions are used for attributes V and t_d whereas linear utility functions are used for μ and ϕ. The selection of these functions depend solely on the preferences and the risk attitude of the decision maker. Thus, the actual utility functions might look different than the ones presented in this section.

Utility function for V: The two boundary conditions are established using the minimum and maximum values (0 and 50%) of probability of failure (equation 6.8). The third equation is obtained by assuming a hypothetical value of 15% for the u-value of 0.5. This number is hypothetical and will change depending on the decision maker's values. However, this number is representative of the fact that any small increment with lower levels of probability is valued more and shows a risk averse attitude illustrating the importance of probability of failure. The final u-value function is given in equation (6.9).

$$\begin{aligned} 0 &= \alpha_1 + \alpha_2 e^{0c} \\ 1.0 &= \alpha_1 + \alpha_2 e^{0.5c} \\ 0.5 &= \alpha_1 + \alpha_2 e^{0.15c} \end{aligned} \qquad (6.8)$$

$$u_V = 1.19778(1 - e^{-3.06214V}) \qquad (6.9)$$

Figure 6.1 shows the utility function defined by equation (6.9). To assess the u-value for a pair or triplet of bridges first the probability of being at a collapse level for the pair or the triplet needs to be calculated and then the u-value can be calculated from equation (6.9).

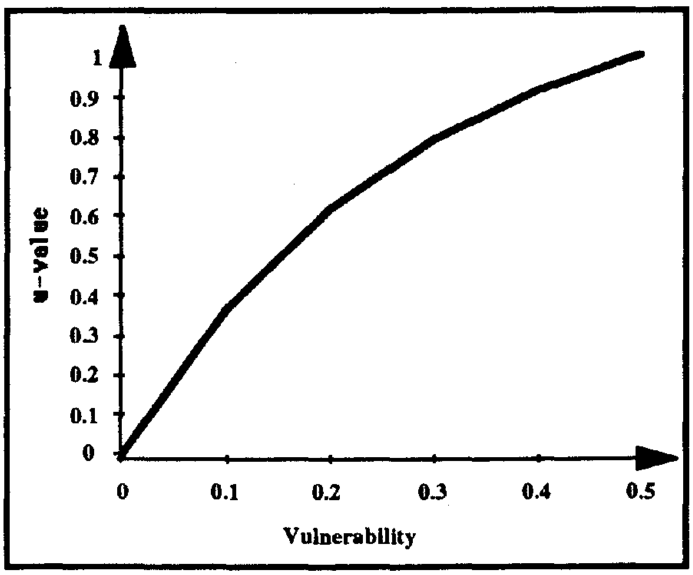


Figure 6.1 Utility Function for Vulnerability

<u>Utility function for t_d</u>: The two boundary conditions are established using the minimum and maximum values (0 and 90 minutes) of time delay (equation (6.10)). In this case, a hypothetical value of 75 minutes is used for a value of 0.5 for the third equation. Similar to the attribute V, this number is hypothetical and will change depending on the decision maker's values. However, this number is representative of the fact that any small increment with lower levels of time delay is not as important as a longer delay.

$$
\begin{aligned}
0 &= \alpha_1 + \alpha_2 e^{0c} \\
1.0 &= \alpha_1 + \alpha_2 e^{90c} \\
0.5 &= \alpha_1 + \alpha_2 e^{75c}
\end{aligned}
\tag{6.10}
$$

The final utility function is given in equation (6.11) and is shown in Figure 6.2.

$$
u_{t_d} = -0.0134718(1 - e^{0.048006 t_d}) \tag{6.11}
$$

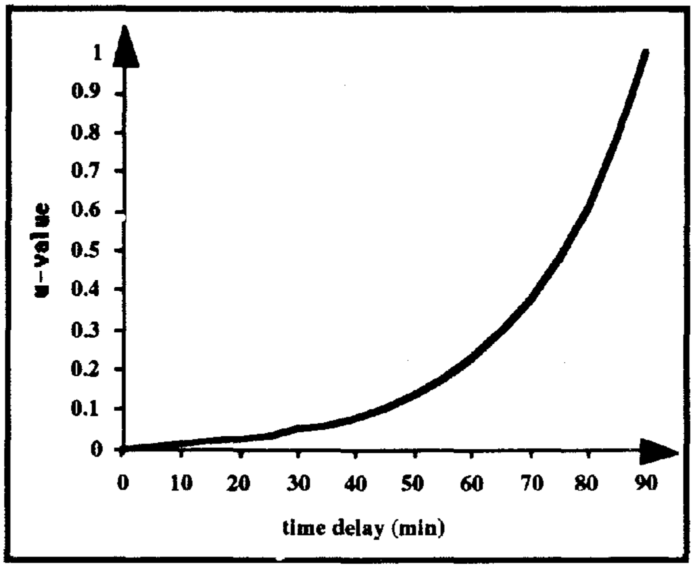


Figure 6.2. Utility Function for Time Delay

<u>Utility function for μ</u>: The same set or sets of bridges might destroy the connectivity of different origin-destination pairs at the same time. Thus, the repeated critical sets must be rated higher as they indicate a possible interruption of more than one route. For this purpose, a linear value curve is used and the constant is assumed to be 2.5 percent which represents the decision maker's values and preferences assessed by the decision maker himself or herself. The equation for this attribute is given in equation (6.12).

$$
u_{\mu} = 0.025\mu \tag{6.12}
$$

<u>Utility function for ϕ</u>: When some of the routes are not available, the fastest route from any of the origins to a given destination includes bridges that might not be used in the original

fastest path. However, such bridges are important as they act like a passive standby system. Some of the bridges in the system constitute the standby role more than others, thus such bridges should be given higher priority rates. For this purpose, the fraction of a set of bridges being on the fastest path is used to obtain the u-value function as defined in equation (6.13).

$$u_{\phi} = \sum_{j}^{N_{OD}} \left(\frac{N_{i\in P}}{N_P}\right)_j \tag{6.13}$$

where N_{OD} = Number of origin-destination pairs,
$N_{i\in P}$ = Number of times that a bridge is on the shortest time path, and
N_P = Total number of available paths for the given origin-destination pairs.

6.4.2 Network Analysis for Emergency Response

In an emergency situation it is essential to identify the routes that are available to allocate resources for rescue and/or fire fighting to the disaster area. The knowledge of available connectivity of the transportation network between locations of resources and disaster area provides a basis for emergency services and resource allocation. Connectivity for a given group of origin-destination pairs is usually defined as accessibility to a destination point from the respective origin point. However, in an emergency case all available resource locations can serve the disaster area. Hence, connectivity for emergency purposes is defined as the accessibility of the destination point from any of the origin points. For example, if there are two fire stations close to the disaster area, it is assumed that the disaster area can be reached as long as any one of the fire stations has accessibility to the disaster area. However, this assumption considers the availability of unlimited resources at any of the origin site. Only bridges that have collapsed are considered as inaccessible for emergency purposes.

Time to reach the disaster area is another important factor that needs to be considered for emergency purposes. For example, a delay of two hours to reach the disaster area might be unacceptable in case of a fire starting immediately after the earthquake. In the case that the original fastest path does not yield any access to the disaster area, some alternate routes to reach the area for emergency services need to be determined immediately. The importance of bridges on these alternate routes also need to be considered.

Thus, a bridge is considered to be *critical* and is given the highest importance ranking if the following conditions hold:

- The failure of the bridge will cause complete isolation of one or more disaster areas.
- The failure of the bridge will cause an unacceptable amount of time delay between a given origin and destination pair.
- The bridge is used as a connection point more often than the other accessible bridges following the failure of any bridge or bridge sets in the network.

Any set of bridges that destroys the connectivity between a given origin and destination is defined as a *critical bridge set.* Depending on the redundancy of the network, single, pairs, triplets or quartets of bridges might form critical bridge sets.

A procedure that is used to provide results for the above three conditions has been developed. A well-known shortest path algorithm, Dantzig and Dijkstra (D&D) algorithm (Ford and Fulkerson, 1962) has been used in this procedure.

A shortest path algorithm can be defined as the task to find a directed path, $\boldsymbol{P}$, from origin to destination with minimum total length. The total length can be described as the distance or time to travel from origin to destination for the transportation systems. A highway transportation system can be modeled as a directed graph that is defined as follows:

Let $\mathcal{G} = (\boldsymbol{N},\boldsymbol{A})$ be a directed network, where $N = \{n_1, n_2, \ldots, n_N\}$ is a finite set with element n_i called as a node and $\boldsymbol{A} = \{a_1, a_2, \ldots, a_m; a_k = (i,j) \in N\}$ is a finite set with element a_k called as an arc. For each arc $a_k = (i,j)$, i is called the tail node and j the head node of a_k. It is assumed that $i \neq j$, for any arc $(i, j) \in \boldsymbol{A}$.

Let $s \in \boldsymbol{N}$ and $t \in \boldsymbol{N}$ be two distinct nodes of $\mathcal{G} = (\boldsymbol{N},\boldsymbol{A})$. Then a path $\boldsymbol{P}$, from node s to node t is a sequence of arcs $(j_1, j_2, \ldots, j_w)$, such that:

$\boldsymbol{w}$ = Total number of arcs, $\boldsymbol{w} \geq 0$ and

$$\begin{gathered} j_1 = (s, n_i) \\ j_w = (n_k, t) \\ (n_l, j_p) = (j_p, n_{l+1}) \end{gathered} \tag{6.14}$$

where $\boldsymbol{l}$ = 1,2,...$\boldsymbol{w}$-1, and n_i, n_k, n_p.and $n_{p+1} \in \boldsymbol{N}$.

