Performance-Based Decision-Making in Post-Earthquake Highway Bridge Repair

by

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Abstract

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Post-earthquake highway bridge repair is an ever-present part of the lifecycle of transportation systems in seismic regions. These repairs require multi-level decisions involving various stakeholders with differing values. The improvement of the repair decision process, repair decision itself, and repair decision outcomes, requires an evaluation of current practices in post-earthquake repair decision-making.

This dissertation assesses these current practices within the California Department of Transportation (Caltrans), outlines areas where the current process is ineffective, and highlights areas for improvement. Current repair decision-making practice is focused on the repair of individual bridges given a limited set of established repair methods.

To improve upon these practices, this dissertation presents the Bridge Repair Decision Framework (BRDF), a new and unique methodology that allows for simultaneous consideration of all earthquake-damaged bridges as individual elements of a larger regional transportation system. This systematic approach enables the achievement of short- and long-term transportation system performance objectives while accounting for engineering, construction, financing, and public policy constraints. Furthermore, the BRDF allows for continuous refinement of the decision-making process to incorporate engineering and construction innovations, changes in the financial and public policy environment and, most importantly, changes in transportation system performance goals. While existing methodologies allow the incorporation of some of these changes, the BRDF provides a flexible structure that can account for all of these changes simultaneously.

This is accomplished through a rigorous, performance-based, and risk-informed decision-making approach that presents repair decisions using a traditional engineering demand-capacity inequality. As a result, the BRDF empowers decision-makers with a holistic understanding of the transportation network condition on a microscopic (bridge) as well as macroscopic (overall system) level.

The BRDF also accounts for the probabilistic nature of the earthquake hazard, bridge seismic capacity, and subsequent repair decisions, providing decision-makers with transparency regarding the uncertainties of system condition, repair method reliability, construction workforce availability, and public and business risks. BRDF decision-outcomes are technology-neutral as a result, greatly expanding the range of repair method alternatives that a decision-maker may consider while allowing for tradeoffs to be made between performance, cost, and time in light of transportation system condition and constraints.

The BRDF is validated using a simulated bridge system case study that requires post-earthquake repair. This study was designed to demonstrate the functionality of the framework and to examine two alternate decision-making strategies: one with complete and the other with incomplete post-earthquake bridge damage state information. This case study led to refinements in the framework and insights about the benefits of additional information on the damage state of bridges in terms of overall repair time and cost of the regional transportation system. Additionally, the validation revealed areas where the current BRDF can be improved in future studies.

The BRDF was created for large public transportation organizations such as the California Department of Transportation (Caltrans), where implementation of the BRDF requires several important prerequisites, including new database creation and additional training for engineers. Once implemented however, the BRDF allows decision-makers to potentially reduce repair costs and times, minimize system downtime, make better investments, and account for transportation system performance goals given current financial and public policy constraints.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ABME	=	Area Bridge Maintenance Engineer
AFT	=	Alternative-Focused Thinking
BRDF	=	Bridge Repair Decision Framework
Caltrans	=	California Department of Transportation
CBA	=	Choosing by Advantages
CCRM	=	Center for Catastrophic Risk Management
CDM	=	Complete Information Decision-Making
CSMIP	=	California Strong Motion Instrumentation Program
DCC	=	District Command Center
DES	=	Division of Engineering Services
DI	=	Decision Input
DM	=	Division of Maintenance
DRR	=	Delay to Repair Ratio
DS	=	Damage States
DV	=	Decision Variable
EDP	=	Engineering Demand Parameter
FEMA	=	Federal Emergency Management Agency
HAZUS-MH	=	Hazards U.S. Multi-Hazard
IDM	=	Instantaneous Information Decision-Making
MMS	=	Moment Magnitude Scale
NAS	=	National Academy of Sciences
NRC	=	National Research Council
ODOT	=	Oregon Department of Transportation
OSMI	=	Office of Structure Maintenance and Inspection
PBEE	=	Performance-Based Earthquake Engineering
PEER	=	Pacific Earthquake Engineering Research
PEQIT	=	Post-Earthquake Investigation Team
PG	=	Performance Group
RM	=	Repair Method
ShakeCast	=	Shakemap Broadcast
SMART	=	Structure Maintenance Automatic Report Transmittal
STAP	=	Structures Technical Advisory Panel for Research
USGS	=	United States Geological Survey
VFT	=	Value-Focused Thinking
WashDOT	=	Washington Department of Transportation

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Chapter 1

Introduction

The development of transportation systems in densely populated urban areas in seismic regions has created the necessity for post-earthquake response and repair procedures to quickly restore system function. In the hours, days, and months after an earthquake, engineers in lifeline maintenance organizations are faced with the necessity of making repair-related decisions that require immediate and rational actions over a limited period of time.

While much emphasis has been placed on how to make these decisions most effectively in light of the given constraints (time, budget, importance, impact, etc.), a post-factum evaluation of the effectiveness of these decisions is seldom conducted. At the same time, only such an evaluation may facilitate the development of the most effective methods of analysis and decision-making.

This dissertation presents a unique analysis-, experience-, and performance-based framework for the evaluation and improvement of post-earthquake decision-making in public transportation organizations. This framework is flexible, practical, and user-friendly, enabling decision-makers to:

1. Assure more cost- and time-effective repairs;
2. Reduce redundancy, downtime, and cost;
3. Better understand and improve the repair decision-making process;
4. Base future decision-making on the past lessons learned;
5. Achieve short- and long-term strategic goals.

1.1. Scope

In spite of the media-propagated high exposure of most spectacular seismic damage (e.g., 1989 Bay bridge, 1994 I14-I5 overpass), past major seismic activity in California has yielded a limited number of highway bridges that sustained major damage. When major damage does occur, transportation agency bridge engineers face only binary decision outcomes: either a) demolition and clearing or b) demolition and reconstruction. When minor damage occurs, bridges can either continue functioning as they stand or be cosmetically repaired at a later date. Moderate bridge damage, in contrast, is more widespread and the most costly overall.

Therefore, significant gains are to be made by focusing on the evaluation and improvement of repair decisions for moderate bridge damage. For these reasons, this dissertation will focus primarily on repair method decisions for moderately damaged highway bridges in California, which has an extensive and well documented seismic history has been the center of earthquake engineering advancements within the United States. It should be noted that the insights, findings, and recommendations of this dissertation can also be extended to cases of major damage.

1.2. Approach

Like this dissertation, repair decisions represent the fusion of project management, structural engineering, and public policy principles as applied to post-earthquake response procedures. As a result, it is necessary to define what is meant by repair decisions within this specific context.

A repair decision is defined as a choice or judgment about the modification of the existing condition of one or more bridges. Therefore, repair decisions can address any of the following subjects:

1. Whether bridges should be repaired;
2. How bridges should be prioritized;
3. Which bridges to repair;
4. When bridges should be repaired;
5. How bridges should be repaired.

These subjects pose challenges to decision-makers throughout the post-earthquake response, as time pressure and incomplete information add levels of depth to repair decisions beyond traditional maintenance questions. Furthermore, the variables that influence repair decisions are correlated, interdependent, and probabilistic.

Existing strategies for making repair decisions cannot take these complexities into account while providing decision-makers with a situational understanding that scales from microscopic individual elements to macroscopic system function. The decision framework presented in this dissertation however, fills these requirements through a thorough understanding of current practices in highway bridge repair decision-making, a rigorous accounting of the entities and elements that influence repair decisions (structural risk estimates, public policy issues, financial limitations, public pressure), and a systematic data model that allows stakeholders to make experience-driven, performance-based, risk-informed, and technology-neutral repair decisions.

1.3. Organization

This dissertation is organized according to the steps of development for this new repair decision-making methodology.

Post-earthquake repair decision-making represents the fusion of several different research fields. Therefore, Chapter 2 presents the current state of academic knowledge and work, examining the relevant developments and research conducted in the fields of earthquake engineering and decision-analysis.

With past work examined, Chapter 3 introduces the Bridge Repair Decision Framework (BRDF) as a new, holistic, and performance-based decision-making methodology. Earlier parts of the chapter describe how established tools from past academic work were applied to the evaluation and analysis of highway bridge repair decisions. Next, current practices in highway bridge repair decision-making are described, highlighting potential areas for improvement and the attributes of ineffective decision-making.

The methodology behind the BRDF is then examined in detail, with each of the decision inputs and outputs represented in a traditional design inequality where system capacity is greater than or equal to system demand. The final sections of Chapter 3 document the attributes of effective decision-making, and the prerequisites to the implementation of the BRDF into Caltrans policies.

Since the BRDF represents a new approach to repair decision-making, the methodology and model were validated by applying BRDF principles to a simulated bridge system in order to choose between making decisions with complete or incomplete information. This validation, presented in Chapter 4, led to refinements in the model and insights about the benefits of information in terms of overall repair times.

Finally, Chapter 5 summarizes the work and contributions of this dissertation, comparing the BRDF to current practices. The last section of Chapter 5 discusses avenues for future work involving the BRDF.

Chapter 2

Background

The Bridge Repair Decision Framework presented in this dissertation is the culmination of the author's research in the field. This research is highly based upon the scholarly contributions of countless others across a variety of academic research areas. The following chapter summarizes the most relevant developments that occurred as a result of this research, and that place the BRDF within the context of past work.

2.1. Earthquake Engineering

Significant progress within the context of earthquake response, repair, and engineering is typically made in the aftermath of major earthquakes that test the boundaries of established engineering knowledge. Therefore, the advancements in these fields are organized chronologically by earthquake.

2.1.1. San Fernando Earthquake (1971)

The 1971 San Fernando Earthquake (magnitude 6.6 on the moment magnitude scale – MMS) caused $500 million to $1 billion (not adjusted for inflation) in damage, which was considered severe at the time (Jennings 1997). Although the Loma Prieta and Northridge earthquakes would eventually redefine "severe" earthquake damage in California, the San Fernando earthquake inspired broad changes in seismic design practice and specifically Caltrans procedures.

After major bridge damage and collapses throughout the affected area, Caltrans began making sweeping changes that marked a new era in earthquake engineering. In less than a month after the earthquake, Caltrans issued a Memo to Designers that significantly modified design standards for bridges in California, requiring increased transverse column and top mat reinforcement (Keever 2008).

In order to address seismic vulnerabilities in existing bridges, Caltrans began a three-phase Bridge Seismic Retrofit Program (Moehle et al. 1995). The first phase of the program focused on joint separation and unseating, which Caltrans engineers judged to be the biggest vulnerability of existing bridges (the second and third phase of the Caltrans Bridge Seismic Retrofit Program are presented in Sections 2.1.2 and 2.1.3, respectively). Additionally, Caltrans worked with the California Division of Mines & Geologists (now known as the California Geological Survey) to create statewide fault maps that helped engineers associate ground motion accelerations with bridge locations.

The National Academy of Sciences (NAS) released a report immediately following the earthquake that called for rigorous post-earthquake reconnaissance, citing funding and jurisdictional issues that presented impediments to proper assessment of system conditions after the San Fernando earthquake (NAS 1971). Caltrans subsequently instituted Post-Earthquake Investigation Teams (PEQIT), who continue to investigate earthquake damage immediately after significant earthquakes (Keever 2008). Finally, Caltrans began adopting the lessons learned in post-earthquake response into official Emergency Response Procedures for their Division of Structure Maintenance and Investigation (Lam 2009).

2.1.2. Whittier Narrows Earthquake (1987)

The bridge column shear failures of the Whittier Narrows Earthquake (magnitude 5.9 on the MMS) in 1987 initiated the second phase of the retrofit program and focused on single column bridges due to their perceived greater vulnerability over multicolumn bridges. Retrofit strategies included providing additional confinement, column ductility, and shear capacity through the installation of steel shells on existing columns (Keever 2008). These steel column jackets were the result of rigorous academic research in leading structural engineering programs throughout the state and country (Chai et al. 1991).

2.1.3. Loma Prieta Earthquake (1989)

The Loma Prieta Earthquake (magnitude 6.9 on the MMS) was the first major earthquake in Northern California in over two decades. The earthquake caused extensive damage to, and the collapse of, major lifelines in the San Francisco Bay Area, including the double-deck Cypress Viaduct and San Francisco-Oakland Bay Bridge. The earthquake also marked the beginning of the third phase of the retrofit program, which sought to retrofit multicolumn bridges through steel column jacketing.

The earthquake highlighted the severe lack of funding for seismic retrofit and repair method research (NRC 1994). As a result, substantial additional funding was allocated for the study of seismic performance and retrofit of bridges. Additionally, the Loma Prieta Earthquake provided valuable insight into areas for improvement of the Caltrans emergency response procedures, and illustrated the benefits of new repair policies such as in-field bid awarding (Clinton 2000).

2.1.4. Northridge Earthquake (1994)

The Northridge Earthquake (magnitude 6.7 on the MMS) occurred in approximately the same location as the 1971 San Fernando Earthquake, and provided vital insights into the effectiveness of the Caltrans seismic retrofit program, which was ongoing at the time. While retrofitted bridges and those designed to modern Caltrans specifications performed well in the earthquake, multicolumn bridges with skew and geometric complexities exhibited significant earthquake damage (Keever 2008). These types of bridges became the focus for the third phase of the Caltrans seismic retrofit program, which included substantial funding toward research on the performance, repair, and retrofit of these types of bridges.

The Northridge Earthquake, as other earthquakes since 1971, provided an opportunity for Caltrans to improve its post-earthquake response procedures. Lessons were learned about the emergency and transportation equipment mobilization, availability of power and communications, and required systematic approaches to large-scale structural investigation. Instead of bridges exhibiting major damage, Caltrans engineers struggled with moderately damaged bridges due to their sheer quantity and complex assessment (Kaslon 2000). Opening, closure, and repair decisions were made by two-person teams of one maintenance engineer and one design engineer, and were based on their judgment (Kaslon 2000). Emphasis was placed on the creation of bridge damage reports, which Caltrans engineers knew would eventually form the foundation for structural funding, retrofits, and research. The documentation of specific repair methods that were employed in the aftermath of the Northridge and past earthquake were not explicitly documented outside of as-built drawings and contract documents archived in Caltrans libraries. Therefore, the justifications for repair method selection and other post-earthquake decisions remained with the Caltrans engineers who made them.

2.1.5. Since Northridge

While seismic activity throughout California is ever-present, no earthquakes comparable to Loma Prieta and Northridge (in terms of damage) have taken place within the state to date. This lack of seismic activity provided researchers with an extended period of time to make significant strides in the earthquake engineering body of knowledge.

In 1996, nine of western civil engineering universities in the United States formed the Pacific Earthquake Engineering Research (PEER) Center, which focused on performance-based earthquake engineering across multiple disciplines including structural and geotechnical engineering, geology/seismology, lifeline organizations, transportation, risk management, and public policy (Mackie et al. 2007). Since its establishment, the PEER center has consistently and substantially contributed to the understanding of performance-based engineering and its benefits.

At the University of California, San Diego, PEER researchers defined and quantified limit states for bridge seismic performance, creating a library of photographic and quantitative data for individual bridge components, sub-assemblies, and overall structures (Hose et al. 1999). Funded by Caltrans, this library provided the link between visual depictions of earthquake damage and the respective losses in load-bearing capacity. Building upon this work, PEER researchers at Stanford University created a probabilistic foundation for seismic performance assessment that consisted of discrete decision variables (e.g., annual exceedance of one or more limit states), damage measures (e.g., maximum interstory drifts), and intensity measures (e.g., spectral acceleration) (Cornell et al. 2000). These principles formed the PEER Performance-Based Earthquake Engineering (PBEE) methodology.

Mackie and Stojadinovic (2006) applied the PEER PBEE to the assessment of highway bridges, performing an analytical study to link engineering demand parameters to intensity measures, and subsequently to damage measures (Mackie et al. 2006). Limit states for highway bridges were formulated at the structural component and bridge levels. Mackie and Wong extended this research to develop a nomenclature and accounting of bridge components in order to systematically calculate repair costs and durations (Mackie et al. 2007; Wong 2008). The research presented in this dissertation builds upon the work done by Mackie, Wong, and Stojadinovic, as described in the Tools section in Chapter 2.

In 2006, the Caltrans Structures Technical Advisory Panel for Research (STAP) developed a coordinated research agenda that contained strategic organizational goals. These goals addressed a wide array of Caltrans research areas, including system preservation, worker safety, accelerated project delivery, transportation security, and operational improvement (STAP 2006). Among these goals was an emphasis on system and facility restoration, seeking the development of effective tools and techniques to repair damaged structural components and restore system functionality. The research presented in this dissertation addresses these Caltrans strategic goals.

2.2. Decision-Making

In addition to the above earthquake engineering developments, this dissertation is built upon elements of several established decision-making approaches.

2.2.1. Decision Analysis

Decision analysis represents the traditional decision-making approach, seeking to disaggregate large, complicated decision problems into smaller, manageable ones that have more understandable outcome preferences (LaValle 1978). The solution of each smaller problem can subsequently be synthesized into a solution for the large problem as a whole.

Decision analysis problems can be represented through the use of decision trees that account for the viable alternatives for action, the consequences of each action, and the probability of each consequence (Raiffa 1968). While the principles of decision analysis represent one possible methodology for examining post-earthquake repair decisions, other decision-making approaches take into account the particularities of repair decisions in more holistic ways.

2.2.2. Value-Focused Thinking

Value-focused thinking (VFT) developed as an extension of utility theory that allows decision-makers to identify decision problems and create alternatives to achieve their overall objectives (Keeney et al. 1976; Keeney 1992). While traditional decision-making approaches are oriented around alternatives for a given decision, VFT emphasizes decision-maker values in not only the evaluation of alternatives but also the identification of desirable decision opportunities (Keeney 1992).

