# ShakeCast: Automating and Improving the Use of ShakeMap for Post-Earthquake Decision-Making and Response

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When a potentially damaging earthquake occurs, utility and other lifeline managers, emergency responders, and other critical users have an urgent need for information about the impact on their particular facilities so they can make appropriate decisions and take quick actions to ensure safety and restore system functionality. ShakeMap, a tool used to portray the extent of potentially damaging shaking following an earthquake, on its own can be useful for emergency response, loss estimation, and public information. However, to take full advantage of the potential of ShakeMap, we introduce ShakeCast. ShakeCast facilitates the complicated assessment of potential damage to a user's widely distributed facilities by comparing the complex shaking distribution with the potentially highly variable damageability of their inventory to provide a simple, hierarchical list and maps of structures or facilities most likely impacted. ShakeCast 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 maps and other Web-based products for both public and private emergency managers and responders. [DOI: 10.1193/1.2923924]

## INTRODUCTION

Situational awareness in the immediate aftermath of a disastrous earthquake is of fundamental importance for an effective societal response. While overall disaster management is critical, a successful, organized response is dependent on the collective efforts of the community at large. When a potentially damaging earthquake occurs, businesses, utility and other lifeline managers, emergency responders, and others have an urgent need for information about the impact on their own facilities so they can make informed decisions and take quick actions to ensure safety, restore system functionality, and minimize losses.

The U.S. Geological Survey's (USGS) ShakeMap (Wald et al. 1999b, 2005) is now a widely known and available tool used to portray the extent and severity of ground shak-

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ing following an earthquake. Although ShakeMap was initially designed to be primarily a Web-based real-time display, ShakeMap products have evolved to include high-resolution graphics files, maps made specifically for television, GIS files for direct input into the FEMA's HAZUS (NIBS and FEMA 2003) loss estimation software, as well as gridded extensible markup language (XML) and Google Earth (KML) data files, all of which are now also automatically generated. ShakeMaps can be used for a wide range of needs, including emergency response, loss estimation, scientific and engineering analyses, and public information. However, the full potential of ShakeMap is only beginning to be realized.

For example, Ranf et al. (2007) found that using shaking parameters provided by ShakeMap for the 2001, Nisqually, Washington (M6.7) earthquake would have been highly useful in prioritizing post-earthquake response and inspection. By modifying existing HAZUS (NIBS and FEMA 2003) fragility curves to accommodate the older, particularly vulnerable bridges in the region that dominated bridge damage, and by focusing on 0.3 sec period spectral acceleration, they noted that their prioritization strategy would have made it possible to identify 80% of the moderately damaged bridges by inspecting only 14% of the 3,407 bridges within the boundaries of the ShakeMap. Hence, despite the popularity and acclaim of ShakeMap for emergency response and post-earthquake information, and the proven potential for facilitating prioritization of response efforts, there is still a lack of implementation of tools that take advantage of the full potential of ShakeMap for post-earthquake assessments (as well as for planning exercises). Critical users need to move beyond simply looking at ShakeMap, and begin implementing response protocols that utilize the known shaking distribution in fully automated systems in order to fully realize this potential in order to prioritize and coordinate response efforts. To this end the USGS has developed ShakeCast.

ShakeCast (http://earthquake.usgs.gov/shakecast), short for ShakeMap Broadcast, is a fully automated, open-source system for delivering specific ShakeMap products to critical users and for triggering established post-earthquake response protocols. ShakeCast allows utilities, transportation agencies, and other large organizations to automatically determine the shaking value at their facilities, set thresholds for notification of damage states (typically green, yellow, and red) for each facility and then automatically notify (via pager, cell phone, or e-mail) specified operators, inspectors, and others within their organizations responsible for those particular facilities in order to prioritize inspection and response. A schematic diagram showing the ShakeMap/ShakeCast flow of data and information is shown in Figure 1. The basic pre-earthquake set up and post-earthquake response timeline is outlined in Figure 2.

As an example, the California Department of Transportation (Caltrans) is operating the ShakeCast system and is responsible for tens of thousands of California bridges and overpasses. Having a near-instantaneous estimate of the potential damage to each bridge is fundamental for enabling them to prioritize rerouting traffic, closures, and inspections following a significant earthquake. In general, businesses, utilities, and agencies could develop their own strategies and tools for the utilization of ShakeMap given their unique facilities and communication paths. However, such efforts can be costly and complex. The USGS is facilitating this process with the development of ShakeCast, by building a

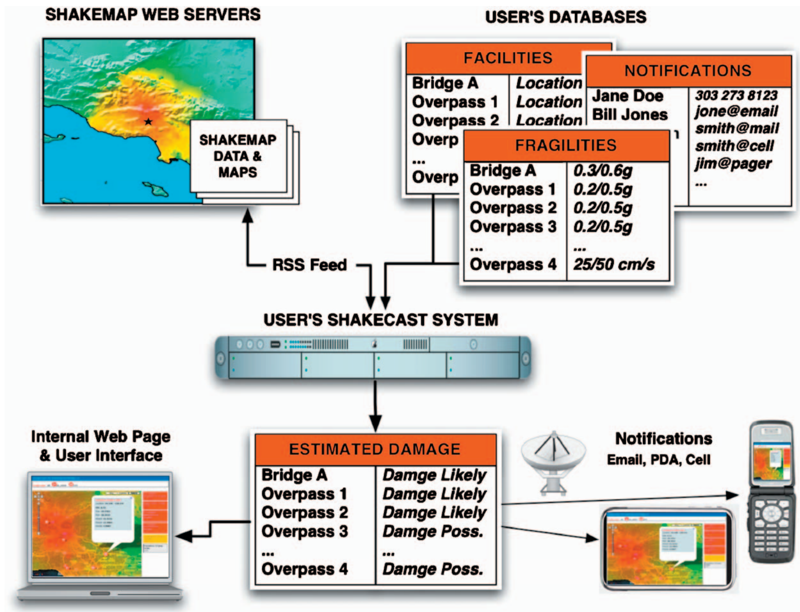


**Figure 1.** ShakeCast flow chart indicating flow of USGS ShakeMap data, users' ShakeCast inventory and user databases, and notifications.

more general use tool that accomplishes most of the critical user needs. As a critical user, Caltrans has been instrumental in providing the resources and the motivation to further enhance the ShakeCast system, allowing USGS to progress from a prototype system (Version 1.0, Wald et al. 2003) to a fully functional system described herein (Version 2.0).

