Using ShakeMap and ShakeCast to Prioritize Post-Earthquake Dam Inspections

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Abstract: The use of ShakeMap in conjunction with the U. S. Geological Survey (USGS) ShakeCast software provides an effective means to notify engineering and field inspection staff of the occurrence of a potentially damaging earthquake and its potential impact at all dam locations around the State of California. The ShakeCast software automatically downloads a ShakeMap immediately after it is generated, and evaluates whether selected sites have experienced ground motions exceeding predefined threshold levels. ShakeCast automatically sends a customizable notification to identified individuals via e-mail, PDA, or cell phone apprising them of the results. Instrumental Intensity, based on a combined regression of recorded peak acceleration and velocity amplitudes, is our chosen threshold parameter because it better indicates damage potential than PGA alone. In the absence of custom threshold values determined by engineering analysis, we have selected Instrumental Intensity 5 as the "damage possible" threshold and Instrumental Intensity 8 as the "damage likely" threshold. The latter was selected because a significant percentage of dams that experienced Instrumental Intensity 8 and greater in the Loma Prieta and Northridge earthquakes, were damaged.

Introduction

Dam inspections immediately after a potentially damaging earthquake are required to insure structural integrity. In the event a dam has suffered damage, quick decisions are needed to protect life and property. The Division of Safety of Dams (DSOD) staff notifies dam owners of the need for such inspections immediately after the occurrence of moderate and large earthquakes in California. In many cases, DSOD staff is immediately dispatched to personally inspect the dam and coordinate any emergency action that is required. With over 1,200 dams under our jurisdiction, a major earthquake in a metropolitan area can result in the need to inspect over 100 dams distributed over a wide area in the hours and days after the event.

Information about the location and severity of an earthquake event has improved significantly in recent years. For many years, the magnitude and epicenter was the only information available immediately after an earthquake. Although helpful, magnitude and epicenter do not provide reliable information on the distribution and intensity of strong ground motions. Moving beyond magnitude and epicenter is especially important for the larger magnitude events in which large fault dimensions can result in significant shaking over immense regions, particularly in areas of variable geology where site amplification can further complicate the pattern of strong shaking. With the advent of telemetric strong motion networks such as the California Integrated Seismic Network (CISN), details of the ground shaking can be obtained, transmitted and reported in near real time via ShakeMap (Wald et al., 1999).

This paper discusses the Division of Safety of Dams use of the USGS-developed ShakeCast software, a program that retrieves ShakeMap, evaluates the earthquake's likely effect on engineered structures, and notifies personnel immediately after the occurrence of the event on a 24 hour/7 day basis. We describe the technical aspects of the ShakeCast software and the current implementation of the software at the Division of Safety of Dams. We also discuss potential future modifications to the ShakeCast software, more detailed dam vulnerability function assessments, and additional seismic monitoring that could all further contribute to improve our ability to effectively prioritize post-earthquake dam inspections.

Technical Description of ShakeCast

ShakeCast, short for ShakeMap Broadcast, is a fully automated system for delivering specific ShakeMap products to critical users and triggering established post-earthquake response protocols. The computer application is built upon open source code. ShakeCast employs the Apache Web server and 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 (Wald et al., 2008).

ShakeCast was developed with the intent of providing the users the ability to run their own response operations in-house rather than providing notification as a centralized USGS service. The rational for this decision includes data security and quality assurance, as specific information on a given structure, such as fragility and contact information, can be proprietary, and can change often. In addition, users will need to make periodic changes to the facilities database and responders contact information. Needs of individual agencies vary, and the software is flexible enough to allow customization of the notification content and protocols.

Secure automated electronic delivery of information to distributed systems is a primary concern for operators of computer networks, and assuring connectivity via "push" technology has become a maintenance nightmare. By utilizing Really Simple Syndication (RSS) and interval polling, the users' computer initiates all

communication with the redundant USGS Web servers that host ShakeMaps, and retrieve selected products as a request rather than a data "push". This allows ShakeCast users to avoid most typical corporate and governmental agency concerns and firewall restrictions.

The Division of Safety of Dam uses the full version of the ShakeCast software, developed for critical users, which required the user to provide robust communications, power reliability, and round the clock computer support. It is further expected that critical users develop their own facility-specific vulnerability functions for more reliable assessments of potential damage. The new version of program (ShakeCast2) also provides two easier-to-use, limited function versions for non-critical users called ShakeCast "Lite" and ShakeCast "Remote" (see Wald et al., 2008, for more details).

