Developing ShakeCast Statistical Fragility Analysis Framework for Rapid Post-Earthquake Assessment

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SUMMARY
When an earthquake occurs, the U. S. Geological Survey (USGS) ShakeMap estimates the extent of potentially damaging shaking and provides overall information regarding the affected areas. The USGS ShakeCast system is a freely-available, post-earthquake situational awareness application that automatically retrieves earthquake shaking data from ShakeMap, compares intensity measures against users' facilities, sends notifications of potential damage to responsible parties, and generates facility damage assessment maps and other web-based products for emergency managers and responders. We describe notable improvements of the ShakeMap and the ShakeCast applications. We present a design for comprehensive fragility implementation, integrating spatially-varying ground-motion uncertainties into fragility curves for ShakeCast operations. For each facility, an overall inspection priority (or damage assessment) is assigned on the basis of combined component-based fragility curves using pre-defined logic. While regular ShakeCast users receive overall inspection priority designations for each facility, engineers can access the full fragility analyses for further evaluation.

Keywords: ShakeCast, ShakeMap, Fragility Analysis, HAZUS, Caltrans Generation 2 Fragility

1. INTRODUCTION

The U.S. Geological Survey (USGS) ShakeCast is an application for automating ShakeMap delivery, damage assessment and notification for critical lifeline operators. When an earthquake occurs, ShakeMap portrays the extent of potentially damaging shaking and provides overall information regarding the affected areas. ShakeCast provides post-earthquake situational awareness that automatically retrieves earthquake shaking data from ShakeMap, compares intensity measures against users' facilities, sends notifications of potential damage to responsible parties, and generates facility damage assessment maps and other web-based products for emergency managers and responders.

Under the auspices of the California Department of Transportation (Caltrans), the U.S. Nuclear Regulatory Commission (NRC), the International Atomic Energy Agency (IAEA), and the U.S. Department of Veterans Affairs (VA), we are developing the next generation ShakeCast application (Version 3). One main objective of the project is to create a comprehensive fragility analysis framework for assessing structure vulnerabilities due to seismic loading. This framework will complement the ShakeMap-based damage assessments of the existing ShakeCast system (Version 2) (Lin and Wald, 2007) to provide both near real-time damage notification and comprehensive fragility analysis functions.

The scope of fragility analysis includes two major categories, conditional rule-based statements and conditional probability statements. For rule-based statements, ShakeCast evaluates structure fragility based on a predefined rule set to determine the level of concern that ties directly with the users' post-earthquake response protocol. An example implementation is the system called "Nuclear ShakeCast" operating at the IAEA and to be installed at the NRC. The Nuclear ShakeCast system utilizes the rule-based statements to determine exceedance of regulatory levels in addition to the standard ShakeMap-based damage assessments. These rules include regulatory thresholds for Operating Basis Earthquake ground motion (OBE and SL1), Safe Shutdown Earthquake ground motion (SSE and SL2), Review

Level Earthquake ground motion (RLE), and RG 1.166 Appendix A criteria.

The probability statements adopted by ShakeCast V3 describe seismic fragility curves regarding the vulnerability of users' structure. Predefined damage states related to the vulnerability in ShakeCast continues to follow the same terminology of the Federal Emergency Management Agency (FEMA) "Hazards U.S.—Multi-Hazard" (HAZUS-MH; FEMA 2009) program. Users can modify the damage state classifications to meet the needs of their own application.

In this paper, we present the design of statistical fragility analysis framework for USGS ShakeCast V3. Input data with decreasing quality, from actual strong motion parameters to predicted peak values from Ground Motion Prediction Equations (GMPE), are used to assess structure vulnerability. Uncertainties associated with the input data are available as an optional field included as part of the fragility analysis. Caltrans' ShakeCast system, with system-level fragility curves, is used as an example of this new functionality and to show how they prioritize bridge inspection state-wide after earthquakes.

2. OVERVIEW OF THE USGS SHAKEMAP/SHAKECAST VERSION 3

2.1. ShakeMap V3.5 Upgrade

ShakeMap is a system for rapidly characterizing the extent and distribution of strong ground shaking following significant earthquakes worldwide (e.g., Wald et al., 2008). Current ShakeMap systems are deployed and operating at several regional networks within the United States, in various networks worldwide, and at the USGS National Earthquake Information Center (NEIC) in Golden, Colorado, for the production of ShakeMaps for significant earthquakes around the world.