We first describe the technology behind ShakeCast and provide a brief overview of the procedure for installing and using ShakeCast software. We then address the procedures available for assessing potential damage to users' facilities. Next, example uses and users are provided to illustrate the range of potential ShakeCast applications. Finally, ongoing enhancements and development of new ShakeCast applications and functions are outlined in the section on *Ongoing Development* prior to our concluding remarks. While this report provides an overview of the ShakeCast system, potential users are encouraged to consult the users manual for more comprehensive system and operational details (Lin and Wald 2007).

## SHAKECAST TECHNOLOGY

The ShakeCast application is built upon open-source code, providing standard, freely available software for all users. All ShakeMap and ShakeCast files and products are non-proprietary to simplify interfacing with existing users' response tools and to encourage user-made enhancement to the software. ShakeCast employs the Apache Web server and

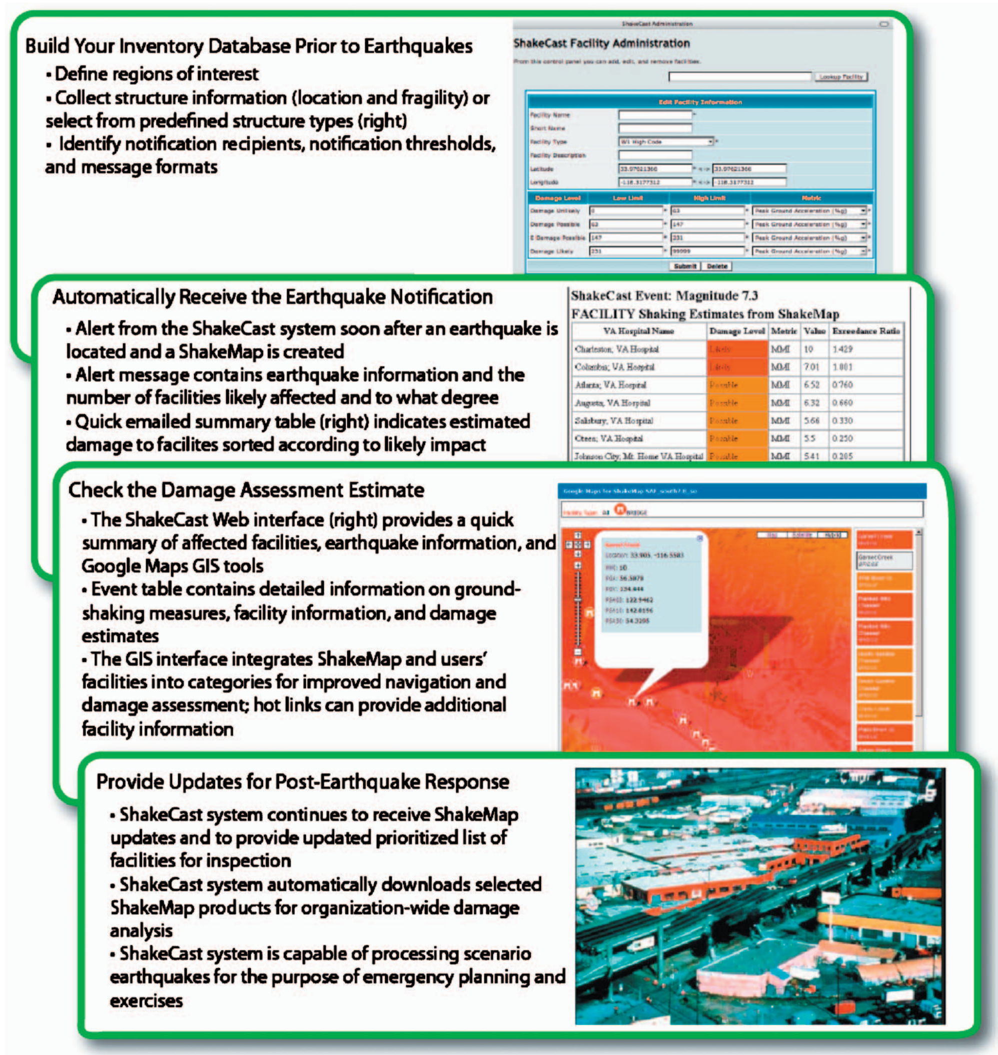


**Figure 2.** ShakeCast summary–elements of how the system works.

PHP for dynamic Web content, MySQL for facility and notification databases, and it is wrapped in PERL scripting. Exchange files are in Extensible Markup Language (XML) for standardized interfacing with Web, GIS, spreadsheets, databases, and other applications.

Information Technology (IT) security is a primary concern for users requiring automatic, electronic delivery of data to internal operations centers, for example. By taking advantage of standard Internet protocols (HTTP, port 80), ShakeCast users avoid *most* typical corporate and governmental concerns and firewall restrictions. Specifically, by utilizing Really Simple Syndication (RSS) and interval polling, users initiate all communications with the USGS Web servers that host ShakeMaps, and retrieve selected products as a request rather than a "push." We have established that this approach works within fairly restrictive internal systems, including those using proxy servers. This same RSS approach will also (optionally) allow users to update software automatically under conditions of their own choosing. ShakeCast also taps into the existing infrastructure built to serve ShakeMap and other earthquake information redundantly and under extreme load conditions by the widely-distributed and heavily mirrored USGS Earthquake Program Web servers.

A conscious decision was made in the development of ShakeCast to provide critical users the software to run their own response operations in-house rather than providing this as a centralized service (like ShakeMap) for a number of reasons. First, a user's inventory may be proprietary and thus analyses must be made in-house. Second, for large and changing inventory the user is the most likely to keep an up-to-date database, and it would be unproductive for USGS to take on such a role. Finally, users can customize damage functions, modify recipient contact information, and customize who receives notifications, what they receive, and under what conditions at their convenience. However, as described below some public inventory may be well suited for USGS to evaluate and display, and that can be accommodated with USGS's in-house operations of ShakeCast (see ShakeCast "*Remote*," as described below).

## SHAKECAST SOFTWARE VARIATIONS

An important innovation in the development of the ShakeCast2 system stemmed from the recognition that some potential users need just a subset of the full ShakeCast functionality, and prefer to avoid the responsibility and overhead required to install and operate the entire package. Recognizing the highly variable needs and resources available to the wide range of potential users, we have also developed a subsystem that requires minimal technical expertise to install and operate, but which fully automates access and processing of ShakeMap data. Hence, ShakeCast is available in three basic "flavors": ShakeCast, ShakeCast "*Lite*," and ShakeCast "*Remote*."