Previous Post-Earthquake Response Procedures at DSOD

The Division of Safety of Dams historically has relied on the seismographic network operated by the Department of Water Resources (DWR) as part of the California State Water Project for notification of the occurrence of a major earthquake. The DWR network consists of instruments at the major facilities of the State Water Project as well as data feeds from additional instruments operated by the USGS and Caltech, to provide coverage throughout the state. When the network records an event, acquisition software automatically calculates the magnitude and epicenter, which would be confirmed by a seismologist within an hour of the occurrence.

Upon telephone notification, Division staff would input the magnitude and epicenter into a Fortran-based computer program that identified jurisdictional dams within a magnitude-dependant circular search area. The search area was selected based on a standard attenuation function to define the area believed to have experienced a PGA of 0.05g or greater. Division staff immediately contacted the dam owner and required that a post-earthquake inspection be performed of the facility. For events greater than magnitude M5.5, Division staff traveled to the region to personally inspect the dams.

Although a magnitude and epicenter certainly provides timely information on the occurrence, size, and general location of an earthquake, the approach had several limitations. The decision to inspect is based on assumed rather than observed parameters. For most earthquake events, the ground motion distribution is not circular about the epicenter; rather it is more elliptical along the rupture zone. Therefore, dams away from the rupture probably do not experience the threshold ground motion. During larger magnitude events with extended rupture dimensions and forward rupture directivity, high ground motions can occur at very large distances from the epicenter. Important geologic controls on the severity of ground motion, such as soil site amplification, were not considered. Finally, the magnitude and epicenter provided little insight into the actual character of the ground motion, such as

peak amplitude, frequency content, or durational aspects, which are the fundamental predictors of the performance of engineered structures.

With the development of Web-based ShakeMap reports in the late 1990's, the Division moved toward using "observed" rather than "predicted" ground motion data. This first consisted of physically overlying maps containing manually plotted areas, for example, overlying the 0.05g-observed area and 0.05g-predicted radius about the epicenter. During the planning of staff inspections in response to the 2000 M5.1 Napa Valley earthquake it was found that the observed area actually extended further south than the predicted area. This required that dams that fell within either area be inspected. In retrospect, a similar situation occurred during the 1989 M6.9 Loma Prieta earthquake because of soil amplification on the margins of San Francisco Bay; but the phenomena could not recognized immediately after the event because strong motion data was manually compiled and distributed and thus not available for rapid post-earthquake decision making.

When DSOD acquired GIS capability in 2002, we developed an application that directly compares observed ground motion from ShakeMap to a layer containing our jurisdictional dams (Figure 1). The ShakeMap shape file was manually downloaded from the Internet and the ground motion data were overlain on a composite base map containing shaded surface relief, fault traces, jurisdictional dams, major roads, and