The VFT approach in its most basic form consists of two decision-making steps: first identifying what one wants and second figuring out how to get it. Within highway bridge repair for example, VFT would first require the identification of performance criteria (values), and then the selection of a repair method that satisfies those criteria. For comparison, traditional, or alternative-focused thinking (AFT), involves decision-makers first identifying the alternatives and second choosing the best one of the group (Keeney 1992). Using the previous example, AFT would first identify a set of available repair methods and then choose the best one of the set. It should therefore be noted that the VFT approach allows decision-makers to better achieve the desired outcomes because they are not limited by the existing alternatives, creating instead alternatives based on their values.

The underlying difference between VFT and AFT applies directly to post-earthquake decision-making in large public transportation organizations, which currently employ AFT principles in their decisions about repair methods. The Bridge Repair Decision Framework builds upon VFT and performance-based earthquake engineering principles to systematically expand the array of repair decision alternatives and create decision outcomes that correspond directly to stakeholder values.

2.2.3. Choosing by Advantages

Choosing by Advantages (CBA) is a decision-making system created by Jim Suhr that enables users to make sound decisions based on the importance of advantages. The CBA system is centered around four primary principles (Suhr 2005):

1. Sound decisions are based on the importance of the differences among alternatives;
2. Sound decisions are based on the importance of advantages;
3. Sound decisions are based on relevant facts;
4. Engineers, architects, organizational leaders, and the like are professional decision-makers who require sound methods of decision-making.

Using these principles, the CBA system can be applied through a variety of methods that each compare the respective advantages of different alternatives (Koga 2008). This focus on advantages is similar to VFT, since both methodologies emphasize the identification of user values and desired outcomes before the identification of alternatives.

Decision-makers using the CBA system prioritize advantages by importance, either through simple ordering or through the use of a numerical scale that reflects each advantage's relative importance. These advantage priorities can be summed for each alternative, resulting in a total importance of advantages value.

Decision outcomes are then based on the alternative with the greatest total importance value. It should be noted that CBA also includes a second decision-making process for decisions involving money. The CBA system encourages the reconsideration of each of these processes if the decision outcomes are not satisfactory to the decision-makers.

While elements of the CBA system exist within the research presented in this dissertation, the principles behind the CBA system provide a course for the further extension of this research (Section 5.3).

Chapter 3

Methodology

3.1. Tools

Making a repair decision is an individual process within an engineered system. Modeling this system in a flexible and cohesive way is vital to not only understanding the system as a whole, but also to ensuring an appropriate and accurate outcome.

Therefore, the author's research builds upon several established tools that provide structure and methodological guidance for analyzing, understanding, and improving post-earthquake bridge repair decisions.

3.1.1. PEER Performance-Based Earthquake Engineering

The PEER Performance-Based Earthquake Engineering (PBEE) probabilistic framework and methodology provides a common analytical model and terminology for the evaluation of performance of various types of engineered systems under design and extreme loads. This dissertation presents a highway-bridge specific application of the PBEE in order to examine post-earthquake decision-making.

PEER Probabilistic Model

The PBEE probabilistic model allows for the definition of performance objectives under uncertainty from hazards, information, and other parameters. These uncertainties are addressed through stochastic variables such as damage measures (DMs), engineering demand parameters (EDPs), and seismic hazard intensity measures (IMs). EDPs function as thresholds for data variables such as displacements, drifts, strains, curvatures, moments, and residual formations. IMs are used to describe seismic hazards, such as peak ground acceleration.

These parameters provide the quantitative and probabilistic foundation for decision variables within the PBEE, which for highway bridges typically include load rating, lane closures, downtime, repair cost, repair time, and loss of life.

PEER Methodology

The PEER PBEE framework provides a methodology for the probabilistic structural analysis of highway seismic bridge performance.

Within this framework, a bridge is treated as a collection of components divided into correlated performance groups (PGs). Each PG is linked to a collection of damage states (DSs), which indicate the possible conditions of a given PG. Each DS, in turn, is linked to a repair method (RM). Each element in the PBEE methodology (PG, DS, RM) contains sub-parameters that provide additional relevant information. These elements provide a detailed structure for the evaluation of a single bridge.

In order to examine multiple bridges across a given area, a higher-level (global) organizational unit must be defined. Therefore, just as a network of performance groups defines a bridge, a network of bridges is defined as a system, consisting of individual bridges grouped and evaluated together due to a shared descriptive parameter such as location or level of damage (Figure 1).

The accounting of bridge components within the PBEE methodology is used to determine, characterize, and quantify repair methods for earthquake-damaged bridges. Once a structure for bridge components, their condition, and repair methods is established, bridge repair decisions can be understood and evaluated on a system level.

Performance Groups

The PBEE methodology disaggregates every bridge in a given system into its performance groups (PGs), which consist of structural components that act as system-wide indicators of structural performance and contribute significantly and discretely to repair-level decisions (Mackie et al. 2007). PGs as organizational units provide more comprehensive damage assessments (and therefore repair decisions) than grouping by individual component. It is important to note that PGs may consist of non-load-resisting components, since they also contribute to repair costs, time, and resources.

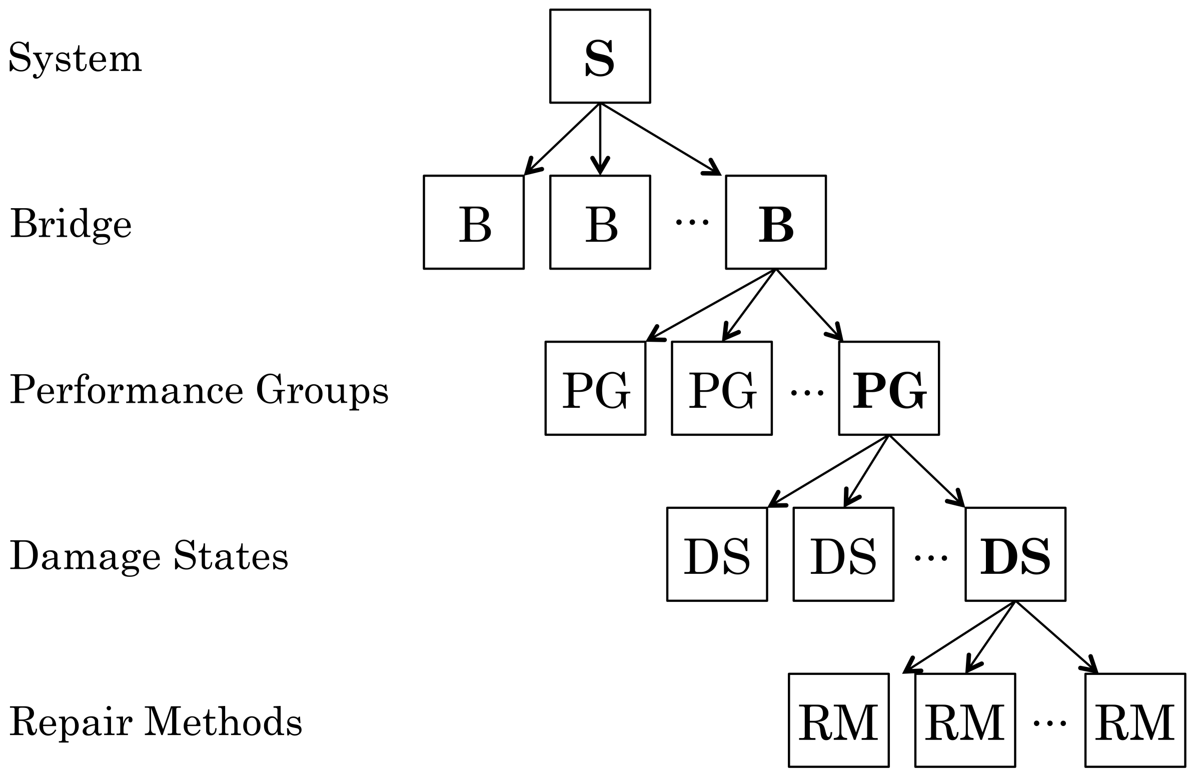

Figure 1: Example branch of the PEER PBEE Framework Structure after Mackie et al. (2007).

Performance groups are characterized primarily by two distinct parameters. First, a unique performance group number differentiates the contained components from other PGs. Second, an inventory of the individual structural components included in the performance group provide both qualitative descriptions as well as location information. Different PGs may contain similar types of bridge components, since performance groups contain bridge components that are generally observable as a unit. For example, if a bridge has four columns, each of the columns will be included in its own unique PG. This type of grouping is ideal for repair estimation, since performance groups contain components that are generally repaired together as a unit.

Damage States

The PBEE methodology assigns to each performance group a Damage State (DS), which characterizes the condition of the respective performance group at an instance in time. Therefore, each performance group has a variety of possible damage states, but can only be described by one of them at any given time. DSs are defined by known limit states, based on engineering demand parameters established by Mackie and Wong (2007). For example, a column performance group can have five distinct damage states:

DS0: Original Condition
DS1: Negligible damage, initial cracking
DS2: Cover concrete spalling
DS3: Longitudinal rebar buckling
DS4: Column failure

Each DS is characterized by lognormal distribution parameters λ and β, which represent the median and standard deviation of the damage triggers, respectively. These triggers are the limit states which, when exceeded, indicate that a performance group now exists in a higher DS. Damage States range from the original as-built condition (DS0, above) to complete failure of the performance group as a whole (DS4, above). Therefore, the higher the DS number, the greater the level of damage for that PG.

Repair Methods

Since a given damage state indicates the condition of a performance group, there are likely to be one or more repair methods associated with this DS. Similar to the relationship between PGs and DSs, each damage state is associated with one or more repair methods (RMs), but only one RM can be chosen for any given DS.

The repair methods used by Mackie and Wong restore a given PG from its damage state to its original condition. However, this dissertation defines repair methods more broadly, with repair methods functioning as collections of actions that change the damage state of a given performance group from a higher state to a lower state. Although typical RMs restore performance groups to the lowest possible damage state, RMs may also provide palliative measures for the temporary restoration of system function.

RMs are linked to child parameters that contain information about the cost, time, and resources associated with a particular repair method. The resource parameter is a “catch-all” category, providing room for items such as construction equipment as well as general overhead items.

Estimation

This dissertation builds upon the existing PBEE to have each performance group DS also linked to a group of subsequent estimation parameters. These parameters include information about the time, cost, and resources associated with the repair estimation process for a performance group in a given damage state. The resource parameter is similar to the one for RMs, which contains miscellaneous relevant items associated with estimation. It should be noted that the estimation differs from inspection, which contains significant cost, time, and resource demands that are not taken into account in this dissertation.

3.1.2. Quality and Reliability

Highway bridge networks are examples of vast engineered systems that require continual monitoring and maintenance in terms of system performance. The Center for Catastrophic Risk Management (CCRM) uses a quality and reliability approach based on the management of offshore structures, which describes systems in terms of their serviceability, safety, compatibility, and durability (Bea 2007). These parameters are defined as follows:

Serviceability:	suitability for intended purpose
Safety:	acceptability of risks
Compatibility:	acceptability of impacts
Durability:	freedom from unanticipated degradation

Together, these parameters describe an engineered system's quality, defined as freedom from unanticipated defects in each of these parameters. Quality describes the ability of a system to meet the requirements of its users and operators. Likewise, the reliability of a system may also be defined in terms of the above parameters: reliability is the likelihood that a system will achieve desirable levels of serviceability, safety, compatibility, and durability.

Achieving desired levels of quality and reliability require the use of three fundamental and complimentary approaches: proactive, interactive, and reactive. For offshore structures, these approaches are used to minimize, prevent, and learn from system malfunctions, incidents, near misses, and failures. When applied to highway bridge networks, the definitions and goals of these approaches are refocused onto earthquakes and their subsequent effects:

Proactive: actions prior to earthquake
Interactive: actions immediately after an earthquake (short-term)
Reactive: actions after earthquake occurs (medium- to long-term)

The quality and reliability of transportation networks must, to the degree possible, remain constant, despite large, unavoidable, and unpredictable fluctuations in demands on the system (earthquakes). Therefore, the assurance of quality and reliability must utilize this varied and holistic approach in order to not only mitigate the effects of past and current demands, but also improve the system to better respond to demands of the future. The BRDF incorporates these approaches in the accounting of repair decision parameters, as discussed in later sections.

3.2. Existing Decision Framework

3.2.1. Current Practices in Highway Bridge Repair Decision-Making

Caltrans Structure

Repair decisions are the product of a variety of different groups who, over time, shape and influence the decision process and eventual outcome. For post-earthquake highway bridge repair decisions, the majority of these groups come from the departments of transportation in charge of the given system. The California Department of Transportation (Caltrans) has been a consistent leader in the field, providing the basis for standards and practices of other departments of transportation in states with seismic zones, such as Washington and Oregon (ODOT 2009). Furthermore, Caltrans' extensive overall size and well-defined organizational structure present the ideal medium for the study of post-earthquake repair methods.

Caltrans is organized in two distinct ways. Physically, Caltrans is divided into 12 different districts of various sizes and terrains across the State of California, with state headquarters in Sacramento. Local offices function within each district and report to the district director. Organizationally, Caltrans is divided into over 30 different divisions, each of which help control and operate transportation for the state of California. Each of the divisions is represented in every district throughout California, reporting to their respective directors in Sacramento (Caltrans 2009).

This dissertation primarily focuses on two distinct engineering divisions within the larger Caltrans organizational structure: the Division of Engineering Services and the Division of Maintenance. The Division of Engineering Services is charged with structural design, structural construction, earthquake engineering, materials testing and engineering, water engineering, and geotechnical services. The Division of Maintenance is charged with all the maintenance operations for the entire State of California transportation system, including inspections and monitoring. These two divisions are the primary channels in the repair decision process, receiving, collecting, and analyzing all the relevant information prior to making repair decisions.

Before bridge repair decisions can be analyzed however, it is important to examine the context in which repair decisions are made, particularly with respect to the sequence of events that result in a repair decision.

Proactive Measures

Caltrans, working with the United States Geological Survey (USGS), uses a system called Shakemap Broadcast (ShakeCast) in order to provide post-event structural system analysis (Turner et al. 2009). Although ShakeCast does not provide real-time monitoring, the system integrates existing Caltrans inventory databases with measured ground motion data from a network of more than 1,900 sensors throughout California (Turner et al. 2009).

Post-Earthquake Response

Caltrans Engineers are officially notified about significant seismic activity through two primary channels. First, the California Strong Motion Instrumentation Program (CSMIP) transmits seismic activity information through pagers. Second, ShakeCast provides engineers with information about the affected area radius as well as a prioritized bridge inspection list (Sahs 2008). The ShakeCast system functions both as a pull and push system, allowing users to retrieve post-earthquake analyses while also providing notification as more information becomes available.

Caltrans engineers may also experience an earthquake themselves, or be notified through traditional media such as radio and television. Given the instantaneous nature of wireless and online communication, these media are often used as triggers for further Caltrans investigation and information gathering.

Stratified Earthquake Response

Although notification through the CSMIP and ShakeCast occurs regardless of earthquake magnitude (above a specific threshold), the breadth of response within

Caltrans is highly correlated to the magnitude of the given earthquake. The Caltrans Emergency Response Plan establishes response thresholds at magnitudes 5.5 and 6.2 on the Richter scale, which define the minor, moderate, and major seismic events (Sahs 2008). This results in a stratified response to chronologically unpredictable events, escalating with earthquake magnitude.

The Emergency Response Plan is the culmination of more than 40 years of Caltrans earthquake response experience, maintained by senior bridge engineers in the Division of Maintenance. The evolution of the Caltrans Emergency Response Plan occurs as the result of changes in applicable technology, systematic organization, and the needs of the state, all combined with the lessons from each subsequent earthquake that takes place within California as well as abroad. The lack of significant earthquake-induced damage in California since the Northridge Earthquake highlighted the need to build upon the current response procedures using the experience of other state departments of transportation and international engineering experience (the major – magnitude 7.2 on the MMS – Baja California Earthquake in April 2010 caused shaking in parts of San Diego and Los Angeles, but damage was minimal). Even moderate seismic events, such as the 2008 Chino Hills Earthquake (magnitude 5.4 on the MMS) and the 2010 Eureka Earthquake (magnitude 6.5 on the MMS) help Caltrans improve upon their established response methods and practices.

Although both the Division of Maintenance (DM) and Division of Engineering Services (DES) participate in post-event response, the DM, and more specifically the Office of Structure Maintenance and Inspection (OSMI) within the DM, is the initial primary responder. This is because OSMI Area Bridge Maintenance Engineers (ABMEs) are likely to be in the field immediately following a seismic event, and have substantially better access to structures requiring inspection. Therefore, ABMEs have lower mobilization and response times, both of which are vital to ensuring public safety in the aftermath of unforeseen events.

The 2008 revision of the Caltrans Emergency Response Plan dictates the following stratified approach (Figure 2):

> If the earthquake is of a magnitude less than 5.6 (considered "minor"), the OSMI managers remain on alert, but ABMEs are not required to act. Managers use the information provided by ShakeCast in order to identify any potential problem bridges.