This report mainly describes in detail the full ShakeCast system, which allows users to estimate impact to numerous facilities, each potentially with different structure type and notification recipients. We expect this to be deployed by critical users in an earthquake-hardened, operational environment. Critical users are expected to have robust ($24 \times 7$) communications, power, computer and operations, to develop at least a basic assessment of their facility fragilities. However, we have also made available and herein describe ShakeCast "*Lite*," a subset of the system that allows users to automatically receive ShakeMap products on their laptop or desktop computers, and launch predefined applications using those maps or data. For example, many users employ ShakeCast "*Lite*" to automatically pop-up a Web browser to the latest ShakeMap in their region, launch Google Earth® with the ShakeMap KML file, download ShakeMap grid files and initiate loss-estimation applications, or deliver ShakeMap GIS files to their corporate GIS department for further analyses. ShakeCast "*Lite*" is simple to install and use; it is meant for individuals as well as any entities simply trying to automate ShakeMap download and post-processing.

A third-tier application, ShakeCast "*Remote*," in development, will allow users to sign up for shaking levels to be determined and sent to them via e-mail and cell notification after inserting a limited number of locations into a remote web-based database. This third-tier application is expected to be a service provided by USGS but the scope of the service is still under consideration. The basic functionality as well as sample uses and users of these variants of ShakeCast are outlined below, whereas more detailed descriptions are provided as examples in the section on ShakeCast users.

*ShakeCast*

- *Users:* Large organizations and utilities extensive, distributed facilities
- *Examples:* Caltrans, California Division of Dam Safety
- *Functions:* All features of ShakeCast
- *Requirements:* Database (MySQL), Web Server (Apache), Scripting (PERL), PHP

*ShakeCast "Lite"*

- *Users:* Media, scientists, business (e.g., insurance, portfolio loss estimation)
- *Examples:* CBS, FEMA, USGS, numerous individuals
- *Functions:* Easy installation, automatic download of ShakeMap files; initiate post- processing scripts
- *Requirements:* Windows executable or UNIX scripts, Web access

*ShakeCast "Remote"*

- *Users:* Individuals, organizations
- *Examples:* USGS National Earthquake Information Center, Veteran's Administration
- *Functions:* USGS provides ShakeCast delivery of notifications for publicly available inventory, for example, at a list of cities in a region.
- *Requirements:* Publicly available inventory database

## SHAKECAST INSTALLATION

Organizations using the full ShakeCast system first download and install the ShakeCast software package (Version 2) on a hardened in-house computer system. Installation is done with an interactive installation script which acquires and configures the proper versions of the required open-source software online from the authoritative sources. Facility, vulnerability, and notification data are input using import tools and simple, comma separated user data files (CSV). ShakeCast comes preconfigured, but custom configuration is simplified via ShakeCast tools and the Web portal (Figures 3 and 4). The Web portal allows an administrator to perform all functions of the local ShakeCast system

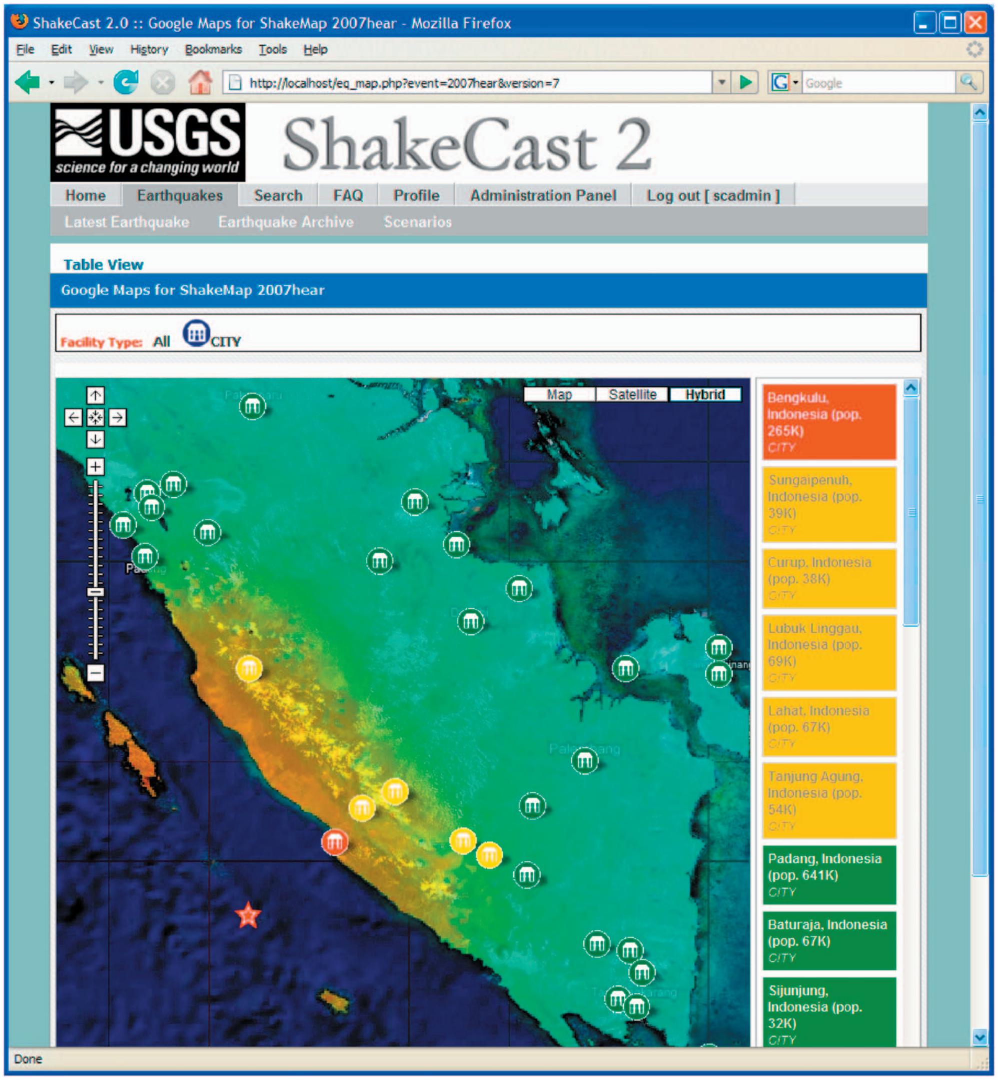


**Figure 3.** Example of the USGS ShakeCast Users' Web portal showing an example event (M8.4, September 12, 2007 Sumatra, Indonesia) with cities (dots), a list of cities, their intensity of shaking, and their population on the right column.

and any end user is able to manage his or her own personal information and notification preferences. Users can also customize the Web portal, making it an integral part of their intranet or other Web pages. Initial setup involves four steps:

1. Populate a database of facility locations and structure types.
2. Assign to each facility a ShakeMap ground motion parameter (e.g., instrumental intensity or spectral acceleration) and the corresponding thresholds of ground