Starting in 2012, the NEIC Global ShakeMap system and most regional networks have upgraded their ShakeMap application to the latest Version 3.5. ShakeMap V3.5 represents a major change in the way ShakeMaps are computed and has improved in both data handling and precision over prior implementations (Worden et. al, 2010). However, existing ShakeMap users may not be able to interpret the data products based on V3.5 appropriately without understanding the inner working of the new application. For example, macroseismic observations are now a valid input data type and converted observations are a new class of data in ShakeMap. With the introduction of Intensity Prediction Equation (IPE), the ground-motion estimate at a grid point is a weighted sum of the different types of contributing information among observations, converted observations, and GMPE/IPE estimates, weighted inversely by their uncertainties. The underlying, spatially-varying uncertainty grid is preserved for use in loss-estimation algorithms, including ShakeCast. Another upgrade is the bias correction (for removing inter-event variability) scheme in ShakeMap V3.5, which is now a magnitude adjustment rather than an amplitude multiplier. To a great extent, ShakeCast V3 will help the end user transit to ShakeMap V3.5 and to take advantage of the new data and uncertainty products.

2.2. Earthquake/Ground-motion Information for ShakeCast V3

Since its release in 2004, ShakeCast utilizes ground shaking information and related products from ShakeMap. The current ShakeCast V2 system, released in 2008, and subsequently followed with four incremental updates, evolved to work closely with the ShakeMap V3.2 application regarding available products and semantics. The ShakeCast V3 system, currently under development, continues the same design principle. Specific ShakeMap data related to damage assessment that have been made available to ShakeCast users include: (1) detailed processing parameters about the ShakeMap run; (2) ground shaking estimates at bedrock (before site corrections) and site amplifications at the grid level; and (3) uncertainty estimates for each computed metric at the grid level.

Also implemented into ShakeCast V3 is the capability of the new system to track and receive earthquake products via multiple sources instead of from ShakeMap producers only. For critical lifeline users, ShakeCast V3 further integrates the new USGS Product Distribution Layer (PDL) as a redundant source to receive earthquake and ShakeMap products, additional earthquake information (e.g., focal mechanisms and tectonic summaries), and earthquake related products including the "Did You Feel It?" (DYFI) and the Prompt Assessment of Global Earthquakes for Response (PAGER). All these products are (optionally) stored locally as part of the ShakeCast data repository, accessible by ShakeCast users, and can thus be included to expand the scope of post-earthquake situational awareness.

2.3. Output Products of ShakeCast V3

ShakeCast is fundamentally a database application by design. The application consists of six independent processes running in parallel, attached to the central database. Metadata from various sources about the earthquake, processed information related to the ShakeMap, and the facilities are stored inside the ShakeCast database. Notifications and products generated by the ShakeCast system are unique to the local installation using the built-in templating mechanism. The ShakeCast administrator defines the format and directives of the template to be generated in real-time. Fig. 1 is an example showing the ShakeCast summary report in Portable Document Format (PDF) from the prototype Nuclear ShakeCast system at IAEA after the 2011 M5.8 Mineral, Virginia earthquake. The North Anna Nuclear Power Station, which was shut down temporarily, was identified in the automated summary report.