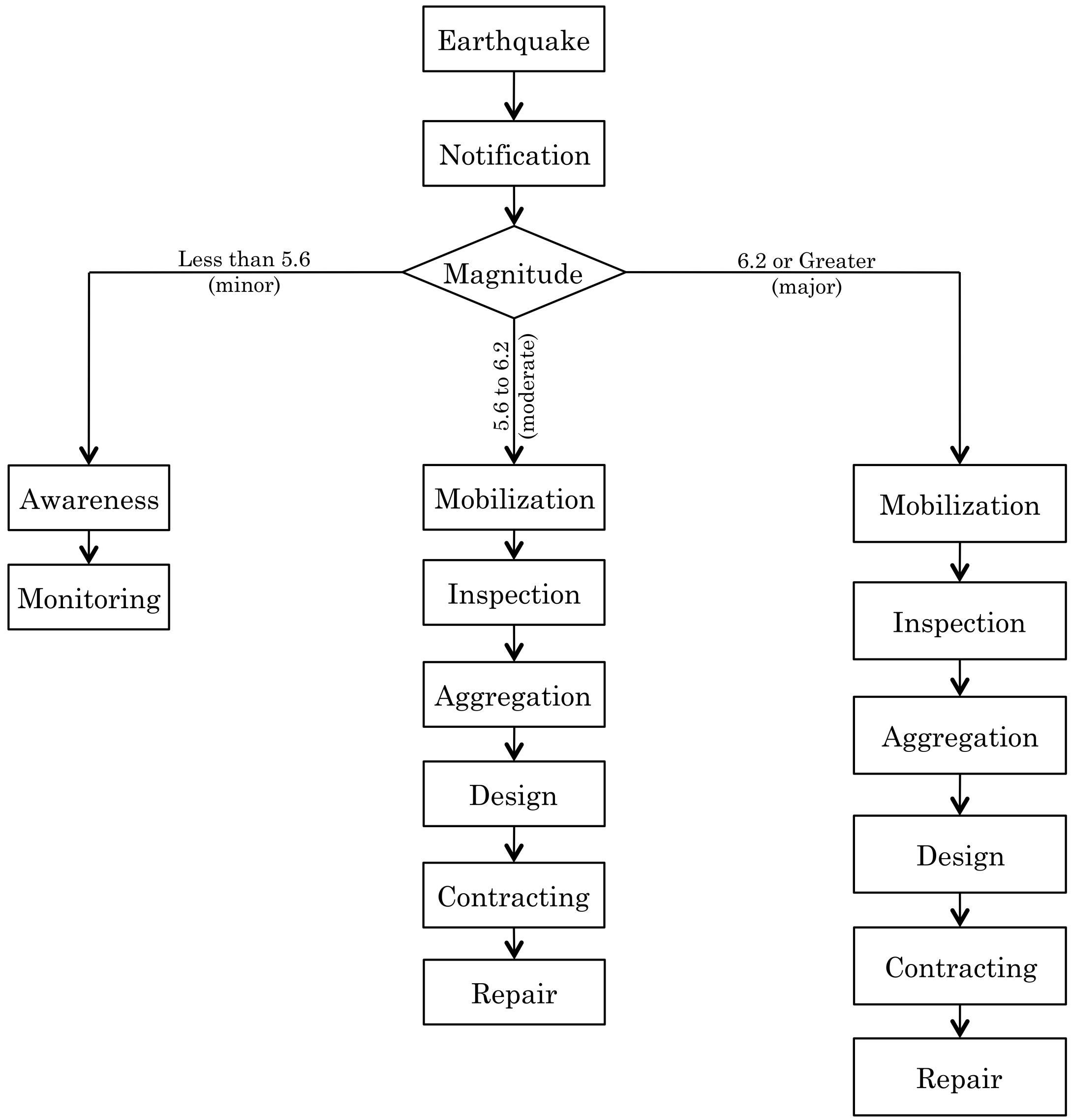

Figure 2: The stratified Caltrans post-earthquake response procedure (larger boxes indicate larger scale of action).

> If the earthquake is between magnitude 5.6 and 6.2 (considered “moderate"), OSMI managers use ShakeCast data to determine the scope of Caltrans resources that must be tapped in order to conduct post-earthquake bridge inspections. ABMEs are required to notify their seniors of availability for work and direction.
>
> If the earthquake is greater than magnitude 6.2 (considered “major”), the OSMI office managers use ShakeCast data to determine the Caltrans resources that must be tapped in order to conduct post-earthquake bridge inspections. With this information, the office managers map and identify potential damaged bridges and create inspection routes. The ABMEs must report to their respective offices. Office managers also decide whether or not to activate the District Command Center (DCC), which will provide direction for the Caltrans resources in response to the given earthquake (Sahs 2008).

In practice, OSMI managers combine ShakeCast data, preliminary field information, and media reporting to determine the necessary response scope. For moderate and major earthquakes, the Sacramento-based DCC functions as the information clearinghouse and governing body. The DCC concept was the result of the Chino Hills Earthquake, which, despite its “minor” magnitude (5.5) highlighted the need for a centralized decision-making body for post-earthquake response.

Mobilization

After a moderate to major earthquake occurs, and the CSMIP and ShakeCast systems provide notification to senior Caltrans officials, the mobilization of resources begins. The size and breadth of this mobilization is highly uncertain however, since response procedures must be initiated with imperfect information. This uncertainty occurs as the result of three primary unknowns.

First, it is unknown when, in a given week, an earthquake will occur within the State of California. The amount of available response resources within Caltrans fluctuates significantly depending on if the earthquake occurs on a weekday, weekend, or holiday. For example, the Northridge Earthquake occurred on a weekday in January that happened to be a national holiday. Although the timing of this earthquake helped minimize the loss of life on California roadways, it also resulted in initial shortages of Caltrans employees and other resources.

Therefore, the timing of the earthquake can result in sizeable fluctuations in mobilization and response time. It should be noted that Caltrans has a variety of additional sources of personnel, equipment, and expertise both within the state (other non-maintenance Caltrans departments) and outside of it (federal Department of Transportation and Departments of Transportation of nearby states). These sources may be called upon as necessary, but the response time increases due to additional mobilization, travel time, and coordination.

Second, the distance between bridge damage and earthquake epicenter is highly correlated to the amount of resulting damage, and subsequent response scope. Earthquakes occurring in densely populated areas (such as large cities) will require significant additional time to inspect and repair. Conversely, a major earthquake in an unpopulated area will reduce the amount of required emergency response resources. It should be noted that region population is directly correlated to the amount of Caltrans resources available for inspection: densely populated areas are likely to have the greatest amount of Caltrans resources for post-earthquake response.

For example, the 2010 Eureka earthquake was considered “major” (magnitude 6.5 on the MMS), but the required response was small because the earthquake occurred in a relatively unpopulated area.

Third, the magnitude of the earthquake may be large, which can reduce the capacity of the communication and transportation networks that are required for post-earthquake response. Damage to the highway system, such as the bridge damage from the 1994 Northridge Earthquake, limited the ability of Caltrans engineers to conduct inspections and estimation due to inaccessible freeways and streets.

In order to measure available resources, and to provide engineers with instructions, drawings, and equipment, current Caltrans response policy requires ABMEs to report to their office after a moderate to major earthquake. The scale of the above unknowns directly impacts the feasibility of this requirement. These unknowns affect response scope and time, which in turn will affect the overall time required to repair and restore the system.

Inspection & Estimation

After teams are organized and mobilized, work begins on inspecting and estimating earthquake damage. The bridge inspection process is a coordinated effort, with local, district, and headquarter-based information clearinghouses gathering all of the recorded information and deploying additional inspections. The priority of bridges is determined by lists generated the ShakeCast system and combined with field reports from ABMEs, emergency responders, the media, and the public.

The Caltrans Emergency Response Plan outlines the roles and responsibilities of the various management positions within the Division of Maintenance, as well as that of their subordinates. These duties are outlined by position (seniors, ABMEs, Inspectors), as well as by location (local, district, Disaster Command Center) (Sahs 2008).

Caltrans inspectors, combined into teams and assigned to bridges, are charged with conducting rapid surveys of impacted areas. These areas are inspected in several phases, with initial phases focusing on public safety and subsequent inspections focusing on detailed damage assessment and repair estimates. Inspection information is recorded using the OSMI Earthquake Field Report, which is filled out for each bridge. The report contains a summary of damage, description of the condition of various bridge components, current operating status, and a repair cost estimate. Completed inspection forms are called in, faxed, emailed, or returned in person to the DCC, which inputs the data into the SMART database, an internal inspection collection and report generation software.

Repair costs are estimated on the field report through a series of discrete checkboxes which detail low, medium, medium-high, and high repair costs for the given bridge. Although the form does not include any specific estimating parameters, bridge inspectors may attach more detailed cost estimates to the report upon submission.

Repair cost estimation is conducted by experienced Caltrans estimators, and are based on repair costs used in normal situations combined with additional emergency repair costs. Typical emergency repair costs are increased by the following values: 40% for extra work surcharge costs, 20% for additional labor costs, 25% for equipment and material costs (Lam 2009).

Aggregation

Inspection reports, similar to inspectors, arrive at the DCC in phases, resulting in an understanding of the system that improves over time. As more information arrives, Caltrans officials can make more informed decisions about additional inspection, closure, or opening of their transportation network.

After receiving information about a bridge, Caltrans decides between several bridge availability options: remain open, partially closed, closed except for emergency vehicles, and completely closed (Lam 2009). Both the timing and the outcome of this decision depend on the following decision variables: the type and extent of damage, bridge location, average daily traffic, and the physical appearance of the bridge structure. Physical appearance, despite its qualitative and non-technical nature, is an important decision variable because the appearance of damage negatively impacts the traveling public's trust of California's transportation network, causing public distress and reducing road use.

This phase of the emergency response is vital to the restoration of system function, and later sections in this dissertation will focus on the decision made in this particular phase.

Design

Once Caltrans has completed the inspection, estimation, and aggregation phases of their post-earthquake response, the design phase begins with Caltrans engineers incorporating the inspection and estimation reports into new structural and construction drawings. The Division of Maintenance handles the design drawings for minimal repairs, while the Division of Engineering Services is charged with the design of major repairs and rebuilding of highway bridges. The determination of minor or major repairs is made within the OSMI through cooperation with other bridge engineers. When major repairs need to be designed, the OSMI typically opens an internal contract with the DES due to accounting structures with Caltrans. If additional design resources are required, such as after major earthquakes causing sizeable bridge damage, Caltrans will hire third-party structural engineering firms with bridge design experience to aid in the design process.

For bridges that require repair work – instead of redesign and rebuilding – Caltrans aims to restore the damaged bridge to as-built condition. This means that they design their repairs such that the post-repair bridge performs according to the original design, calculations, and specifications (Lam 2009). This focus on restoration instead of improvement is the result of restrictions in Federal emergency funding, guaranteed through State of Emergency proclamations by the Governor or Federal agencies. This funding can cover up to 90% of post-emergency repair costs, as long as the funded work is classified as repair rather than retrofit or improvement. Additionally, a typical time limit of two years is mandated by the state for the repair funding coverage, since construction work outside of that two year window is classified as scheduled maintenance rather than emergency repair (Lam 2009).

Contracting

As the repair design documents for each bridge are finished, the contracting phase begins with Caltrans using their Contractor Interest Registry, a database populated by contractors containing their contact information, location, abilities, equipment, insurance information, and work history. Each Caltrans district also maintains a list of contractors who have experience with Caltrans projects and are capable of completing emergency repair contracts with short mobilization time. Additionally, contractors from throughout the state and surrounding areas arrive at the district headquarters by the time that the contracting phase begins, ready to bid on emergency repair contracts (Kaslon 2000).

Post-earthquake highway bridge repair contracts are typically conducted as emergency contracts, which must be authorized by the Caltrans district director's order. A director's order allows the bypassing of normal contracting procedures in order to expedite the start of construction activity. These contracts are typically emergency force account contracts, which provide for an informal bid process that minimizes overhead, coordination, environmental, and paperwork requirements for the bidding process (Caltrans 2001).

Caltrans "contractor selection coordinators" may choose a contractor for the given job, considering such factors as availability of resources, mobilization response time, and proven management abilities (Caltrans 2001). Performance incentives may or may not be included in the emergency contract, depending on bridge use and other relevant factors. Additionally, repair work may be grouped together for nearby or similarly damaged bridges, in order to benefit from economies of scale.

Repair

After contracts are offered, bid upon, and awarded, repair work begins with close cooperation between Caltrans and the contractor, in order to ensure that Caltrans performance and construction goals are met. The demand for immediate restoration of full system capacity, while minimizing overall cost and ensuring public safety during repairs, add complexity to the repair phase that extend beyond the scope of routine maintenance.

Construction is completed through the joint collaboration of the contractor, subcontractors, Caltrans engineers, and public safety officials such as the highway patrol. Figure 3 depicts an overall view of the post-earthquake response process, including the major involved entities and their chronological actions.

3.2.2. Attributes of Ineffective Decision-Making

Maintaining and governing engineered systems, particularly by large public agencies, involve inefficiencies that scale with both the size of the system as well as the agency itself, resulting in ineffective decision-making processes and outcomes. Caltrans, as one of the leaders in the public engineering sector around the world, continually works to reduce these inefficiencies and improve its standards and practices. These reductions and improvements should be supplemented by a focus on three distinct areas for improvement within Caltrans' post-earthquake highway bridge repair decision-making processes: informational completeness, long-term strategy, and organizational learning. The attributes of effective decision-making are discussed in Section 3.3.5.

Informational Completeness

As the inspection and estimation phase of Caltrans' emergency response procedures continue in the aftermath of an earthquake, data becomes available about the current state of various bridges on the ShakeCast bridge priority list. This data becomes available incrementally, as Caltrans engineers complete bridge inspections and relay the information to the Disaster Command Center.

Current Caltrans policy mandates that prior to moving into the repair phase of the emergency response, condition information about the entire system of earthquake-affected bridges must be known (Lam 2009). As a result, a potentially significant time delay is incurred from the moment that conditions for a particular bridge are reported, until the preparation of construction documents begins. During the Northridge Earthquake for example, complete inspection information took approximately three weeks (Kaslon 2000), which resulted in moderately damaged bridges remaining closed or partially closed while Caltrans engineers gathered information about other bridges.

This policy of informational completeness is grounded in the potential gains from complete understanding of the entire system condition. These gains include possible grouping of bridgework for contracting and construction purposes, as well as a more efficient use of repair resources. However, these gains come at the cost of additional

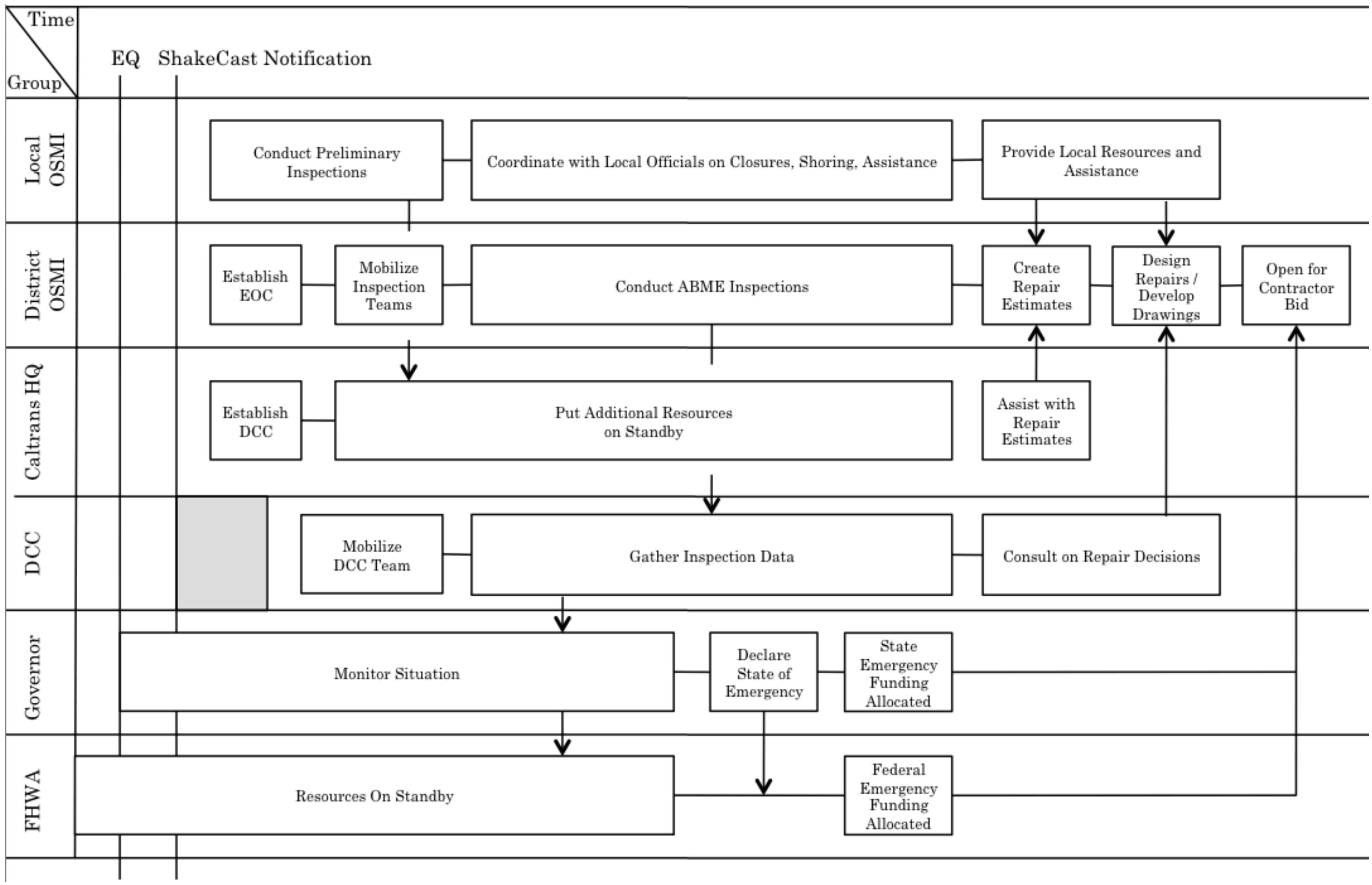

Figure 3: Post-earthquake response process and the major entities involved.

bridge downtime across the system, which can result in direct and indirect economic losses.

Long-Term Strategy

The design of repairs for moderately damaged highway bridges currently focuses on the restoration of bridges to their as-built condition. In addition to being eligible for federal emergency funding for up to 90% of the repair, as-built restoration simplifies the design phase of Caltrans' post-earthquake response (Caltrans 2008).