Let $\bar{l}(j)$ denote the length of each arc j. Then the length of the path P is defined as the sum of the arc lengths of the path (equation 6.15).

$$\begin{aligned} \bar{l}_P &= \sum_j^w \bar{l}_j \\ \bar{l}_j &\geq 0 \end{aligned} \tag{6.15}$$

For the emergency purposes the path length $\bar{l}(j)$ is defined as the time to travel from i to k where $a_j = (i,k)$. The steps of the procedure that finds μ, t_d and ϕ is given in Figure 6.3. In Figure 6.3, the following notations are used:

$\varnothing$	= Null set,
ξ	= Number of deleted arcs from the original directed network $\mathcal{G} = (N,A)$,
S_l^{ξ}	= l^{th} set of arcs with ξ deleted arcs, $l = 0,1,...,L$ where L = total number of sets with ξ deleted arcs,
B_k^{ξ}	= k^{th} critical bridge set with ξ deleted arcs,
$\backslash$	= Negation sign where $A' = A \backslash a_m$ implies that set A' includes all the arcs of set A but a_m,
P_r^{ξ}	= Arcs of the fastest path for the directed network $\mathcal{G}'' = (N,A'')$,
$(t_d)_r^{\xi}$	= Time delay in using the directed network $\mathcal{G}'' = (N,A'')$,
r, k, l, n, t	= Counters.

In addition to the shortest path algorithm, other algorithms are also available for the identification of critical bridges for a given highway transportation network. For example, in Basöz and Kiremidjian (1993), the critical bridges are identified by the application of *maximum flow minimum cut* theory. In that paper, the maximum flow minimum cut theory has been modified to solve the specific problem of finding all the critical bridge sets. However, the shortest path algorithm is adopted in this research for the following two reasons:

- Computational efficiency: Maximum flow minimum cut approach requires more iterations than shortest path algorithm to obtain all the critical bridge sets.
- Redundancy: The procedure to calculate the u-value for the emergency response, u_E, requires calculating the effect of time delay and participation for each failure scenario of bridges. A method using the shortest path algorithm has been developed to determine the effects of these two attributes. However, shortest path algorithm can be

```
Initialize: S_0^0 = ∅;
            B_0^0 = ∅;
            ξ = 0;
            donext = TRUE

Find the fastest path P_0^0, of directed network G = (N,A),

while (donext is TRUE) {
        Initialize:   r = 0; k = 0;
        For each set S_r^ξ with ξ deleted arcs,
          Define A' = A \ S_r^ξ
          For each arc a_m, on the fastest path P_r^ξ
               Define A'' = A' \ a_m
               For each number of deleted arc n, n = 1, ..., ξ
                      For each critical bridge set t with n deleted arcs
                             if (B_t^n ⊂ A \ A'') then { Goto END }
                      end for
               end for
          Compute the fastest path P_r^(ξ+1) and time delay (t_d)_r^(ξ+1)
          if a fastest path P_r^(ξ+1) exists then {
               S_r^(ξ+1) = A \ A''
               Call TDELP
               r = r + 1
          } else {
               B_k^(ξ+1) = A \ A''
               k = k + 1
          end if
         END
          end for
        end for
        ξ = ξ + 1
        if (S_0^ξ = ∅) then   donext = FALSE
end while
```

Figure 6.3 Pseudo Code for the Network Analysis

For the set of arcs, $A = \{a_1, a_2, ..., a_m\}$,

Let $time_m$ = travel time from source to sink for $\{A'\} = \{A\} \setminus a_m$,

$frequency_m$ = number of times a_m is used to get from source to sink in all possible paths,

$frequency\text{-}count_m$ = counter for $a_m (frequency)$,

$pointer_m$ = pointer to the next arc on the fastest path.

Initialize: $time_m = 0$

$frequency_m = 0$

$frequency\text{-}count_m = 0$

$pointer_m$ = NULL

TDELP (module for time delay and participation factor analyses)

Order arcs $a_j \in P_r^{\xi+1}$, $j = 1,..., q$ where q = total number of arcs on the fastest path

Order arcs $a_i \in S_r^{\xi+1}$, $i = 1,..., z$ where z = total number of arcs in set $S_r^{\xi+1}$

Assign $time_z = (t_d)_r^{\xi+1}$

$$Q = \{A''\} - q - (frequency - count_q)$$

$$frequency_q = frequency_q + z + \sum_{i=1}^{Q} \binom{Q}{i}$$

$$frequency\text{-}count_q = frequency\text{-}count_q + 1$$

Figure 6.3 Pseudo Code for the Network Analysis (continued)

used simultaneously to identify the set of bridges that destroy connectivity between given origins and a destination. That is , if a set of bridges destroy the connectivity, the shortest path algorithm will declare the nonexistence of a path and in the case that a shortest path exists, it will enable to calculate the time delay and participation attributes. Hence, it is redundant to perform a separate analysis using maximum flow minimum cut theory just to identify the critical bridge sets.

In the algorithm shown in Figure 6.3, highway system is modeled as a network where arcs represent the roads and bridges, and nodes represent the connection points such as cities. The level of detailing in the network depends upon the analyst's preferences. Figures 6.4.a and 6.4.b illustrate a hypothetical network and a possible extended form of the same network. For example, the network shown in Figure 6.4.a can be used for an analysis at the county level, where the bridges, and interstate and county highways are represented by the arcs. The details of city streets can be excluded by grouping city streets as nodes. In contrast, the network shown in Figure 6.4.b can be used in a more detailed analysis. However, it is important not to lose any existing redundancy in the process of simplifying the network model. For example, the simple network of Figure 6.4.a is accurate only if the arcs depicted as dashed lines in Figure 6.4.b do not exist. The redundancy of the system is lost in the simple network of Figure 6.4.a, when the routes represented by the dashed lines exist in the real system.

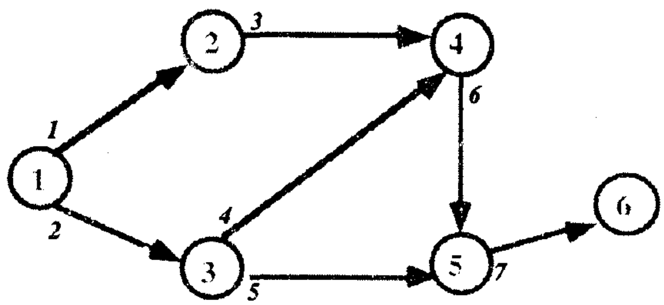


Figure 6.4.a Simple Network

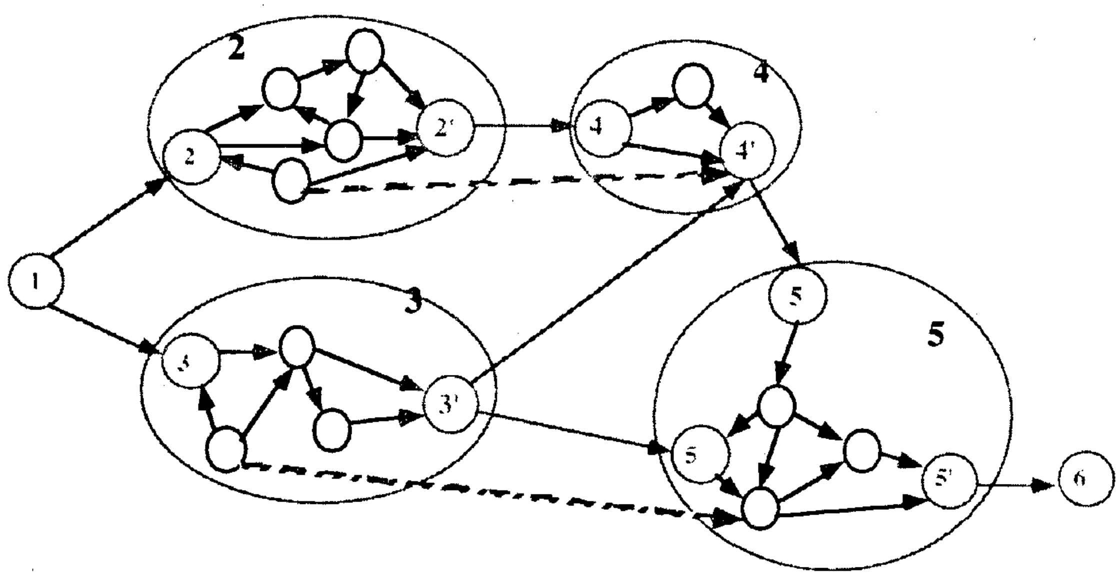


Figure 6.4.b Extended Network

CHAPTER 7

EXAMPLE APPLICATION

An example application of the bridge prioritization methodology is presented in this chapter. The objective of the example is to rank a set of bridges for the emergency response conditions. The example is designed to help understand how to implement the methodology for prioritization of bridges. The ranking of seven bridges is presented here only for illustration purposes and is not intended as a final result to be implemented in practice.

7.1 DESCRIPTION OF THE EXAMPLE NETWORK SYSTEM

Network size: A system with only seven bridges is considered in order to clearly illustrate the steps of the methodology. Since the details of the specific computations would make it harder to follow the steps of the methodology, a more complicated system is avoided in this introductory example.

Network system details: The main assumptions made to simplify the example network system are summarized below.

Network configuration. In this example, the nodes represent highways and streets, and the links represent only bridges. In a real highway system, there are many streets and highways connecting bridges and for a more realistic modeling the streets and highways also need to be modeled as links of the network. However, the level of detail in network configuration can be adapted to the user's needs as discussed in Section 6.4.2. The level of detail does not require any change in the network algorithm that is illustrated in here.