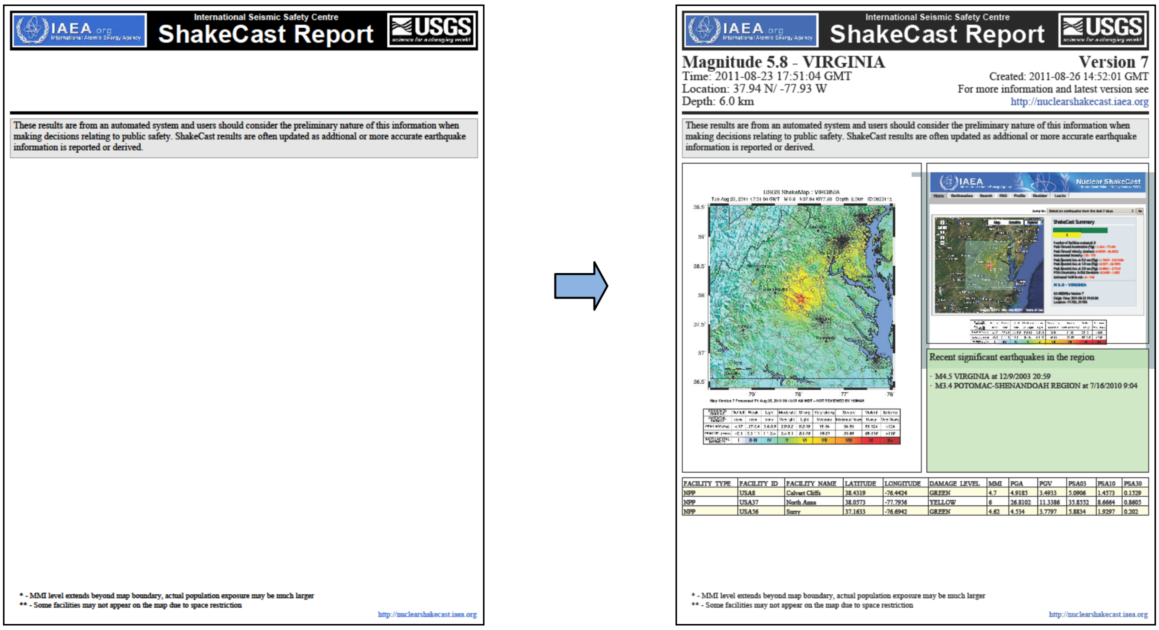

Figure 1. ShakeCast summary report of the prototype Nuclear ShakeCast system at IAEA. The template (left) can be locally-configured with ShakeMap, ShakeCast, and other earthquake information as desired.

3. GROUND-MOTION MEASURES FOR FRAGILITY ANALYSIS

There are three sources of intensity measure (IM) data that can be used for fragility analysis in ShakeCast V3 with decreasing quality in the order of actual strong motion recording, ShakeMap intensity measure, and predicted IM. In particular, the predicted intensity measure is a new class of data for situations when the facilities are located outside the ShakeMap boundaries, or when there is no ShakeMap available for the earthquake. ShakeCast generates either extrapolated or simple predicted intensity measure using similar ShakeMap procedures. Fig. 2 shows a ShakeCast schematic relating input ground-motion measures and damage assessment. User-defined metric and damage assessment is an established ShakeCast function to create additional metrics, such as Arias intensity and Newmark displacement, with predicted ground-motion measures.

ShakeMap IMs are the data of choice for damage assessments under normal operation. The standard IMs are MMI, peak ground acceleration (PGA), peak ground velocity (PGV), pseudo-spectral acceleration (PSA), and supplemental uncertainty information. Contrary to the uniform measure of uncertainty that ties to the sigma of GMPE in previous implementations, ShakeMap V3.5 provides metric-specific uncertainties at each grid point.