The result of this type of design philosophy however is that the repaired bridge is likely to perform under similar seismic loads in a similar fashion, leading to rework that would not otherwise be necessary if a higher performance standard were used. Furthermore, since Caltrans maintains seismic retrofit schedules for all of its bridges, earthquake-induced bridge damage requires that construction work on the bridge take place in the short-term anyway, presenting an opportunity to conduct repair work and seismic upgrades concurrently. Instead, Caltrans, through taxpayer funds, bears the cost of duplicate equipment rentals, mobilization, construction administration, and bridge closures.

Learning and Improvement

With a rich history of seismic activity in California and around the world, Caltrans as an organization is built upon the lessons of past successes and failures. The vast wealth of quantitative and qualitative data that can now be recorded before, during, and after earthquakes serves little purpose if not incorporated effectively and holistically into policies and databases for future use.

Currently, Caltrans' post-earthquake engineering work is primarily divided between the maintenance and structural design divisions, who infrequently work together to improve upon currently implemented policies. Although the lessons of recent major (and minor) earthquakes have been implemented broadly within Caltrans, the lack of holistic documentation of relevant data such as inspection rates, repair methodologies, and repair times leaves large efficiency gaps within the current bridge repair decision methodology.

These gaps are further widened by long periods of time between California earthquakes, an aging Caltrans workforce, and high employee turnover rates, all of which result in a loss of the rich post-earthquake experience and knowledge.

Unaddressed, these three inefficiencies represent a significant burden to Caltrans, its partners, and the public at large. In order to overcome these issues, the author has created a new decision framework that is sufficiently flexible to take into account the dynamic and multifaceted nature of highway bridge repair decisions.

3.3. Bridge Repair Decision Framework

Bridge repair decisions occur at the crossroads between large public agencies and private industry, and therefore reflect a variety of different and often contradictory perspectives. These perspectives interact with large systems that consist of bridges built with different structural design approaches, technological applications, and repair and retrofit histories. The context of these decisions adds yet another layer of complexity, as time pressure and general disorder significantly influence the decision-making process and outcome.

Current practices are unable to account for the complex nature of this entire process, which requires a logical, holistic, and understandable framework to discuss, analyze, and evaluate the various components involved. Therefore, this dissertation presents the Bridge Repair Decision Framework (BRDF) as the culmination of the author's research in this field.

3.3.1. Approach

The BRDF is a model for the various participating components of bridge repair decisions. This model provides a flexible logic and structure for these components, allowing clear identification and representation for each component, as well as their relationship to the other components within the model.

Data Structure

The BRDF functions as a specialized infrastructure maintenance database, containing various data structures to house inputs, computations, logic, and outputs. This database does not currently support a graphical user interface, but instead operates within a series of cross-referenced Microsoft Excel spreadsheets. Examples of these spreadsheet tables can be found in the tables at the end of this chapter.

Each term within the BRDF has a unique identifier, which follows a hierarchical naming convention so that each term can be clearly identified as the child (or grandchild) of a parent term.

Since bridge repair decisions can be made on a variety of levels, the BRDF data structure is hierarchically tiered. These tiers, called "levels" within the BRDF, allow the user to examine the framework on a microscopic (bridge performance group, for example) as well as a macroscopic (overall system) level.

Columns within each BRDF data table contain the terms that correspond to an individual subgroup of that level. For example, in Table 1, the first data column of the performance group (PG) contains terms regarding the first PG, the second data column contains terms describing the second PG, and so on. Rows within each BRDF data table contain terms that correspond to the variable name. For example, within the performance group level, the first row contains damage state names, the second row contains damage state descriptions.

Logic

The BRDF treats repair decisions as specialized engineering design problems, which are traditionally expressed by an inequality containing system demand on one side and system capacity on the other (Figure 4). While some BRDF parameters are known, since they represent the results of an applied load (earthquake), other parameters are unknown or variable, since the capacity side must equal or exceed the demand. Failure is therefore defined as system demand exceeding system capacity.

With this approach, the BRDF inequality can be "solved" for the unknown system capacity terms given the known terms on both the capacity and demand sides. Therefore, the known inequality terms are called decision inputs, and the unknown terms are called decision outputs.

3.3.2. Decision Inputs

Decision Inputs (DIs) consist of the quantitative data that influence a bridge repair decision, and come from a wide array of sources, each of which shapes the overall decision and outcome. Inputs are not mutually exclusive, but are often correlated with one another, since both sides of the BRDF inequality contain both capacity and demand inputs.

In order to examine DIs individually, they can be organized into Demand DIs and Capacity DIs.

	Bridge Level			
Performance Group	1	2	m	**Bridge Total**
Name	B1_PG1	B1_PG2	B1_PGm	**B1**
Damage State	B1_PG1_DS	B1_PG2_DS	B1_PGm_DS	**B1_CD**
Estimation Time	B1_PG1_ET	B1_PG2_ET	B1_PGm_ET	**B1_ET**
Estimation Cost	B1_PG1_EC	B1_PG2_EC	B1_PGm_EC	**B1_EC**
Estimation Resources	B1_PG1_ER	B1_PG2_ER	B1_PGm_ER	**B1_ER**
Repair Method	B1_PG1_RM	B1_PG2_RM	B1_PGm_RM	**B1_RM**
Repair Cost	B1_PG1_RM_RC	B1_PG2_RM_RC	B1_PGm_RM_RC	**B1_RC**
Repair Time	B1_PG1_RM_RT	B1_PG2_RM_RT	B1_PGm_RM_RT	**B1_RT**
Repair Resources	B1_PG1_RM_RR	B1_PG2_RM_RR	B1_PGm_RM_RR	**B1_RR**

Table 1: BRDF demand inputs at the bridge level.

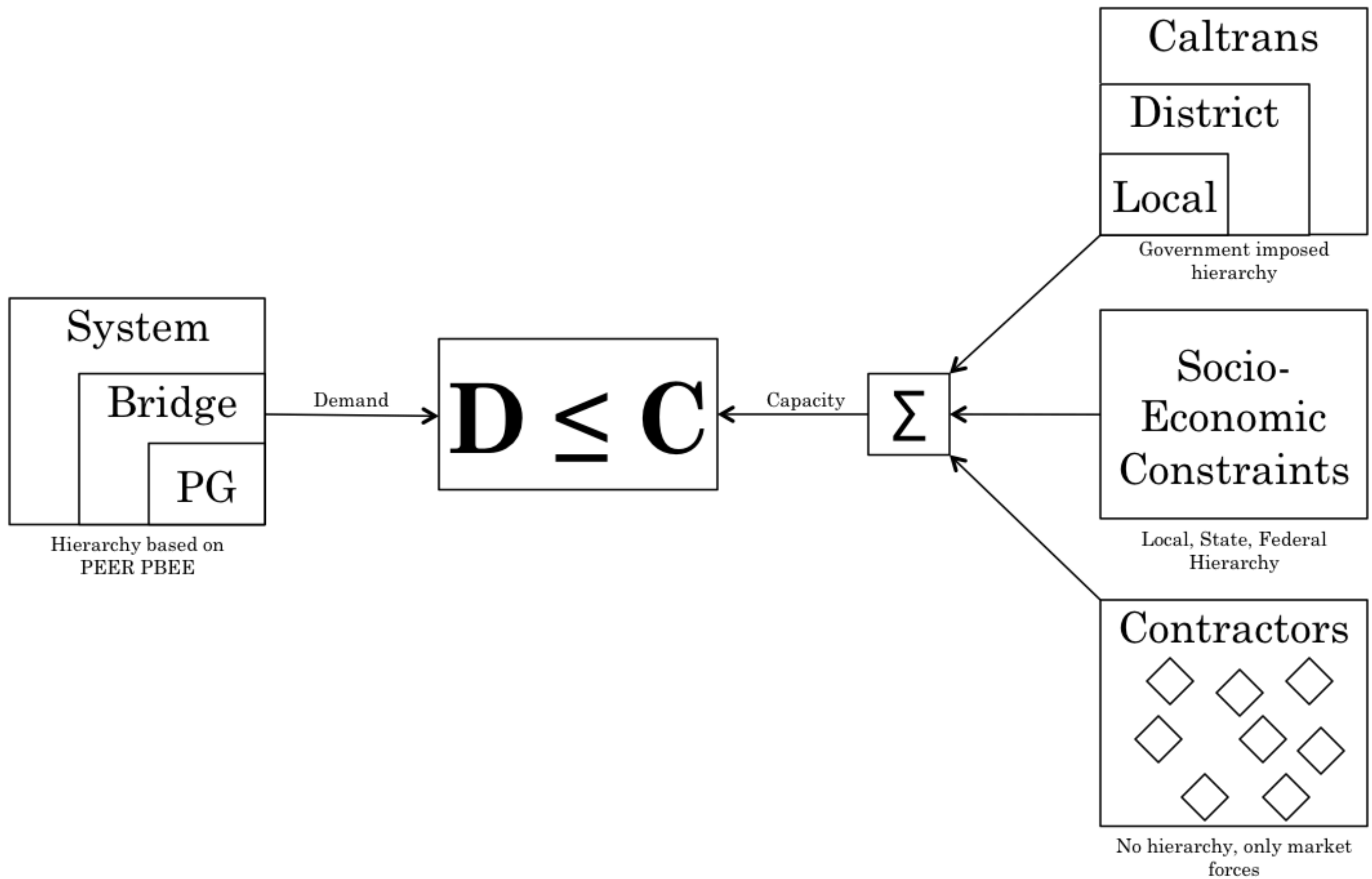

Figure 4: BRDF inequality and overall organization.

Demand Decision Inputs

Since the demand side of the inequality (and therefore the BRDF) consists of four distinct levels, Demand DIs should be examined at each one.

Performance Group Level

The most fundamental Demand DIs are found at the performance group (PG) level, which contains data about each of the damage states (DSs) applicable for a given performance group (Figure 5 - shaded lines distinguish unselected parameters).

A PG can exist in only one damage state at any given time. The performance group level in BRDF therefore contains a list of the applicable damage states that can be selected once bridge engineers enter the performance group condition from inspection reports. The columns within the performance group level are the various damage states available for the given performance group.

Within the BRDF, damage states are linked to DIs regarding estimation, including Estimation Time, Estimation Cost, and Estimation Resources (Table 1).

Estimation Time quantifies the amount of time required to conduct repair estimation after inspection of the bridge has occurred. Although Caltrans includes rudimentary estimation during the inspection phase, these values serve primarily as an indicator of level of damage rather than for repair decisions (Lam 2009).

Estimation Cost is a placeholder for additional costs associated with the estimation process, typically overhead costs (Table 1). These costs may also be associated with estimation resources, the third Demand DI.

Estimation Resources contains a list of resources that are necessary to conduct the post-earthquake estimation during the Inspection and Estimation phase of the post-earthquake response. These resources include items such as equipment for transportation and close-proximity examination.

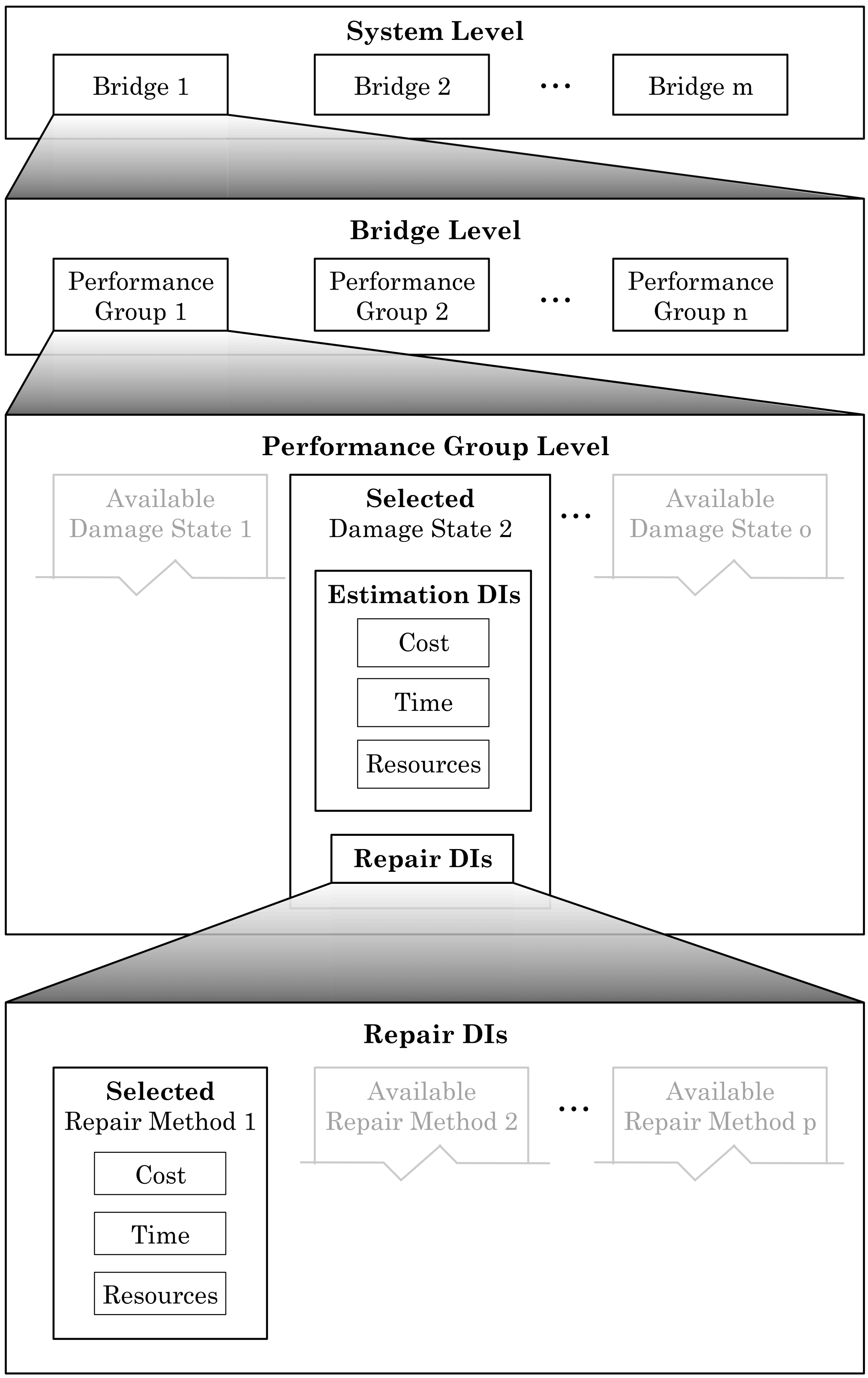

Figure 5: Bottom four demand input levels of the BRDF.

In addition to damage state and estimation variables, the performance group level contains repair method DIs that are linked to a specific damage state DI. As a result, damage states have one or more repair methods associated with them in a parent-child relationship (Figure 5). The amount of considered repair methods associated with each damage state is discussed in the Model Validation section, below.

Each repair method DI describes – qualitatively – a repair approach for a given damage state. This approach consists of a series of detailed actions required to improve the damage state of a given performance group from a lower state to a higher state. Repair methods are quantitatively accounted for through repair quantities for each action. Each repair method is subsequently linked to DIs describing repair cost, repair time, and repair resources. Similar to the estimation group of DIs, repair resources contain information regarding overhead costs associated with a given repair method, such as transportation and equipment costs.

Each row within the performance group level is aggregated into a collection vector, which is displayed as the rightmost column entry of the BRDF data table (Table 1). For example, the BRDF can be queried for repair cost data for all of the available damage states for a given performance group. The result is a unique vector of costs, in sequential (damage state) order. It is important to note that these vectors may by quantitative (such as DIs that contain cost or time data) or qualitative (such as damage state descriptions or resource DIs).

Bridge Level

The next level after the performance group level is the bridge level, with data columns pertaining to each individual performance group on the bridge. Therefore, the first DI within the bridge level is the performance group name, containing a short description of the PG that can be used to easily identify it on the bridge.

The bridge level is the first level that contains input DIs that are entered from inspection reports. These reports provide information about each performance group's damage state, which is selected through a dropdown list of available damage states. This list of available damage states is generated through a query of the performance group level "Available Damage State" vector.

Once a damage state for a performance group is selected, the BRDF automatically populates the estimation and repair DIs associated with that damage state. This process is the result of lookup queries performed on the performance group level data.

System Level

The next tier above the bridge level is the system level, which is made up of columns pertaining to each individual bridge. The first group of system level DIs serves to identify the bridge within the given system: bridge name, number, location, and configuration. Configuration is a multi-term DI that contains bridge-specific data regarding geometry, age, material type, as well as retrofit and repair history. This information can be retrieved through queries on existing Caltrans infrastructure maintenance databases such as the Structure Maintenance Automatic Report Transmittal (SMART) system.

Further identifying the bridge is the bridge priority DI, based upon the ShakeCast exceedance ratio. This ratio is the result of a ShakeCast-specific implementation of FEMA's HAZUS-MH earthquake module that compares the probability of exceeding a corresponding HAZUS structural damage state with the probability of exceeding the next-higher HAZUS structural damage state (Lin et al. 2009). The exceedance ratio is also based on custom bridge fragilities that Caltrans maintains for each bridge and overpass under their jurisdiction.

Combined with the repair and estimation DIs that are aggregated for each bridge, the system level contains three additional DIs for design time, maintenance time, and maintenance resources. Design time is a quantitative measure of the time requirements for the design phase of the bridge repair once the condition (damage state) of the bridge is established. Maintenance time and resources describe the requirements for construction administration and oversight during the repair process. Both the design and maintenance DIs are only present at the system level because they are most accurately measured as bridge-wide terms rather than for each performance group.

The aggregated row vectors at the system level combine the DIs of each bridge across the entire system. These vectors represent the terms on the demand side of the inequality.