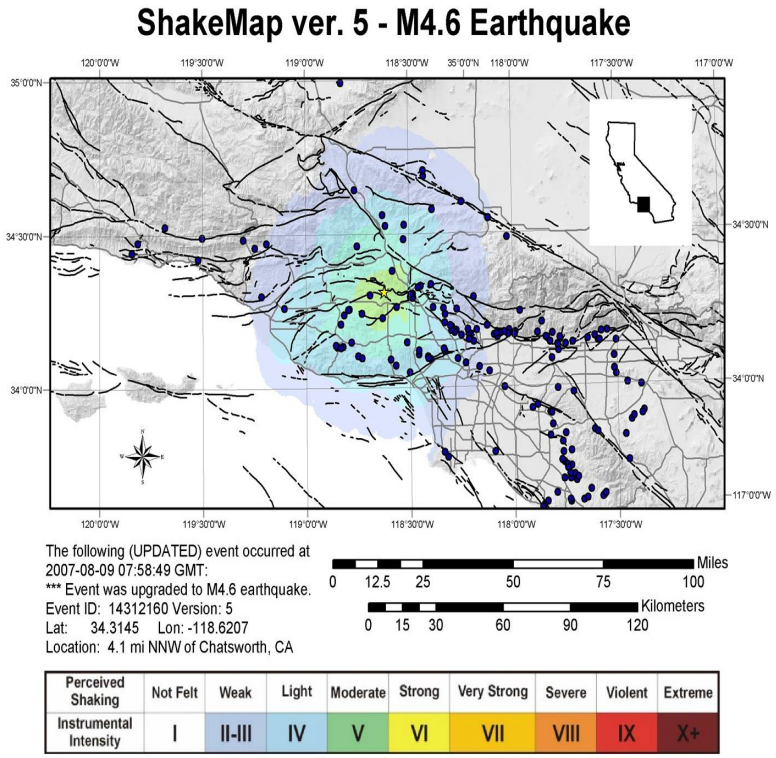

Fig. 1. GIS-developed overlay of ShakeMap and jurisdictional dams

populated areas compiled using ArcView 8.3 software. A table listing the interpolated ground motion at each jurisdictional dam accompanied the map. The GIS software is flexible enough to allow the operator to include any auxiliary information deemed necessary to coordinate post-earthquake dam inspections. Furthermore, the map and table could be readily converted to a file type such as Adobe Acrobat, allowing it to be conveniently e-mailed out of the office. However, while computer-savvy staff can create the map easily, the GIS software has a relatively steep learning curve and generating the map was time consuming for staff.

Current ShakeCast Capabilities at DSOD

The USGS approached the Division in 2004 and asked if we were interested in evaluating the beta version of the ShakeCast software. Since acquiring the software, a few moderate size earthquakes have occurred in California and we have been able to provide feedback regarding the functionality of the program.

Initially, the ShakeCast software ran on a computer located in our offices in Sacramento. However, because the building is subject to periodic power outages and there is no around-the-clock staffing, our system reliability was questionable. The solution involved entering into a cooperative agreement with the seismologic staff from the Department of Water Resources State Water Project, the same group that has historically provided DSOD with earthquake alerts. Two identically equipped Dell Power Edge 2850 computers were purchased to run the ShakeCast software. Each computer was equipped with three 36 GB hard drives to provide back up in case of a hard drive crash.

The primary system is housed in a secure computer area in DWR headquarters, a facility with around-the-clock computer maintenance staffing. The backup system is located at the State Water Project Operations Center located several miles to the east, also a facility with 24-hour staffing. Both installations are “hardened”, with the servers rack-mounted and bolted to the floor, running on conditioned power with uninterrupted power supply (UPS) backup power source. The State Water Project Operations Center has additional provisions for emergency power, as State Water Project and California Flood Operations are located there.

Setting up the software required an upfront effort by a computer technician to load the software, and a staff geologist to act as data administrator. Loading the operating system for the early version of ShakeCast proved difficult, and maintaining the installation was challenging. The installation and software stability have been greatly improved in ShakeCast Version 2. The program issues a daily heartbeat, indicating that is working properly, which the data administrator monitors.

ShakeCast set-up requires the data administrator to enter the location of each dam, its fragility information, and manage notification protocols and contact information that are used in the event that any of the facility’s shaking vulnerability thresholds are exceeded. The data on the 1,200 jurisdictional dams were entered in bulk from

existing databases, and edits to data records can be accomplished either individually or by bulk reloading of an edited database file. For reference, the data administrator charges approximately 150 hours per year (8 percent of his total chargeable hours) to the various ShakeCast software development, maintenance and reporting activities.

Specifying Fragilities

ShakeCast can use any of the ground motion parameters currently transmitted by ShakeMap for specify fragilities. These include peak acceleration (PGA), peak velocity (PGV), response spectral acceleration (SA) at 0.3 second, 1.0 second, and 3 seconds, and Instrumental Intensity (Wald et al., 1999).

Since PGA is commonly used in simplified engineering analyses and since formulas that predict it have been available for many years, it is not surprising a PGA-based fragility was traditionally used to predict damage. However, this approach ignores important frequency-dependent and durational aspects that are important for certain structures.

An interim solution is using the Instrumental Intensity parameter for expressing fragilities. Instrumental Intensity is based on a combined regression of peak acceleration and peak velocity vs. observed Modified Mercalli Intensity for eight significant California earthquakes (Wald et al., 1999). The relationship to the Modified Mercalli Intensity Scale is for user convenience as Modified Mercalli intensities have been a historically important parameter in damage assessments.

