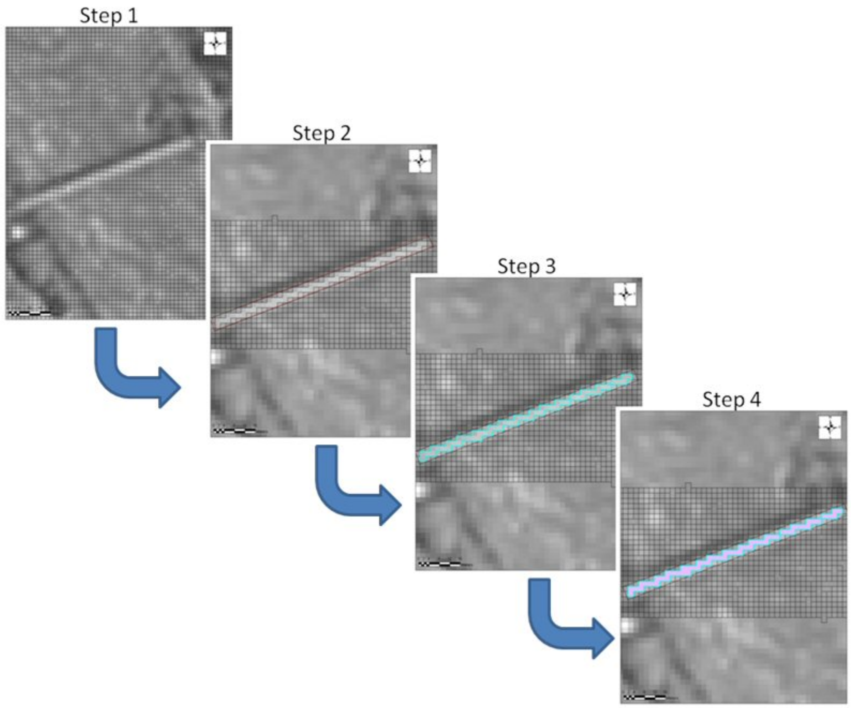
Final Report

Remote Sensing for Post Disaster Management of Freight Transportation Networks



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ABSTRACT

In the event of a natural disaster, assessing the status of our transportation network and repairing it is of critical importance to recovery efforts. We must also consider terrorist attacks worldwide in terms of infrastructure integrity assessment and recovery. Major roadways, if damaged at key locations, can be rendered useless for commercial traffic and more importantly, for emergency response and law enforcement vehicles. The delay or inability to answer emergency calls can lead to the loss of numerous lives. With the use of several geographic techniques and tools, these dangers can be minimized.

This report documents the test of developing a method of research utilizing remote sensing techniques to detect damage to road bridges. Through using derived pixel data and algorithms, pre- and post- earthquake images are compared to identify difference in the pixels' brightness values (BV's). With these techniques we can develop an expedient assessment of the transportation infrastructure's integrity throughout Shelby County, Tennessee if it were to play host to one of these disastrous evens. These techniques could be implemented throughout the rest of the world.

This research develops methodology for damage detection for a possible future event. Our goal was to test these methods of bridges change detection on an area for which we have data on the integrity of multiple bridges (damaged or not), and high spatial resolution imagery of both before and after an earthquake. We developed two methods, the Taff Method and the Hybrid Method, and found the Taff Method to give poor results and the Hybrid Method to give quite good results. In addition, we digitized coordinates of the outlines of bridges in Shelby County with high accuracy to expedite this analysis in Shelby County in the event of an earthquake or other disaster that may affect integrity of bridges throughout the County.

ACKNOWLEDGEMENTS

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This research would not have had the essential ground-truthing data without the combined efforts of MicroSoft, EPICentre, Multidisciplinary Center for Earthquake Engineering Research (MCEER), Earthquake Engineering Research Institute (EERI), ***Engineering and Physical Sciences Research Council*** (EPSRC), Earthquake Engineering Field Investigation Team (EEFIT), and ImageCat, Inc. Their team was able to travel to our Area of Interest (AOI) in 2008 shortly after the massive earthquake that devastated the Chinese countryside. The team made available locations of damaged bridges and the types of damage to the bridges, i.e. cosmetic or structural. This information was retrievable through the Virtual Disaster View, an online geographic information systems (GIS) tool developed for disaster cataloging purposes.

We would also like to recognize the work done by the Tennessee Department of Transportation Structure Inventory and Appraisal Office. The Structure Inventory and Appraisal Office was kind enough to assist with our research by letting us have their data on all the bridges in Shelby County, TN. The data included information on bridge features, most importantly, the bridge coordinates. This data will be used for future application of our research methods.

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INTRODUCTION

In extreme circumstances, such as natural disasters or terrorist attacks, the functionality of key infrastructure components, such as road bridges, is critical. Bridges become bottlenecks or gaps in transit when not functioning correctly. Damage to these components can influence our ability to continue commercial shipping or to supply aid to those who are in need of emergency response or law enforcement personnel, which can lead to undue loss of life. For example, the 1989 Loma Prieta Earthquake in California collapsed the Cypress Street Viaduct claiming 42 lives and the I-80 Oakland Bay Bridge claiming 1 life (Figure 1a and Figure 1b), and the Queen Isabella Causeway in Texas collapsed due to a barge collision in 2001 claiming 8 lives (Figure 1c). These collapsed bridges were part of a more important transportation network.

The Cypress bridge was destroyed completely and was finally rebuilt at the cost of 1.25 billion (Windmiller, 1999) dollars and reopened in 1997, nine years after the Loma Prieta earthquake. The Cypress Street Bridge was critically important to the Bay area's road network because it connected what was then the US-40/ SR-17 traffic to the Oakland Bay Bridge. The Queen Isabella Causeway was the only connecting roadway from South Padre Island to Texas. The estimated cost to fix the bridge was 5 million dollars, not including the cost of the ferries used in the mean time or the cost of convenience (TxDOT Public Information Office, 2002).

(a) Cypress Street Viaduct (b) Oakland Bay Bridge (c) Queen Isabella Causeway

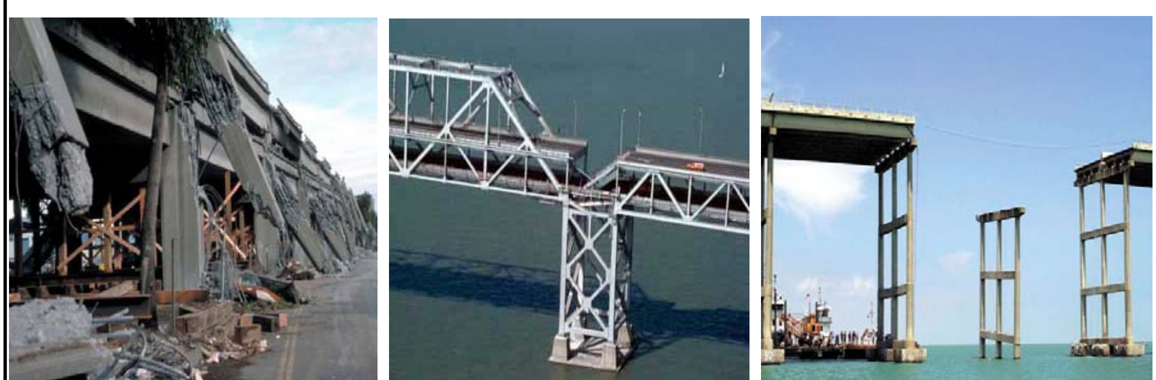


Figure 1. Bridge failures and collapses claiming lives and disrupting infrastructural systems. Images taken from Wikipedia; original sources: PD-USGOV-INTERIOR-USGS (Images a and b), and the U.S. Coast Guard Visual Information Server (Image c).