Redundancy of the network system. The example network system assumes that a bridge is the only link between its starting and ending nodes. This assumption is appropriate for systems with little redundancy, such as systems with water crossing bridges. However, most of the real highway systems would have several roads that connect the starting and ending nodes of the bridge. When the bridge is inaccessible, these roads would constitute the detour for the bridge. The more detours are available, the more redundant is the system. No redundancy is assumed in this example. By this assumption, more bridges are designated as the critical structures in the network system.

Impedance functions for the network components. The impedance factor is selected as the travel time because after a major earthquake the shortest distance from any source to a sink does not necessarily constitute the fastest route. The impedance function on a link is defined as the free-flow (zero-density) time, since commute traffic is assumed to be nonexistent during the emergency response period. However, for long term economic recovery analysis, the link impedance factor should be defined as a function of volume and capacity of the link.

As discussed earlier in Chapter 6, in a less detailed network configuration, the nodes can represent a group of streets. For example, an interstate highway network system can be modeled in such a way that a group of city streets are represented as a node. In this case, a constant time to travel through the city streets can be assumed and this travel time can be assigned to the respective node. In this example, each node is assigned a constant travel time indicating that the travel time to reach the starting point of a bridge is the same regardless of the city streets route taken.

Traffic flow direction. In a directed network, a two-way traffic on a highway or street is usually modeled by two separate arcs. Figure 7.1 shows one-way and two-way traffic flow models of a road segment. Although the selected bridges carry two-way traffic in reality, they are assumed to carry one-way traffic in this example, to minimize redundancy.

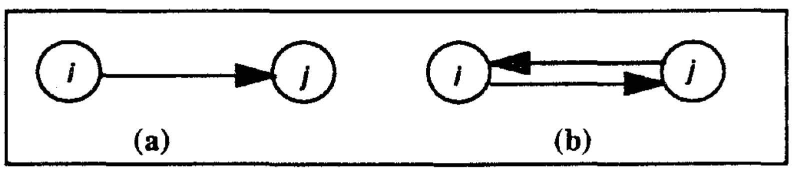


Figure 7.1 (a) One-way Traffic Flow Model
(b) Two-way Traffic Flow Model

7.2 VULNERABILITY ASSESSMENT

The steps of vulnerability assessment are summarized in Chapter 3 (see Figure 3.2) and implemented here for the example set of bridges.

• *Obtain structural information Y and Y' from the inventory.*

Seven Palo Alto, California bridges are selected from the Caltrans database. The structural information for the selected bridges is listed in Table 7.1. A legend for Table 7.1 and the inventory code descriptions are given in Appendix D.

BRIDGE ID	LAT	LONG	SUB STR_ MAT	SUPER STR_ TYPE	SPAN CONTIN	TOTAL SPAN_NO	PIER TYPE	ABUT TYPE	COLUMN HEIGHT	SKEW	YEAR BUILT	YEAR RECONST	LENGTH (ft)	DECK WIDTH (ft)	COLUMN FOUND	ABUT FOUND	SCOUR CONDTN
37 0449	37°42'5	-122°09'7	C	QI	C	4	H	A	A	19	1990	0	253	325	C	C	*
37C0222	37°43'6	-122°11'9	*	QS	*	1	*	A	N	8	1988	0	40	620	*	C	6
37C0345	37°43'6	-122°08'6	C	CS	C	3	N	A	A	12	1987	0	93	785	C	C	6
37C0346	37°42'8	-122°19'4	C	QI	C	3	N	A	B	35	1989	0	222	620	S	S	7
37C0561	37°40'6	-122°16'1	*	CG	*	1	*	D	N	60	1918	0	24	240	*	F	6
37C0766	37°41'7	-122°13'6	C	CS	C	2	N	N	A	45	1929	1975	31	390	X	X	6
37C0768	37°43'6	-122°13'6	*	QS	*	1	*	A	N	1	1989	0	38	720	*	C	6

Table 7.1 Structural Attributes of the Selected Bridges

BRIDGE ID	ADT	CONDN	DEFNS DESGN	DESGN	TRAFFIC DIRECT	KIND	FEATR_INT	FUNCTN CLASS	HIST SIGN	LANE O/U	ENCR	PSD	ROUTE	SERV TYPE
37 0449	184200	A	1	1	1	2	Renstorff Ave OC	12	5	208	*	L	101	11
37C0222	3000	A	0	0	2	5	Matadero Creek	17	4	200	*	N	C411	65
37C0345	4000	A	*	0	2	5	Permanente Creek	17	4	400	*	N	C321	65
37C0346	15500	A	0	0	2	5	San Francisquito Creek	08	5	300	*	N	C015	15
37C0561	194	A	0	0	2	4	Matadero Creek	08	5	200	*	N	0000	15
37C0766	2300	A	0	0	2	5	Matadero Creek	19	5	200	*	N	0000	65
37C0766	1250	A	0	0	2	5	Matadero Creek	19	4	200	*	N	0000	65

Table 7.2 Importance Attributes of the Selected Bridges

• *Assign the bridge to one or at most two of the bridge class sub-categories, C_n^j, defined in Section 4.1.*

The structural information for the seven bridges is stored and processed in the expert system. For example, the inventory codes are converted to the common terms used in bridge class definitions and necessary missing information is inferred from the available data. The final classification of bridges is shown in Table 7.3. For bridges that are classified into two classes, the normalized distance, Δ_{ij}, between the bridge and the sub-category C_n^j is also listed in Table 7.3. For example, bridge 37C0766 is classified into C_1, with a normalized distance of 89% to sub-category C_1^4 (multiple span most vulnerable sub-category for bridge class 1) and 11% to sub-category C_1^3 (multiple span least vulnerable sub-category for bridge class 1). This bridge has monolithic abutments, continuous spans and pier walls and the effect of these characteristics are reflected on the classification which implies that the bridge will experience a seismic behavior closer to that described by the sub-category C_1^3.

Bridge ID	Bridge_no	Class No.	Δ_{ij} (%)
1	37 0449	C_1^3	100
2	37C0222	C_1^1	100
3	37C0345	C_1^3 C_1^4	76 24
4	37C0346	C_1^3 C_1^4	76 24
5	37C0561	C_1^2	100
6	37C0766	C_1^3 C_1^4	89 11
7	37C0768	C_1^1	100

Table 7.3 Classification of the Selected Bridges

• *Determine if any modifiers, β, need to be assigned.*

The secondary structural attributes that are necessary for the modifiers, such as skew, year built and so on, are also listed in Table 7.1.

• *Perform seismic hazard analysis to compute the seismicity parameter.*

The software STASHA (Kiremidjian et. al., 1994) is used to compute the probability of exceedance for 50 years in a given peak ground acceleration (pga). In this example, soil characteristics at all bridge sites are assumed to be uniform, i.e., rock sites. Figure 7.2 shows the hazard curves obtained for each bridge site. As uniform soil conditions are assumed for all bridge sites, the hazard curves are exactly the same for some bridges that are spatially too close. However, in order to compute the seismic hazard at a given bridge site more accurately, one needs to consider the soil profile for each bridge site in the utilized attenuation relationships. In Figure 7.3 hazard curves for bridge 37C0766 are shown for rock site and soil site to emphasize the effect of soil characteristics.

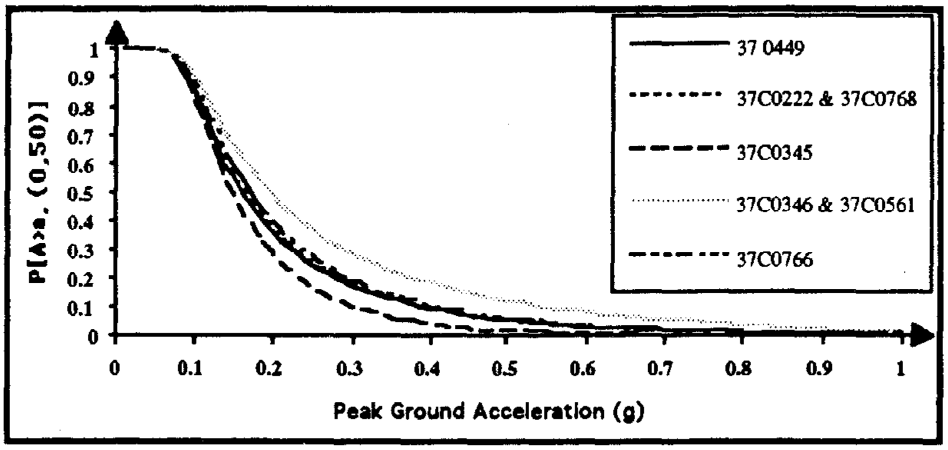


Figure 7.2 Seismic Hazard Curves for Uniform Soil Characteristics at Different Bridge Sites

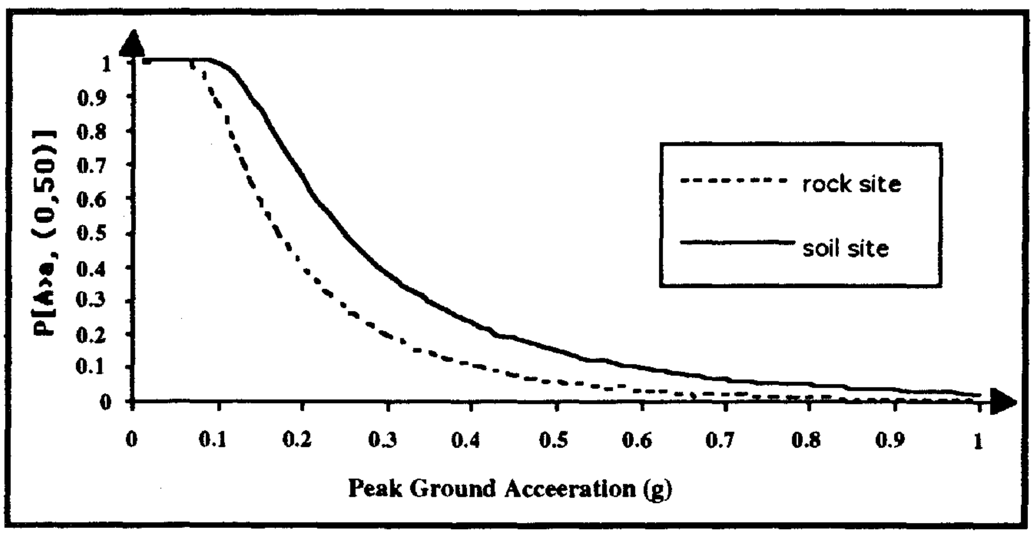


Figure 7.3 Seismic Hazard Curves for Different Soil Characteristics

• *Select the corresponding ground motion-damage relationship for the bridge class that the bridge is assigned to and find* $q_c(A)$ *where subscript* **c** *represents collapse damage state.*

The need to develop fragility curves for each bridge class has been emphasized earlier. Since, fragility curves are not available for each bridge class, hypothetical values for $q_c(A)$ are used in the remaining parts of the example. Table 7.4 lists the hypothetical fragility values, $q_c(A)$, for each bridge.