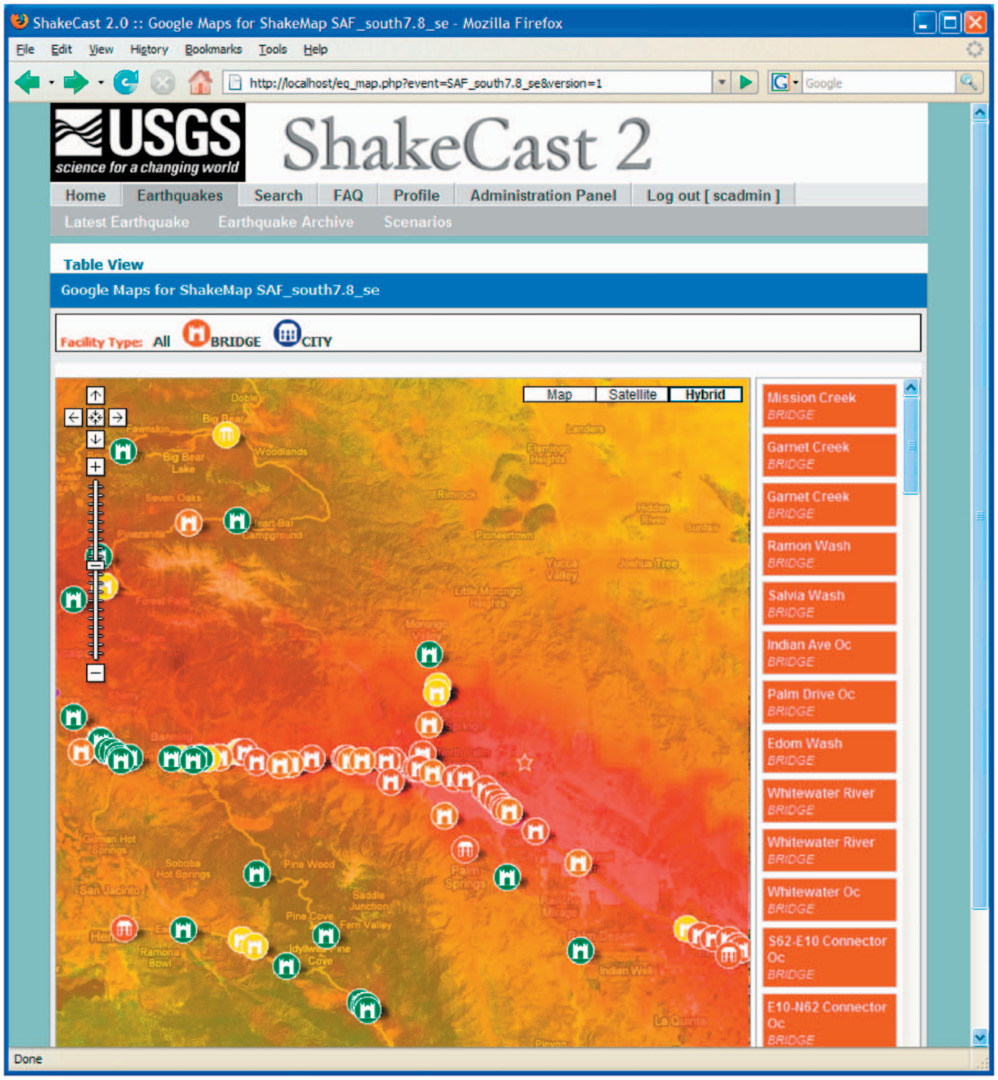


**Figure 4.** The ShakeCast summary page in mapping mode for an Earthquake Scenario (magnitude 7.8, southern San Andreas fault, California). The unique features in the mapping mode includes zoom capabilities, variable image size, selectable facility type, and customizable facility icons. The ShakeCast Google Maps interface switches between placemarker mode and image mode to handle limitation on the number of allowed points on the map. The current USGS ShakeCast system shown in the figure has a total of more than 45,000 facilities in its inventory.

motion separating various damage states. The default configuration established four damage state levels: “green”, “yellow”, “orange”, and “red” (These can correspond to any states of interest to the user, such as “damage unlikely,” “minor damage possible,” and “damage likely,” for example). However, ShakeCast allows the user to specify the number of damage states. The ground motion thresholds can be user-defined or predefined, such as by using ground motion levels corresponding to changes in HAZUS damage states, as described later.

3. Specify who receives notifications by listing addresses of facility managers and response personnel (e-mail, cell phone), and
4. Select under which circumstances the alerts are sent (e.g., damage “possible” at specific facilities).

In addition, the local ShakeCast Administrator can customize the content of the summary report that is delivered to provide not only a prioritized list of facilities based on their estimated damage state, but also organization-specific links, event-specific notes, and images. The notion of Notification Templates further allows users to generate potential impact summary files in a variety of useful formats depending on the user’s standard software applications, or to customize their notifications. While the default format is an HTML table—a hierarchical list of facilities e-mailed to the user list—one can choose to export an XML table (for GIS, Excel, and other spreadsheet/database input) as well as KML (for Google Earth or Google Maps). Example user and earthquake data, notification templates, tutorials, and documentation is provided with the installation package (for more details, see Lin and Wald 2007).

## SHAKEMAP-BASED DAMAGE ASSESSMENTS

ShakeCast offers users different options for estimating damage to their facilities and infrastructure, and thus allows different criteria for sending notifications. Damage estimates can be made based on current ShakeMap ground motion parameters, namely peak horizontal ground acceleration, peak ground velocity, and damped elastic spectral acceleration (0.3, 1.0, and 3-sec periods) as well as Instrumental Intensity (Wald et al. 1999a). Conceptually, any combination of these measured or estimated ground motion parameters and any damage relationships that can be pre-computed, and produce a 3- or 4-state discrete output can be accommodated with the current system. At present, three common approaches are being used to provide users with an indication of damage: HAZUS-based, Intensity-based, and customized damage functions.

### PREDEFINED (HAZUS) STRUCTURE TYPES

For users whose portfolio of structures is comprised of common, standard designs, ShakeCast offers a simplified structural damage-state estimation capability adapted from the HAZUS-MH earthquake module (NIBS and FEMA 2003). For any site of interest, the user begins by selecting from among the available HAZUS model building types (Table 1), of which there are 36 (NIBS and FEMA 2003). “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).