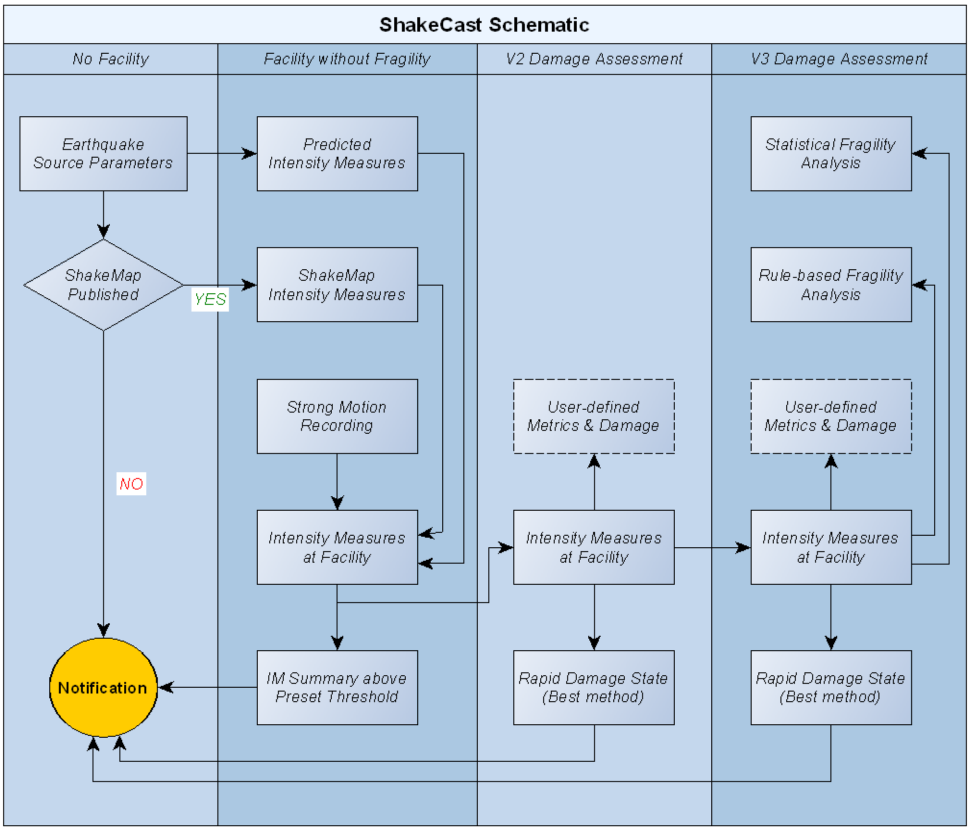

Figure 2. ShakeCast schematic for input ground-motion and damage assessment

3.1. Actual Strong Motion Recordings

ShakeCast has a configurable option applicable where a facility is near a seismic station. Currently only station data used by ShakeMap are permitted for data override. This option provides input data with the highest quality and carries fixed uncertainty in term of spatial variability. Disadvantages include no observed MMI assignment and the facility is not immune from stations with faulty data reported.

3.2. ShakeMap Intensity Measure

For ShakeMap IMs, ShakeCast automatically extracts ground motion estimates and supplemental uncertainty data to the nearest grid point for a given facility. Due to the composite effect of ground-motion estimates combining weighted data of observations, converted observations, and GMPE/IPE predictions, data quality varies from one grid point to another and often improves with subsequent revision of the ShakeMap.

3.3. Predicted Intensity Measure

The goal of this new data class is to satisfy the need to obtain ground-motion estimates for user's facilities when they fall outside the ShakeMap boundaries or when a ShakeMap is not available. Functionality-wise, this is a major undertaking for ShakeCast as it requires the application to extend the ShakeMap process from the contributing network producer to inside user's ShakeCast installation. The implementation in ShakeCast V3 allows a user to specify a magnitude and distance threshold where predicted intensity measures will be computed. A simple prediction applies when there is no published ShakeMap and consists of ground-motion estimates using the pre-configured GMPE, GMPE-specific distance measure, and a general NEHRP-style site amplification scheme. The uncertainty estimate is simply the GMPE model uncertainty. An extrapolated prediction applies the same GMPE used in ShakeMap, distance to fault measure, bias corrections, and appropriate site amplifications, if available.

4. SHAKECAST DAMAGE ANALYSIS

The ShakeCast V3 system uses information from facility damage functions for both statistical interpretations and rapid notifications.

4.1. Form of Damage Functions

Facility damage functions are in the form of lognormal fragility curves that relates the probability of being in, or exceeding, a damage state for a given intensity measure parameter. The probability that structural damage reaches or exceeds a specific damage state, *ds*, for a given intensity measure, *IM*, is approximated as a cumulative lognormal distribution function:

$$P[ds \mid IM] = \Phi\left(\frac{1}{\beta_{ds}} \ln\left(\frac{IM}{\alpha_{ds}}\right)\right) \tag{4.1}$$

where

α_{ds} is the median value of input intensity measure at which the structure reaches the threshold of the damage state *ds*,
β_{ds} is the standard deviation of nature logarithm for the damage state *ds*, and
Φ is standard cumulative lognormal distribution function.