Bridge ID	1	2	3	4	5	6	7
$q_c(A)$	0.16	0.19	0.05	0.14	0.14	0.1	0.05

Table 7.4 Hypothetical Fragility Values, $q_c(A)$, for the Selected Bridges

• *Evaluate the vulnerability parameter V using equation (3.4).*

$$V = \beta f[q_c(A)] \quad (7.1)$$

As discussed earlier in Section 5.2.2, modifiers need to be determined for each bridge class. Similar to $q_c(A)$ values, hypothetical β values are used for illustration purposes in this example. In particular, bridge 37C0561 has a 60° skew which is expected to increase the vulnerability of the structure. The final value for the vulnerability criterion is obtained by modifying the $q_c(A)$ values by β values. The V values listed in Table 7.5 are hypothesized such that they reflect the expected effects of the modifiers.

Bridge ID	1	2	3	4	5	6	7
V	0.19	0.27	0.07	0.16	0.21	0.18	0.05

Table 7.5 Hypothetical Vulnerability Values, *V*, for the Selected Bridges

7.3 IMPORTANCE ASSESSMENT

• *Obtain a decision maker's values, develop utility functions and scaling factors for all importance attributes.*

The only importance factor used in this example is the emergency response and its attributes are defined in equation (3.6.b) as μ (critical set member), t_d (time delay), and ϕ (participation). The hypothetical utility functions developed in Section 6.3 are used in this example. The utility function for vulnerability, *V*, is also included. Hypothetical scaling factors are defined both for level one and level two analysis. The hypothetical scaling factors are listed in Table 7.6 below.

Analysis Level	Scaling Factors			
	k_μ	k_{t_d}	k_ϕ	k_V
Level one	0.4	-	-	0.6
Level two	-	0.5	0.5	-

Table 7.6 Hypothetical Scaling Factors for the Emergency Response Attributes

• *For a given bridge obtain attributes for lifeline network analysis.*

Table 7.2 lists the importance attributes for the seven bridges as obtained from the Caltrans database. In order to minimize the computational efforts and to give a more clear presentation of the network analysis algorithm, the information listed in Table 7.2 is not incorporated to the network used in this example. The network analysis is based on a hypothetical network configuration for the reasons discussed in Section 7.1.

• *Perform network analysis: connectivity analysis for emergency response.*

The algorithm that is described in Figure 6.3 is used for the network analysis. Three different examples are analyzed to illustrate the effects of emergency response attributes on the final ranking.

Example 1: The hypothetical network configuration used for this example is shown in Figure 7.4. The objective of this example is to reach *node 6* from either *node 1* or *node 2* during the emergency response period. This objective can be considered as the model of conveying rescue teams located at *nodes 1* and *2* to the disaster area. Unlimited resources at any of the resource nodes is assumed. A supernode is used to connect the two origin nodes for computational efficiency. The arcs connecting the supernode to the origin nodes are assigned zero impedance values. By this means, the fastest path from either of the origin nodes to the destination node is captured. The notations used in Table 7.7 are summarized for convenience and the steps of the network algorithm are presented afterwards.

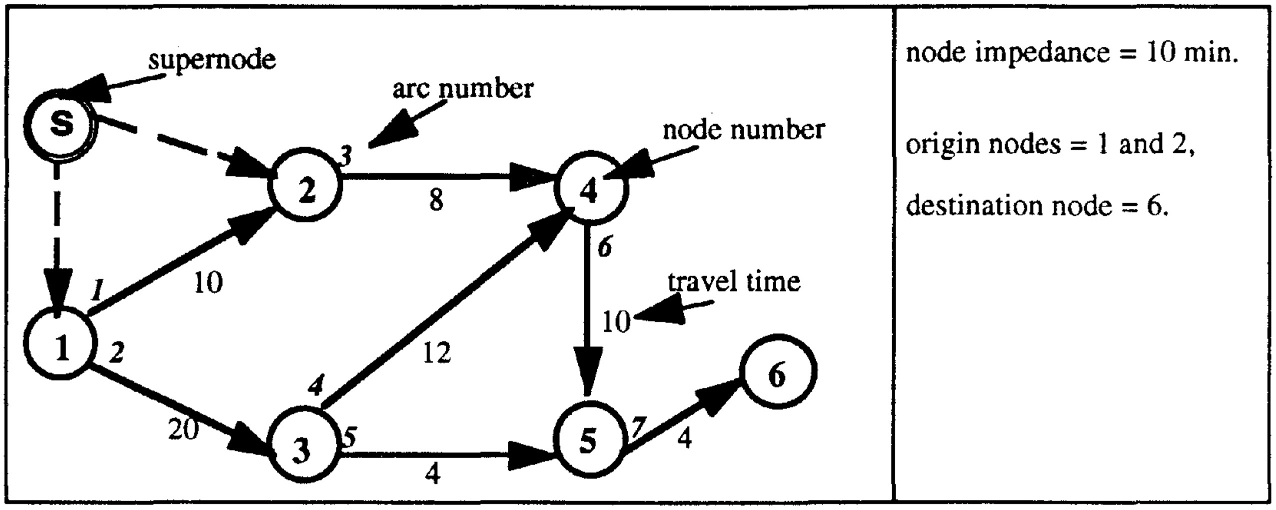


Figure 7.4 Hypothetical Network Configuration

Notations used in Table 7.7

$\mathcal{G}(N, A)$ = Directed network with set of nodes $N = \{n_1, n_2, ..., n_6\}$ and set of arcs $A = \{a_1, a_2, ..., a_7\}$,

$A' = A \setminus a_m$ = Set of arcs that includes all the elements of set A except a_m, where a_m is called as a *deleted arc*,

$A'' = A' \setminus a_k$ = Set of arcs that includes all the elements of set A' except a_k,

ξ = Number of deleted arcs in set A'',

$S_r^{\xi+1}$ = r[th] set of arcs with $\xi + 1$ deleted arcs,

$P_\bullet^\bullet$ = Set of arcs on the fastest path of the original set $\mathcal{G}(N, A)$,

$P_r^{\xi+1}$ = Set of arcs on the fastest path of r[th] set with $\xi + 1$ deleted arcs,

$T_\bullet^\bullet$ = Total time to travel on the original fastest path $P_\bullet^\bullet$,

$T_r^{\xi+1}$ = Total time to travel on $P_r^{\xi+1}$,

$(t_d)_r^{\xi+1}$ = Time delay for $P_r^{\xi+1}$, where $(t_d)_r^{\xi+1} = T_r^{\xi+1} - T_\bullet^\bullet$,

$B_k^{\xi+1}$ = k[th] critical set of bridges for the directed network with $\xi + 1$ deleted arcs,

B_t^n = t[th] critical bridge set for the directed network with n deleted arcs where $n = 1, ..., \xi$.

Steps of the Network Algorithm Implementation

I) Initialize: $S_\bullet^\bullet = \varnothing$

$B_\bullet^\bullet = \varnothing$

$\xi = 0$

II) Original fastest path from any source to sink is obtained as $P_\bullet^\bullet = \{3, 6, 7\}$
$T_\bullet^\bullet = 52$ minutes.

III) Initialize: $r = 0; k = 0.$

$A' = A$

a_m	A''	$B_t^n \subset A \setminus A''$	$P_r^{\xi+1}$	$S_r^{\xi+1}$	$T_r^{\xi+1}$	$(t_d)_r^{\xi+1}$	$B_k^{\xi+1}$	remarks
3	{1,2,4,5,6,7}	FALSE	{2,5,7}	{3}	58	6	-	r = 1
6	{1,2,3,4,5,7}	FALSE	{2,5,7}	{6}	58	6	-	r = 2
7	{1,2,3,4,5,6}	FALSE	-	-	∞	∞	{7}	k = 1

Table 7.7 Intermediate Results for Network Analysis

$B_\bullet^1 = \{7\}$; ∴ Bridge 7 is a critical single bridge.