Shelby County has the 19th largest metropolitan city by population density (Memphis) according to the 2000 U.S. Census Bureau's census (U.S. Census Bureau, 2008). Of course, these data do not account for all of the people who travel through the city, by the interstate or connect with other flights in through Memphis International Airport. Shelby County also sits on top of the New Madrid seismic zone. Those two facts coupled together create a situation for which we must be prepared with appropriate knowledge and tools. Consider the damage and chaos that resulted after Hurricane Katrina, and the fact that New Orleans is only the 59th largest city by population according to the U.S. Census Bureau, about half the size of Memphis. One can only imagine the chaos that would ensue across the Mid-South's highway system when and if a major earthquake would occur on the New Madrid fault line.

There are about 500,000 bridges and 4 million miles of road at risk in the U.S. (Williamson 2002). Emergency preparedness and response to a disaster require an expedient way of gathering and processing massive amounts of damage data. Remote sensing using aerial photographs and satellite imagery can be a useful tool to aid this effort. However, methods must be developed that can use these available datasets and assess damage in an acceptable time frame.

Summary of Current State of Practice in Remote Sensing Damage Detection

The objective the project was to review current research on remote sensing application in transportation modeling and assess their applicability to the freight transportation network in the Memphis metro area. The following section will outline the state of practice in the field of remote sensing and transportation modeling in a post-disaster environment. Much of the information gathered for this study comes from the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The Remote Sensing Institute of MCEER serves as a hub of research and information about the application of remote sensing technologies and applications. One of the chief contributors to the work of MCEER and the remote sensing institute is ImageCat. Headed by Ron Eguchi, ImageCat is a research group that has pioneered the use of remote sensing in pre- and post-disaster environment.

There are several different types of remotely sensed data that could be used to assess the damage state of bridges and other freight transportation members after an earthquake. This study investigate: (1) satellite or aircraft optical imagery, (2) synthetic aperture radar (SAR), (3) aerial imagery, and (4) GPS based photo/video imagery.

ImageCat Report Summary

The remote sensing research that is most applicable to this project has been performed by ImageCat for a project funded by the U.S. Department of Transportation. The study, "Application of Remote Sensing Technologies in Post-Disaster Damage Assessment of Highway Systems," was published in 2004. Researchers from The University of California at Irvine and The University of Nevada at Reno were also involved in the project. The project focused on two types of remote sensing technology, damage detection algorithms based on optical imagery, the evaluation of Synthetic Aperture Radar (SAR) techniques. Their main research goal was to demonstrate that pre and post event images can be used to determine damage to transportation elements, more specifically bridges.

The optical imagery based damage detection methods were developed using bridge damage from the 1994 Northridge earthquake, and modified for use with higher resolution images with images from the Utah Department of Transportation. The result of the research was a two-part damage detection algorithm. Part 1, termed *Bridge Hunter* uses bridge location and attribute information from the National Bridge Inventory (NBI) combined with optical images of the bridges to automatically select and identify target bridges. The second part, termed *Bridge Doctor* compare images of the bridges from before and after the earthquake, and compares the difference and correlation values of the two images to determine whether the bridge is damaged or not.

The *Bridge Hunter* and *Bridge Doctor* algorithms were developed and tested using bridge damage from the 1994 Northridge earthquake. The optical imagery used was SPOT4 Panchromatic satellite imagery with 10m resolution. Higher resolution images (1m spatial resolution) from the USGS were available from after the earthquake, but not from before. Several challenges were presented by using 10m resolution images for the correlation. For example, 10m resolution means that 1 pixel covers a 10m x 10m area. For small bridges the entire width of the bridge is represented by 1 single pixel. The bridges used from the Northridge earthquake were all large, multi-lane highway bridges, so there was always more than one pixel width that covered a bridge. The major challenge was when a pixel fell partially on the bridge and partially on the roadway or ground below the bridge. To overcome these issues, a line was drawn down the middle of the bridge, called a central transect. Only the pixels intersecting that transect were used to correlate the before and after images. This is why the Bridge Doctor algorithm needed to be modified using the higher resolution optical imagery from the UDOT. The aerial photographs from the UDOT had spatial resolution ranging from 15cm to 1m. These photos are comparable to the high resolution satellite imagery that is widely available today. The higher resolution images from Utah posed a different set of image processing challenges than the low resolution Northridge images. Smoothing filters had to be applied to the data to filter out the increased noise that accompanies the higher resolution. To perform an accurate comparison of the high resolution before and after photos, a 7.5m smoothing filter was applied.

The second phase of the ImageCat research was to evaluate the applicability of using Synthetic Aperture Radar (SAR) to rapidly detect bridge damage. SAR has several advantages over optical imaged based damage detection. Because it is radar based, and not light based, SAR data from planes or satellites can be collected in any lighting or weather conditions. SAR data also has the capability of detecting changes in elevation. Instead of detecting visible changes, SAR data can detect changes in the structure and geometry of the bridge. This capability would allow different levels and modes of bridge damage to be detected. For example, optical imagery may have trouble detecting a large abutment settlement because from overhead, the pavement looks the same as in the undamaged state, it is just lower than the bridge pavement. But newly formed edge of the bridge where the abutment has settled could produce a higher return of the radar, and potentially be recognized.

The SAR method was tested by simulating 3 separate modes of bridge collapse with a 60' section of a double T concrete beam set on small bridge piers. An airplane equipped with a GeoSAR instrument flew over the test area on the campus of The University of Nevada at Reno 4 separate times on the same flight path. The simulated bridge was in a different state for each pass. The four states of the bridge were: undamaged, partly fallen span, fully fallen span, and fallen/twisted span. The testing that was performed had generally good results, and it correlated well with a digital simulation of the SAR tests. However, this research was the first of its kind performed and much more research and validation is required before SAR is able to rapidly used in a post disaster environment.