Demand Level

The highest-level demand data array is the demand level, which organizes the aggregated row vectors from the system level into discrete categories. Time, cost, and resource DIs are combined into their own respective demand row vectors, and repair methods are combined into a new row vector called demand capabilities.

The demand level functions as the main collection and organization point for all of the demand DIs and information, which can subsequently be used to interface with the capacity decision inputs.

Capacity Decision Inputs

Whereas demand DIs document the effects of an earthquake on a transportation infrastructure system, capacity DIs document the effects of the transportation infrastructure system on the engineering organizations that are tasked with the subsequent repair. Therefore, capacity DIs focus on assets, which consist of resources and personnel.

The capacity side levels can be examined as two fundamental groups – Caltrans levels and contractor levels – that house all of the capacity DIs (Figure 6 - shaded lines distinguish unselected parameters). It is important to note that while the relationships between different demand side levels were hierarchical, capacity side levels are independent, resulting in a capacity side structure that is organizationally flat. This results in an added level of complexity when demand and capacity inputs are matched to one another. Therefore, the BRDF maps the relationships between demand and capacity inputs, while systematically assuring dimensional fidelity (Section 3.3.3).

Caltrans Levels

Since Caltrans employees and resources are distributed throughout the state (Section 3.2.1), there are three different Caltrans levels on the capacity side of the BRDF: district, state, and local.

The district level contains DIs that describe the various types of resources in a given district, including construction or transportation equipment. The amount of estimators, design engineers, and maintenance engineers are also represented as DIs at the district level. Each of these DIs are linked to availability DIs, consisting of a percentage that indicates what portion of a given asset (resource, estimator, engineer) is available for work. For some assets, only binary availabilities are available, while others may be partially available (expressed as a percentage).

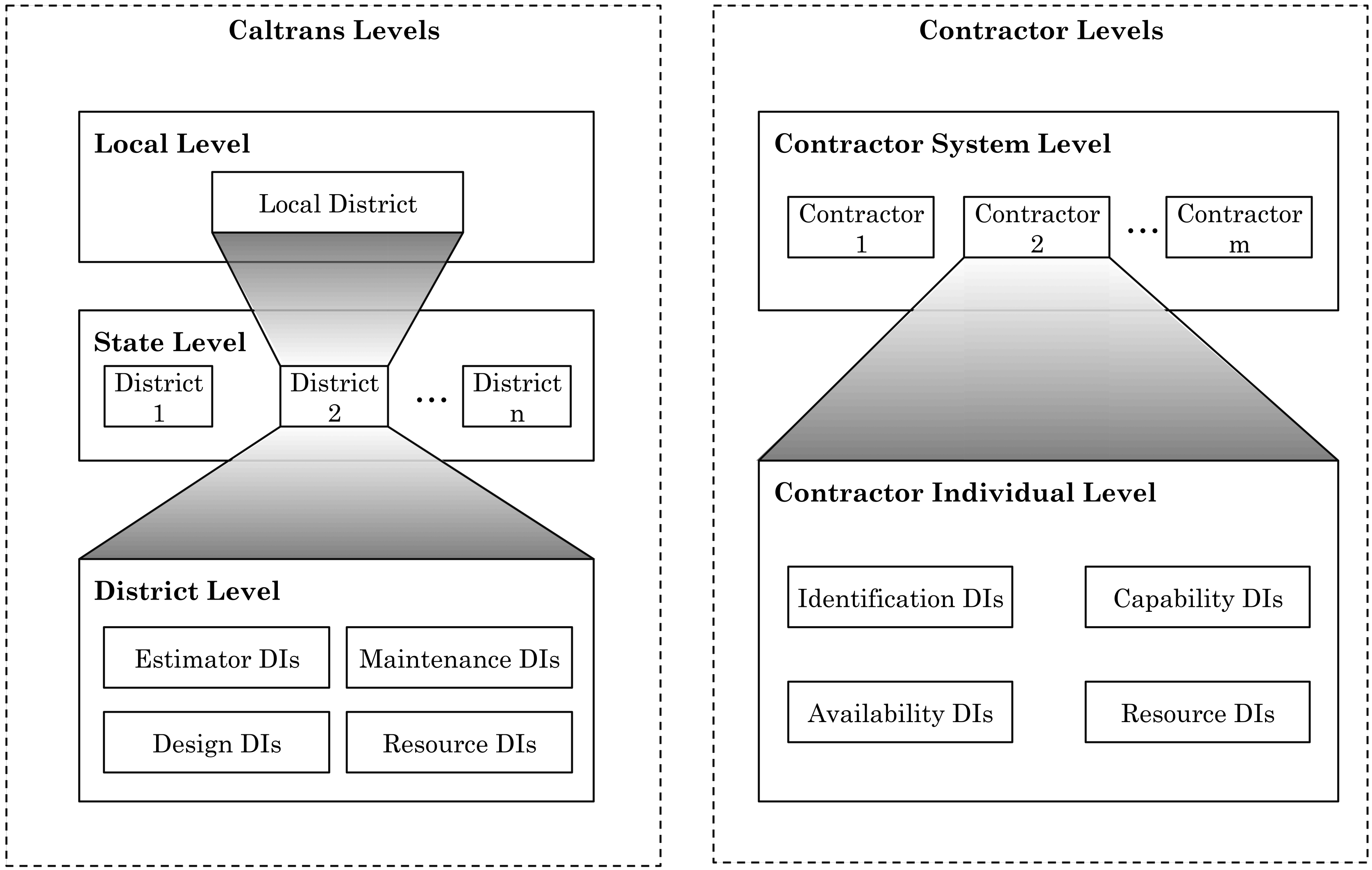

Figure 6: Flat capacity side organizational structure.

The state level contains the aggregated assets in each district, including available and overall assets. Additionally, a district proximity factor DI is included for each district within the state of California. This factor quantifies the normalized proximity between the earthquake epicenter and the district headquarters.

The final Caltrans level within the capacity side of the BRDF is the local level, which functions as a subset of the state Caltrans level. The local level does not contain any DIs, but instead uses the district proximity factor from the state level to determine the available assets local to the earthquake epicenter. Non-local available assets are combined into "supplemental" row vectors. The assets within these vectors are sorted by proximity to earthquake epicenter in terms of district headquarters.

Contractor Levels

Within the BRDF there are two levels that contain contractor DIs: the individual contractor level and the contractor system level.

The first DIs within the individual contractor level pertain to the identification of a contractor, listing the name, location, and binary overall availability, which indicates the contractor's availability to perform repair work at the present time.

The subsequent DIs describe contractor capabilities and resources. Contractor capability details the established ability of a contractor to perform a specific type of construction work. Therefore, the individual contractor level lists all of the primary contractor capabilities, and combines them into a contractor capability row vector. Since the capabilities of a contractor vary over time due to other jobs and contracts, an availability DI is also linked to each contractor capability that describes the availability of the contractor to perform the given capability. Contractor resources function in a similar fashion, listing the various resources and their respective availability.

The contractor system level serves to collect the individual contractor row vectors into one data array. Each of the contractors' names, locations, available capabilities, and overall availability is represented, providing a system-wide understanding of contractor DIs.

Capacity Level

The final and highest-level capacity data array is the system capacity level, containing the aggregated row vectors from each of the aforementioned capacity levels. These row vectors are organized into vectors containing time, cost, resource, and capability DIs.

Socioeconomic Inputs

The aforementioned demand and capacity inputs describe the engineering components that shape repair decisions. In practice, however, these engineering components are supplemented by ever-present socioeconomic inputs that further influence these decisions, but cannot be entirely placed within the demand or capacity sides. These inputs are grouped into categories relating to funding and political/bureaucratic inputs.

Funding Inputs

There are three distinct sources of funding for emergency highway bridge repair, providing the financial foundation for repair work. First, Caltrans maintains an emergency fund for expenses incurred after unforeseen events. This funding source is typically limited due to the presence of additional and substantial state and federal funding.

Second, emergency funding can be provided by the State of California through a declaration of emergency by the governor. The 2008 California Emergency Services Act permits the governor to declare a state of emergency, releasing state funds to begin repair work and facilitation system restoration.

Third, a declared state of emergency requires that the Federal Highway Administration fund 100% of emergency repair work for the first 180 days after disaster declaration. After 180 days, federal funds will continue to pay for repair work at a lower percentage, approximately 88% for local highways for up to 2 years (Caltrans 2008).

Combined, these three funding sources describe the financial aspects of repair decisions. However, their allocation, as well as timing, is a function of the political and bureaucratic inputs that shape repair decisions.

Political/Bureaucratic

Political and bureaucratic inputs are inevitable in the decision-making processes of large public organizations such as Caltrans. These inputs are the product of two primary factors: public pressure and public policy.

In the aftermath of a moderate-to-major earthquake, state financial and physical resources are significantly strained, resulting in a shift of political priorities from ordinary governance to a necessary and visible assurance of public safety. This shift occurs as a response – both proactive and reactive – to public pressure, which requires immediate restoration of system function and accurate assessment of system performance.

It should be noted that political and bureaucratic inputs may influence emergency response procedures and repair decisions to a greater extent than the above capacity and demand (engineering) inputs. For example, Caltrans will routinely close a fully functioning bridge after an earthquake if it exhibits extensive cosmetic damage. Despite the bridge's adequate post-inspection load-bearing capacity after the earthquake, decisions about its closure are instead grounded in necessary preservation of the traveling public's trust in the state's transportation system. Within the BRDF methodology, the assurance of public safety is therefore essentially a system-level demand input, with extensive cosmetic bridge damage representing a bridge-level demand input.

In addition to public pressure, public policy also shapes Caltrans repair decisions through established incentive structures. For example, current Caltrans policies require engineers to repair damaged bridges after an earthquake to as-built condition, regardless of the bridge's long-term retrofit schedule. This policy is the direct result of financial incentives established by federal funding guidelines, providing 80-100% funding reimbursement for emergency relief. In this context, federal guidelines define emergency relief as the repair or restoration of a highways, roads, and trails (USC 2009). This federal reimbursement policy significantly limits Caltrans decision-makers in the scope of applicable repair methodologies that can be used to repair damaged bridges, since concurrent seismic upgrades are not covered by federal funding.

Socioeconomic inputs are described outside of the demand-capacity convention since they do not fit completely into either side of the inequality. For example, more financial inputs describe the capacity of the system to pay for the given demands, but the federal financial incentives described above also institute a demand on the system to structurally restore rather than seismically improve damaged bridges.

Despite this, the BRDF, by accounting concurrently for engineering and socioeconomic inputs, provides a comprehensive model for repair decisions. Before the decision-model outputs can be examined, it is important to understand how the BRDF uses all of the above inputs to make bridge repair decisions.

3.3.3. Model Attributes

Improving bridge repair decisions requires that the individual steps of the decision process be disaggregated and examined individually. By categorizing the components of these steps into inputs and outputs, the BRDF is able to improve upon current repair decision practices.

Current Caltrans repair decisions are greatly simplified by only allowing a single available repair method for a performance group in a given damage state. This means that while there might be several appropriate repair methods for a given damage state, the Caltrans repair method selection process is automatic, since Caltrans only considers one “trusted” repair method. As a result, only one target performance level is available for the performance group (the performance level provided by the single repair method). Furthermore, decision-stakeholders are presented with little or no information about the uncertainty associated with this performance level.

This single repair method approach is the result of Caltrans’ conservative engineering design philosophy that relies on rigorously tested repair methods in order to ensure public safety. The testing of these repair methods, conducted at various universities throughout the United States (Hose et al. 1999), provides Caltrans with a degree of trust in its repair strategies. This trust, which can be expressed in terms of the probability of failure for a repair method, is not currently quantified, preventing an adequate comparison of alternatives. The BRDF improves upon these practices, expanding the range of appropriate repair decisions for any given damage state by encouraging the quantification of this trust, which results in a performance-based, risk-informed, and technology-neutral repair decision-making approach.

Performance-Based

The BRDF seeks to quantify the elements of the repair decision process using metrics that are meaningful to each of these decision-making stakeholders, a core principle of the PEER performance-based earthquake engineering methodology (PBEE). These repair decision elements are quantified by describing the various achievable performance levels using attributes that are meaningful to decision stakeholders. As a result, stakeholders are able to compare alternatives using metrics specific to their particular values.

The advantages of this approach are highlighted during the design phase of the repair method selection. The BRDF provides a structure to house not one but multiple repair methods for any given damage state. These repair methods are linked to several descriptive metrics that have meaning to the various stakeholders involved in the repair decision. Therefore, engineers can scrutinize the engineering demand parameters of a given repair method (displacements, strains, etc.), while politicians and Caltrans senior officials can scrutinize decision variables such as repair costs. As a result, repair methods for bridges are selected based on a holistic assessment of performance and appropriate tradeoffs between stakeholder values.

Risk-Informed

The BRDF improves decision outcomes by providing stakeholders with a thorough understanding of risk. This understanding is the result of presenting stakeholders with three distinct risk parameters:

1. Probability of the design-basis earthquake;
2. Probability of repair method failure given design-basis earthquake occurrence;
3. Confidence level in the above parameters.

The BRDF allows for the accounting of each of these parameters for each repair method. While much research has been made into the quantification of the first parameter (Power et al. 2008), little information is currently available for the second parameter.

This second risk parameter describes the probability that the repair method will perform as intended given the occurrence of the design-basis earthquake. Currently, Caltrans employs a collection of repair methods that they trust because the repair methods have been extensively tested and used in the field. Since it is not quantified, this trust amounts to a very low assumed probability of failure for these repair methods given the respective hazard level. Repair methods that lack this trust are not considered by Caltrans engineers, significantly limiting the amount of available repair alternatives.

To overcome this, the BRDF allows for the input of the second risk parameter, which explicitly quantifies this trust and therefore allows Caltrans engineers to consider a greater variety of repair methods based on the priority of their values (performance, cost, time, etc.) at the given moment.

The third parameter exists because performance metrics for all bridge repair stakeholders are based on inputs containing various levels of uncertainty that prevent them from being deterministic. The BRDF accounts for these uncertainties, which can be epistemic as well as aleatory.

Epistemic uncertainty arises from a lack of knowledge about the system. Within the BRDF, quantitative Demand DIs such as repair cost and repair time are based on lognormally distributed data that accounts for the lack of reliable information about a particular variable with in the model. Lognormal distributions were used for these inputs due to existing lognormal repair data gathered by Mackie and Wong (2007). Capacity inputs (such as contractor and Caltrans engineer availability) as well as socioeconomic inputs (such as public pressure) are also examples of inputs that contain inherent epistemic uncertainty.

Aleatory uncertainty arises from the inherent, irreducible, and natural randomness within the system. Within the BRDF, the DIs that result from ground motion analysis, such as the ShakeCast-based bridge priority, contain aleatory uncertainty.

The characterization of DI uncertainty provides decision-makers with confidence intervals for the performance levels of their decision outcomes. For example, a given repair method may have a probability of failure of 1% that is known with a 95% confidence interval. Empowering decision-makers with these confidence intervals results in gains for all stakeholders within the repair decision process due to an explicit understanding of the risk involved.

Technology-Neutral

The advantages of stakeholder understanding of risk and performance are supplemented by a third and equally important advantage of the BRDF: technological neutrality. Shifting the focus of the decision-maker from a prescriptive repair method to a desired, risk-informed performance criterion expands the collection of viable alternatives, without limiting the user to any specific repair technology or method.

This results in an experience-driven, long-term decision-making approach where decision outcomes are independent of the available knowledge at any one point in time. Accordingly, this allows for past non-technology-neutral repair decisions to be analyzed and evaluated against current practices, leading to a complete understanding of decision outcomes in terms of relevant stakeholder values.

Additional Attributes

The vast number of participatory entities, individual components, and distinct chronologies complicate the analysis of bridge repair decisions on a system level. Therefore, the BRDF provides a common language and established set of parameters that have significance for all participants involved. This unified nomenclature allows for the discussion, comparison, analysis, and evaluation of various repair decision strategies within and outside Caltrans' jurisdiction.

The incorporation of the PEER PBEE allows bridge component and overall condition information to be described using discrete categories of damage, which correspond to time and cost parameters. The BRDF supplements the PBEE methodology with repair and estimation parameters, thereby accounting for the major repair decision elements. As a result, thresholds for participating engineers can be established in terms of engineering demand parameters (EDPs), while policy-makers and the public can set their thresholds in familiar terms such as the "Three Ds": dollars, deaths, and downtime (Comerio 2006).

Dimensional Fidelity

While the BRDF unified nomenclature ensures that each component of the bridge repair process is well defined, the interaction between the demand and capacity inputs requires dimensional fidelity in order to achieve accurate results. Fidelity of dimension within the BRDF is provided through the verification of identical units of respective capacity and demand parameters.

For example, the estimation time demand input is linked to the available estimator time capacity input, and both terms are in the same units of time (hours). Through a specific dimensional fidelity worksheet, the BRDF confirms that all respective terms are entered in the same units. Those DIs that contain vectors of item descriptions are presented in units of "items." Since the BRDF verifies dimensional fidelity for each individual input, the aggregated vectors and arrays that contain these inputs (in corresponding sequence) also maintain dimensional fidelity.

Informational Availability

The BRDF provides a logic and organizational structure for a vast amount of repair decision information. Therefore, it is important to explicitly understand not only the content of this information, but also how each piece fits within the timeline of a repair decision. The BRDF accomplishes this by adapting the CCRM quality management methodology to repair decisions, classifying BRDF inputs into three categories: proactive, interactive, and reactive.

Proactive inputs contain information that can be gathered prior to an earthquake event. For example, current information about a bridge system, including bridge names, numbers, locations, and geometries can be gathered, organized, and accessed at any time. Proactive inputs represent the long-term accumulation and organization of bridge repair data.

