Transportation Infrastructure System Resilience Through Performance-Based Decision-Making in Post-Earthquake Highway Bridge Repair

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SUMMARY:
The Bridge Repair Decision Framework (BRDF), using a systematic, performance-based, and risk-informed decision-making methodology, provides decision-makers with a holistic understanding of their transportation network post-earthquake condition on a microscopic, as well as macroscopic level. The BRDF is a combination of data structures, decision-making processes, and logistical tools. It provides decision-makers in transportation department with the relevant information needed to make individual and system-wide repair decisions. In its most fundamental form, the BRDF presents repair decisions using a traditional engineering demand-capacity inequality. With the identification, collection and organization of the relevant post-earthquake information using the BRDF, repair decisions can be made in light of time, cost, repair resource availability and demand, and other constraints, to contribute to the post-earthquake resilience of the transportation infrastructure systems.

Keywords: Resilience, Performance-Based Decision Making, Highway Bridge Repair, Decision Framework

1. INTRODUCTION

In the short- to long-term period 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 and with limited available information. The Bridge Repair Decision Framework (BRDF) accounts for all of the participating components of bridge repair decisions through flexible logic and an organized structure, allowing clear identification and representation for each component as well as their relationship to the other components with the framework (Gordin, 2010). The framework functions as a specialized infrastructure maintenance database, containing various data structures to house event-specific inputs, computations, logic, and outputs. In its current state, the BRDF does not support a graphical user interface, but instead operates within a series of cross-referenced spreadsheets.

2. FRAMEWORK ORIGIN

The BRDF is based on the Pacific Earthquake Engineering Research (PEER) Center's performance-based earthquake engineering (PBEE) framework. The 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.

Within the PBEE framework (Figure 1), a bridge is treated as a collection of components divided into correlated performance groups (PGs) (Mackie et al. 2007). Each PG is linked to a collection of damage states (DSs), which indicate the possible conditions of a given PG (Mackie and Wong, 2007). 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, the BRDF defines a higher-level (global) organizational unit as a system, consisting of individual bridges grouped and evaluated together due to a shared descriptive parameter such as location or level of damage.

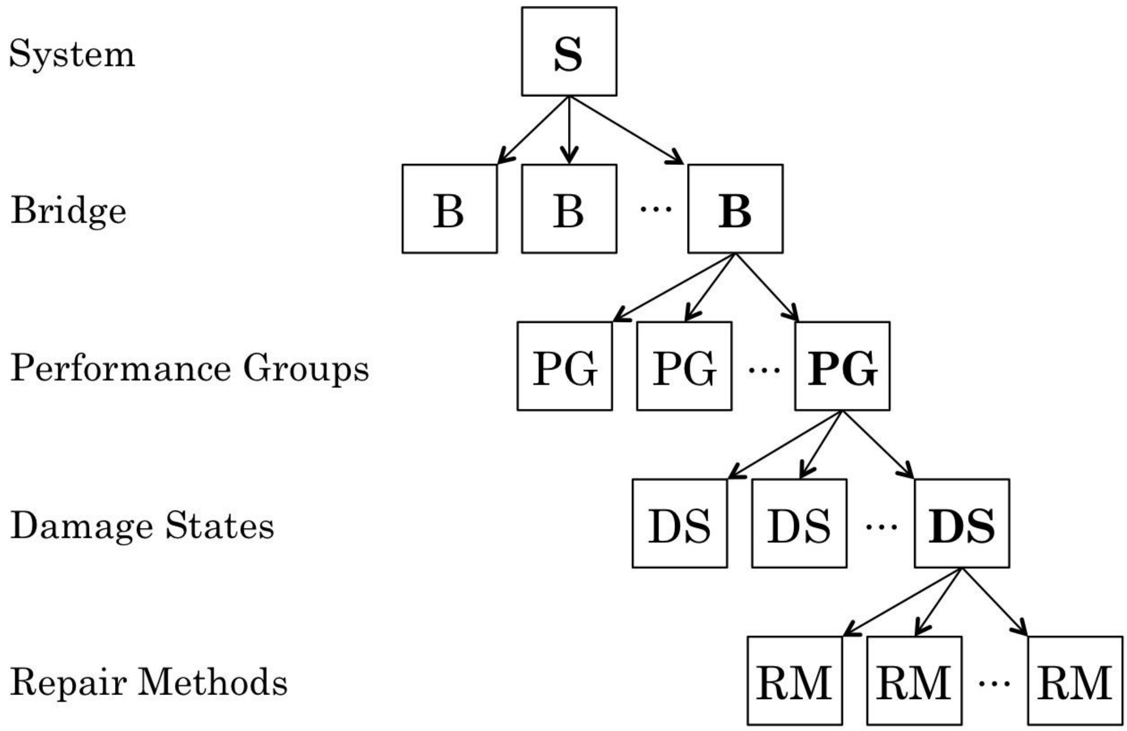

Figure 1. Example branch of the PEER PBEE Framework Structure after Mackie et al. 2007

2.1. Framework Structure

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 2**).** While some BRDF parameters are known, such as those that directly represent the results of an applied load (earthquake) e.g. column damage, other parameters are unknown or variable, since they represent the indirect consequences of the earthquake and the ability of the transportation system maintenance organization to respond to meet the system demand with sufficient repair capacity. Failure is therefore defined as system demand exceeding system capacity in terms of the repair effort.