Memphis Earthquake Scenario and Likely Bridge Damage

In the event of a large magnitude earthquake on the New Madrid seismic zone, the freight transportation network in the Memphis, TN metropolitan area will be affected. In order to quickly and efficiently assess the status of the regions' transportation system, remotely sensed data can be obtained and automatically analyzed to detect major bridge damage. After collapsed bridges have been identified, a transportation model of the regional highway system built in REDARS would be updated with the bridge damage status. Immediately after the earthquake, this transportation model will calculate the best detour routes for emergency personal and freight traffic. In the recovery phase, the REDARS model will be an important tool used by emergency management and transportation officials to decide the order in which damaged bridges should be repaired, and to estimate total system recovery time.

The freight transportation network in Memphis consists of four major modes. Memphis International Airport is home of the FedEx fleet of aircraft, and handles more air freight than any other airport in the world. West of Memphis Metropolitan area sits on the Mississippi river and handles large of amounts of river barge cargo. The railroads system in Memphis is one of the busiest of any major city in the United States. And with the intersection of large cross country interstate highways like I-40, I-55, and the future I-69, Memphis area highways handle a large portion of the nations truck freight. A large earthquake on the New Madrid seismic zone, which comes within 50 miles of downtown Memphis, could potentially have disastrous effects on the regions freight transportation infrastructure. Some of the damage that could potentially happen could include liquefaction or lateral spreading induced failure of the runways and taxiways at Memphis International airport. The Port of Memphis on the Mississippi could experience a sheet-pile wall failure, or large settlement of the infill behind the retaining sheet-pile wall. Given the generally flat terrain of Mississippi embayment, there will not be a large landslide hazard. But because of the generally high water table and the geologic conditions of the regions, liquefaction hazards could affect rail lines, or rail and highway bridge foundations or approach fills. And with expected ground motions predicted by some models approaching 1g, serious damage to bridges can be expected. Using satellite or fixed-wing airplane optical images from before and after the earthquake, serious bridge damage could be automatically detected.

There are many different types of earthquake induced bridge damage. A popular hazard loss estimation tool (HAZUS), separates bridge damage from earthquakes into five categories (FEMA 2002). Level 1 represents no damage. Level 2 includes minor cracking or spalling of abutment, column or deck requiring only cosmetic repair. Level 3 includes moderate cracking or spalling of concrete without causing structural instability, failure of minor bridge elements like shear keys and rocker bearings, and moderate abutment settlement. Level 4 represents shear failure of columns without collapse, significant connection deformation, and major abutment settlement. And level 5 includes all “collapsed” bridges which is defined by the collapse of any column, deck collapse, and foundation failure. Traffic most likely would not be greatly affected for level 2 damage, the bridge would open soon after inspection if it was closed at all, and repairs would only require lane closures. Level 3 damage would most likely result in the closing of the bridge or a severe reduction in traffic (multiple lane closures, no heavy traffic) for several weeks or months. For level 4 damage, the bridge would be closed and require several months of repairs, may require a complete replacement of the bridge. Collapse of the bridge would obviously result in a long term closure of the bridge. This information is summarized in Tables 1 and 2.

Table 1: Bridge Damage State Description

Damage State Designation		Description
Number	Level	
1	None	First Yield
2	Slight	Minor cracking and spalling of the abutment, cracks in shear keys at abutment, minor spalling and cracking at hinges, minor spalling of column requiring no more than cosmetic repair
3	Moderate	Any column experiencing moderate shear cracking and spalling (with columns still structurally sound), moderate movement of abutment (< 2 inches), extensive cracking and spalling of shear keys, connection with cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of approach.
4	Extensive	Any column degrading without collapse (e.g., shear failure) but with column structurally unsafe, significant residual movement of connections, major settlement of approach fills, vertical offset or shear key failure at abutments, or differential settlement.
5	Complete	Collapse of any column, or unseating of deck span leading to collapse of deck Tilting of substructure due to foundation failure.

Table 2: Bridge Damage Repair Procedure

Damage State	Repair Procedure		Traffic State	
	Description	Duration	Bridge	Underlying Roadway
1) None	None	None	Fully open	Fully open
2) Slight	Epoxy injection of cracks.	2-3 weeks	Fully open	Fully open
3) Moderate	1. Close Bridge for inspection and shoring 2. Repair columns, i.e., remove damaged concrete, design/implement repair (e.g., increase lap splice, add transverse steel, grouting, jacketing). 3. Repair abutments, bearings, etc.	1-3 days. 3-span bridge: 2-4 weeks. 4-span bridge: 2.5-5 weeks. 5-span bridge: 3-6 weeks.	Closed Paritally open to reduced traffic during duration of repairs.	Partially closed (one lane each direction) during cleaning, shoring, column repair operations (2-3 weeks). Open to emergency vehicles.
4) Extensive	1. Close Bridge for inspection and shoring 2. Repair columns, i.e., remove damaged concrete, design/implement repair (e.g., increase lap splice, add transverse steel, grouting, jacketing). 3. Repair abutments, bearings, etc.	1 week 3-span bridge: 4-8 weeks. 4-span bridge: 5-10 weeks. 5-span bridge: 6-12 weeks.	Closed Paritally open to reduced traffic during duration of repairs.	Partially closed (one lane each direction) during cleaning, shoring, column repair operations (3-4 weeks). Open to emergency vehicles.
5) Collapse	Replace bridge for case of severe structural damage. Replace fallen deck span, replace bearings, and repair or replace damaged substructure.	3-span bridge: 3-6 months. 4-span bridge: 4-8 months. 5-span bridge: 5-10 months. 3-6 months.	Closed during duration of reconstruction of Closed during duration of bridge repair, replacement.	Fully closed during demolition & cleaning (3- Partially closed (one lane each direction) during cleaning, shoring, column repair operations (4-8 weeks). Open to emergency vehicles.

Table 3: Partially Closed Bridge Definition

Damage State	Total number of lanes each way before earthquake				
	1	2	3	4	5
	Number of lanes each way open to traffic after earthquake				
1) None	1	2	3	4	5
2) Slight	1	2	3	4	5
3) Moderate	0	1	2	3	4
4) Extensive	0	1	1	2	2
5) Collapse	0	0	0	0	0

Optical satellite imagery would only be able to detect certain types of bridge damage. The easiest type of damage to detect would be a collapse of the roadway. It may be possible to notice large abutment settlement or the titling of the entire bridge. But any damage less than level 5 collapse is not going to be able to be accurately detected. Any damage to the bridge columns, connections or abutments that is hidden under the bridge deck has no chance of being detected from overhead imagery. This is one reason why it may be more feasible to use a ground, helicopter, or low-altitude fixed wing aircraft based rapid visual inspection system like VIEWS to rapidly assess the condition of the freight transportation system. Another advantage of a near ground based method is that more than just the bridge damage could be recorded. Large cracks or pavement failure could be recognized. Infrastructure important to other modes of freight transportation could be investigated and recorded, places like the river port or rail yards. In ideal conditions the satellite images could be taken delivered and processed in less than 24 hours after an earthquake, assuming a helicopter or small plane was available, the near ground reconnaissance would still be faster. In order for the satellite images to be ready for analysis, the satellite has to in position which happens on average every 24-36 hours (Landsat). But it has to be during the daylight, with minimal cloud cover. And smoke from potential earthquake induced fires could also block some portions of the image.