Interactive inputs are not available prior to an earthquake, but are collected immediately after an earthquake occurs. The information for these inputs is the product of emergency response procedures, and is therefore generally generated within the first two weeks after an earthquake. For example, inputs regarding bridge priority and asset availability are dependent on the particular context of the earthquake, and are therefore only available after an earthquake.

Reactive inputs are collected over an extended period of time after an earthquake occurs. For example, repair cost and time inputs for implemented repairs only become available after the repairs are completed. While some reactive inputs merely require extended periods of time to gather, others are identified in order to gather information into proactive inputs for future use.

The BRDF assigns proactive, interactive, and reactive labels to inputs rather than dividing inputs into categories, allowing each input to have multiple labels. For example, federal funding inputs are labeled as both interactive and reactive, since they participate in both the short- and long-term to pay for repair work (Table 2).

3.3.4. Decision Outputs

Once the BRDF model attributes are applied to the decision inputs, decision outputs are generated. Decision outputs within the BRDF consist of actions, repercussions, and results of the repair decision process. Primarily, decision outputs consist of system capacity understanding and relevant repair method alternatives.

	Proactive	Interactive	Reactive
Bridge Identification Information	◆		
Bridge Priority		◆	
Asset Availability		◆	
Repair Costs			◆
Repair Times			◆
⋮	⋮	⋮	⋮
Funding Sources		◆	◆

Table 2: BRDF parameters and their informational availability (a full list is presented in Table 7).

System Capacity

As discussed, the BRDF treats repair decisions as a traditional design inequality between system demand and system capacity. All BRDF inputs are random variables that consist of mean and standard deviations. Immediately after an earthquake, demand inputs contain high levels of uncertainty and that uncertainty decreases as more information is revealed through investigation. Likewise, capacity input uncertainty decreases as Caltrans gathers more resources and contractor availability is determined. The BRDF accounts for this variable uncertainty and makes its effects transparent to decision-makers. As a result, the BRDF provides a comprehensive understanding of not only the system uncertainty, but also the capacity of the system to meet or exceed system demands. This understanding functions as one of the primary decision outputs, forming the foundation for future repair short- and long-term decisions.

Repair Method

The most fundamental output of a bridge repair decision is a suitable repair method for a performance group in a given damage state. The suitability of the selected repair method is determined by adhering to criteria established by stakeholder values and contextual limitations. Stakeholder values are determined by establishing performance-based risk-informed decision criteria, while contextual limitations are determined through the BRDF capacity decision inputs. These inputs describe the ability of a system to cope with the post-earthquake demands.

Using this approach, the BRDF outputs a repair method that achieves or exceeds the desired stakeholder performance level given the system constraints. Since the BRDF allows analysis on the performance group, bridge, and system levels, the selection of repair methods can be made for individual performance groups, individual bridges, or for the system as a whole.

Additionally, the BRDF highlights an important and subtle tradeoff that Caltrans engineers make during repair method selection. Currently Caltrans employs a limited collection of repair methods that are well tested and trusted by Caltrans engineers. The use of these high-confidence, high-cost methods does not permit a dynamic system where tradeoffs can be made between repair method confidence, repair cost, and repair time. The BRDF enables stakeholders to make these types of tradeoffs through performance-based, risk-informed, and technology-neutral decision framework.

3.3.5. Attributes of Effective Decision-Making

The current Caltrans post-earthquake bridge repair decision-making process is the result of past earthquake experience combined with technological improvements in the understanding of earthquakes, structures, and their interaction. This implemented process can be supplemented through the incorporation of the BRDF model and methodology, which provides fundamental improvements in system understanding and organizational learning.

System Understanding

The BRDF provides a structure for the multitude of elements that go into, participate in, and result from post-earthquake bridge repair decisions. This results in a situational understanding at the performance group, bridge, and system levels, ensuring that decision-makers take advantage of all known information, and are aware of missing information that can affect decision outcomes. Furthermore, the BRDF accounts for the uncertainties associated with decision inputs, making risks transparent to decision-makers at the microscopic as well as system levels.

The BRDF methodology simplifies the repair decision process to an inequality between system demand and system capacity, allowing decision-makers to minimize system downtime and repair cost while maximizing long-term structural performance. This is accomplished through the availability of multiple repair methods for each performance group damage state, allowing stakeholders to arrive at performance-based, risk-informed, and technology-neutral decision outcomes.

Organizational Learning

Since current Caltrans practices are based on past earthquake experiences, it is vital to both collect and incorporate this information for use after future earthquakes. The wealth of information documented within the BRDF allows for the evaluation of past repairs as a platform for future repair decisions.

Effective decision-making requires the implementation of new repair methods and approaches while accounting for their respective uncertainties. This requires Caltrans to examine the probabilistic nature of new repair technologies in order to choose between alternatives given organizational values (risk-attitude) and system constraints. This type of organizational learning enables technological neutrality of decision outcomes.

The documentation of repair methods, costs, and times, along with inspection and estimation data in the BRDF grounds future repair decisions in lessons of the past. Furthermore, the documentation of this type of data ensures that its existence is independent of any single employee or department, available for the benefit of Caltrans as a whole and not limited by the effects of employee turnover.

3.3.6. Prerequisites to Implementation

Since the BRDF embodies not just a model but also a methodology for making sound post-earthquake repair decisions, the implementation of the BRDF requires making adjustments to current Caltrans practices.

Through their internal and external research, Caltrans has traditionally strived to implement new technological advancements into its policies and procedures. While the benefits of new technologies are clear, it is equally vital to document and build upon past and existing technologies in order to learn from past experience and improve the overall reliability of engineered systems.

It is therefore that the implementation of the BRDF requires the explicit recording and documentation of repair methods used in the past. Although Caltrans expressed interest in the creation of repair method databases, and researchers at PEER center have proposed possible implementations, no such databases currently exist. The creation of these types of databases, containing repair quantities, costs, times, resources, and the respective uncertainties for each, would allow Caltrans engineers to use the BRDF to holistically select and assess appropriate repair methods in light of stakeholder values and system constraints. Through this documentation, BRDF demand and capacity inputs can improve in accuracy, providing decision-makers with a better understanding of risk.

This type of data collection allows vital repair information to exist independently of any specific Caltrans engineers or divisions, minimizing the effects of employee turnover and preserving repair knowledge for future use. As these types of databases are created, it becomes increasingly important that they are widely available to, and accessible by, the various Caltrans divisions and departments. Repair decision outcomes are improved as additional information is inputted into BRDF databases. Therefore, all Caltrans engineers who work on bridge repairs should be able to not only access but also contribute to the body of knowledge contained with these repair databases.

The collection and organization of additional data, combined with increased internal collaboration will enable the Caltrans to implement the BRDF, increasing post-earthquake response efficiency and improving post-earthquake repair decision outcomes.

Demand Level					
System	Estimation	Design	Repair	Maintenance	**Total**
Demand Time	D_ET	D_DT	D_RT	D_MT	**D_T**
Demand Cost	D_EC		D_RC		**D_C**
Demand Resources	D_ER		D_RR	D_MR	**D_R**
Demand Capabilities			D_RM		**D_CA**
System Demand	D_EV	D_DV	D_RV	D_MV	**D**

System Level					
Bridge	1	2	…	n	**System Total**
Name	B1	B2	…	Bn	**D_B**
Location	B1_L	B2_L	…	Bn_L	**D_L**
Configuration	B1_CF	B1_CF	…	B1_CF	**D_CF**
Priority	B1_SE	B2_SE	…	Bn_SE	**D_PR**
Condition	B1_CD	B2_CD	…	Bn_CD	**D_CD**
			…		
Estimation Time	B1_ET	B2_ET	…	Bn_ET	**D_ET**
Estimation Cost	B1_EC	B2_EC	…	Bn_EC	**D_EC**
Estimation Resources	B1_ER	B2_ER	…	Bn_ER	**D_ER**
			…		
Design Time	B1_DT	B2_DT	…	Bn_DT	**D_DT**
Maintenace Time	B1_MT	B2_MT	…	Bn_MT	**D_MT**
Maintenance Resources	B1_MR	B2_MR	…	Bn_MR	**D_MR**
			…		
Repair Method	B1_RM	B1_RM	…	B1_RM	**D_RM**
Repair Cost	B1_RM_RC	B1_RM_RC	…	B1_RM_RC	**D_RC**
Repair Time	B1_RM_RT	B1_RM_RT	…	B1_RM_RT	**D_RT**
Repair Resources	B1_RM_RR	B1_RM_RR	…	B1_RM_RR	**D_RR**

Bridge Level					
Performance Group	1	2	…	m	**Bridge Total**
Name	B1_PG1	B1_PG2	…	B1_PGm	**B1**
Damage State	B1_PG1_DS	B1_PG2_DS	…	B1_PGm_DS	**B1_CD**
Estimation Time	B1_PG1_ET	B1_PG2_ET	…	B1_PGm_ET	**B1_ET**
Estimation Cost	B1_PG1_EC	B1_PG2_EC	…	B1_PGm_EC	**B1_EC**
Estimation Resources	B1_PG1_ER	B1_PG2_ER	…	B1_PGm_ER	**B1_ER**
Repair Method	B1_PG1_RM	B1_PG2_RM	…	B1_PGm_RM	**B1_RM**
Repair Cost	B1_PG1_RM_RC	B1_PG2_RM_RC	…	B1_PGm_RM_RC	**B1_RC**
Repair Time	B1_PG1_RM_RT	B1_PG2_RM_RT	…	B1_PGm_RM_RT	**B1_RT**
Repair Resources	B1_PG1_RM_RR	B1_PG2_RM_RR	…	B1_PGm_RM_RR	**B1_RR**

Performance Grp Level					
	1	2	…	o	
Damage State Name	B1_PG1_DS1	B1_PG1_DS2	…	B1_PG1_DSo	**B1_PG1_AD**
Damage State Description	B1_PG1_DS1_DC	B1_PG1_DS2_DC	…	B1_PG1_DSo_DC	**B1_PG1_AD_DC**
			…		
Estimation Time	B1_PG1_DS1_ET	B1_PG1_DS2_ET	…	B1_PG1_DSo_ET	**B1_PG1_ET**
Estimation Cost	B1_PG1_DS1_EC	B1_PG1_DS2_EC	…	B1_PG1_DSo_EC	**B1_PG1_EC**
Estimation Resources	B1_PG1_DS1_ER	B1_PG1_DS2_ER	…	B1_PG1_DSo_ER	**B1_PG1_ER**
Repair Method	B1_PG1_DS1_RM	B1_PG1_DS2_RM	…	B1_PG1_DSo_RM	**B1_PG1_RM**
Repair Cost	B1_PG1_DS1_RM_RC	B1_PG1_DS2_RM_RC	…	B1_PG1_DSo_RM_RC	**B1_PG1_RM_RC**
Repair Time	B1_PG1_DS1_RM_RT	B1_PG1_DS2_RM_RT	…	B1_PG1_DSo_RM_RT	**B1_PG1_RM_RT**
Repair Resources	B1_PG1_DS1_RM_RR	B1_PG1_DS2_RM_RR	…	B1_PG1_DSo_RM_RR	**B1_PG1_RM_RR**

Table 3: BRDF demand side parameters and organization.

System Capacity Level

System	Estimation	Design	Repair	Maintenance	**Total**
Capacity Time	C_ET	D_DT	C_AV	D_MT	**C_T**
Capacity Cost	D_EC		C_F		**C_C**
Capacity Resources	C_ER		C_R	D_MR	**C_R**
Capacity Capabilities			C_CA		**C_CA**
System Demand	C_EV	C_DV	C_RV	C_MV	**C**

Contractor: System Level

Contractor	1	2	...	n	
Name	CO1	CO2	...	COn	**CO**
Location	CO1_L	CO2_L	...	COn_L	**C_L**
Available Capabilities	CO1_CA	CO2_CA	...	COn_CA	**C_CA**
Available Resources	CO1_R	CO2_R	...	COn_R	**C_R**
Availability	CO1_AV	CO2_AV	...	COn_AV	**C_AV**

Contractor: Individual Level

				Contractor Total
Name	CO1			
Location	CO1_L			**CO_L**
Contractor Availability	CO1_CA			**CO1_AV**
Available Capability	CO1_CA1	CO1_CA2	CO1_CAn	**CO1_CA**
Capability Description	CO1_CA1_CD	CO1_CA2_CD	CO1_CAn_CD	**CO1_CD**
Capability Availability	CO1_CA1_AV	CO1_CA2_AV	CO1_CAn_AV	
Available Resource	CO1_R1	CO1_R2	CO1_Rm	**CO1_R**
Resource Description	CO1_R1_RD	CO1_R2_RD	CO1_Rm_RD	**CO1_RD**
Resource Availability	CO1_R1_AV	CO1_R2_AV	CO1_Rm_AV	

Caltrans: Local Level

	Local Available	Supplemental Available	
Total Available Resources	LC_R	SA_R	**C_ER**
Total Estimator Time	LC_ET	SA_ET	**C_ET**
Total Design Engineer Time	LC_DT	SA_DT	**C_DT**
Total Maintenance Eng. Time	LC_MT	SA_MT	**C_MT**

Caltrans: State Level

District	1	2	...	n	
Name	DR1	DR2	...	DRn	**DR**
Available Resources	DR1_AR	DR2_AR	...	DRn_AR	**DR_AR**
Resources	DR1_R	DR2_R	...	DRn_R	**DR_R**
Available Estimator Time	DR1_ET_AT	DR2_ET_AT	...	DRn_ET_AT	**DR_ET_AT**
Estimator Time	DR1_ET	DR2_ET	...	DRn_ET	**DR_ET**
Available Design Engineer Time	DR1_DT_AT	DR2_DT_AT	...	DRn_DT_AT	**DR_DT_AT**
Design Engineer Time	DR1_DT	DR2_DT	...	DRn_DT	**DR_DT**
Available Maintenance Engineer Time	DR1_MT_AT	DR2_MT_AT	...	DRn_MT_AT	**DR_MT_AT**
Maintenance Engineer Time	DR1_MT	DR2_MT	...	DRn_MT	**DR_MT**
District Proximity Factor	DR1_PX	DR2_PX	...	DRn_PX	**DR_PX**

Caltrans: District Level

	1	2	...	p	
Resource Description	DR1_R1	DR1_R2	...	DR1_Rp	**DR1_R**
Resource Availability	DR1_R1_AV	DR1_R2_AV	...	DR1_Rp_AV	**DR1_AV**
Available Resources	DR1_R1_AR	DR1_R2_AR	...	DR1_Rp_AR	**DR1_AR**
Estimator Time					**DR1_ET**
Estimator Availability					**DR1_ET_AV**
Available Estimator Time					**DR1_ET_AT**
Design Engineer Time					**DR1_DT**
Design Engineer Availability					**DR1_DT_AV**
Available Design Engineer Time					**DR1_DT_AT**
Maintenance Engineer Time					**DR1_MT**
Maintenance Engineer Availability					**DR1_MT_AV**
Available Maintenance Engineer Time					**DR1_MT_AT**

System Funding Level

Governing Body	State	Federal	
Caltrans Emergency Fund	CT_EF	-	
CESA Declaration	SC_EF	-	
FHWA Emergency Fund	-	FD_EF	
System Funding	SC_F	FD_F	**C_F**

Table 4: BRDF capacity side parameters and organization.

	Demand	Capacity	Unit
Estimation Time	D_ET	C_ET	hours
Estimation Resources	D_ER	C_ER	items
Estimation Cost	D_EC	C_EC	dollars
Design Time	D_DT	C_DT	hours
Repair Method	D_RM	C_CA	method
Repair Time	D_RT	C_AV	hours
Repair Cost	D_RC	C_F	dollars
Repair Resources	D_RR	C_R	items
Maintenance Time	D_MT	C_MT	hours
Maintenance Resources	D_MR	C_MR	items
Total	**D**	**C**	

Table 5: BRDF demand-capacity mapping and dimensional fidelity.

AC	Available Capability
AD	Applicable Damage States
AM	Applicable Repair Method
AR	Available Resources
AT	Available Time
AV	Availability
B	Bridge
C	Capacity
CA	Capability
CD	Capability Description
CD	Condition
CF	Bridge Configuration
CO	Contractor
CN	Contractor Name
CS	Cost
CT	Caltrans
CV	Capability Availability
D	Demand
DC	Description
DE	Design Engineer Time
DR	Caltrans District
DS	Damage State
DV	Design Variables
EC	Estimation Cost
EE	Effort Estimation
EF	Emergency Fund
ER	Estimation Resources
ET	Estimator Time
EV	Estimation Variables
F	Funding
FD	Federal
L	Location
LC	Local
LR	Available Local Resources
LT	Available Local Time
MR	Maintenance Resources
MT	Maintance Time
MV	Maintenance Variables
PG	Performance Group
PR	Priority
PX	Proximity
R	Resources
RA	Resource Availability
RC	Repair Cost
RD	Resource Description
RL	Resource Location
RM	Resource Method
RR	Repair Resource
RT	Repair Time
RV	Repair Variable
SA	Supplemental Available
SC	State of California
ST	Design Time
T	Time

Table 6: The BRDF parameter legend.