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 (performance group) as well as a macroscopic (overall system) level. With this approach, the BRDF demand-capacity inequality can be "solved" for the unknown system capacity terms given the known terms on both the capacity and demand sides. The known inequality terms are called decision inputs, and the unknown terms are called decision outputs.

3. DEMAND 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. For clarity, individual DIs are organized into Demand DIs and Capacity DIs.

3.1. Performance Group Level

The most fundamental Demand DIs are found at the performance group (PG) level (Figure 3), which contains data about each of the damage states (DSs) applicable for a given performance group. 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. Within the BRDF, damage states are linked to DIs regarding estimation (Estimation Time, Estimation Cost, and Estimation Resources) and repairs (damage states have one or more repair methods associated with them using a parent-child relationship).

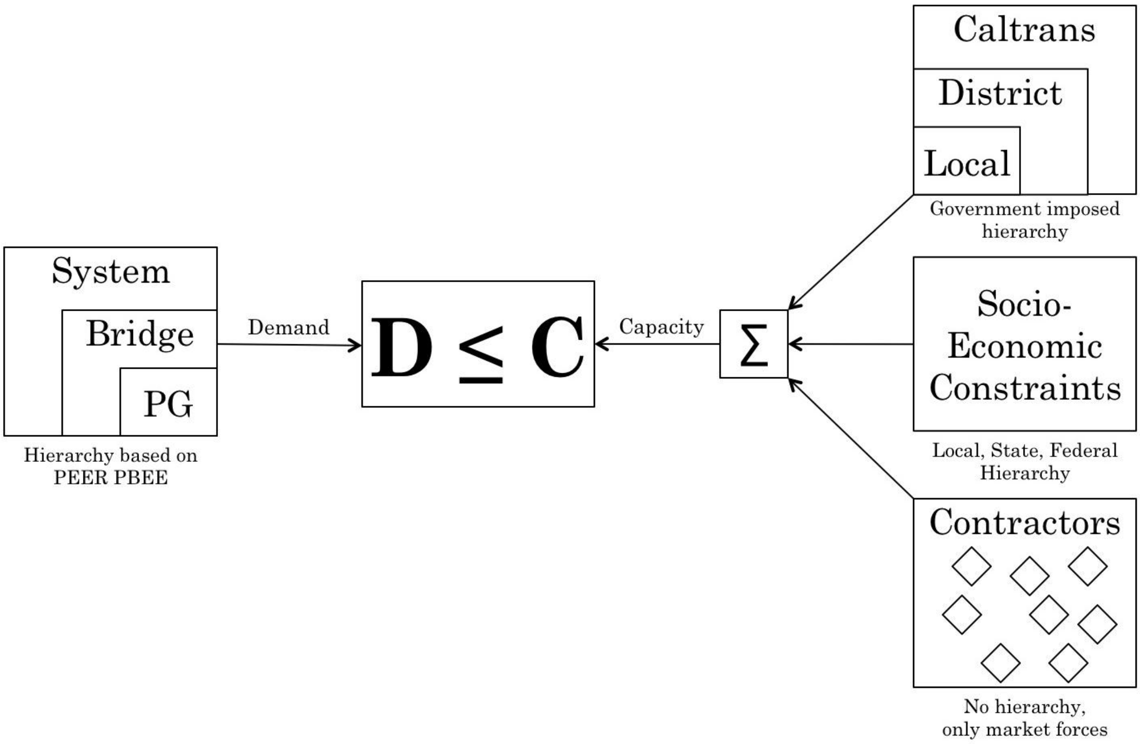

Figure 2. BRDF demand-capacity inequality and overall organization

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. 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).

3.2. 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.