METHODOLOGY

Satellite image change detection techniques have been used to verify damage to bridges. Research was conducted to develop methodology to use different techniques and data to assess bridge damage by ImageCat, Inc. in 2004. We tested two new techniques, which for the purposes of this report, we call the "Taff Method," and the "Hybrid Method." The techniques developed by ImageCat, Inc. pioneered this research; however, due in part to the data available at that time, the techniques used by ImageCat required a lengthy georectification process and still produced some uncertain results.

ImageCat's technique was based on georectifying and overlaying one (pre-earthquake) image of each bridge with another (post-earthquake) image of the same bridges such that each pixel of the first image is very accurately overlayed onto each corresponding pixel of the second image. Then, ImageCat calculated the change in Brightness Values (BV's) from each pixel in the first image to each pixel in the second image (Eguchi 2004). Due to recurring problems with georectification accuracy and the time needed for highly accurate georectification, ImageCat's technique is difficult to implement. For instance, the angle of one image will usually not be the same as the angle of the other because of orbital flights of satellites and the times when photos are taken.

The Taff Method combines the entire set of pixels that make up a bridge to find an overall change in the bridge's reflectivity as a singular object. This method does not require georectification of the pre-earthquake image to the post-earthquake image; the bridge outline may be detected using object-oriented classification approaches, using ancillary information – the coordinates of the bridges we digitized for this project. This project focused on detecting damage vs. no damage to bridges once we have identified the precise outline of the pre- and post-earthquake bridges. Further research will test the object-oriented classification approach to find the bridges in the images. The potential for this method to allow rapid determination of bridge damage would allow emergency and public vehicles to react sooner to a crisis.

When we developed the Taff Method, we set out to discard as much noise as possible when running the damage detection on the chosen bridges. By using 2.4 meter resolution images, we were able to select pixels that were clearly within the boundaries of the bridges and discard those pixels that may incorporate some area from nearby non-bridge landcover types.

METHODS IMPLEMENTED

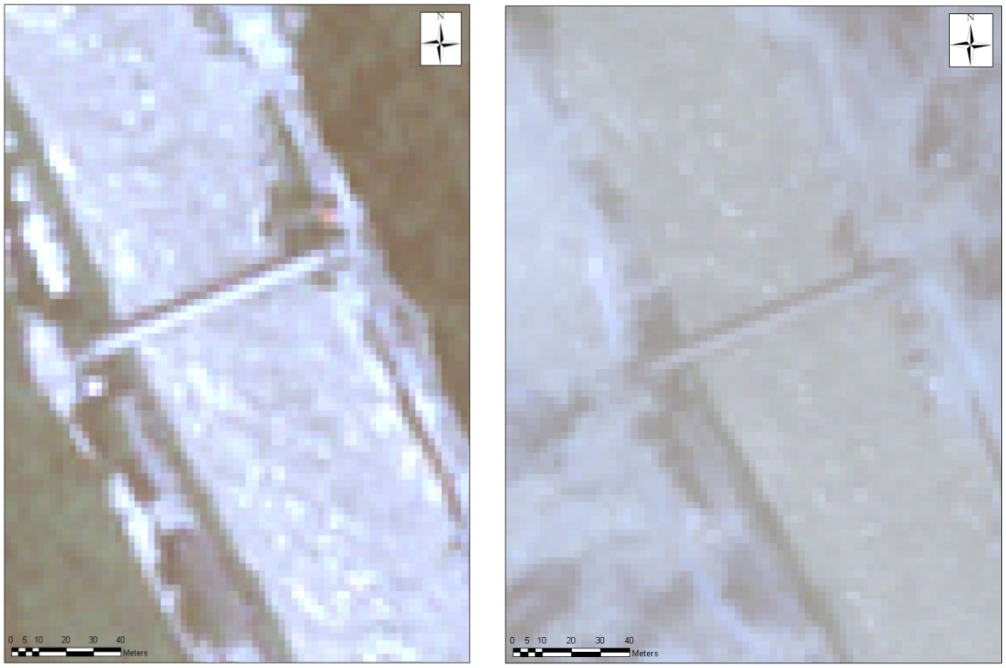
Taff Method

The Taff Method requires the use of two images, one pre-earthquake and one post-earthquake of the same location. The main idea behind this method is that damage to part of the bridge should show up on the post-earthquake image being more variable (i.e., the damaged portions of the bridge should look different from the undamaged portions, relative to an intact bridge where most of the bridge should look quite similar). In the event that the full bridge collapsed, it is also expected that the landcover where the bridge formerly existed would not likely have pixel values as consistent as an intact bridge would. Therefore, the goal is to calculate the variance in pixel values of the full bridge in the pre- and post-earthquake images. Bridges whose pixel value variance substantially increased from the pre- to the post-earthquake image would likely be damaged bridges.

As a test case, we studied bridges in the proximity of the 2008 Sichuan earthquake in China. This earthquake was chosen because of the availability of good documentation about bridge damage in the area, and the availability of cloud-free pre- and post-earthquake QuickBird satellite images. We used Quickbird images due to its superior spatial resolution relative to other available image products – the two images we were able to find of our research site were three years apart. The first image was from June 26, 2005, three years before the Sichuan earthquake and the second image was dated June 30, 2008, only forty-eight days after the earthquake. We found information about the earthquake and associated damage on the USGS website and on the Virtual Disaster View at www.VDV.com, which contains data and tools from MicroSoft, EPICentre, MCEER, EPSRC, EEFIT, and ImageCat, Inc. We were made aware of the available imagery of the AOI by ImageCat, Inc. The damage to the bridges was documented on the VDV website that uses MicroSoft's interactive mapping program through Bing.com.

We found that the three years between the images negatively impacted our ability to conduct this research, because development and other changes occurred in that timeframe, in addition to changes brought on by the earthquake. This led us to conclude that it is important to find a cloud-free, pre-earthquake image that is as recent as possible.

The 2005 image was of good quality and contained eleven bridges. The 2005 image was also cloud free and atmospheric conditions were quite good. The 2008 image was missing two of the bidges that the 2005 image contained, and had two new bridges in different but nearby locations. It was determined that the two missing bridges had been purposely removed prior to the earthquake, because of infrastructure upgrades to the town. These bridges were not used in our analysis. We were then left with nine bridges to run our analysis. We were able to use only eight of the nine bridges; however, because one of the bridges (Bridge #3) was not wide enough to encompass a full 2.4m pixel within the edges of the bridge (it was likely a footbridge) – therefore other nearby landcover types would add too much noise to the analysis of this bridge.