4.2. Database Schema for Statistical Fragility Analysis

The ShakeCast V3 system contains an expanded database to store fragility information for each facility. Stored information includes damage state, intensity measure, median value α_{ds} for the damage state, and standard deviation β_{ds} for the damage state. Fig. 3 shows the database schema that correlates facility fragility curves, probability computation, and damage state probability. Additional ShakeCast routines have been created to support data import and export, user interface, and output products and notification triggering. An example output plot of fragility analysis is shown in Fig. 5.

4.3. Accounting Ground-motion Data Variability

As part of the statistical fragility analysis framework, Eqn. 4.2 (Luco and Karaca, 2007) was introduced in ShakeCast V3 to incorporate uncertainty information associated with ground-motion estimates, which are the best estimate of intensity measure *im* based on ShakeMap or a GMPE:

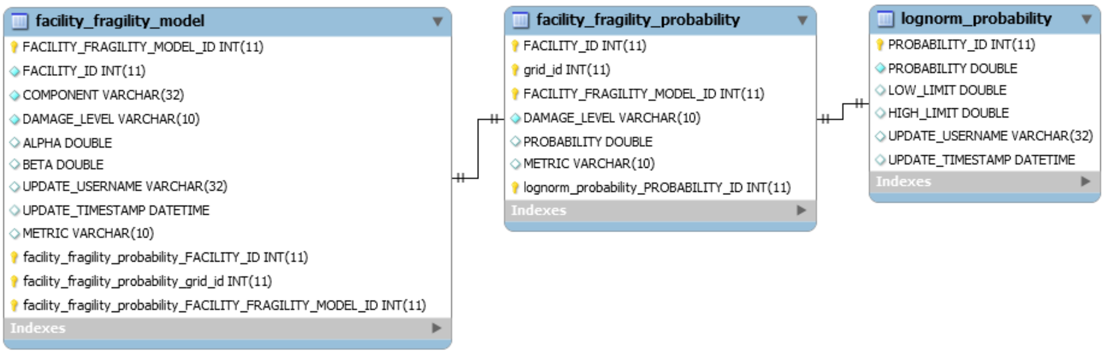

Figure 3. Database schema for statistical fragility analysis

$$P[DS = ds \mid IM] = \int_{IM} P[DS = ds \mid IM = x] f_x(x; im, \sigma) dx \tag{4.2}$$

where

$f_{im}(im, \sigma)$ is the probability density function of intensity measure *im* and
σ is the uncertainty for intensity measure *im*.

Fig. 4 shows an example of the ShakeMap best estimates of PGA and its associated uncertainty values. The uncertainty map gives the ratio of the estimated uncertainty to the PGA.