3.3. 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

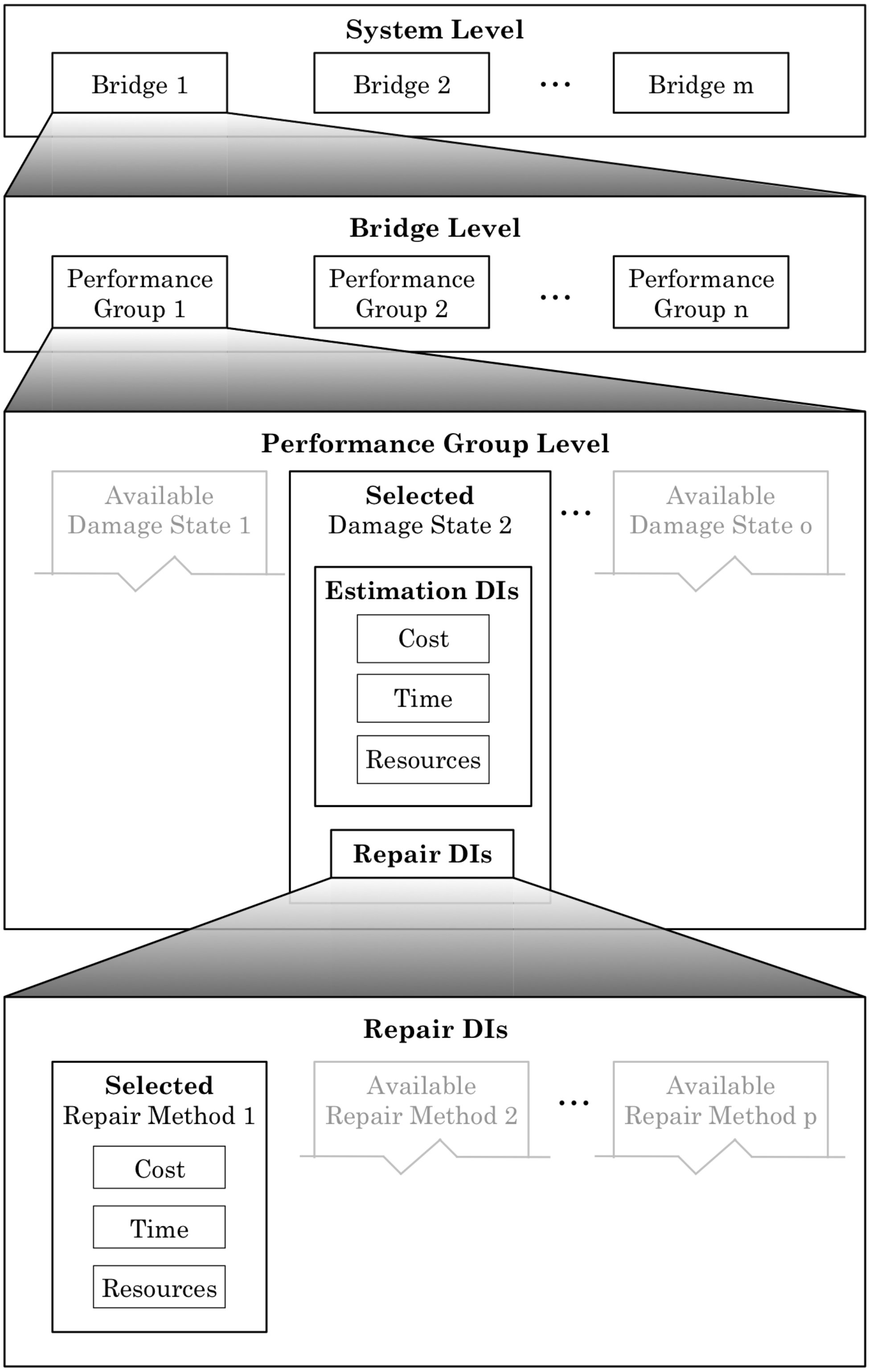

Figure 3. Bottom four demand input levels of the BRDF

history. This information can be retrieved through queries on existing bridge inventory maintenance databases such as the Caltrans Structure Maintenance Automatic Report Transmittal (SMART) system.

Further identifying the bridge is the bridge priority DI, based upon an existing infrastructure priority system such as Caltrans' ShakeCast exceedance ratio (Lin et al. 2009). 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 the individual component fragilities which was integrated to get a custom bridge fragility for each bridge and overpass.

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.

3.4. 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.

4. 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 (Figure 4**)** can be examined as two fundamental groups – department of transportation (DOT) levels and contractor levels – that house all of the capacity DIs. 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.

4.1. Department of Transportation Level

For the purposes of this research, the existing Caltrans structure was used for the DOT levels. Since Caltrans employees and resources are distributed throughout California, there are three different Caltrans levels on the capacity side of the BRDF: district, state, and local. The lowest (district) level contains DIs that map the various types of resources in a given area, including construction or transportation equipment, the numbers of estimators, design engineers, and maintenance engineers.

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 possible, while others may be partially available (expressed as a percentage). For example, some of the maintenance engineers may be engaged with taking care of their family because their home or school may have been damaged in the earthquake. 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.

4.2. 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.