(a) (b)

Figure 2. Multi-Spectral Image Set to 3,2,1 Band Combination, (a) 2005 and (b) 2008).

True Color 2.4m resolution QuickBird images in Figure 2(a) and Figure 2(b) (using the 3-2-1 band combination – that is Red, Green Blue) show pre- and post-earthquake images of a bridge in the Sichuan area. They look quite different because of the large amount of sediment that covered the area after the earthquake. The landslides in the area transformed this portion of the Sichuan Province.

Our next step was to define the edges of the bridges. While our future research will use an object-oriented classification approach to determine this, we did this by hand for these analyses, as was done in the Eguchi (2004) study. To determine the bridge borders, we used the QuickBird panchromatic band, which has a spatial resolution of 0.6 meters, much more precise than the multispectral. We digitized the edges of the bridges in both images on-screen by hand using ESRI's ArcGIS, and created shapefiles for each bridge's outline. These "footprint" files would allow us to better select pixels to sample for change detection. In our analyses, we do not select pixels that fall outside the boundaries of these footprint shapefiles. Pictured in Figure 3 is an image of the 2005 panchromatic image with one bridge shapefile overlaid on top.

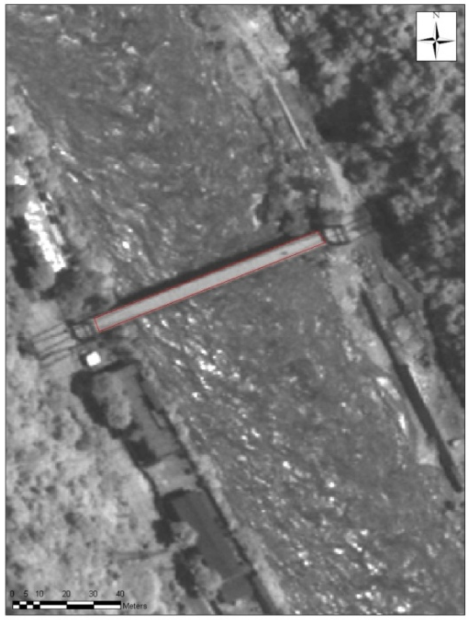


Figure 3. 2005 Panchromatic Image with Footprint Shape File Overlaid.

Once we created these footprint shapefiles, we performed a Tasseled Cap transformation on both of the images. The tasseled Cap transformation is a spectral enhancement that transforms the four spectral bands via a linear combination into bands that can be characterized as brightness, greenness, and wetness (Crist & Kauth 1986, Kim 1997). As with roads, bridges are most visible in the brightness component, so we used the brightness component instead of an individual band to conduct our analyses. Figure 4 shows the 2005 image before and after it has undergone the tasseled cap transformation (tasseled cap transformation shown in grayscale of the brightness component).

Figure 4. 2005 Image Before and After Tasseled Cap Transformation (Tasseled Cap Image is set to 1,1,1 Band Combination for Brightness).

We then placed the bridge footprint shapefiles onto the Tasseled Cap-transformed images. Figure 5 shows a footprint shapefile overlayed onto a 2005 Tasseled Cap-transformed grayscale image.

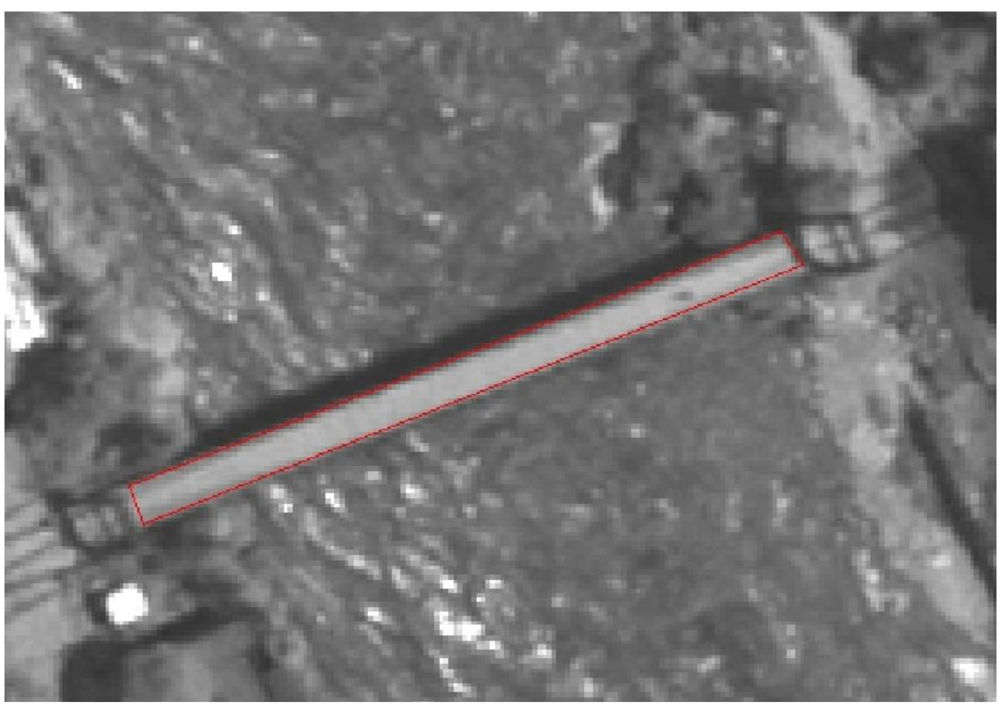


Figure 5. 2005 Tasseled Cap Image with Footprint Shape File Overlaid.

We then selected all individual pixels that lay within the footprint boundaries. The process for selecting the pixels was accomplished in ArcGIS in four steps.

1. In step one, we converted our images from a raster format to a vector format, where each 2.4m pixel became a unique polygon.

2. Step two was slightly more complicated. Very few of the pixels lay completely within most of the bridges' boundaries, because the bridges were all just two lane (relatively narrow) bridges. Due to this issue, we selected pixels that were either contained completely with the boundary of the bridge, or that had just a small portion of the pixel extending beyond the boundary (we later repeated the analysis with only pixels that fell wholly within the bridge footprints, but the results did not significantly improve).

3. Once the pixels were selected, in step three, we merged all the pixels within each bridge into one polygon.

4. In the fourth and final step, we used Hawth's Zonal Statistics ++ Tool to gather and calculate the summary statistics for all of the pixels that fell within each bridge footprint. The Hawth's Tools set is designed to perform spatial analysis and functions that cannot be conveniently accomplished with out-of-the-box ArcGIS," (Beyer, 2004). Though the extension was originally developed for ecology uses, it has proven to be helpful for many other statistical applications. The Hawth's Zonal Statistics ++ Tool, defined by its creator, "writes a statistical summary of the values in the raster layer that fall within the bounds of each zonal polygon (i.e. min, max, mean, standard deviation, and count)," (Beyer, 2004). This tool gathers information on pixels whose centers fall within the boundaries of the polygon or mask layer. We were interested in the standard deviation of pixels within each bridge footprint (based on the pixel values of the Brightness component of the Tasseled Cap transformation).