$\xi = 1$

IV) Initialize: $r = 0; k = 0.$

$A' = A \setminus S_\bullet^1 = \{1,2,4,5,6,7\}$

a_m	A''	$B_t^n \subset A \setminus A''$	$P_r^{\xi+1}$	$S_r^{\xi+1}$	$T_r^{\xi+1}$	$(t_d)_r^{\xi+1}$	$B_k^{\xi+1}$	remarks
2	{1,4,5,6,7}	FALSE	-	-	∞	∞	{3,2}	k = 1
5	{1,2,4,6,7}	FALSE	{2,4,6,7}	{3,5}	86	34	-	r = 1
7	{1,2,4,5,6}	TRUE						no calculations needed

Table 7.7 Intermediate Results for Network Analysis (continued)

$$A' = A \setminus S_1^{\,1} = \{1,2,3,4,5,7\}$$

a_m	A''	$B_t^{\,n} \subset A \setminus A''$	$P_r^{\,\xi+1}$	$S_r^{\,\xi+1}$	$T_r^{\,\xi+1}$	$(t_d)_r^{\,\xi+1}$	$B_k^{\,\xi+1}$	remarks
2	{1,3,4,5,7}	FALSE	-	-	∞	∞	{6,2}	k = 2
5	{1,2,3,4,7}	FALSE	-	-	∞	∞	{6,5}	k = 3
7	{1,2,3,4,5}	TRUE						no calculations needed

Table 7.7 Intermediate Results for Network Analysis (continued)

$B_0^{\,2} = \{2,3\}$; $B_1^{\,2} = \{6,2\}$; $B_2^{\,2} = \{6,5\}$;

∴ Bridge pairs (2,3), (2,6) and (5,6) are pairs of critical bridge sets.

$\xi = 2$

V) Initialize: $r = 0; k = 0.$

$$A' = A \setminus S_0^{\,2} = \{1,2,4,6,7\}$$

a_m	A''	$B_t^{\,n} \subset A \setminus A''$	$P_r^{\,\xi+1}$	$S_r^{\,\xi+1}$	$T_r^{\,\xi+1}$	$(t_d)_r^{\,\xi+1}$	$B_k^{\,\xi+1}$	remarks
2	{1,4,6,7}	TRUE						no calculations needed
4	{1,2,6,7}	FALSE	-	-	∞	∞	{3,4,5}	r = 1
6	{1,2,4,7}	TRUE						no calculations needed
7	{1,2,4,6}	TRUE						no calculations needed

Table 7.7 Intermediate Results for Network Analysis (continued)

$B_0^{\,3} = \{3,4,5\}$; ∴ Bridge triplet (3,4,5) is a triplet critical bridge set.

$\xi = 3$

VI) $S_0^{\,3} = \varnothing$ ∴ **STOP**

7.4 RANKING OF THE SELECTED BRIDGES

The level one and level two calculations are summarized in this section. Table 7.8 gives the summary of level one calculations. Equation (6.5) is repeated here for convenience and is used for the calculations to rank critical bridge sets.

$$U_m{}' = k_V u_{Vj} + k_\mu u_{\mu j} \tag{7.2}$$

where $k_V = 0.6$ and $k_\mu = 0.4$ as defined in Table 7.6.

$B_k{}^\xi$	V	u_V	μ	u_μ	$U_m{}^s$
7	0.05	0.1974	1	0.025	0.128
(2,3)	0.0189	0.0788	1	0.025	0.058
(2,6)	0.0486	0.1924	1	0.025	0.125
(5,6)	0.0378	0.1525	1	0.025	0.102
(5,3,4)	0.0024	0.0103	1	0.025	0.016

Table 7.8 Summary of Results for Ranking of Critical Sets - Example 1

The ranking of the critical bridge sets as obtained by using the last column of Table 7.8 is given below.

$$B_7 > \{B_6, B_2\} > \{B_6, B_5\} > \{B_2, B_3\} > \{B_5, B_4, B_3\}$$

In order to rank bridges within a critical set, level two calculations are performed as defined by equation (6.6) and (6.7), and repeated here for convenience as equations (7.3.a) and (7.3.b). Equation (7.3.c) is used for combining importance and vulnerability. Table 7.9 summarizes the computations. For level two calculations $k_{t_d} = 0.5$ and $k_\phi = 0.5$ defined in Table 7.6 are used. For the final ranking $k_V = 0.4$ and $k_I = 0.6$ are used.

$$\hat{u}_{Ei} = k_{t_d} u_{t_d i} + k_\phi u_{\phi i} \tag{7.3.a}$$

$$U_{Ii} = \alpha\left(U_m{}'(\overline{R}_{r-1}) + \Delta U_m{}' * \hat{u}_{Ei}\right) \tag{7.3.b}$$

$$\hat{U}_i = k_V U_{Vi} + k_I U_{Ii} \tag{7.3.c}$$

The final ranking based on the values obtained from Table 7.9 is as follows:

$$B_7 > B_6 > B_2 > B_5 > B_3 > B_4$$

Arc No	t_d	u_{t_d}	ϕ	u_ϕ	$\hat{u}_E$	U_I	V	U_V	$\hat{U}$
2	0	0	13	0.81	0.405	0.870	0.27	0.745	0.82
3	6	0.0045	14	0.88	0.442	0.270	0.07	0.267	0.27
4	0	0	2	0.12	0.060	0	0.16	0.525	0.21
5	0	0	11	0.69	0.345	0.572	0.21	0.636	0.60
6	6	0.0045	16	1	0.502	0.887	0.18	0.871	0.88
(3,4)	6	0.0045	0	0	0.002	0	0.011	0.047	-
(3,5)	34	0.0554	0	0	0.028	0	0.015	0.062	-
(4,5)	0	0	0	0	0	0	0.152	0.506	-

Table 7.9 Summary of Results for Ranking Bridges within the Critical Sets - Example 1

The results listed in Tables 7.8 and 7.9 show that $\mathbf{B_1}$ is not needed in order to reach *node 6* either from *node 1* or *node 2*. This result is reflected in the ranking such that $\mathbf{B_1}$ does not appear in the final ranking indicating that for the given objective the bridge should not be ranked high despite of its high vulnerability assessment. Bridges that are not included in the ranking are ranked separately based on u_V. Thus, the final ranking of the seven bridges with the objective of getting from either *node 1* or *node 2* to *node 6* is determined to be as follows:

$$\mathbf{B_7 > B_6 > B_2 > B_5 > B_3 > B_4 > B_1}$$

<u>Example 2</u>: This example uses the same network configuration defined in Example 1. However, in addition to the existing origin-destination pair (*origins: node 1 and 2; destination node 6*); a new origin destination pair is introduced to the system (*origin node: 1, destination: 4*). The objective is to reach both destinations from the respective origin points reflecting a situation where two disaster areas might need different rescue teams: one (e.g. *node 6*) may need health crew for the people after rescue from structural collapses; the other (e.g. *node 4*) may need fire fighting equipment. It might well be the case that *node 1* has resources both for fire fighting and rescuing purposes whereas *node 2* has only casualty rescue teams.

The steps of the network algorithm are repeated for each origin-destination pair and the results are presented in Tables 7.10 and 7.11. The results listed in Table 7.10 are different than the ones presented in Table 7.8 as critical bridges and the number of times they are found to be critical, ϕ, have changed based on the objective.

The ranking of the critical bridge sets as obtained by using the last column of Table 7.10 is given below.

$$B_7 \cong \{B_1,B_2\} > \{B_6,B_2\} > \{B_6,B_5\} > \{B_1,B_4\} > \{B_2,B_3\} > ...$$

The ranking is stopped before all the critical bridge sets are included since all seven bridges are already considered in the ranking. The ordering of the remaining critical bridge sets does not affect the ranking of bridges in this case.

The final ranking of the seven bridges with the objective of getting from either *node 1* or *node 2* to *node 6*, and *node 1* to *node 4* is determined to be as follows:

$$B_7 \cong B_2 > B_1 > B_6 > B_5 > B_4 > B_3$$

B_k^{ξ}	V	u_V	μ	u_μ	U_m^s
7	0.05	0.197	1	0.025	0.13
(1,2)	0.0513	0.202	1	0.025	0.13
(1,4)	0.0304	0.124	1	0.025	0.08
(2,3)	0.0189	0.079	2	0.050	0.07
(2,6)	0.0486	0.192	1	0.025	0.12
(3,4)	0.0112	0.047	1	0.025	0.04
(5,6)	0.0378	0.153	1	0.025	0.10
(5,3,4)	0.0024	0.010	1	0.025	0.02

Table 7.10 Summary of Results for Ranking of Critical Sets - Example 2

Arc No	t_d	u_{t_d}	ϕ	u_ϕ	$\hat{u}_E$	U_I	V	U_V	$\hat{U}$
1	14*	0.0129	*3***	0.153	0.083	0.97	0.19	0.594	0.84
2	0	0	*16*	0.818	0.409	1	0.27	0.745	0.90
3	14	0.0129	*17*	0.869	0.441	0.43	0.07	0.267	0.35
4	0	0	*5*	0.256	0.128	0.57	0.16	0.525	0.54
5	0	0	11	0.687	0.344	0.70	0.21	0.636	0.66
6	6	0.0045	16	1	0.502	0.87	0.18	0.871	0.86

* The time delay is obtained as the maximum of the two values for the given bridge.
** Numbers in italics have a total of 33 possible paths where the others have 27 possible paths.

Table 7.11 Summary of Results for Ranking Bridges within the Critical Sets - Example 2

A significant change in ranking is observed when the results of Example 1 and Example 2 are compared. In Example 1, bridge **B_1** is rated as the last candidate for retrofitting decisions whereas the same bridge is ranked the third in this example. This result illustrates the effect of different objectives on the ranking for retrofitting decisions.

<u>Example 3</u>: The link impedance of the network in Example 1 are artificially increased to show the effect of time delay in the final ranking. The modified network is shown in Figure 7.5.