**Table 1.** HAZUS-MH earthquake model building types (NIBS and FEMA 2003, Table 3.1)

| No. | Label | Description | Height: Range Name | Height: Range Stories | Height: Typical Stories | Height: Typical Feet |
|---|---|---|---|---|---|---|
| 1 | W1 | **Wood, Light Frame** (≤5,000 sq. ft.) | | 1–2 | 1 | 14 |
| 2 | W2 | **Wood, Commercial and Industrial** (>5,000 sq. ft.) | | All | 2 | 24 |
| 3 | S1L | **Steel Moment Frame** | Low-Rise | 1–3 | 2 | 24 |
| 4 | S1M | | Mid-Rise | 4–7 | 5 | 60 |
| 5 | S1H | | High-Rise | 8+ | 13 | 156 |
| 6 | S2L | **Steel Braced Frame** | Low-Rise | 1–3 | 2 | 24 |
| 7 | S2M | | Mid-Rise | 4–7 | 5 | 60 |
| 8 | S2H | | High-Rise | 8+ | 13 | 156 |
| 9 | S3 | **Steel Light Frame** | | All | 1 | 15 |
| 10 | S4L | **Steel Frame with Cast-in-Place Concrete Shear Walls** | Low-Rise | 1–3 | 2 | 24 |
| 11 | S4M | | Mid-Rise | 4–7 | 5 | 60 |
| 12 | S4H | | High-Rise | 8+ | 13 | 156 |
| 13 | S5L | **Steel Frame with Unreinforced Masonry Infill Walls** | Low-Rise | 1–3 | 2 | 24 |
| 14 | S5M | | Mid-Rise | 4–7 | 5 | 60 |
| 15 | S5H | | High-Rise | 8+ | 13 | 156 |
| 16 | C1L | **Concrete Moment Frame** | Low-Rise | 1–3 | 2 | 20 |
| 17 | C1M | | Mid-Rise | 4–7 | 5 | 50 |
| 18 | C1H | | High-Rise | 8+ | 12 | 120 |
| 19 | C2L | **Concrete Shear Walls** | Low-Rise | 1–3 | 2 | 20 |
| 20 | C2M | | Mid-Rise | 4–7 | 5 | 50 |
| 21 | C2H | | High-Rise | 8+ | 12 | 120 |
| 22 | C3L | **Concrete Frame with Unreinforced Masonry Infill Walls** | Low-Rise | 1–3 | 2 | 20 |
| 23 | C3M | | Mid-Rise | 4–7 | 5 | 50 |
| 24 | C3H | | High-Rise | 8+ | 12 | 120 |
| 25 | PC1 | **Precast Concrete Tilt-Up Walls** | | All | 1 | 15 |
| 26 | PC2L | **Precast Concrete Frames with Concrete Shear Walls** | Low-Rise | 1–3 | 2 | 20 |
| 27 | PC2M | | Mid-Rise | 4–7 | 5 | 50 |
| 28 | PC2H | | High-Rise | 8+ | 12 | 120 |
| 29 | RM1L | **Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms** | Low-Rise | 1–3 | 2 | 20 |
| 30 | RM2M | | Mid-Rise | 4+ | 5 | 50 |
| 31 | RM2L | **Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms** | Low-Rise | 1–3 | 2 | 20 |
| 32 | RM2M | | Mid-Rise | 4–7 | 5 | 50 |
| 33 | RM2H | | High-Rise | 8+ | 12 | 120 |
| 34 | URML | **Unreinforced Masonry Bearing Walls** | Low-Rise | 1–2 | 1 | 15 |
| 35 | URMM | | Mid-Rise | 3+ | 3 | 35 |
| 36 | MH | **Mobile Homes** | | All | 1 | 10 |

**Table 2.** HAZUS-MH guidelines for selection of damage functions for typical buildings based on UBC seismic zone and building age (NIBS and FEMA 2003, Table 5.20)

| *UBC Seismic Zone (NEHRP Map Area)* | Post-1975 | 1941–1975 | Pre-1941 |
|---|---|---|---|
| **Zone 4 (Map Area 7)** | High-Code | Moderate-Code | Pre-Code (W1=Moderate-Code) |
| **Zone 3 (Map Area 6)** | Moderate-Code | Moderate-Code | Pre-Code (W1=Moderate-Code) |
| **Zone 2B (Map Area 5)** | Moderate-Code | Low-Code | Pre-Code (W1=Low-Code) |
| **Zone 2A (Map Area 4)** | Low-Code | Low-Code | Pre-Code (W1=Low-Code) |
| **Zone 1 (Map Area 2/3)** | Low-Code | Pre-Code (W1=Low-Code) | Pre-Code (W1=Low-Code) |
| **Zone 0 (Map Area 1)** | Pre-Code (W1=Low-Code) | Pre-Code (W1=Low-Code) | Pre-Code (W1=Low-Code) |

The user also selects for each facility its building-code era, of which there are 4 (high code, moderate code, low code, and pre-code; Table 2). 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 exist (e.g., high-code unreinforced masonry bearing wall), so in total there are 128 choices of HAZUS model building type and code era. Note that code era is largely a function (Figure 5, ICBO 1997) of location and year built, so in principal ShakeCast could simplify the user's job of selecting a code era by asking for era of construction (pre-1941, 1941–1975, or post-1975) instead, and looking up the code era via internal GIS database (a planned enhancement).

The user then selects between 3 and 4 alert levels, meaning that any facility affected by an earthquake is noted green, yellow, or red (3 levels), or alternatively green, yellow, orange, or red (4 levels). These colors index the likely structural damage state of the facility, in HAZUS terms: 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. These terms (slight, moderate, etc.) are described via likely effects of the earthquake on the structural system. For example, for a small wood-frame building (W1, regardless of code era), "green" corresponds to "Undamaged or small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer." These descriptions can be found in the HAZUS-MH Technical Manual (NIBS and FEMA 2003) Section 5.3.1.

When an earthquake occurs, its shaking intensity at each facility location is estimated in terms of ShakeMap's interpolated peak horizontal ground acceleration (PGA).