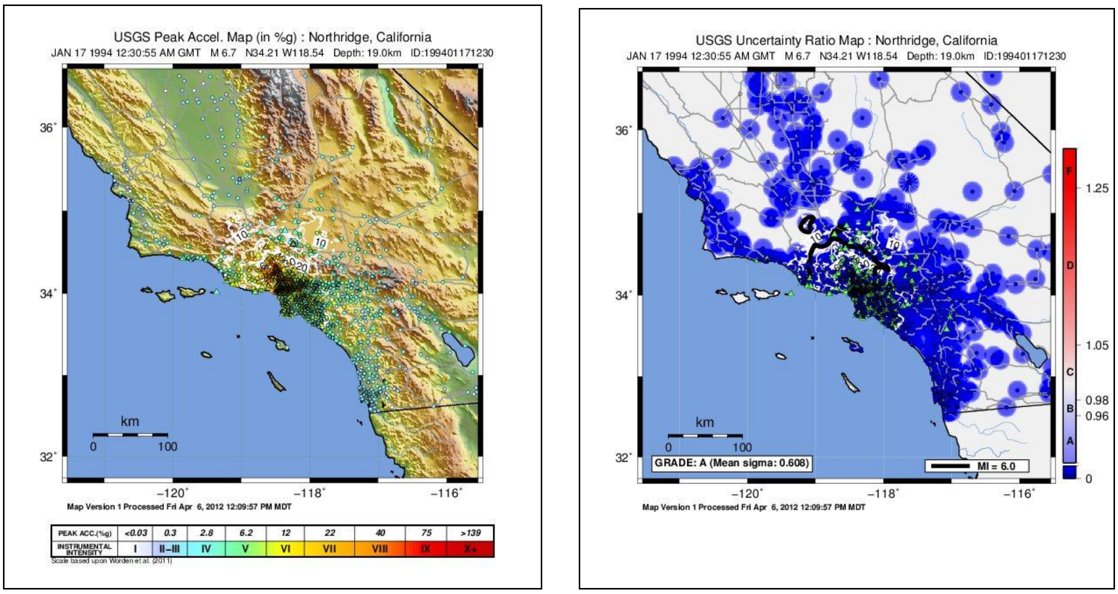

Figure 4. PGA and uncertainty estimates for the 1994 M6.7 Northridge ShakeMap

4.4. Damage State Probability

As the last stage of the statistical fragility analysis, the probability of each structural damage state for a given facility is expressed as a function of *IM*:

$$P[DS = ds \mid IM] = 1 - P[DS = 0 \mid IM] \qquad ds = 0$$

$$= P[DS = ds \mid IM] - P[DS = ds+1 \mid IM] \quad 1 <= ds <= \text{n-1}$$

$$= P[DS = n \mid IM] \quad ds = \text{n} \tag{4.3}$$

where

$P[DS = ds \mid IM]$ is the probability of structural damage state *ds* for a given *IM*.

Fig. 5 is an example showing the output plot of full fragility analysis for a Caltrans bridge using a M7.2 San Andreas ShakeMap scenario. In this example there were three fragility curves defined for the bridge that represent inspection priority: low (filled green curve), medium (filled yellow curve), and high (filled red curve). Thus a total of four damage state probability estimates were produced (histogram) as a result; high inspection priority is the state of highest probability.

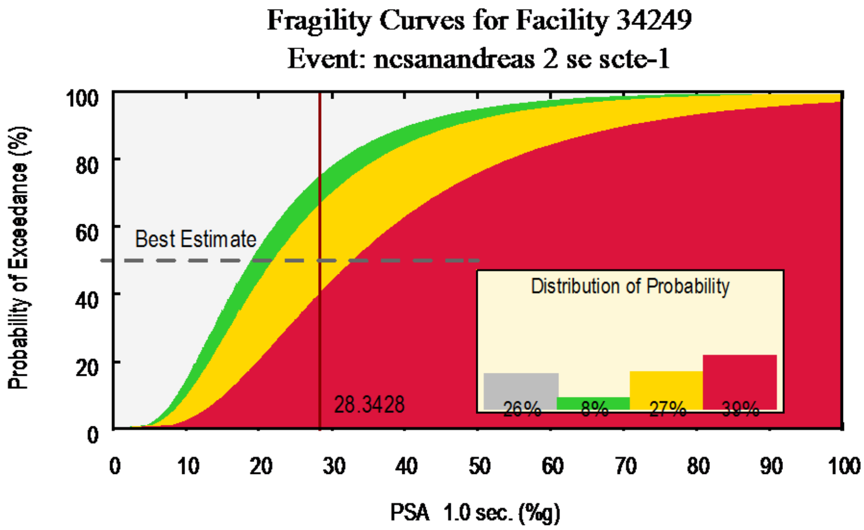

Figure 5. ShakeCast V3 damage state probability plot for a Caltrans bridge

4.5. Best Estimates for Notifications

The best estimate of damage state in ShakeCast V3 is a separate process for the purpose of rapid notifications. It determines the preliminary damage state by correlating the input intensity measure with the 50th percentile of fragility curves. As an example shown in Fig. 5, the facility was labelled as damage state yellow (medium in inspection priority) defined by Caltrans.

5. ADAPTING FRAGILITY MODEL TO SHAKECAST V3

5.1. HAZUS-Based Fragility Model

A total of 36 HAZUS model building types (Table 5.1 of NIBS and FEMA, 2009) were converted to ShakeCast structural damage levels for the Version 2 system. “Model building type” refers to the materials of construction (wood, steel, reinforced concrete, etc.), the system used to transmit earthquake forces from the ground through the building (referred to as the lateral force-resisting system), and sometimes height category (low-rise, mid-rise, and high-rise, which generally correspond to 1-3, 4-7, and 8+ stories, respectively). Further included as a modifier to fragility models for each model building type is the building-code era, of which there are 4 (high code, moderate code, low code, and pre-code; Table 5.3 of NIBS and FEMA, 2009). Code eras reflect important changes in design forces or detailing requirements that matter to the seismic performance of a building. Sixteen combinations of model building type and code era do not exist (e.g., high-code unreinforced masonry bearing wall), so in total there are 128 choices of HAZUS model building type and code era.