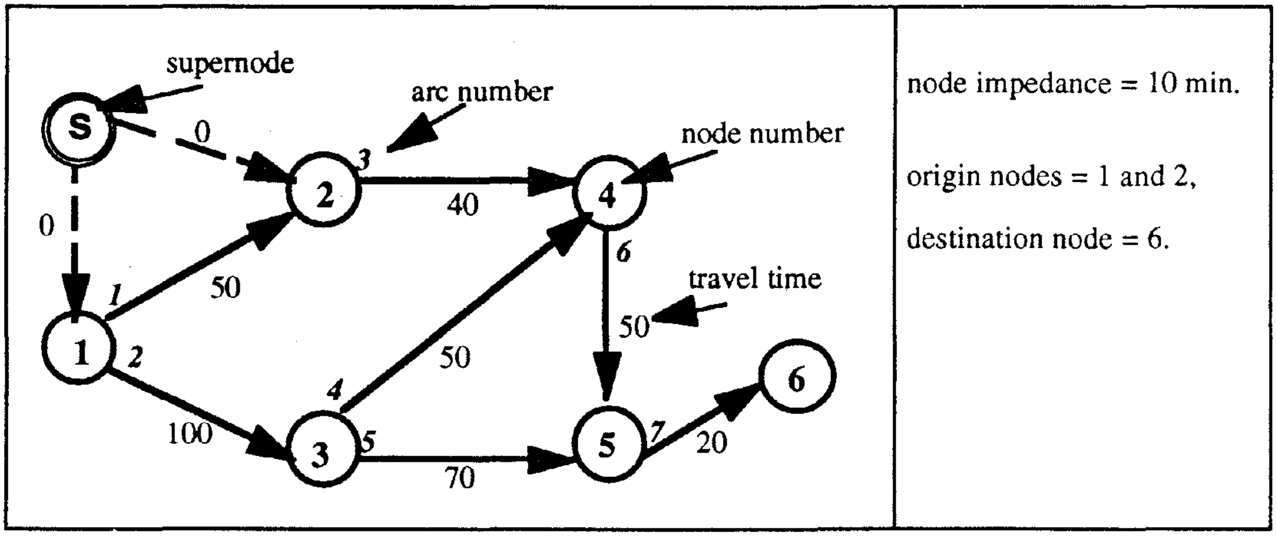


Figure 7.5 Hypothetical Network Configuration with Modified Link Impedance

Since time delay does not contribute to the level one calculations, the results of level one calculations remain the same as given in Table 7.8. Level two calculations are summarized in Table 7.12.

The ranking of the critical bridge sets as obtained by using the last column of Table 7.12 is given below.

$$B_7 > B_6 > B_2 > B_5 > B_3 > B_4 > B_1$$

In this example, only ranking of two bridges, bridges **B_2** and **B_6**, have changed dur to the change in the travel time but for a different network configuration the effect of t_d can be more prominent.

Arc No	t_d	u_{t_d}	ϕ	u_ϕ	$\hat{u}_E$	U_l	V	U_V	$\hat{U}$
2	0	0	13	0.81	0.405	0.898	0.27	0.745	0.84
3	80	0.614	14	0.88	0.747	0.370	0.07	0.267	0.33
4	0	0	2	0.12	0.06	0.002	0.16	0.525	0.21
5	0	0	11	0.69	0.345	0.588	0.21	0.636	0.61
6	80	0.614	16	1	0.807	0.751	0.18	0.871	0.8
(3,4)	80	0.614	0	0	0.307	0.038	0.011	0.047	-
(3,5)	120	1	0	0	0.500	0.063	0.015	0.062	-
(4,5)	0	0	0	0	0	0	0.152	0.506	-

Table 7.12 Summary of Results for Ranking Bridges within the Critical Sets - Example 3

Effect of Scaling Factors: The scaling factors can have a significant impact on the final ranking. In this example, the ranking is not highly sensitive to the scaling factors mainly due to the network configuration. Different critical bridge sets include the same bridges. For example, critical sets {$\mathbf{B_2}$, $\mathbf{B_1}$} and {$\mathbf{B_6}$, $\mathbf{B_2}$} include $\mathbf{B_2}$, and {$\mathbf{B_6}$, $\mathbf{B_2}$} and {$\mathbf{B_6}$, $\mathbf{B_5}$} include $\mathbf{B_6}$ in Example 2. The final ranking is dominated by the level one calculations and if one of the bridges in a pair critical set is already ranked, their relative ranking is irrelevant. For example as {$\mathbf{B_2}$, $\mathbf{B_1}$}>...>{$\mathbf{B_6}$, $\mathbf{B_2}$}, regardless of u_{E_6} and u_{E_2}, bridge 2 is ranked higher than bridge 6. This supports the idea that in an emergency response the main objective is to reach from origin to destination which is governed by the connectivity of the system utilized in level one analysis. However, since the effect of scaling factors can be significant in a more redundant and complex network system, it must be ensured that the scaling factors represent the decision maker's value and preferences.

CHAPTER 8

SUMMARY AND FUTURE WORK

A prioritization method based on vulnerability and importance criteria has been developed for seismic retrofitting of bridges. This method is more comprehensive than the currently available prioritization methods. The prioritization methodology presented here is formulated within a general framework which can be applied for ranking of bridges or other structures under seismic and other hazards.

In this report the components of the general prioritization methodology are defined and analytical procedures are developed. First, new bridge classes are defined. Next, an expert system, **ESCOB**, for classification of existing bridges is developed. A mathematical model is incorporated into **ESCOB** that provides flexibility for the values of the key parameters. Inference schemes for incomplete information are also included in this expert system. Then, the importance of the network system performance in retrofitting decisions is emphasized and a network analysis procedure for emergency response is developed. The methodology considers ranking for different objectives. For example, the ranking for only emergency response purposes would be different than a ranking that considers both emergency response conditions and the long term economic impacts. The ranking is also dependent on the decision maker, i.e., the objectives can change from one decision maker to another. For example, a ranking for a federal funded retrofitting decision would be different than a locally funded one. In this methodology, the importance of the decision maker's values and preferences are reflected by the decision analysis tools used in the overall ranking procedures.

Further research is recommended in the following areas in order to improve the final ranking:

Improvement of the vulnerability assessment: The vulnerability assessment is highly dependent on how well the ground motion-damage relationships represent the seismic behavior of a given bridge. In order to better assess the vulnerability, the following tasks need to be accomplished:

- Develop definitions of physical and functional damage states and relationships between the physical and functional damage states,

- Develop fragility curves for each bridge class for different damage states, and
- Formulate modifiers that consider the effect of secondary vulnerability attributes on the seismic behavior of the bridge.

Improvement of the importance assessment: In order to achieve an importance assessment that considers both short-term and long-term demands, the long term economic impacts of bridge failures in a highway system need to be studied. This involves mainly the serviceability analysis of the highway system during the restoration period of bridges.

Use of GIS environment: Regional evaluation of transportation lifeline facilities for emergency planning and seismic retrofitting criteria can be accomplished by the use of computer-based Geographic Information Systems (GIS). A GIS-based approach provides a general, flexible methodology which enables to substitute or modify any of the components such as damage model or hazard model. In a study by King and Kiremidjian (1994), a GIS-based methodology for conducting regional seismic hazard and risk analysis is developed. This study illustrates the effectiveness of GIS in regional seismic hazard assessment. GIS has been used extensively for several lifeline systems other than transportation network systems (e.g., Shinozuka and Sato, 1991, Djokic and Maidment, 1993 and Shinozuka, 1994). In another study by Kim (1993), GIS is used in the regional evaluation of transportation lifeline facilities that may be impacted by seismic and other natural hazards.

The definition of damage states, development of preliminary fragility curves and integration of the necessary tasks for prioritization under the GIS environment are currently in progress in another research project. The research project is funded by National Science Foundation (NSF) to conduct a study for the post-earthquake performance of the transportation systems in the areas affected by the 1994 Northridge earthquake. The objectives include the identification of critical bridges and available routes for emergency management purposes, estimation of possible time delays and the estimation of damage and loss to transportation systems.

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APPENDIX A

BRIDGE CLASSES AND SUB-CATEGORIES

Bridge Class 1

{concrete piers/columns (y_{11})- concrete girder (y_{21})}

$y_{31} = 1$ (single span)

C_1^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_1^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_1^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_1^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Bridge Class 2

{concrete piers/columns (y_{11})- steel girder (y_{22})}

$y_{31} = 1$ (single span)

C_2^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_2^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_2^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_2^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Table A.1 Bridge Classes and Sub-categories

Bridge Class 3
{concrete piers/columns (y_{11})- steel truss (y_{23})}

$y_{31} = 1$ (single span)

C_3^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_3^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_3^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_3^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Bridge Class 4
{steel columns (y_{12})- steel girder (y_{22})}

$y_{31} = 1$ (single span)

C_4^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_4^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_4^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_4^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Table A.1 Bridge Classes and Sub-categories (continued)

Bridge Class 5

{*steel columns (y_{12})- steel truss (y_{23})*}

$y_{31} = 1$ (single span)

C_5^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_5^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_5^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_5^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Bridge Class 6

{*concrete piers/columns (y_{11})- suspension/cable-stayed (y_{24})*}

$y_{31} = 1$ (single span)

C_6^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_6^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_6^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_6^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Table A.1 Bridge Classes and Sub-categories (continued)

Bridge Class 7
{*concrete /steel/timber/masonry, Y- arch* (y_{25})}

$y_{31} = 1$ (single span)

C_7^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_7^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_7^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_7^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Bridge Class 8
{*timber columns* (y_{13})*- any structure type except arch* ($Y_2 \setminus y_{25}$)}

$y_{31} = 1$ (single span)

C_8^{sl} (least vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_8^{sm} (most vulnerable single span sub-category)

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

$y_{31} > 1$ (multiple spans)

C_8^{ml} (least vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_8^{mm} (most vulnerable multiple span sub-category)

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Table A.1 Bridge Classes and Sub-categories (continued)