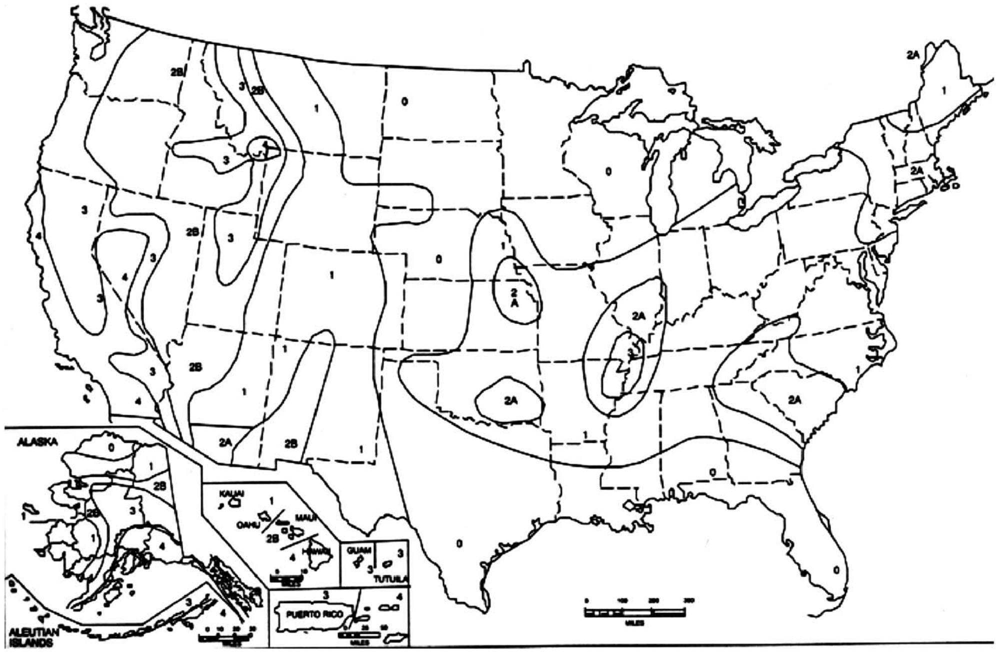


**Figure 5.** Seismic zone map of the United States (ICBO 1997, Fig. 16-2).

Buildings and ground motions are highly variable, even given a model building type and PGA level, so it is uncertain the exact level of PGA that will cause a given facility to experience structural damage of any particular level. The relationship between PGA and damage state is therefore probabilistic, meaning for example that one can estimate the *probability* of a given building experiencing a given structural damage state when the building experiences a certain level of PGA. It is more convenient here to estimate the PGA at which there is a given probability of damage exceeding a given structural damage state. In ShakeCast, a facility is indicated as damage level *x* (i.e., green, yellow, orange, or red) when the PGA is such that there is at least a 50% probability of exceeding the corresponding HAZUS structural damage state and less than a 50% probability of the next-higher HAZUS structural damage state. These PGA values are taken from the HAZUS-MH Technical Manual Table 5.16a-d.

For ground motion parameters, ShakeMap uses the maximum peak value of the two horizontal components whereas HAZUS requires geometric mean values; as for other ShakeMap/HAZUS products, we reduce the peak motion values on the ShakeMap grid by 15% to convert (approximately) to geometric mean prior to evaluating potential damage. Since ShakeMap is currently available in the western US, we use the HAZUS western US spectral shape factors, and assume mid-magnitude ranges and B-C soil amplification factors.

**Table 3.** Layout of damage lookup tables

| Field name | Type | Description |
|---|---|---|
| ID | Integer | A unique index |
| Facility Type | String | HAZUS model building type and seismic design level |
| Color | String | Green, Yellow, Orange, or Red |
| Damage Level | String | Equivalent HAZUS structural damage level(s) |
| Low Limit | Integer | Intensity with 50% probability of this damage level occurring |
| High Limit | Integer | Intensity with 50% probability of next damage level occurring |
| Metric | String | Intensity metric |

For use in ShakeCast, two database lookup files in CSV format are provided for each structure/zone/code level combination; one for a 3-level damage scheme, the other for a 4-level damage scheme. Each has 7 columns or fields, listed in Table 3. The fields correspond to data appearing in the ShakeCast Facility Administration screen. To use these predefined damage schemes, the local ShakeCast administrator simply chooses the number of levels (3 or 4) and uses the drop-down menu to assign the appropriate structure type, zone, and code-level to each facility. For numerous facilities, these structure-type assignments can be quickly populated into the users' ShakeCast facility database with the facility import tool provided; it ingests a spreadsheet, CSV, or table of facilities, locations, and structure type assignments.

## INTENSITY-BASED

For locations with poorly established damage relationships, that contain disparate structures, or that represent exposed populations (cities, for example), users may simply want to be notified when the shaking reaches or exceeds some predefined intensity levels. In this way, users fall back on the average effects described for each Modified Mercalli Intensity (MMI) value. Users select the range of intensities that constitute thresholds of concern (for example, green, yellow and red at intensity ranges MMI $<$ V, V $\leq$ MMI $<$ VII, and MMI $\geq$ VII, respectively) and receive notifications based on ShakeMap Instrumental Intensity values if the trigger thresholds assigned are matched or exceeded.

The Intensity-based approach is also useful for an organization's preliminary installation of ShakeCast while they further investigate the development of damageability relationships specific to their inventory, perhaps via performance-based earthquake engineering analysis.

## CUSTOMIZED DAMAGE LEVELS

Users who have previously analyzed the damageability of their structures can encode their fragility information in look-up tables that contain discrete ground-motion thresholds between damage states. For instance, as described in the section on ShakeCast users, the California Department of Transportation (Caltrans), has produced its own set of damage functions that correspond to the specific details of each California bridge or overpass in its jurisdiction. Having detailed, structure-specific information about its inventory, allows Caltrans to more adequately assess potential damage due to variable design vintage, retrofit state, natural periods, skewnesses, and other unique structural aspects.

# SHAKECAST USES AND USERS

In this section we begin to explore the potential uses of ShakeCast by describing approaches taken by some current ShakeCast users. As a benefit for users, we maintain and moderate a ShakeCast Users Forum (listserv) where users can exchange ideas and solutions, or query the developers for answers/ideas that may be of benefit to other users. Since the USGS made ShakeCast2 software available online in November, 2007, dozens of potential users have downloaded the full software package. The personnel and cost of installation, implementation, operations, and maintenance of ShakeCast2 can vary depending on the size and extent of an organization's inventory, and importantly, what level of effort is required to establish the desired sophistication for inventory vulnerability functions. As a rough guide, a utility, for example, may need to purchase a dedicated personal computer and expect perhaps a 1/8 time effort on the part of a capable systems engineer or equivalent personnel.

## FULL SHAKECAST USERS

### California Department of Transportation (Caltrans)

Of all current ShakeCast users, Caltrans perhaps has the greatest exposure of infrastructure. It is responsible for over 11,000 bridges and overpasses in California and operates road management out of 12 Traffic Management Centers (TMC), which act as nerve centers for this critical California lifeline. Following a major earthquake, Caltrans faces an array of decision-making challenges. One urgent task is to assess the condition of all bridges and roadway corridors in the highway system. Timely response is important to ensure public safety, aid routing of emergency vehicle traffic, and (re-) establish critical lifeline routes. Caltrans recognizes that ShakeMap, as used in conjunction with ShakeCast, can dramatically improve its post-earthquake situational awareness (Wald et al. 2003).