Name	Variable	Known	Knowable	Proactive	Interactive	Reactive
Bridge Priority	SE	1	1		1	1
Bridge Names/Contents	B	1	1	1		
Bridge Configuration	CF	1	1	1		
Bridge Location	LO	1	1	1		
Bridge Condition	CD	0	1			1
Performance Groups	PG	0	1	1		
Damage States	AD	0	1	1		
Current Damage State	DS	0	1		1	
Repair Method	RM	0	1	1		
Repair Cost	RC	0	1	1		
Repair Time	RT	0	1	1		
Repair Resources	RR	0	1	1		
Resource Description	R	0	1	1		
Resource Availability	R_AV	0	1		1	
Available Resources	R_AR	0	1		1	
Estimator Time	ET	0	1		1	
Estimator Availability	ET_AV	0	1		1	
Available Estimator Time	ET_AT	0	1		1	
Design Engineer Time	DE	0	1		1	
Design Engineer Availability	DE_AV	0	1		1	
Available Design Engineer Time	DE_AT	0	1		1	
Maintenance Engineer Time	ME	0	1		1	
Maintenance Engineer Availability	ME_AV	0	1		1	
Available Maintenance Engineer Time	ME_AT	0	1		1	
Local Available Resources	LC_R	0	1		1	
Local Avail. Estimator Time	LC_ET	0	1		1	
Local Avail Design Engineer Time	LC_DE	0	1		1	
Local Avail Maintenance Eng. Time	LC_ME	0	1		1	
Supplemental Available Resources	SA_R	0	1		1	
Sup. Avail. Estimator Time	SA_ET	0	1		1	
Sup. Avail. Design Engineer Time	SA_DE	0	1		1	
Sup. Avail. Maint. Engineer Time	SA_ME	0	1		1	
Estimation Time	ET	0	1	1		
Estimation Resources	ER	0	1	1		
Estimation Cost	EC	0	1	1		
Caltrans Local Resources	LR	1	1	1		
Caltrans Local Time	LT	1	1	1		
Caltrans Available Resources	AR	0	0		1	
Caltrans Available Time	AT	0	0		1	
Contractor Name	CO	1	1	1		
Contractor Capability	CO_CA	1	1	1		
Contractor Capability Availability	CO_CV					
Contractor Resources	CO_R	1	1	1		
Contractor Resource Availability	CO_RA					
Contractor Location	L	1	1	1		
Contractor Availability	AV	1	1		1	
Caltrans Emergency Fund	CT_EF	0	1		1	1
CESA Declaration	SC_EF	0	1		1	1
FHWA Emergency Fund	FD_EF	0	1		1	1

Table 7: Informational availability and knowability of BRDF parameters.

Chapter 4

Model Validation

In order to highlight the benefits of applying the BRDF model to bridge repair decisions, the BRDF model and methodology were validated in a hypothetical bridge system under simulated conditions. For validation purposes, the BRDF was used to determine the optimum repair decision-making approach between two choices: instantaneous or complete-information decision-making. Instantaneous decision-making is the process of selecting and conducting repair actions in light of incomplete information about the current state of the entire system and its parts. Conversely, complete-information decision-making is the process of selecting and conducting repair actions in light of complete information about the current state of the entire system and its parts. Currently, Caltrans employs complete information decision-making for post-earthquake repair decisions.

With the selection of a decision-making approach as its goal, the BRDF model validation served two distinct purposes. First, it allowed the verification of the BRDF methodology and model, highlighting the advantages and limitations. Second, the model validation provided insight into how current repair decision practice can be improved through the incorporation of BRDF principles.

4.1. Methodology

The BRDF was designed in order to allow the input of information about an entire system of bridges, instead of solely focusing on individual bridges within the system. Therefore, a system of five identical bridges was created for the model validation. The validation bridges were identical in order to simplify the analysis while focusing on the results of the BRDF methodology instead of bridge particularities. The properties of these bridges needed to reflect the design and construction philosophies of typical bridges within the California bridge inventory. The PEER Benchmark Bridge was selected as the ideal candidate this type of simulation.

4.1.1. PEER Benchmark Bridge

The validation of the BRDF required the use of a standard bridge with well known properties, including construction type, geometry, damage states, performance groups, and repair methodology. The PEER Benchmark Bridge, as created by PEER researchers and studied by Mackie and Wong (2007), contained reliable, probabilistic data for these properties, and reflected a standard highway bridge in the state of California (Mackie et al. 2007).

The benchmark bridge is a continuous, five-span, straight, post-tensioned, cast-in-place, box girder bridge matching Bridge Type 1/11 (Figure 7) developed by Ketchum et al. and based on the Caltrans Design Criteria "ordinary bridge" specification (Ketchum et al. 2004). Mackie et al. evaluated the fragility of the benchmark bridge, generating demand, damage, loss, and repair models. These models include benchmark-bridge-specific probabilistic data for damage state thresholds, downtime estimates, repair production rates, unit costs, and repair quantities.

4.1.2. Repair Costs

For model validation, the benchmark bridge data was incorporated into a repair cost model, which calculated the cost of each damage state for each performance group. This was done by isolating the repair action required for each damage state and multiplying the respective mean repair quantities by their unit cost, resulting in the mean cost and standard deviation of a single repair action. The mean and standard deviation repair action costs can subsequently be summed respectively for each damage state, resulting in a total repair cost for a given performance group in a given damage state.

4.1.3. Damage Scenarios

The overall condition of the individual bridges within the system is based on the "minor damage scenario," which was established by Mackie et al. in order to refine the benchmark unit cost and repair time models (Mackie et al. 2007). Verified and calibrated by Caltrans engineers, the minor damage scenario is not based on a particular ground motion, but instead accurately reflects the expected damage that the benchmark bridge would exhibit in a design-basis earthquake, which is smaller in magnitude than maximum earthquake the bridge was designed to withstand (Figure 8).

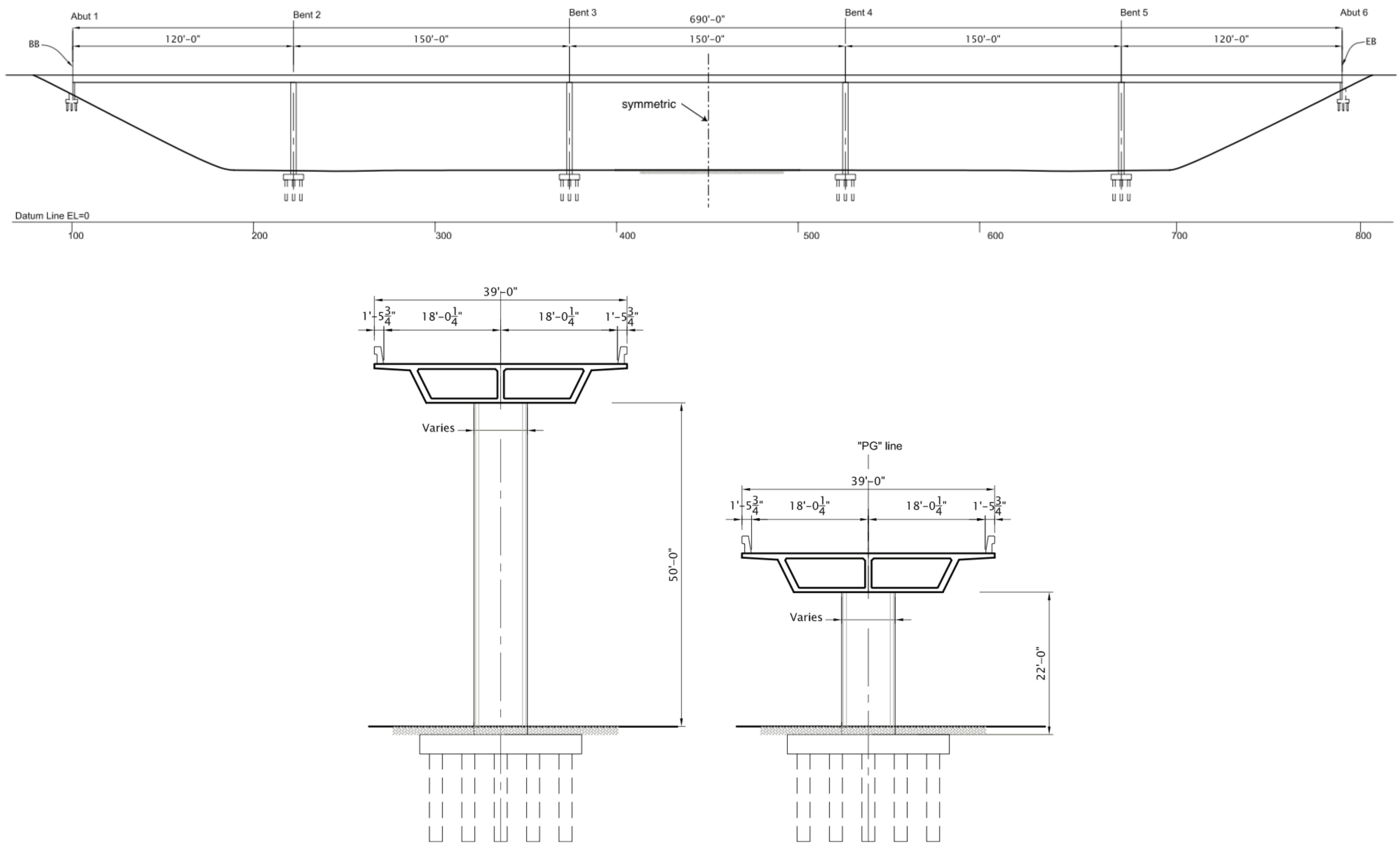

Figure 7: Drawings of the the PEER Benchmark Bridge based on Caltrans Type 1/11 bridges (Ketchum et al. 2004; Mackie et al. 2007).

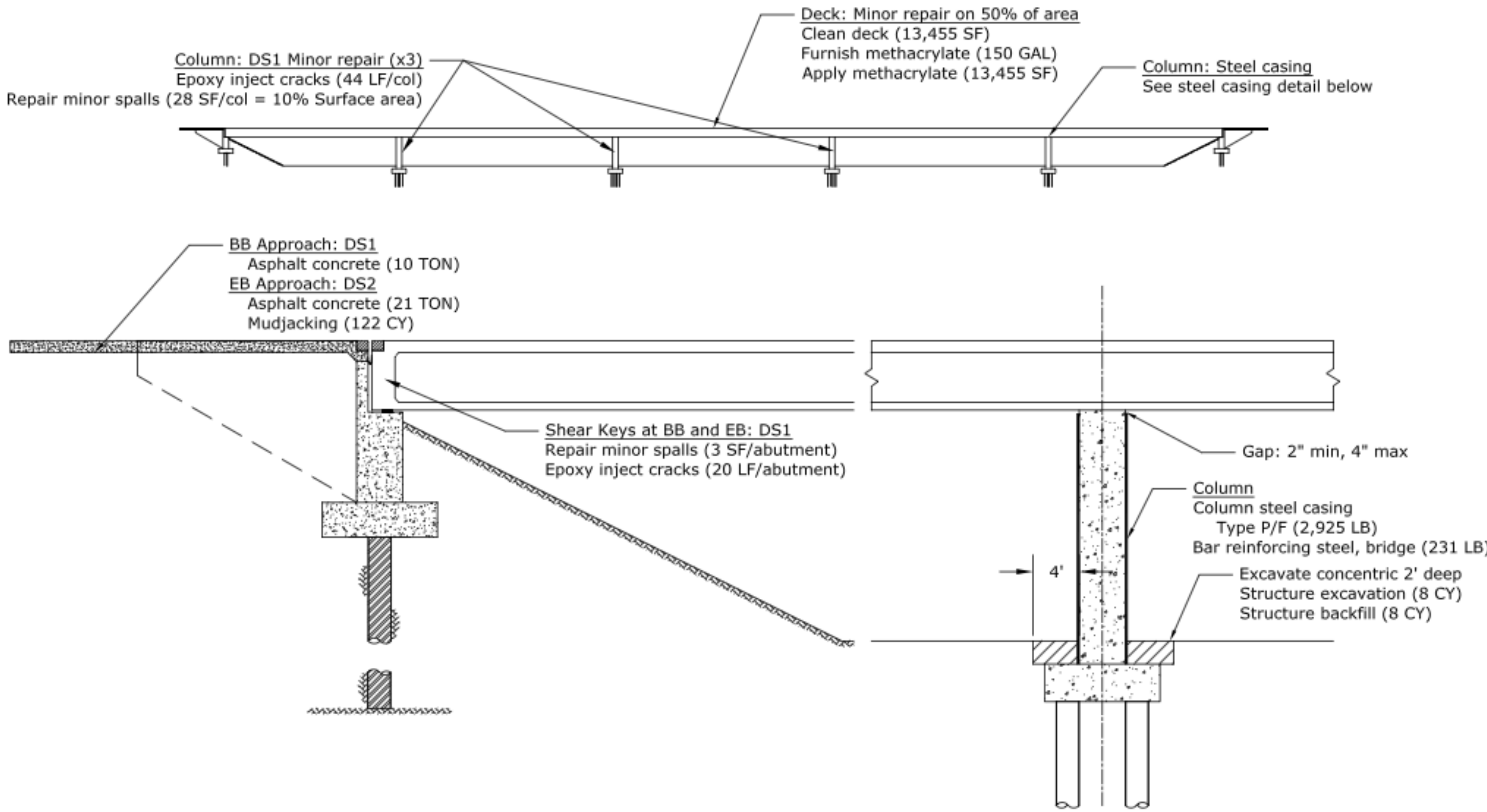

Figure 8: Moderately damaged PEER testbed bridge (minor damage scenario) (Mackie et al. 2007).

The incorporation of the minor damage scenario into the model validation required that the performance groups of each of the five bridges be placed within specific damage states that accounted for the correlation effects of earthquake damage between bridge elements. Therefore, two types of simulation thresholds were established for the level of damage for any particular performance group in the benchmark bridges.

First, “damage level” thresholds indicate the upper and lower bounds of damage for a given performance group. For example, moderately damaged bridges may not have any “maximum column displacement” performance groups in damage states above DS2.

Second, “performance group set” thresholds indicate the amount of performance groups within a similar set (such as the all of the maximum column displacement performance groups) that can exist within the damage level threshold. For example, the “performance group set” threshold requires that between 2 and 4 of the maximum column displacement performance groups are in DS1.

Combined, these simulation thresholds place each of the benchmark bridges in a realistic, well documented, and moderate damage level.

System Costs

Once the performance groups within each bridge are assigned damage states, the BRDF calculates each corresponding repair cost. These costs are then summed for the entire bridge (presented in Table 8 at the end of this chapter).

Once the bridge repair costs are calculated, mobilization (10% of bridge repair costs) and contingency (20% of repair costs) costs are added to the repair costs in order to get a total bridge repair cost as per Caltrans estimating standards (Caltrans 2005). These costs are also summed across the system, revealing a total system repair cost.

The BRDF methodology allows for unique system assessment beyond bridge-level data, revealing repair cost for similar performance groups across the system. Additionally, the mobilization and contingency costs are aggregated over the entire system, providing an additional evaluation parameter. It should be noted that while a 10% mobilization cost is reasonable for bridge repair work, the 20% contingency costs present a significant increase in overall repair cost, particularly when aggregated over the entire system. Caltrans includes this contingency factor to all estimates to cover the costs of unforeseen design changes and the uncertainty of early estimations of quantity (Caltrans 2005).

4.1.4. System Time

Beyond cost, time measurements across the bridge system are vital parameters in post-earthquake repair decision-making. Repair time for each bridge within the system is identical, since all of the bridges are placed in the minor damage scenario. As calculated by Mackie et al., the "minor damage scenario" requires 72 days to complete, limited by the longest repair sequence (column repair time).

Repair time is compounded by two additional parameters: inspection time and contingency time. Inspection time represents the average time required to conduct a complete post-earthquake inspection of a moderately damaged bridge, taking into account initial and follow-up inspection. Within the validation model, inspection times were randomly generated by the BRDF to be between 1 and 3 days, based on actual inspection times for damaged bridges after the Northridge earthquake (Kaslon 2000). Contingency time functions as a buffer for mobilization of inspection teams as well as other time-dependent actions. Since the validation model bridge system only contains five bridges, contingency time was assumed to be two days. Contingency time is otherwise highly correlated to the size of the bridge system.

As opposed to system costs, system times cannot be summed across the entire system since repair work can take place concurrently. Instead, the BRDF provides a minimum system repair time, based on the maximum overall repair time of any bridge within the system combined with the maximum inspection and contingency times.

4.2. Findings

Mean total repair costs for a moderately damaged bridge was approximately $240,000, but varied up to 0.3% between different bridges within the system. This variation was due to the simulated performance group damage states and overall bridge geometry. The overall mean system repair cost was approximately $1.2 million, including mobilization and contingency costs.

Time calculations resulted in a minimum system repair time of 72 days, and a total delay time of 5 days due to mobilization and inspection time. Therefore, if the date of loss was assumed to be January 1st, 2010, the completion of repairs would occur on April 20th, 2010.

4.3. Analysis

The purpose of the model validation was to 1) verify the BRDF model and methodology and 2) determine the ideal decision-making approach for the bridge system under the simulated conditions.

The first purpose was achieved by modeling a hypothetical but realistic 5-bridge system, including performance group damage states, repair costs, and repair times. Analysis was conducted the performance group, damage-state, and system levels, resulting in a holistic assessment of system condition while applying the logic and structure of the BRDF methodology.

The second purpose was achieved by revealing the maximum amount of benefit that can be derived from adopting an instantaneous decision-making (IDM) approach versus a complete-information decision-making (CDM) approach.

The CDM approach requires decision-makers to delay until condition information is known for all of the bridges within the system prior to initiating repair action. The maximum delay time (worst-case) is calculated by adding the maximum inspection time (3 days) to the contingency time (2 days). This results in a total delay time of 5 days for the validation model.

The IDM approach would alternatively allow decision-makers to begin the repair process without having complete information about the condition of the other bridges within the system. This therefore minimizes the total delay time of the system, resulting in a minimum savings of 5 days – a conservative estimate of the minimum amount of time required to attain complete information about the system condition.

The potential time-savings of adopting the IDM approach is therefore only 7% of the total repair time. This represents an insignificant benefit that comes at the cost of potential inefficiency due to incomplete understanding of system conditions and improper allocation of system resources.

For comparison, the ratio of delay to repair time for the Northridge earthquake was also calculated based on Caltrans experience (Kaslon 2000). The Northridge earthquake response represented the most recent extensive post-earthquake response within the state of California, involving local, state, and federal workers.