Shake Cast (version 1) allowed three levels of fragilities to be set; damage unlikely (green alert), damage possible (yellow alert), and damage likely (red alert). In the absence of custom fragility assignments, an assignment of general fragilities is necessary. Our philosophy was to set the "damage possible" fragility low enough to include moderate levels of ground motion that could conceivably damage the weakest of dams and would thus, conservatively, warrant inspection. We chose Instrumental Intensity 5, based on its correlation with the 0.05g PGA threshold historically used by the Division. In reality, well-built dams will not be affected by this moderate level of shaking.

For the "damage likely" threshold, we wanted a set the fragility high so there was a likelihood damage had occurred. Early recognition of dams shaken at the severe levels is important to effectively prioritize post-earthquake inspections. We chose Instrument Intensity 8 as the "damage likely" fragility based on our analyses that indicate 35% to 50% of the dams that experienced Instrument Intensity 8 during the Loma Prieta and Northridge earthquakes were actually damaged to some degree.

Selecting custom fragilities for each dam is the best use of the software. Ultimately, each structure's fragility should be based on engineering analyses. This will be discussed in some detail below.

Custom Notifications

Earthquake notifications can be a text message to a cell phone, an alert to a pager, or e-mail message to a PDA or PC. Because the notifications occur on a 24 hour/7 day a week basis, we wanted the messages to be as clear and user-friendly as possible. ShakeCast offers users the flexibility to customize the style and content of messaging its triggers and this functionally is greatly expanded in Version 2. The cell phone and pager-based messages are somewhat abbreviated due to size limitations of cell phone messaging. However, e-mail transmission allows a clear detail message with considerable supporting information to be included. We transmit a table showing all dams that have been shaken above the fragility levels, along with hypertext links to web-based sources of addition information on the earthquake (Figure 2). Version 2 will take this further by allowing hypertext links to Web-based information on the affected infrastructure. It also automatically generates Web-based maps of shaking and facilities, which can be viewed in-house (Intranet) or linked via messages sent to users.

ShakeCast Event: Magnitude 4.6
ShakeMap (Unnamed Event) Version 5
Event Location: 3.1 mi NNW of Chatsworth, CA
Event Time: 2007-08-09 07:58:49
Generated at 2007-08-10 01:08:44
Reported by: Server ID = 2130, DNS = shakecast.water.ca.gov

Damage Summary
Number of Facilities Reported: 4
Max Value: MMI: 5.27; Acceleration: (not measured)
Number of Reports of Likely Damage: |NULL|
Number of Reports of Possible Damage: 4

Facility Damage Estimates from ShakeMap

Facility	Damage Level	Metric	Value	Exceedance Ratio
86-003 RUNKLE	Possible	MMI	5.27	0.090
775-000 PORTER ESTATE	Possible	MMI	5.16	0.053
6-004 CHATSWORTH	Possible	MMI	5.12	0.040
86-005 LAS LLAJAS	Possible	MMI	5.12	0.040

Note: the MMI values indicated are actually Instrumental Intensity rather than Modified Mercalli values.
Exceedance ratio is a ranking value which indicates the amount by which the threshold intensity is exceeded.
More information can be found regarding this event at
http://www.cisn.org/shakemap/nc/shake/ (Northern California) or
http://www.cisn.org/shakemap/sc/shake/ (Southern California)

Fig. 2. ShakeCast Damage Summary e-mailed to inspection staff

Future Improvements to DSOD Use of ShakeCast

ShakeCast currently provides a very functional means for recognizing the occurrence of an earthquake and provides an early assessment of structures that may have been damaged. The DSOD use of the existing technology is still in the growth stage, as we could do more with the existing technology. Providing custom fragility levels for individual engineered structures represents an area where immediate growth

can occur. Additionally, the ability to recognize when damage has actually occurred at a structure via ShakeCast, in conjunction with additional on-site monitoring, is an exiting idea that will be explored with the USGS as a future improvement to the system.

Custom Fragility Expressions

A custom fragility expression for ShakeCast involves two parts, selecting the appropriate ground motion parameter or parameters and then selecting values that are linked to the expected performance of the dam. When dealing with an inventory of over 1,200 dams this is a somewhat daunting task that will not be undertaken lightly. Several approaches are discussed in this section, as perhaps a phased approach is a more reasonable expectation for organizations with a large, complex facility inventories.