Given the scale of Caltrans inventory, a focused post-earthquake response is essential. The primary method for bridge and roadway damage and functionality assessments is a thorough onsite inspection by trained personnel from Caltrans' maintenance, construction, and design units. However, procedures used in the past for establishing inspection priorities were relatively unfocused because of imprecise information about the distribution of damaging levels of shaking. Absent such information, the practice had been to use the epicentral location, find the closest mapped fault, and develop a list of bridges within a specified buffer zone surrounding the fault and epicenter areas. Maintenance crews were dispersed widely within that region to perform initial reconnaissance.

The problem with epicenter-based or whole-fault based buffer zones is that earthquake shaking levels vary dramatically within the buffer zone. Even if the epicenter is located near a mapped fault, an earthquake rarely ruptures over the entire mapped length. Furthermore, ground shaking at the same distance from a rupture zone varies by nearly a factor of 10 because of various effects such as fault rupture directivity, deep basin effects, and local site response. Buffer zones large enough to account for all areas that *could* be strongly shaken tend to include wide swaths with no damage, thus diverting inspection resources away from critical needs.

In general, highway and bridge engineers are well situated to take advantage of the ShakeCast system since they are concerned with numerous, distributed facilities and they typically have knowledge of the seismic vulnerability of their structures, a major benefit for rapid estimation of potential damage based on ShakeMap ground motion metrics. Hence, ShakeCast is a natural tool for providing Caltrans with an instantaneous snapshot of the likelihood of damage to each facility, allowing them to prioritize rerouting traffic, closures, and inspections following a damaging event. Caltrans evaluates potential impact using ShakeMap's 0.3-sec and 1.0-sec spectral acceleration estimates, in conjunction with thresholds derived from fragility functions.

To create these thresholds, Caltrans compiled information from the following sources: the 2004 Structures Maintenance Automated Report Transmittal (SMART, Caltrans 2002) database, bridge and retrofit status records, the 2003 National Bridge Inventory (NBI, USDOT 2005), the 2002 NEHRP 1-sec spectral acceleration site-condition maps from the California Geological Survey (CGS, Wills et al. 2000), and the 1996 Caltrans Seismic Hazard Map. A spatial analysis was then done to extract the latest soil and fault data for each bridge structure in the inventory.

Combined with the other bridge information, the result was a large database containing all available summary data for each structure. Basoz and Mander's fragility functions (1999), which currently represent the state of the art in category-based bridge fragility, use approximately 20 parameters, mostly those available from the NBI. The new data set by contrast contains over 175 parameters, which suggests the possibility of fragility relationships that account for additional, important bridge features, and therefore might produce lower uncertainty in bridge damage state. For the purposes of ShakeCast, the Mander and Basoz (1999) relationships are appropriate for a first-cut post-earthquake estimate of the status of the Caltrans inventory, helping to determine where damage is likely to be, though of course other things being equal, less uncertainty makes for better decisions. It is anticipated that the success of the ShakeCast system will allow Caltrans to expand its internal usage to include other critical facilities and hazards, such as tunnels and landslides.

Caltrans has served as one of ShakeCast's primary testbeds. It has provided useful feedback on several aspects of the system. It was instrumental in switching from a web-based to a scripted inventory database loading procedure, which is crucial for serving an organization concerned with a large number of structures. Caltrans also suggested enhancements in the event notification procedures and event types, which involve actual, scenario, test, and heartbeat event types and provided advice for better documentation for system tests. These suggestions were implemented in the software and user documentation. Motivated by a desire for additional ShakeCast development, Caltrans provided direct support for further enhancements, effectively funding ShakeCast2.

### California Division of Safety of Dams

With an inventory of about 1,200 dams in the State of California, the California Division of Safety of Dams must respond to any significant earthquake with widely distributed inspection experts. The Dam Safety group uses the ShakeCast system to notify engineering and field-inspection staff via e-mail and mobile phones of the occurrence of potentially damaging shaking at dams in their regions of responsibility (Fraser et al. 2007).

Dam Safety currently uses Instrumental Intensity as its ShakeCast ground-motion parameter. About 80% of the dams are earth dams; the rest are concrete gravity or arch systems (B. Fraser, Div. of Dam Safety, personal communication 2007). Thresholds for intensity-based notifications were assigned based on experience from the 1989 Loma Prieta earthquake, but the Division is actively investigating the use of spectral acceleration, considering the types and natural periods of the dams it operates.

### Los Angeles Unified School District (LAUSD)

LAUSD is using ShakeCast to help improve earthquake monitoring and emergency response in southern California, where it is responsible for nearly 900,000 students, 80,000 faculty and staff, 12,000 buildings, and 1,100 schools. Students and schools are spread across an area larger than entire city of Los Angeles. Under an agreement with the City of Los Angeles, LAUSD buildings are used for emergency operations of the city, serving as emergency shelters to be managed by the Red Cross. Hence, knowing which structures are most likely *damaged* is critical for response, and know which structures are likely *not damaged* is vital for response and recovery, that is, locating emergency shelters.

## SHAKECAST "*LITE*" USES

As described earlier, ShakeCast "*Lite*" is simply a way to reliably, rapidly, and automatically retrieve any ShakeMap product for any ShakeMap regions to one's computer system. It also allows one to configure any post-processing scripts to be run after retrieving the product. A simple configuration file allows one to select which regions, which specific products to retrieve (GIS format, for example), and which, if any, command or script to run following download. Numerous users take advantage of this tools, and a number of creative uses have been implemented.

For example, ShakeCast "*Lite*" can easily be configured on the user's end to automatically transfer ShakeMap files (e.g., GIS shapefiles) to a specified location and initiate additional software processing tools and actions, for example, starting up complex loss-estimation calculations via HAZUS or other software applications. FEMA uses this approach to download ShakeMap HAZUS-formatted GIS files immediately after they are produced for events in the United States (D. Bausch, personal communication 2007). CBS news retrieves maps in KML format for news broadcast via their customized Google Earth-based Seismic Viewer.

Numerous individuals, including the primary author, retrieve and open new or updated ShakeMaps for all regions and open them in a new Web browser window. If a system is offline (a laptop, for example), maps catch up immediately after connecting back up to the Internet.

## SHAKECAST "*REMOTE*" USES

One use for ShakeCast within the USGS is to summarize shaking intensity at a specific list of cities for a given ShakeMap. ShakeMap is now produced for all earthquakes around the globe of magnitude 5.5 or larger. Globally, these ShakeMaps are primarily predictive and thus lack the resolution and relative certainty of shaking estimates for maps made within regions of dense seismic instrumentation for which it was principally developed. Regions in the United States that have ShakeMap operating with reasonable (but variable) seismic station coverage include major portions of California, Washington, Oregon, Nevada, Utah, Hawaii and Alaska. Other regions are improving station coverage over time. Hence, because ShakeMaps are produced for any region of the world, ShakeCast can be deployed for any exposure of facilities worldwide, again with more uncertainty in the results in regions not specifically listed above.