Bridge Class 9 {*masonry columns* (y_{14})*- any structure type except arch* ($Y_2 \setminus y_{25}$)}	
$y_{31} = 1$ (single span)	
C_9^{sl} (least vulnerable single span sub-category)	C_9^{sm} (most vulnerable single span sub-category)
Attribute: Abutment Type, (y_{32}) — Value: monolithic	Attribute: Abutment Type, (y_{32}) — Value: non-monolithic
$y_{31} > 1$ (multiple spans)	
C_9^{ml} (least vulnerable multiple span sub-category)	C_9^{mm} (most vulnerable multiple span sub-category)

C_9^{sl}:

Attribute	Value
Abutment Type, (y_{32})	monolithic

C_9^{sm}:

Attribute	Value
Abutment Type, (y_{32})	non-monolithic

C_9^{ml}:

Attribute	Value
Abutment Type,(y_{32})	monolithic
Span Continuity, (y_{33})	continuous
Columns/bent, (y_{34})	multiple

C_9^{mm}:

Attribute	Value
Abutment Type,(y_{32})	non-monolithic
Span Continuity, (y_{33})	discontinuous
Columns /bent, (y_{34})	single

Bridge Class 10 {*concrete /steel/timber/masonry, Y- others* ($y \notin Y_2$)}
Special class for bridges that need further investigation

Table A.1 Bridge Classes and Sub-categories (continued)

APPENDIX B

BRIDGE CLASSIFICATION QUESTIONNAIRE

BRIDGE CLASSIFICATION QUESTIONNAIRE

The objective of this questionnaire is to obtain information of various bridge characteristics in order to develop an expert system for classifying bridges. As a first step towards the development of this system, it is necessary to define bridge classes that represent typical construction. The list of bridge classes has to be comprehensive in order to enable the classification of as many bridges as possible, yet it has to be simple in order for such a classification system to be manageable.

It is proposed that the bridge classification be based primarily on material and structural type. The material type is taken to correspond to the material of the substructure and the structural type is to reflect the superstructure of the bridge.

Based on these criteria ten bridge classes are defined in Table B.1 below:

Table B.1 Bridge Classes*

Bridge Class Identifier	Substructure Material	Superstructure Material/Type
1	concrete	concrete girder
2	concrete	steel girder
3	concrete	steel truss
4	steel	steel girder
5	steel	steel truss
6	concrete/steel	suspension/cable-stayed
7	concrete/steel/timber/masonry	arch
8	timber	any structure type except arch
9	masonry	any structure type except arch
10	concrete/steel/timber/masonry	others

The seismic vulnerability of a bridge depends not only on the material and structural type but also on other design characteristics. Each of the bridge classes listed in Table B.1 are further subdivided into two categories: *single span* and *multiple span* bridges. In order to better reflect the behavior of the different types of bridges the following attributes are considered to be the most important for bridge class definitions that will be used in the vulnerability analysis:

Single Span Bridges
- abutment type

Multiple Span Bridges
- abutment type
- span continuity
- columns per bent

Please complete the following two questionnaires.

* Table B.1 may be modified during the presentation

QUESTIONNAIRE 1:

For each attribute you are asked to provide relative weights reflecting their importance for vulnerability assessment. The weights assigned to each attribute should reflect how important is this attribute for the safety of the bridge. Vulnerability is intended to reflect various damage states ranging from minor damage to collapse. As an example, if a bridge is concrete girder with concrete piers and has multiple spans, then a possible set of importance weights may be as given in Table B.2:

Table B.2. Example Weights for Class 1 Multiple Span Bridges

Attribute	Expert's Weight	Computed Weights
Abutment Type	6	0.26
Span Continuity	7	0.30
Columns per Bent	10	0.44

In Table B.2, the weights assigned by the experts are listed in the second column and reflect the relative importance of each attribute as it relates to the likelihood of the bridge to be damaged. Thus the most important attribute is assigned a value of 10 and other attributes are assigned a value relative to that attribute and the remaining attributes. The third column lists the normalized weights so that these add to 100%. These weights will be used in the classification system.

In the following pages, bridge classes are listed with their attributes. Please provide weights for each attribute reflecting their relative importance for the given bridge class.

Name:____________________

Bridge Class 1 - Multiple span, concrete girder bridge with concrete piers/columns

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

*Expert's Confidence Level**

1	2	3	4	5	6	7	8	9	10

Bridge Class 2 - Multiple span, steel girder bridge with concrete piers/columns

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

*Expert's Confidence Level**

1	2	3	4	5	6	7	8	9	10

Bridge Class 3 - Multiple span, steel truss bridge with concrete piers/columns

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

*Expert's Confidence Level**

1	2	3	4	5	6	7	8	9	10

* Please provide your level of confidence on your judgment or knowledge about the respective bridge class, 1 corresponds to little confidence and/or knowledge and 10 corresponds to excellent confidence and/or knowledge.

Bridge Class 4 - Multiple span, steel girder bridge with steel columns

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

Expert's Confidence Level*

1	2	3	4	5	6	7	8	9	10

Bridge Class 5 - Multiple span, steel truss bridge with steel columns

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

Expert's Confidence Level*

1	2	3	4	5	6	7	8	9	10

Bridge Class 6 - Multiple span, suspension or cable-stayed bridge with concrete/steel piers/columns

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

Expert's Confidence Level*

1	2	3	4	5	6	7	8	9	10

* Please provide your level of confidence on your judgment or knowledge about the respective bridge class, 1 corresponds to little confidence and/or knowledge and 10 corresponds to excellent confidence and/or knowledge.

Bridge Class 7 - Multiple span, arch bridge with piers/columns of any type of material

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

Expert's Confidence Level*

1	2	3	4	5	6	7	8	9	10

Bridge Class 8 - Multiple span, bridge with timber columns (timber arch bridges are excluded as they are included in Bridge Class 7)

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

Expert's Confidence Level*

1	2	3	4	5	6	7	8	9	10

Bridge Class 9 - Multiple span, bridge with masonry columns (masonry arch bridges as they are included in Bridge Class 7)

Attribute	Expert's Weight
Abutment Type	
Continuity	
Columns per Bent	

Expert's Confidence Level*

1	2	3	4	5	6	7	8	9	10

---

* Please provide your level of confidence on your judgment or knowledge about the respective bridge class, 1 corresponds to little confidence and/or knowledge and 10 corresponds to excellent confidence and/or knowledge.

QUESTIONNAIRE 2:

In order to define the values of attributes listed in Table B.2 for each bridge, it is necessary to map the information available in the bridge inventory to each attribute value. Tables B.3 and B.4 provide the list of attribute descriptions for abutment type and column bents, respectively. The extreme attribute values are also defined with each table. For each attribute the extreme cases are given with corresponding numerical values of 0 and 1. Since a particular bridge may fall between these extreme cases, it is necessary to determine where the bridge attribute should be on a scale from 0 to 1. For example, a monolithic abutment is given a value of 0 and a non monolithic abutment is given a value of 1. In Table B.3, if the inventory specifies that the abutment is a diaphragm for a specific bridge, then the scaling factor for the abutment is 0 as a diaphragm is a monolithic abutment type. As another example, a bin may be given a scaling factor of 0.75 implying that the abutment is closer to being non monolithic than to being monolithic. The same reasoning applies to column bents.

Please provide scaling factors between 0 and 1 reflecting the best mapping of a specific description to the particular attribute value given in Tables B.3 and B.4.

Name:__________________

Reference Scale

0 — **1.0**

monolithic — **non monolithic**

Table B.3 Scaling Values for Abutment Types

Inventory Code	Description	Scale *	Remarks
A	Diaphragm		
B	Seat		
C	Cantilever		
D	Strutted		
E	Rigid Frame		
F	Bin		
G	Cellular Closure		
K	Sill		
M	Crib		
N	Wall		
P	Other		
Q	Cantilever end span		
U	Undefined		

* Please enter NA for *not applicable*.

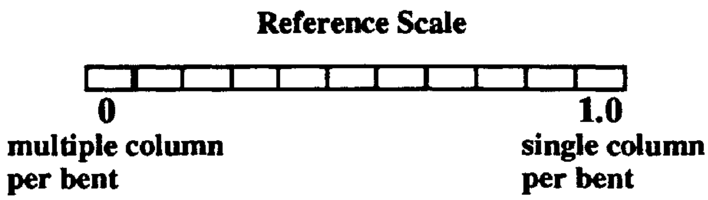

Table B.4 Scaling Values for Bents or Piers

Inventory Code	Description	Scale *	Remarks
H	Column Bent		
I	Pile Bent		
J	Single Column		
N	Pier Wall		
U	Undefined		

* Please enter NA for *not applicable.*

APPENDIX C

EXPERT SYSTEMS

EXPERT SYSTEMS

Expert systems are interactive computer programs incorporating judgment, rules of thumb, intuition, and other expertise to provide knowledgeable advice about variety of tasks (Dym and Levitt, 1991).

Expert systems are based on the idea that rules are an effective way to tell the computers how people do certain kinds of things. Expert systems can be grouped in the following three types:

> Rule-Based Expert System. The system presents the knowledge in a purely empirical form without any knowledge of the underlying causality. Rules encode experiential observations without including any information about why these rules work.
>
> Model-Based Expert System. The system is also called model-based reasoning (MBR). Model-based expert systems supplement the empirical rules with knowledge about the real world. MBR can be applied to engineering problems, for example, many electronic trouble-shooting expert systems are model-based. Symbolic modeling explicitly represents the structure and function of the modeled system in which the model supports multiple uses and users, and facilitates change and extension of applications. Formal symbolic MBR provides methodology which can be used effectively to develop knowledge systems in multiple related areas in which applications may be lacking.
>
> Knowledge-Based Expert System (KBES). The system can be described as a computer program that performs as a task normally done by an expert or a consultant using captured heuristic knowledge. The system is also called as a *metasystem* since the information on which rules to apply are stored in other rules. The sequence of rule firing is determined by an inference engine that is contained within the program. Usually the collection of rules in such a system may incorporate heuristics or rules of thumb that are accumulated by an expert over the years of problem solving.