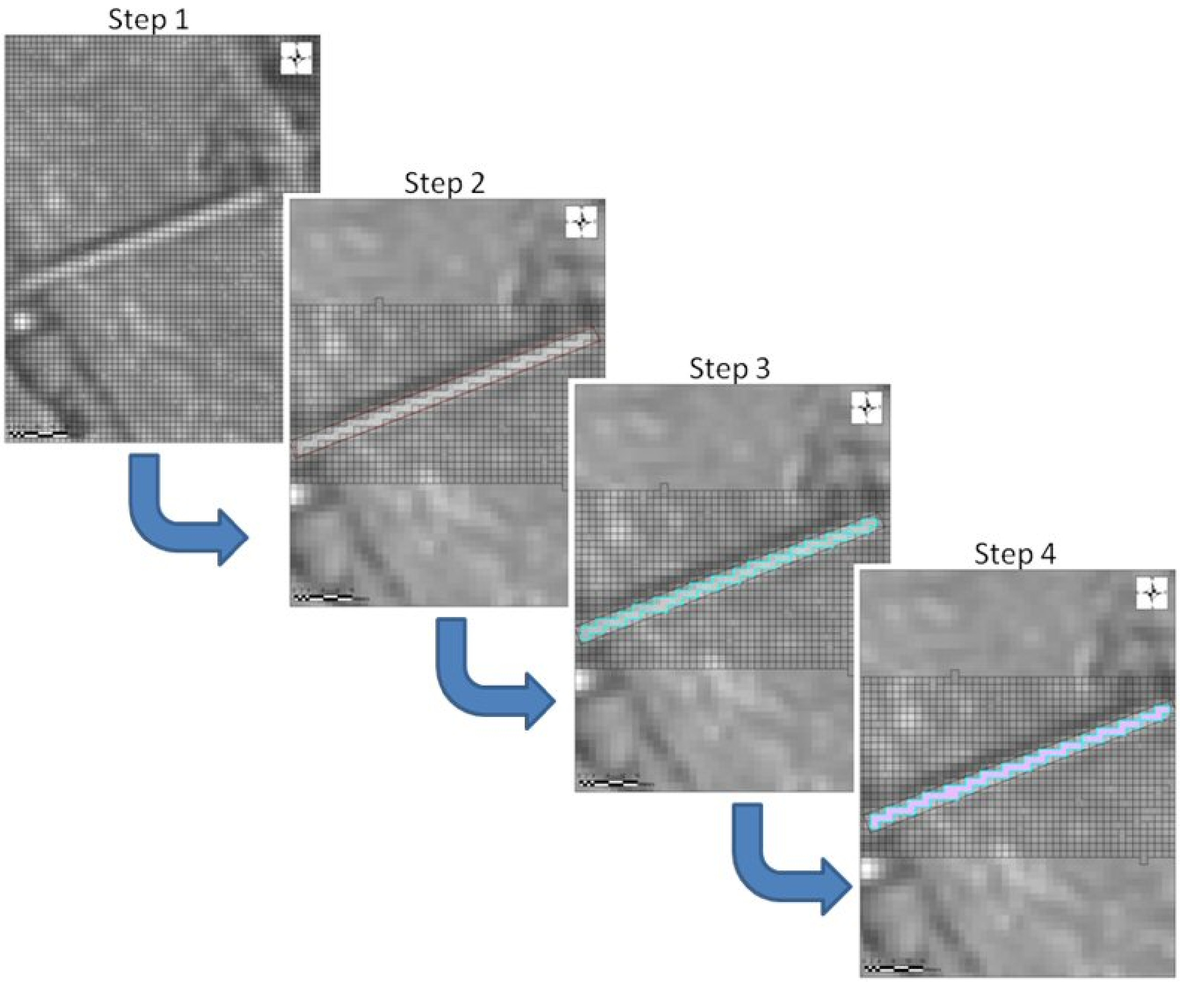
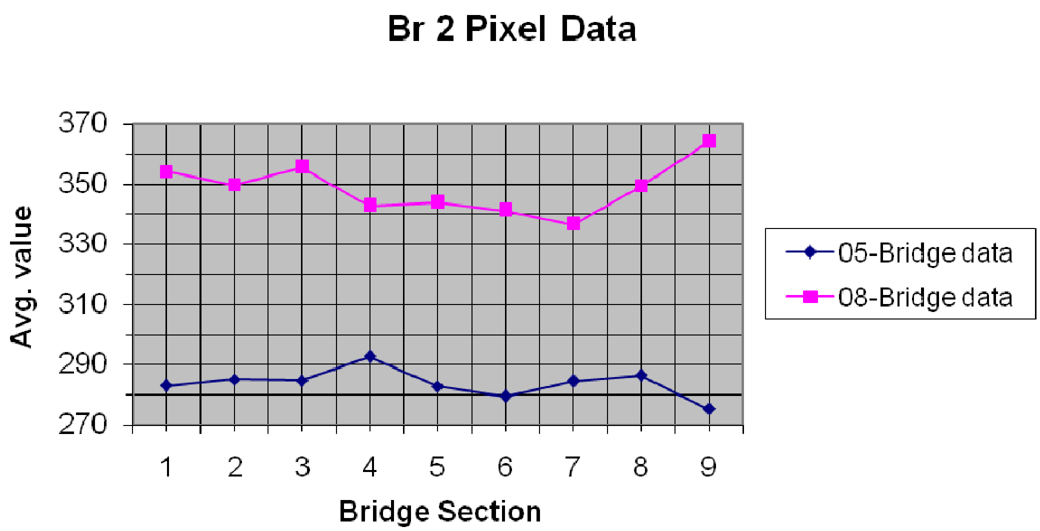


Figure 6. The steps that were needed to convert a raster image to a vector image, group the pixels of the bridge and gathering the data on the individual pixels within the image and measuring them as a whole.

We normalized each standard deviation value by dividing each bridge footprint standard deviation by the standard deviation of all pixels in the full image. We then assessed the change in this normalized standard deviation of the pixels within each bridge footprint between 2008 and 2005. Our hypothesis was that, since damaged bridges are expected to have more variability in Brightness than undamaged bridges, this value (normalized StDev [2008] – normalized StDev [2005]) would result in significant positive values for damaged bridges and values near 0 for undamaged bridges.

Hybrid Method

The Hybrid Method we developed divides the bridge into multiple sections (for both pre- and post-earthquake images) lengthwise across the bridge (we chose to use 10m intervals, though other lengths should be tested for best results). We took average pixel values within each section of the bridge using raw BV's of the 0.6m pixels of the QuickBird panchromatic band. We subtracted the post-earthquake average from the pre-earthquake average for each bridge section. We then plotted this data on line graphs (where the x-values represented bridge sections moving along the bridge from the beginning of the bridge to the end of the bridge) to give us a visual perspective of the patterns created by those values.