We use the term "facilities" loosely; at the NEIC we treat cities as "facilities" and run ShakeCast to determine shaking intensity levels at cities within the US around the global any time a ShakeMap is produced. At NEIC, ShakeCast is configured to list the cities, their populations, and the intensity estimated at each city, generating an HTML e-mail notification that proves very useful for NEIC analysts and for other response purposes. Ultimately, these city-based notifications will be integrated as an option in ENS, the USGS Earthquake Notification Service, but this will not reduce the need for critical users to put their own inventory in an in-house ShakeCast system.

An additional use of ShakeCast "Remote" is to notify specific users of Shaking levels at generally publicly available facilities. USGS notifies Veteran Administration (VA) officials of the shaking intensity at VA hospital locations around the country. The VA plans to further establish damage functions for individual structures at each site and ultimately implement the full ShakeCast system in house.

## SCENARIOS AND HISTORIC EARTHQUAKES

In addition to real-time notification, an additional major benefit of the ShakeMap-ShakeCast combination is its built-in capacity to generate and deliver Scenario Earthquakes (Figure 4) for evaluating system performance and response capabilities under earthquake conditions. ShakeMap is now used routinely to generate Earthquake Scenarios for many users and numerous scenarios are available online for most ShakeMap regions. ShakeCast further allows users to test their response capabilities with the same notification tools that will be available when responding to a real earthquake. With the

ShakeCast configurations, all or just a subset of the users who receive regular earthquake notification can be assigned to receive scenario events, so scenarios can be practiced at a predetermined level of participation within an organization or group of organizations.

As with scenarios, ShakeCast users can access any historic earthquake run through ShakeMap and process to evaluate either the impact that such an event would have or to assess the level of accuracy with their vulnerability assessments (in comparison to actual impacts due to a historic event). What's more, by injecting all regional and sufficiently strong ShakeMaps into their local ShakeCast system, a user can evaluate how often and to what degree any of their inventory has been shaken in the past, a useful analysis that would otherwise be more difficult to make.

## ONGOING DEVELOPMENTS

While the ShakeCast software (ShakeCast2) is currently quite customizable in terms of facilities, fragilities, and notifications, we anticipate additional adaptations will be made by resourceful users since the open-source code is provided. If warranted, any such innovations can then be provided back into the tool kits provided with later updates of the ShakeCast system. In the meantime, ongoing software development of ShakeCast continues at the USGS, and much of it is motivated by current users' experiences and recommendations. ShakeCast, release Version 2.1, is expected to include the following enhancements:

- Additional predefined facility structure types and vulnerability functions, including pipeline, ground deformation, and landslide damage potential.
- Modified HAZUS damage state estimates to accommodate ShakeMap peak (rather than geometric mean) ground motions and use ShakeMap grid-based shaking uncertainty values explicitly. Allow for Vs30 site conditions and regionalized spectral shapes.
- In addition to maps, 2-D profiles along pipeline corridors will be provided.
- User can associate a specific structure and seismic instrument such that data from the recording will be used preferentially over interpolated shaking values from ShakeMap.
- Improved GIS import options will be added (currently, users can readily import XML data into GIS).
- Addition of support for UNIX/ LINUX operating systems (currently runs on Windows).
- Compute and visualize uncertainties in ground shaking and damage likelihood.
- Improved re-notification logic, allowing flexibility in conditions for re-alerting (for example, if damage state changes for one or more facilities, among other possibilities).

Optional, automatic updates of the software will be provided via the RSS feed from USGS Web servers.

## DISCUSSSION AND CONCLUSIONS

ShakeCast is a simple application that provides an opportunity for greatly improving post-earthquake situational awareness among potential users, particularly companies, utilities, and agencies whose earthquake exposure is both widespread and of variable vulnerability. Those motivated to take full advantage of the ShakeMap/ShakeCast combination must have or develop a reasonable evaluation of the fragilities of their inventory, be they structures or other facilities. It is anticipated that the need to improve the accuracy of estimated damage to a portfolio will further motivate critical utilities and other entities to make rigorous assessments of the range of vulnerabilities of structures and infrastructure within their inventories.

Critical facilities can benefit from site-specific recordings rather than relying on ground motions interpolated from ShakeMap from nearby stations. ShakeMaps for different earthquakes come with highly variable constraints from strong motions stations, and therefore the uncertainties vary not only from event to event, but within the domain of a map for a single earthquake (e.g., Lin et al. 2005). While inherent uncertainties are due to the combined effects of inferring and interpolating ground motions, as well as from probabilistic damage functions, the former can be effectively removed by siting strong motion instruments at the site of interest. Indeed this is the case for many dams and VA hospitals, for example. ShakeCast was developed with this potential in mind, allowing users to associate facilities with stations, bypassing the ShakeMap inferences if a station and facility are co-located. For seamless access to facility parametric data as well as improving overall ShakeMap quality for other users, such site recordings should be telemetered through the same regional network approaches used in ShakeMap, including the USGS Advanced National Seismic System (ANSS) and the USGS National or the California Department of Conservation's Strong Motion Instrument Programs.

Future efforts are also needed in instrumentation and communications as well as in rapidly assessing multiple channels of free-field and structural-monitoring recordings to better gauge the impact on individual structures. Likewise, more investigation is needed to incorporate the numerical uncertainty values now provided by ShakeMap (Lin et al. 2005) directly into uncertainties in damage assessments (Luco and Karaca 2007). The grid-based shaking uncertainty values are already available to ShakeCast users via the ShakeMap grid XML file, but they are typically not used explicitly in computing loss uncertainties.

Finally, we anticipate additional and improved predefined damage functions, not only for structures, but also for pipelines, landslide and liquefaction potential, and other forms of "damage" as the use of ShakeCast is expanded. Reducing the uncertainty in rapid impact assessments will benefit from both higher density instrumentation, reducing the hazard input into ShakeCast, as well as from a better understanding of a wide variety of damage functions for different types of inventory as they correlate to ShakeMap peak parameters. If more comprehensive functions (involving shaking duration, for example) are required for more accurate loss estimates, ShakeMap will need to accommodate these parameters as well.

Note that ShakeCast can only assess potential impact to inventory that resides in the domain of the ShakeMap generated for a given earthquake. For additional situational awareness of any recorded seismic activity either regionally, nationally, or globally, it is recommended that users who need to be aware of all significant seismic activity subscribe to the USGS Earthquake Notification Service (ENS, http://earthquake.usgs.gov/ens/) for their regions of interest, in addition to implementing ShakeCast for direct assessment of their own inventory.

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