Therefore, the Northridge earthquake represents an ideal benchmark for the delay to repair ratio (DRR).

After the Northridge earthquake, approximately 1500 bridges were inspected over three weeks of continuous inspection work. Total repair work took 229 days, which, when adjusted for non-moderate repair work resulted in 139 days of repair work for moderately damaged bridges. Therefore, the DRR for the Northridge earthquake was approximately 15%. This DRR was used as the threshold for switching to IDM, since gains of 15% or greater are likely to have significant financial and chronological benefits.

Since the validation model DRR was less than half of the threshold DRR, it was determined that CDM was the proper approach to implement for the given system. It is important to note that it is possible to increase the DRR, and therefore the benefit of adopting the CDM, through two distinct methods. First, the inspection and mobilization delay can be increased, which does not yield any considerable improvements over the current approach. Second, repair time can be decreased. While currently implemented design and construction technology does not produce significant reductions in repair time, new design and construction methods, such as pre-cast bridge elements, offer reductions in repair time that will substantially increase DRRs.

The promise of future technological advancement serves to further highlight the benefit of adopting the BRDF methodology, which results in performance-based decision-making approaches that greatly improves upon current methods.

Event: BRDF Model Validation

System Properties		**Parameters**		**Outputs**		**Northridge**	
Date of Loss	1/1/10	Minimum Buffer	2	Possible Date Savings	5	Number of Bridges	1500
Number of Bridges	5	Maximum Buffer	10	Decision Type	**Complete Information**	Total Inspection Time	21 days
		Contingency Buffer	2	Min Total Repair Tim	77	Inspection Rate	71 bridges/day
		Max Delay Time	3	Finish Date	4/20/10	Repair Work Days	229 days
		Min Delay Time	1			Non-Moderate Repair Work Buf	90 days
		Total Delay	5			Moderate Repair	139 days
		Delay/Repair Ratio	7%			$DRR_{northridge}$	**15%**
		DRR Threshold	15%				

The System	**Bridges** 1	2	3	4	5	**Allow Recalcs**
Priority	3	1	3	3	2	no
Inspection Delay Estimate	3	3	2	1	3	
Repair Time Estimate	72	72	72	72	72	

		Bridge 1		Bridge 2		Bridge 3		Bridge 4		Bridge 5		System	Allow Recalcs
Performance Group	**Description**	**State**	**Mean Cost**	**State**	**Mean Cost**	**State**	**Mean Cost**	**State**	**Mean Cost**	**State**	**Mean Cost**	**Mean Cost**	no
PG1	Column 1 max	1	$ 17,753.80	1	$ 17,753.80	1	$ 17,753.80	0	$ -	1	$ 17,753.80	$ 71,015.22	
PG2	Column 2 max	0	$ -	0	$ -	1	$ 17,753.80	1	$ 17,753.80	1	$ 17,753.80	$ 53,261.41	
PG3	Column 3 max	1	$ 17,753.80	1	$ 17,753.80	1	$ 17,753.80	1	$ 17,753.80	0	$ -	$ 71,015.22	
PG4	Column 4 max	1	$ 17,753.80	1	$ 17,753.80	0	$ -	1	$ 17,753.80	1	$ 17,753.80	$ 71,015.22	
PG5	Column 1 residual	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG6	Column 2 residual	0	$ -	0	$ -	0	$ -	0	$ -	1	$ 29,972.32	$ 29,972.32	
PG7	Column 3 residual	1	$ 29,972.32	1	$ 29,972.32	1	$ 29,972.32	1	$ 29,972.32	0	$ -	$ 119,889.26	
PG8	Column 4 residual	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG9	BB Abutment	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG10	EB Abutment	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG11	BB Bearing	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG12	EB Bearing	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG13	BB Shear Key	1	$ 5,200.00	1	$ 5,200.00	1	$ 5,200.00	1	$ 5,200.00	1	$ 5,200.00	$ 26,000.00	
PG14	EB Shear Key	1	$ 5,200.00	1	$ 5,200.00	1	$ 5,200.00	1	$ 5,200.00	1	$ 5,200.00	$ 26,000.00	
PG15	BB Approach	1	$ 2,756.97	2	$ 51,958.39	2	$ 51,958.39	2	$ 51,958.39	1	$ 2,756.97	$ 161,389.13	
PG16	EB Approach	2	$ 51,958.39	1	$ 2,756.97	1	$ 2,756.97	1	$ 2,756.97	2	$ 51,958.39	$ 112,187.71	
PG17	Span 1	3	$ 6,643.00	3	$ 6,643.00	3	$ 6,643.00	2	$ 4,433.00	3	$ 6,643.00	$ 31,005.00	
PG18	Span 2	2	$ 5,541.25	2	$ 5,541.25	3	$ 8,303.75	3	$ 8,303.75	3	$ 8,303.75	$ 35,993.75	
PG19	Span 3	3	$ 8,303.75	3	$ 8,303.75	2	$ 5,541.25	3	$ 8,303.75	2	$ 5,541.25	$ 35,993.75	
PG20	Span 4	3	$ 8,303.75	3	$ 8,303.75	3	$ 8,303.75	3	$ 8,303.75	3	$ 8,303.75	$ 41,518.75	
PG21	Span 5	3	$ 6,643.00	3	$ 6,643.00	3	$ 6,643.00	3	$ 6,643.00	3	$ 6,643.00	$ 33,215.00	
PG22	BB Abutment Foundation	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG23	EB Abutment Foundation	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG24	Column 1 Foundation	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG25	Column 2 Foundation	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG26	Column 3 Foundation	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
PG27	Column 4 Foundation	0	$ -	0	$ -	0	$ -	0	$ -	0	$ -	$ -	
Subtotal			$ 183,783.85		$ 183,783.85		$ 183,783.85		$ 184,336.35		$ 183,783.85	**$ 919,471.74**	
Mobilization			$ 18,378.38		$ 18,378.38		$ 18,378.38		$ 18,433.63		$ 18,378.38	**$ 91,947.17**	
Contingency			$ 36,756.77		$ 36,756.77		$ 36,756.77		$ 36,867.27		$ 36,756.77	**$ 183,894.35**	
Total			$ 238,919.00		$ 238,919.00		$ 238,919.00		$ 239,637.25		$ 238,919.00	**$ 1,195,313.26**	

Table 8: BRDF model validation spreadsheet.

Chapter 5

Conclusion

The post-earthquake repair of highway bridges is a fundamental and inevitable part of the lifecycle of engineered systems in areas of seismic susceptibility. This inevitability, combined with the sheer size of the system and number of stakeholders, requires that a reliable, efficient, and holistic methodology be used to restore full functionality of transportation systems in the aftermath of an earthquake. The BRDF addresses these requirements, improving upon current practices while creating a flexible foundation for future research, understanding, and improvement of repair decisions.

5.1. Summary of Work

The Bridge Repair Decision Framework (BRDF) consists of two complementary parts that together form an aid for post-earthquake bridge repair decision-making. First, the BRDF model provides the organizational framework for all significant elements of repair decisions, such as infrastructure inventories and bridge conditions. Second, the BRDF methodology provides the logical framework for all significant elements of repair decisions, detailing the relationships between the individual elements in order to make informed repair decisions.

To accomplish this, the BRDF incorporates two distinct tools that, when applied to repair decisions, provide insight and structure for the understanding of complex processes. The Pacific Earthquake Research Center's Performance-Based Earthquake Engineering (PEER PBEE) methodology provides a rigorous approach to the probabilistic analysis and evaluation of highway bridges. The BRDF expands upon the PBEE methodology to include multiple repair methods as well as estimation and inspection parameters, representing vital elements of bridge repair decisions.

Research from the Center for Catastrophic Risk Management (CCRM) provided the BRDF with proactive, interactive, and reactive approaches to chronologically classify repair decision elements and improve user understanding of informational availability within a transportation system.

These PEER and CCRM approaches were subsequently used for two purposes. First, current repair decision-making processes and the overall Caltrans post-earthquake response procedure were researched, examined, and analyzed in order to reveal potential areas for improvement. These areas included an increased focus on informational completeness, long-term strategy, and organizational learning.

Second, these tools were used to create the BRDF, a new systematic approach and model to repair decision-making that addresses each of these areas for improvement. In order to do this, the BRDF approach examines repair decisions through a traditional design inequality between demand and capacity, uniquely applying an established engineering approach to the multi-disciplinary field of post-earthquake decision-making. The BRDF divides decision inputs between the demand and capacity sides of the demand-capacity inequality, with demand inputs describing the loads on the system due to the earthquake, and capacity inputs describing the system's ability to cope with the given demands with quantifiable capacities and political/bureaucratic constraints.

While the majority of decision inputs after an earthquake are given and reflect system demand and capacity state at an instance in time (bridge damage level, contractor availability, bridge priority), other decision inputs function as the unknowns of the repair decision inequality (applicable repair methods, system downtime, overall repair costs). Using the given inputs, the inequality can be "solved" for the unknowns in light of stakeholder values. Due to the variety of stakeholders (and therefore respective stakeholder values) that influence and participate in repair decisions, the BRDF employs a performance-based approach that allows these stakeholders to choose between a collection of relevant performance levels based on meaningful metrics. For example, engineers can evaluate alternatives based on structural performance (strains), politicians and policy-makers based on socioeconomic performance (costs), and the public based on personal impacts (downtime).

Furthermore, the BRDF methodology takes into account the probabilistic nature of repair decision inputs, providing measures of risk associated with decision alternatives. As a result, decision outputs are not only risk-informed, but also technology-neutral, since alternatives are selected based on performance metrics instead of prescriptive technologies. Technology-neutral decision-making also provides an experience-driven approach to highway bridge repair, since decision outcomes are independent of current and available knowledge at any one point in time.

The BRDF methodology is applied to an organizational model that houses all of the repair decision inputs, ensuring dimensional fidelity and detailing the chronology of informational availability. The decision outputs of the BRDF model are twofold. First, the BRDF provides stakeholders with a technical, financial, and probabilistic understanding at the performance group, bridge, and system levels. Second, this understanding allows for the selection of appropriate repair methods for damaged bridges within the system given stakeholder values and system constraints.

The BRDF model and methodology were validated through a case study that sought to compare two distinct repair decision-making processes: instantaneous decision-making (IDM) and complete-information decision-making (CDM). This validation study involved the creation of a hypothetical system consisting of 5 identical bridges based on the PEER benchmark bridge. The performance groups of each bridge were systematically placed into specific damage states, resulting in five moderately damaged bridges. The BRDF model, using reliable Caltrans data, calculated repair costs and times for performance groups, bridges, and the system as a whole. Using this system, IDM was compared to CDM in terms of the ratio of time-savings to overall repair time. As a result, the time-savings from the application of IDM was insignificant relative to the advantages of applying CDM to post-earthquake repairs.

5.2. Contributions to Knowledge

The BRDF model and methodology represent an entirely new approach to post-earthquake highway bridge repair decision-making, providing several unique advantages over current practices due to its performance-based risk-informed foundation, holistic approach, and experience-driven outcomes. Table 3 summarizes these advantages and compares a variety of attributes of the BRDF to current Caltrans practices.

While the BRDF provides many distinct advantages over the current practices (B1 through B5 in Table 3), the implementation of the BRDF does present additional challenges over continuing current practices (B6-B8 in Table 3). Fortunately, these challenges, in addition to the inherent modifications required to implement a new methodology and model to an established organization, can be outweighed by the potential increases in efficiency, productivity, and reliability that the BRDF provides for post-earthquake repair decisions.

	Current Practice		BRDF	
Foundation for repair decisions	A1	Available alternatives and judgment of experienced engineers	B1	Quantified stakeholder-specific metrics based on their respective values
Available repair methods for given damage state	A2	Single, “trusted”, and prescriptive repair method	B2	Any repair method that meets stakeholder probabilistic performance criteria
Treatment of risk	A3	Prescriptive alternatives have an assumed and accepted low probability of failure	B3	Quantified risk for hazard, performance, and system uncertainty
Understanding of System Condition	A4	Condition information for individual bridges	B4	Condition and uncertainty understanding at the system, bridge, and Performance Group levels
Nomenclature	A5	No unified nomenclature to describe system condition or repair decision elements	B5	Unified, holistic, and consistent nomenclature for the elements of the repair decision process
Organization of Information	A6	Existing infrastructure management systems	B6	New database structure based on the PEER Performance-Based Earthquake Engineering Methodology
Long-term repair strategy	A7	As-built drawings document used repair methods	B7	Catalogued repair methods with associated data (cost, time, etc.)
Organizational requirements	A8	Periodic employee training	B8	Employee retraining for shift in design philosophy; increased cooperation between divisions

Table 9: Comparison of current practice to the BRDF methodology (Section 3.3.3 describes the BRDF model attributes in depth).

It should be noted that although the BRDF is based on the author's work with Caltrans, the BRDF model and methodology can also be applied to other departments of transportation that are faced with similar post-earthquake decision-making opportunities, at the state (e.g., Oregon, Washington) and local level.

5.3. Future work

The BRDF establishes a framework and methodology for the evaluation, analysis, and improvement of post-earthquake repair methods. This framework and methodology form a broad foundation for further research work in the following areas.

5.3.1. Repair Method Databases

The BRDF highlights the benefits of using and maintaining repair method databases for post-earthquake repair decisions. However, these databases have not yet been created despite Caltrans' interest in creating them. The creation of the repair database is time-sensitive, as employee turnover and large periods of time between earthquakes result in the loss of data, first-hand experience, and overall information about particular repairs and repair work.

Repair method databases should, as per the established BRDF and PEER PBEE methodologies, contain information regarding each specific repair action, including:

1. Repair quantities, costs, and times
2. Probabilities of effectiveness in restoring bridge capacity
3. Aleatory and epistemic uncertainties within the system

Repair impact data, containing the physical, environmental, and societal effects that a particular repair method may have on the surrounding area, can also be gathered and included in the repair method database.

These repair method databases should be integrated with past research work, such as the UCSD Performance Evaluation Database created by Hose et al. (1999). The Performance Evaluation Database will provide the visual background for linking physical damage to specific repair methods. Previous work at UC Berkeley has also mapped the damage levels described in the Performance Evaluation Database to damage states within the BRDF and PEER PBEE (Gordin et al. 2007).

5.3.2. Instantaneous Decision-Making

As revealed in the BRDF model validation, current technology limits the benefits of applying instantaneous decision-making principles to repair decisions. However, future improvements in repair technology will greatly increase the benefits of applying this approach. It is therefore important to understand not only the probabilistic nature of decision inputs, but also the nature of instantaneous decision-making and its application to the post-earthquake response process.

Instantaneous decision-making is defined as the selection of an alternative in light of imperfect information. Within the context of highway bridge repair, instantaneous decision-making may be applied to the initiation of repair work on one or more bridges without condition information about the other bridges within the given system. Repair work on a given bridge can be deferred or initiated based on triggers that reflect particular system parameters. Future research should be conducted into the determination of which parameters should be taken into account as well as computation of these triggers. For example, the model validation discussed above used time units as triggers (delay time compared to repair time). Future research can be made into using cost as a trigger unit, comparing total repair cost to the societal cost of additional delay for complete bridge condition information.

Instantaneous decision-making requires that bridges be systematically prioritized, either through integration with Caltrans' current ShakeCast system, or through an entirely new prioritization methodology that takes into account vital parameters such as average daily traffic, availability of alternate routes, and susceptibility to aftershock damage.

To aid in future research, parallels to instantaneous decision-making can be drawn to other research fields, such as the inventory replenishment problem that the retail industry faces.

5.3.3. Information Delivery Systems

Large database systems such as the BRDF model are susceptible to information overload problems for users. For example, the current ShakeCast system flooded Caltrans engineers with system status data to the extent that they physically turned off their pagers. Therefore, future research and database systems should be created with relevant informational delivery systems and tiered information packages that can be throttled in the aftermath of significant data collection.

Furthermore, the continual implementation of new communication methods and technologies serves to further complicate the information overload problem. The effects of these new methods and technologies on post-earthquake response have not been measured with significant accuracy due to the 15+ year period of time since the last major California earthquake. Isolated disaster training and simulations such as the Great California Shake Out and Golden Guardian programs have provided insights into how modern technology will affect response (CalEMA 2008), but research is needed into how post-earthquake decision-making methodologies such as the BRDF will be used under these conditions.

5.3.4. Additional Parameters

The current implementation of the BRDF accounts for earthquakes and their subsequent damage as the “load” placed on the system. However, other probabilistic events that may or may not be related to the earthquake can add additional load to the system. For example, the combination of earthquake and fire damage, or earthquake and vehicular damage, may require additional types of repair methods or response procedures for which the BRDF does not currently account. These combined events require accounting of possible failure modes and the creation of probabilistic stakeholder thresholds that distinguish the relevant failure modes. The analysis of combined events will also allow for the extension of the BRDF methodology to bridges exhibiting major damage, which are not currently addressed by the BRDF.

Furthermore, additional decision parameters should be examined and implemented into future versions of BRDF-based decision-making methodologies. For example, impact to the surrounding area is not currently a decision parameter, but could be an important variable in the selection of repair method. This impact may be characterized by effects on the surrounding transportation system, environment, or quality of life.

Greater levels of detail are also required for the socioeconomic inputs within the BRDF. For example, additional data is needed to analyze and quantify the effects of induced demands (public pressure) on political figures to not only appear productive in the restoration of system function, but also to assign responsibility and blame for inefficiencies or lapses in system performance. The incorporation of these additional parameters requires not only their characterization, but also a thorough understanding of their relative priority. Decision-making systems such as Choosing by Advantages (Section 2.2.3) can provide a beneficial structure for this type of analysis in the future.

These analyses and their effects represent significant and vital research challenges. However, the benefits of this future research work will lead to the advancement of post-earthquake decision-making, and keep society moving ever forward.

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