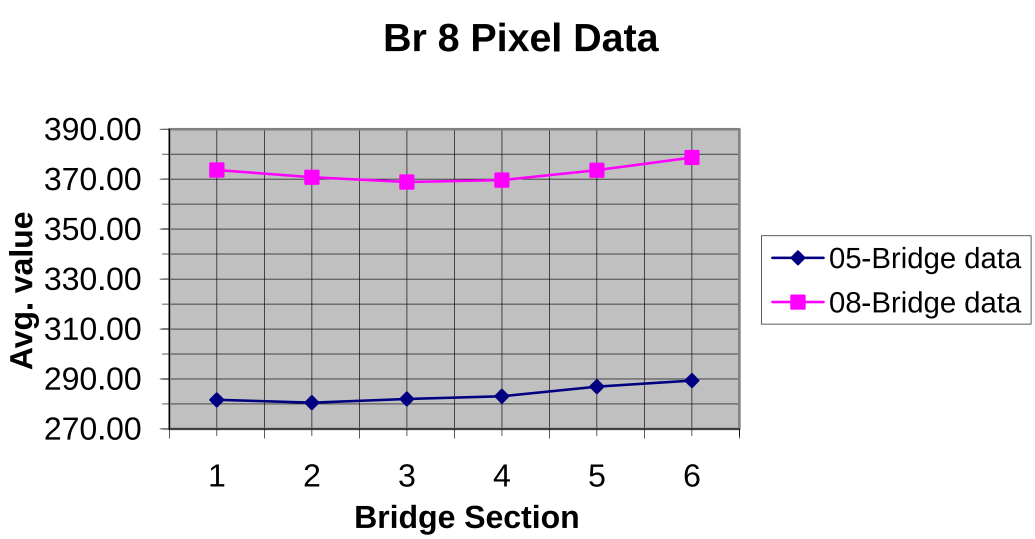


Figure 7. Graph of Hybrid Method output for Bridge #2 and #8.

We identified bridges that had at least one section whose calculated difference was far from any of the others. The lines on our graphs would either noticeably diverge or converge if there was a substantial difference between images dates in one or more sections of the bridges, or lines would maintain the same general shape if the bridges remained relatively unchanged.

To implement this, a vector shapefile was created by hand to outline each bridge. For each bridge, a separate shapefile was created for each image date. This identification of bridge outlines accomplishes by hand what we propose to do automatically in future studies using object-oriented classification, and does not require the time consuming georectification step – a step which may not be feasible at the required level of accuracy within mere days or hours after an earthquake event. To eliminate the noise due to edge pixels that straddle both the bridge and surrounding landcover, a negative 1m buffer was drawn inside the boundary of each bridge, and only pixels within this buffer (as determined using Hawth's Tools again) were used for the analysis.

Preliminary results showed this method would identify damaged bridges but also bridges with one or more large trucks on them, since a large truck would substantially alter the BV's of a bridge section. To solve this problem of identifying false positive damaged bridges, we took a moving average of the calculated differences along the bridge sections. We subtracted the overall average of the calculated differences from each moving average. We then identified those bridges that had at least one moving average significantly far from the overall average of the calculated differences. The idea behind this is that one truck on a bridge will not result in an anomalous moving average even though it may result in an anomalous difference of an individual bridge section. We took the largest absolute value of the calculated differences (which represented the bridge section that was most different between the two image dates), and normalized this difference by dividing it by the standard deviation of calculated differences among the bridge sections. We needed to determine a threshold that was "significantly far" from the overall average that would allow us to determine whether or not each bridge was damaged. Empirically, we found that bridges with values of approximately 1.8 or higher were damaged, while those with lower values were undamaged (see Results section). This result was consistent for all bridges over 30 meters in length.

RESULTS

The results regarding the Taff method (Table 4) were inconclusive at best. These results show that four of the bridges gained (image-normalized) variability between 2005 and 2008, and only three gained substantial image-normalized variability (greater than 0.01). Only one of the bridges that gained variability was damaged, and the others were undamaged. As it was expected that only damaged bridges would gain variability, the method did not give the expected results. There does not seem to be any consistent pattern regarding the differences in results between the damaged and undamaged bridges. We also tried the same method using un-normalized standard deviations, but we obtained similar results.

Table 4 shows our results from the Taff Method.

Bridge #	Damaged?	Change in St Dev (2008 – 2005)
1	No	-0.03
2	Yes	0.03
4	Yes	0.0
5	No	0.04
6	No	0.04
7	No	-0.09
8	No	0.01
9	Yes	-0.01

Though the Taff method did not provide good results, the Hybrid method gave substantially more promising results. All bridges were consistent in that all bridges with a final value (that is, of the normalized absolute value of the maximum difference between the moving average of the section differences and the overall average of the section differences) of 1.8 or greater represented damaged bridges, and all bridges with final values of less than 1.8 represented undamaged bridges. The only exception was for Bridge #9 which was only 30 meters long – this bridge is too short for this method which uses a moving average of 10m sections and a kernel of 3 sections to determine the moving average. We therefore conclude that this method works well, but only for bridges of a minimum length – the minimum length needs to be determined, however we expect this minimum to be approximately 50 meters.

Table 5 shows our results from the Hybrid Method.

Bridge #	Damaged?	(Max ABS of Moving Diff.)/(St. Dev(Diff)):
1	No	1.041
2	Yes	1.837
4	Yes	2.853
5	No	0.990
6	No	1.373
7	No	1.155
8	No	1.108
9	Yes	0.561

REDARS2 Introduction, Implementation, and Testing

The second part of the proposed system is a GIS model of the freight transportation network of Memphis that can be updated with the damage information after an earthquake and be used to re-route traffic assist in the recovery after the event. After evaluating existing programs, the best option is a program called REDARS 2. Risks from Earthquake Damage to Roadways Systems (REDARS) is a software system that models highway networks. Published by MCEER after more than 10 year research and development project, REDARS is a public domain software managed by Seismic Systems and Engineering Consultants in Oakland California. Funded by the U.S. Department of Transportation Federal Highway Administration (FHWA), the original goal of the research was to "develop seismic retrofit and evaluation methodologies for existing highway systems." The first model of REDARS was developed and used to estimate the seismic risks and potential earthquake loss to the highway system in Shelby County, Tennessee (Werner et al. 2000). The software can be used either as a pre-earthquake planning tool, or a post-earthquake disaster management tool. As a pre-earthquake planning tool, it can be used by municipality or transportation officials to predict levels and locations of potential seismic damage, prioritize seismic retrofit strategies, and estimate the total economic loss caused by damage to a highway system. Both probabilistic and deterministic scenarios can be carried out. As a post-earthquake disaster management tool, it can use real time damage status information and calculate the most efficient detour routes for emergency personal and freight traffic, and predict repair and system recovery time.