Certain types of dams such as hydraulic fill dams and multiple arch dams have historically poor performance during earthquakes. An initial step toward custom fragility could be to set values relating to a specific category of dam reflecting the current knowledge of their general earthquake resistance. In addition to design-based categories, age of dam, amount of freeboard, or consequence of failure, could also be used as criteria to assign dams to generalized fragility or risk categories.

Providing fragility values that are determined by detailed engineering analysis is the most defensible approach, but the most time consuming. Both the appropriate ground motion parameter and threshold value need to be selected based on analysis. For example, for a concrete dam whose stability has been confirmed by a peak stress analysis, the limiting spectral acceleration at the fundamental period of the structure may be the appropriate metric and fragility value to use. ShakeCast currently possesses the required functionality to deal with multiple peak ground motion parameters and assign unique vulnerability functions to individual structures. In addition, more than three levels of potential damage can be assigned, but this granularity warrants more detailed vulnerability functions than currently available for most dams.

However, many techniques used to analyze dams in California involve non-linear considerations and acceleration time histories are used to characterize the earthquake loading. This is especially true for earth dams in the higher seismic regions of the State. To calculate fragilities based on these analysis techniques, ShakeMap would need to transmit durational aspects of an acceleration time history, in addition to their peak parameters. A standard metric for this purpose is Arias Intensity (AI), defined as the integral of acceleration squared over the duration of the time history. AI is attractive as it combines both amplitude and durational aspects of an acceleration time history into a single parameter. The Division is considering augmenting its use of AI as a target parameter for the selection and modifications of time histories used in dam analyses (Howard et al, 2008). Use of the AI as a ground motion target has been made possible by the recent publication of two prediction equations that allow

estimation of AI as a function of magnitude, distance, site condition and style of faulting (Travasarou et al., 2003; Watson-Lamprey and Abrahamson, 2006). Based on these considerations, USGS ShakeMap developers are considering adding a duration-based parameter like AI to the list of ShakeMap parameters generated and delivered. However, any new parameters must be also computed by each seismic network contributing data to ShakeMap systems, so there are complications in adding new parameters.

On-Site Instrumentally Based Damage Detection

In as much as most dams do not have resident tenders and the time for even a well-staffed local agency to mobilize inspection teams after hours could be significant, direct instrumentally based identification of damage is an important long-term goal for dam safety. The USGS expects that future capacity can be made available on the ShakeCast system for multiple strong motion instrument arrays and other automated instrumentation data at a given site. The data transmittal and interpretation issues represent technical challenges that need to be addressed. However, to be a significant improvement over a well-constrained custom fragility assessment, the array needs to be designed so the occurrence of actual damage is confidently recognized and false alarms are minimized. There are several possible approaches for remotely recognizing indications of damage at a dam so that swift investigative or remedial action can be taken.

Conceivably, comparisons of the strong motion recordings from a suite of accelerometers at key locations around at a site might indicate the occurrence of damage. For example, lower than expected crest accelerations compared to adjacent abutment and toe records may indicate the inelastic response of an earth dam that resulted from sliding deformation. A more direct approach might be to instrument the crest of a dam with a series of GPS receivers at the survey monuments that could confidently record significant permanent crest settlement and horizontal deformations. The approach could involve other types of deformation measuring instrumentation such as continually reading inclinometers within the shells of an earth dam or extensometers mounted on the face of a concrete dam. Links to digital video camera images of the dam, a technology currently used routinely for traffic monitoring and security applications could provide confirmation of damage in conjunction with the methods listed above.

Conclusions

California Division of Safety of Dams is responsible for a large number of dams distributed over a wide, seismically active region. Under these conditions, DSOD recognizes the value of the USGS ShakeMap/ShakeCast systems as a means for automatically and more effectively coordinating post-earthquake response, in particular, initiating and prioritizing dam inspection activities. While DSOD has had a fully functional ShakeCast running under the prototype (Version 1), the updated Version 2 of ShakeCast provides additional functionality while simplifying use from

the users' perspective. To take full advantage of these developing tools for post-earthquake response, DSOD is further investigating methods for determining dam-specific vulnerability functions as well as exploring new approaches to on-site instrumentation that would allow for direct interpretation of damage at key facilities.

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