Implemented into ShakeCast V3 are the equivalent-PGA structural fragility models (Table 5.16a-d of NIBS and FEMA, 2009) in HAZUS-MH for damage analysis. Current ShakeCast V2 users who selected HAZUS-based fragility model for their facilities will automatically receive the new functionality of statistical fragility analysis. It also applies to the users of the FEMA-sponsored Rapid Observation of Vulnerability and Estimation of Risk (ROVER) application. ROVER adapts FEMA 154 and ATC-20, two de facto international standard methodologies for pre-earthquake seismic risk screening and post-earthquake safety evaluation. A ShakeCast system can interact with ROVER for exchange of pre- and post-earthquake data.

Each of the four defined damage states (or inspection priorities) in the ShakeCast system remains the same and is color-coded to correspond to the definitions in HAZUS: green corresponds to HAZUS' undamaged or slight structural damage states, yellow corresponds to moderate structural damage, orange to extensive structural damage, and red to complete structural damage. Full descriptions can be found in the HAZUS-MH Technical Manual (NIBS and FEMA, 2009) Section 5.3.1.

5.2. Caltrans Bridge Fragility Model

Implemented in the Caltrans ShakeCast V2 system, each bridge in the system's database has a unique fragility, determined with bridge damage models originally published by Basöz and Mander (1) and implemented in the HAZUS software. The fragility models employ 1.0-second PSA and take into account bridge geometry, such as span lengths, number of spans, column heights, and skew; the years of design, construction, and retrofit; and the component material types. The median value α_{ds} for any damage state is used in ShakeCast and implemented as thresholds for inspection priorities. Unique fragility parameters are determined for each of the more than 13,000 facilities in the Caltrans inventory.

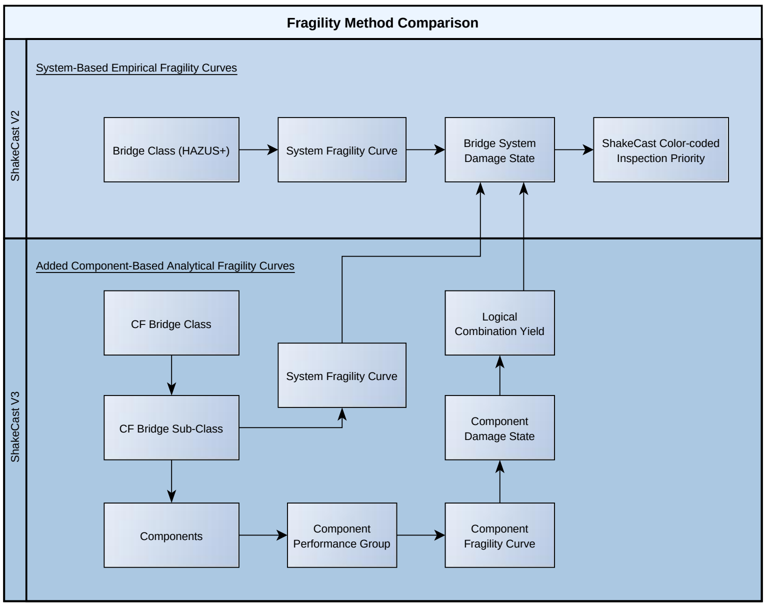

Figure 6. Comparison of fragility methods between Caltrans ShakeCast V2 and V3

The full statistical fragility analysis framework of ShakeCast Version 3 was mainly designed for Caltrans. As Caltrans begins to capture more information on the various components of individual bridges, such as the project for improved bridge fragility relationships using unique California information, their Generation-2 Fragility (g2F) will be used in ShakeCast V3 in addition to the HAZUS-based method for improved near-real-time damage alerting of bridges in California.

Converting the HAZUS-based method from V2 to V3 is a straightforward process since the database only requires the standard deviation β_{ds} value for each damage state of a bridge.