A comparison of conventional (procedural) programming, such as the ones written using FORTRAN or C languages, and knowledge-based (declarative) programming is given in Table C.1.

Tasks	Conventional Programs	KBESs
Represented and used item:	Data	Knowledge
Operation on knowledge and control:	Integrated	Separated
Processing mechanism:	Algorithmic	Inferential
Manipulated media:	Large databases	Large knowledge bases
Uniqueness and completeness requirement:	Ensured by the programmer	Informal
Run-time explanation:	Impossible	Desirable characteristic
Orientation:	Numerical processing	Symbolic processing

Table C.1 Comparison of Conventional and Symbolic Programming (from Dym and Levitt, 1991)

Figure C.1 illustrates the components of a KBES with their relevance. Mainly the whole procedure can be divided into two as knowledge base and reasoning (inference) engine. The components of the architecture of KBES are summarized below (Maher, 1987).

- The *knowledge base* is the component of an expert system that contains facts and heuristics associated with the domain in which the expert system is applied. The facts are typically represented as declarative knowledge, and heuristics take the form of rules. The knowledge base should be transparent enough so that it can be easily modified. Modification is important in most engineering domains since knowledge is continually changing and expanding.

- The *context* is the component of the expert system that contains the information about the problem currently being solved. The context initially contains the information that defined the parameters of the problem and, as the expert system reasons about the given problem, the context expands and contains the information generated by the expert system to solve it. Upon completion of the problem solving process of the expert system, the context contains all the intermediate results of the problem solving process as well as the solution. The context is a declarative form of the current state of the problem the expert system is solving.

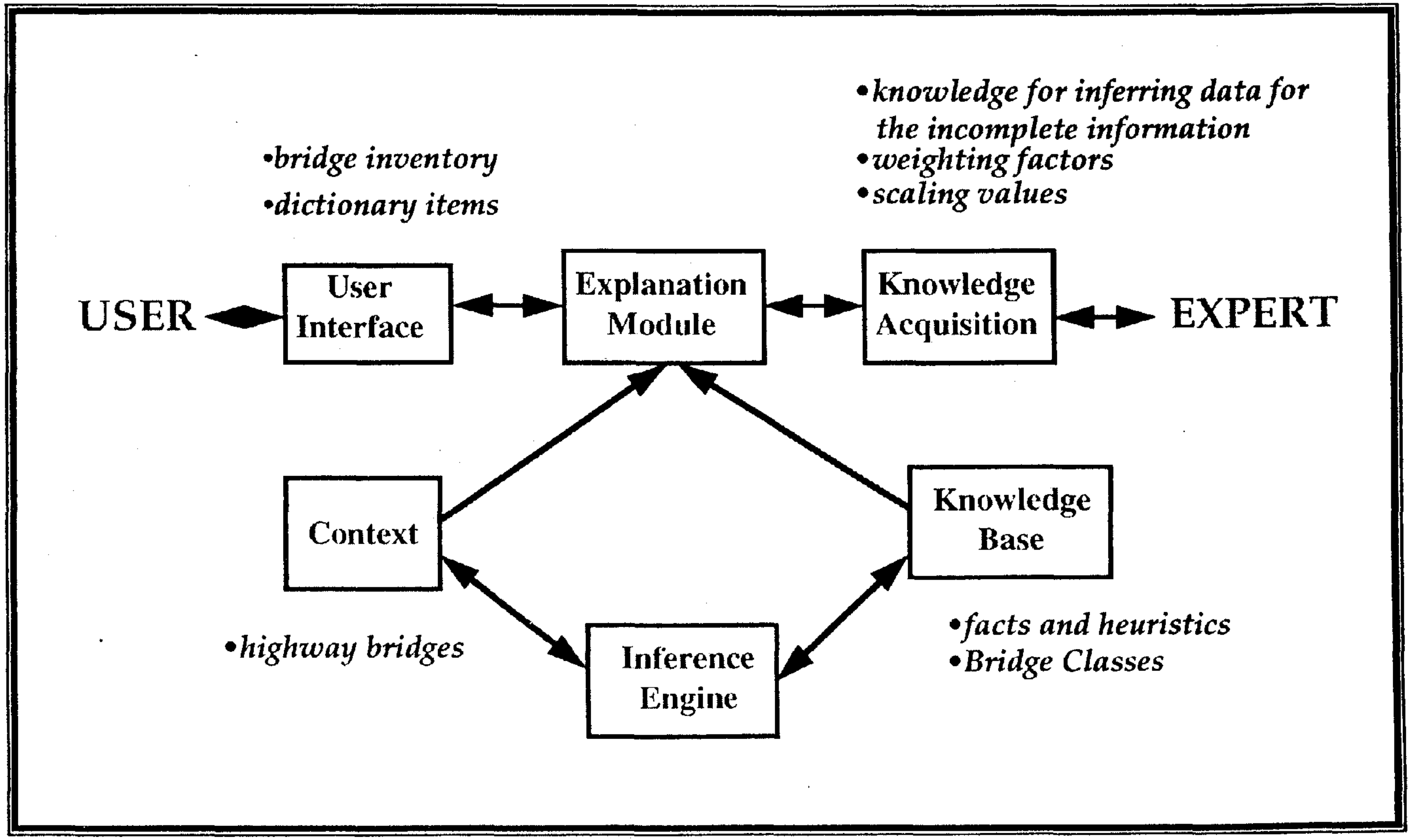

Figure C.1 Components of An Expert System the context. There are many different levels at which the inference mechanism controls the reasoning process. If the inference mechanism operates at a very low level (providing flexibility in solution strategy), the knowledge base must contain additional control information specific to the application domain. The more specific the inference mechanism, the less control information there is in the knowledge base.

- The *explanation facility* in an expert system varies from a trace of execution to the ability to respond to questions about the reasoning process used to develop a solution. An expert system can provide more than a passive trace of execution by responding to questions about specific aspects of the problem solution.

- The *knowledge acquisition* facility in an expert system is the component that facilitates entering knowledge into the knowledge base. In the simplest case, this facility acts as an editor, and knowledge is entered directly in a form acceptable by the software in which the expert system is implemented. On a more sophisticated level, the knowledge acquisition facility understands the inference mechanism being used and can actively help the expert in defining the knowledge base. More commonly, the expert system tool provides a graphical editor through which the system developer can modify the relationship between nodes in a decision network.

APPENDIX D

INVENTORY CODING DESCRIPTIONS

Table D.1 Legend for Table 7.1:[1]
Structural Attribute Abbreviations and Inventory Coding Descriptions

Abbreviation	Attribute	Inventory Code	Description
ABUT TYPE	Abutment type	A	Diaphragm
		B	Seat
		C	Cantilever
		D	Strutted
		N	Wall
COLUMN FOUND / ABUT FOUND	Column foundation / Abutment foundation	C	Concrete piles
		F	Spread footing
		S	Steel piles
		X	Unknown
COLUMN HEIGHT	Column height	A	Height less than 20'
		B	Height greater than 20', less than 30'
LAT	Latitude	xx°yy'z	Latitude of bridge site in degree minutes
LONG	Longitude	-xxx°yy'z	Longitude of bridge site in degree minutes
PIER TYPE	Pier type	H	Frame bent
		N	Wall
SCOUR CONDTN	Scour condition	6	Scour evaluation has not been made yet
		7	Countermeasures have been installed to correct a previously existing problem with scour. Bridge is no longer scour critical
		N	Unknown
SPAN CONTIN	Span continuity	C	Continuous
SUBSTR_MAT	Substructure material	C	Concrete
SUPER STR_TYPE	Superstructure type	CG	Concrete girder
		CS	Concrete slab
		QI	Precast prestressed "I" girder
		QS	Cast in place prestressed slab
TOTAL SPAN_NO	Total span number		
YEAR RECONST	Year reconstructed	0	No reconstruction
		19__	Reconstruction completed in year 19__

[1] * sign refers to N/A for any of the attributes

Table D.2 Legend for Table 7.2:
Importance Attribute Abbreviations and Inventory Coding Descriptions

Abbreviation	Attribute	Inventory Code	Description
ADT	Average daily traffic		
CONDN	Structure operation status	A	Open, no restriction
DEFNS DESGN	Defense designation	0	Not a defense highway
		1	Defense highway
DESGN	Designation	0	None of the eight options[2]
		1	Mainline
ENCR	Encroachment	*	N/A
FEATR_INT	Feature intersected		
FUNCTN CLASS	Functional class	08	Minor collector (rural)
		12	Principal arterial - other freeways or expressways (urban)
		16	Minor arterial (urban)
		17	Collector (urban)
		19	Local (urban)
HIST SIGN	Historical Significance	4	New bridge (no historical significance)
		5	Bridge not eligible for "Historic Places" at this time
KIND	Kind	2	U.S. numbered highway
		4	County highway
		5	City street
LANES O/U	Number of lanes on/under		
PSD	Parallel structure designation	L	Left structure of parallel bridges
		N	No parallel structure exists
ROUTE	Route carried on	C____	Commercial (bus and/or truck) route
		00000	A roadway without a route number
SERV TYPE	Service type (on)	1	Highway
		6	Highway and pedestrians

[2] 1: Mainline, 2: Alternate, 3: Bypass-ramp, 4: Spur, 5: Toll roads, 6: Business, 7: Ramp or wye or connector, 8: Service and/or unclassified frontage road, 9: Truck route, bus route, HOV (high occupancy vehicle) lanes.

SERV TYPE	Service type (under)	1 4 5	Highway Highway and railroad Waterway
TRAFFIC DIRECT	Direction of traffic	1 2	One-way traffic Two-way traffic