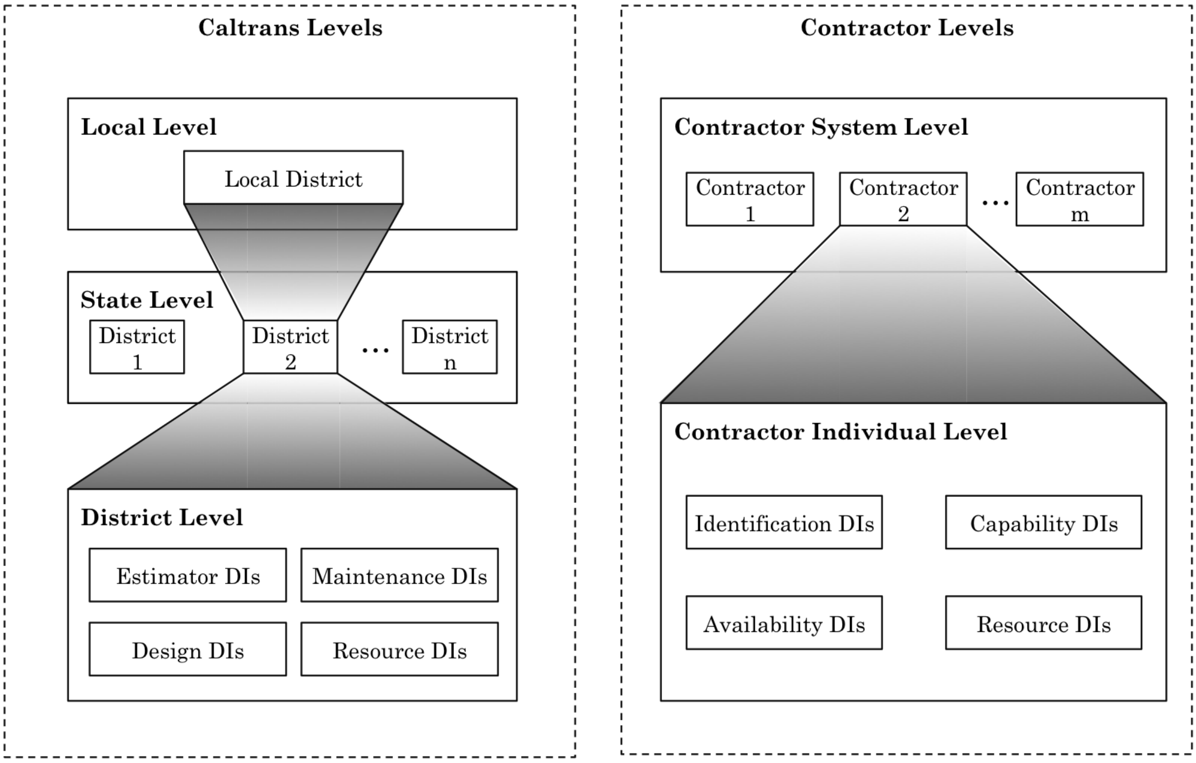

Figure 4. Flat capacity side organizational structure.

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.

4.3. Capacity Level

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

5. 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 everpresent 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.

5.1. Funding Inputs

Funding inputs describe the various sources of funding for emergency repairs. For example, Caltrans has three such sources. First, Caltrans itself maintains an emergency fund for expenses incurred after unforeseen events. Second, emergency funding can be provided by the State of California through a declaration of emergency by the governor. 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).

5.2. Political/Bureaucratic Inputs

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.

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.

6. 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 parameters and relevant repair method alternatives.

6.1. System Capacity

As discussed, the BRDF treats repair decisions as a traditional design inequality between system demand and system capacity **(**Figure 2). 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 short- and long-term repair decisions.

6.2. 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.

7. FRAMEWORK VALIDATION

The BRDF model was validated in order to highlight the advantages of the framework as well as its limitations. A system was created consisting of five identical bridges based on the PEER Benchmark Bridge, created by PEER researchers and studied by Mackie and Wong (2007). The benchmark bridge included reliable, probabilistic data for construction type, geometry, damage states, performance groups, and repair methodology, and reflected a standard highway bridge in the state of California (Mackie et al. 2007).

Incorporating damage scenarios and their subsequent repair costs across the system allowed for unique system assessment beyond bridge-level data, revealing repair cost for similar performance groups across the system. Inspection and repair time was also accounted for based on actual inspection times from previous earthquake response histories. Overall, the model validation revealed the benefits of adopting the BRDF methodology, which results in performance-based decision-making approaches that greatly improves upon current methods.

8. 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 ensure system resilience and restore full functionality of transportation systems in the aftermath of an earthquake. The BRDF addresses these requirements in terms of the repair effort, improving upon current practices while creating a flexible foundation for future research, understanding, and improvement of repair decisions.

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