The proposed g2F methods define initial bridge classes based on NBI and California-specific bridge information, e.g., Structure Maintenance Automated Report Transmittal System (SMART), hinge, and retrofits. Damage states are defined in terms of recognized engineering parameters, or components. Defined components of interest are divided into four categories: (1) primary component, (2) secondary component, (3) general stress indicator, and (4) approach settlement. A total of 23 component categories (4 primary, 11 secondary, and 8 general distress indicators) have been defined in the working draft. Once component-based fragility models have been developed, bridge classes are optimized by combining classes having distinct performance. Fig. 6 shows the comparison of bridge fragility analysis between Caltrans ShakeCast V2 and V3 systems.

In contrast to the empirical HAZUS-based method, the g2F methods analyze the overall bridge state as a function of the individual component fragilities. Assessed damage states are presented at both the system and the component levels. For example, a simple bridge might have unique fragilities defined for the columns, abutments, deck, and foundation elements. Each component could be analyzed separately against a ShakeMap intensity measure with probabilities assigned for various component damage states. Those results would then be aggregated into single damage state metric used for summarizing and prioritizing inspections, while providing additional detail to inspectors on specific components that are likely to be the cause of the overall system failure. Fig. 7 illustrates the process converting component-based fragility modelling to ShakeCast V3 fragility curves.

Figure 7. Converting g2F component-based fragility modelling to ShakeCast fragility curves

6. DISCUSSIONS AND CONCLUSIONS

The USGS ShakeCast is an open-sourced application for post-earthquake response using the ShakeMap technology. ShakeCast Version 3 represents a major upgrade in functionality from the previous release in 2008. The functional aspect of the V3 upgrade is to expand the scope of the earthquake products as input data, to implement comprehensive fragility analysis in conjunction with the new ShakeMap V3.5 data layers, and to deliver rapid notifications and detailed information regarding user's facilities shaken during an earthquake. The first deliverable is the custom Nuclear ShakeCast system with a rule-based fragility analysis framework designed specifically for the nuclear power industry. General release of the Version 3 system with the full statistical fragility analysis function is scheduled for 2013.

ShakeMap V3.5 now produces a weighted combination of native observations, converted observations, and estimated data at every point in the output data grid; it is a significant improvement in data quality over previous revisions. Former ShakeMap combined observations (data) with GMPE-derived estimates computed on a coarse grid, then interpolated (i.e., filled gaps) to a finely spaced grid. Ground motion observations can be used preferentially over IM estimates. Weighting is now determined by the formal uncertainty of each datum. When a major earthquake occurs, it is common to have several ShakeMap updates during response and usually begins with a more predictive version and improves over time. We include input data uncertainty into the fragility analysis in ShakeCast by introducing a new integral of probability over the range of ground-shaking estimates. Damage-state probability is computed using pre-computed probability distribution lookup tables to increase performance. The assumed lognormal probability distribution can be easily switched to other distribution forms by swapping the tables.

ShakeCast computes extrapolated predicated ground-motion estimates using earthquake source information, selected GMPE, GMPE-specific distance measure, NEHRP-style site correction scheme, and the bias correction from ShakeMap. Since not all GMPE's have been implemented in ShakeCast, problems may arise when a ShakeMap was made using a non-specified GMPE or with a custom site correction scheme.

The reliability of the seismic vulnerability assessment results is directly dependent on the reliability of the fragility curves. The variability in the structural parameters and damage state definitions of facilities as well as the uncertainty in the ground-motion parameters make the development procedure of fragility curves a very challenging task. Fragility curves are mostly developed using empirical or analytical approaches with different pros and cons. In Caltrans' case, empirical methods are based on observed damage from real earthquakes but only a small population of inventory is available and the defined damage states are not tied to bridge-specific engineering parameters. The reverse is true for their g2F analytical methods. As it was implicated in the example, for a given facility, ShakeCast allows weighted combinations of fragility curves for the same damage state. All components (primary, secondary, and general stress indicators) in the current design of g2F can raise either a green or yellow (low to medium inspection priority) alert level and only primary components can raise the alert level to orange or red (medium-high to high inspection priority). The combined output is the basis of the component-based system (CBS) fragility assessment for Caltrans bridge inventory.

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