The program uses models from many areas of earthquake engineering to predict damage and recovery time/cost. Some of the models that are incorporated include seismic hazards, transportation network component performance, a traffic system module, and an economic module. The seismic hazard models considered in the program include earthquake walkthrough tables for probabilistic scenarios, local NEHRP soil conditions, ground-motion models, liquefaction models, and surface fault rupture models. Transportation network components include bridge location, structural attributes, abutment and approach fill models, five individual bridge damage states, and a pavement model. The traffic system module includes trip origin-destination zones and traffic demand models. The economic module includes repair costs, losses due to travel time delays, and losses due to trips forgone.

REDARS2 uses an "Import Wizard" to load the data that is required. There are six data sets that need to be input into REDARS2. The titles of the data sets are National Highway Planning Network (NHPN), Highway Performance Monitoring System (HPMS), National Bridge Inventory (NBI), NEHRP Soil Data, Traffic Analysis Zones (TAZ), and finally Origin and Destination (OD) data. The NHPN, HPMS, and NBI data is all published by the Federal Highway Administration (FHWA). The FHWA has recently changed the formatting of its files, and because of this the current version of REDARS2 is not able to handle the new file format. Another release of REDARS is currently under production that will be able to handle the updated format of the FHWA data, but this version is not expected to be completed until sometime in 2010.

The National Highway Planning Network is a data set that includes line features of 450,000 miles of current or planned roads. The NHPN data is currently available in ESRI Shapefile format and can be downloaded from http://www.fhwa.dot.gov/planning/nhpn/. The format that is required for input into the current REDARS2 software is an older GIS format known as an Interchange Format (E00 file). Even if we are able to convert the data into this older E00 format, formatting changes are still required to be able input the data with the Import Wizard. The new release of REDARS2 should eliminate the need for this reformatting. The NHPN data for the Memphis metro area is shown Figure 8.

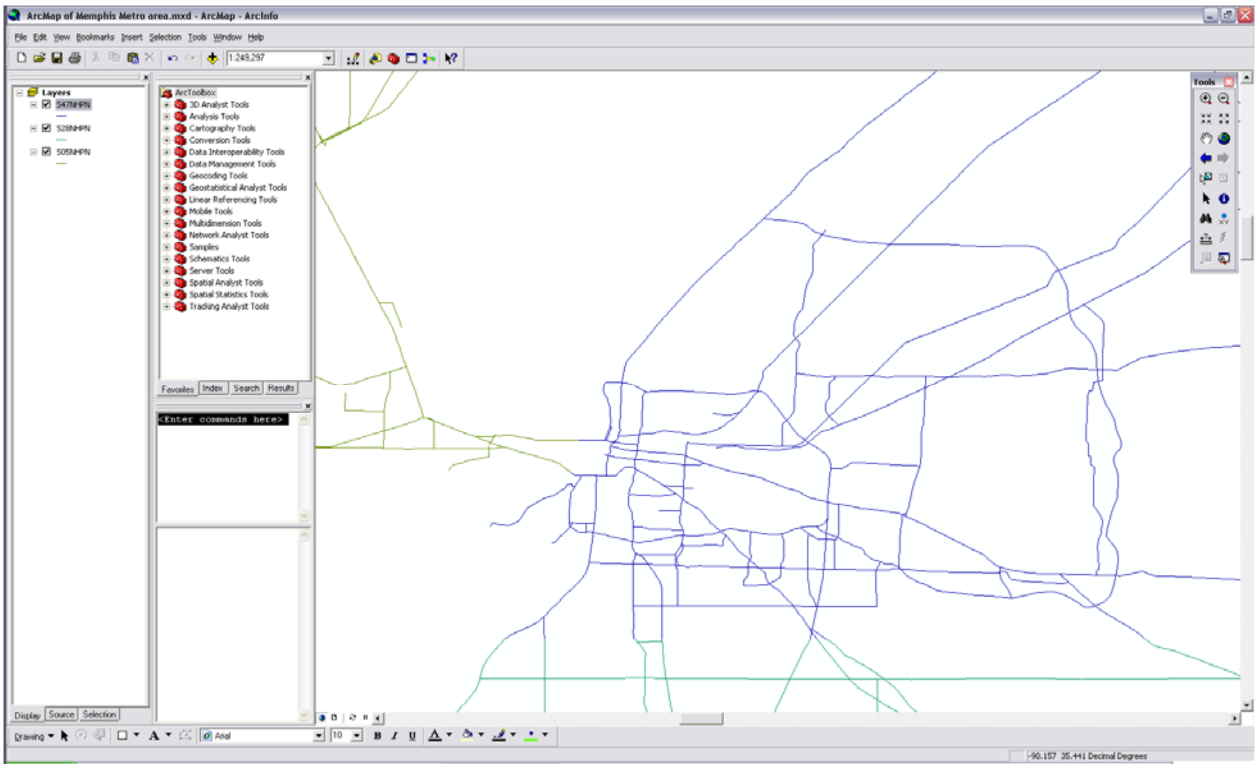


Figure 8: NHPN Road Network in Memphis.

The Highway Performance Monitoring System is a database that tracks public road mileage based off mile markers. The information that is referenced by REDARS2 includes three subjects. Whether the road is in a rural, suburban, or urban area. How many lanes in both directions, and the functional class of the road (interstate, highway, arterials, or rural roads). The HPMS data was obtained by an email request to Ronald Vaughn (ronald.vaughn@dot.gov) at the FHWA. The received data will require drastic reformatting before input into the Import Wizard.

The National Bridge Inventory database contains information about all public highway bridges in the nation, organized by state. There are dozens of attributes included for each bridge, the attributes that are referenced by REDARS2 are listed below. The identification and location fields are; structure number, state name, mile point, inventory route, inventory subroute, and latitude / longitude. The fields that provide structural information are; number of spans, number of approach spans, year built, lanes on the structure, length of maximum span, structure length, deck width, and skew. The 2008 NBI data was downloaded from, http://www.fhwa.dot.gov/bridge/nbi/ascii.cfm?year=2008.

The fourth data set that needs to be input using the Import Wizard is the National Earthquake Hazards Reduction Program (NEHRP) soil classification. There are five levels of classification, A through E. They classes can be defined by several parameters, including rock or soil type, shear wave velocity, shear strength, and SPT blow count. REDARS2 requires a Shapefile that indicates what the site class is throughout the study region. There have been numerous studies that have determined the shear wave velocity in Shelby County Tennessee, however a Shapefile with this information has not been created. The results of the shear wave velocity studies have shown that the Memphis metro region shear wave velocities fall in between 180 m/s and 360 m/s (Figure #), which are the boundaries for NEHRP Site Class D. So a Shapefile of the soil classification is not necessary because the entire REDARS2 study region can be designated as class D.

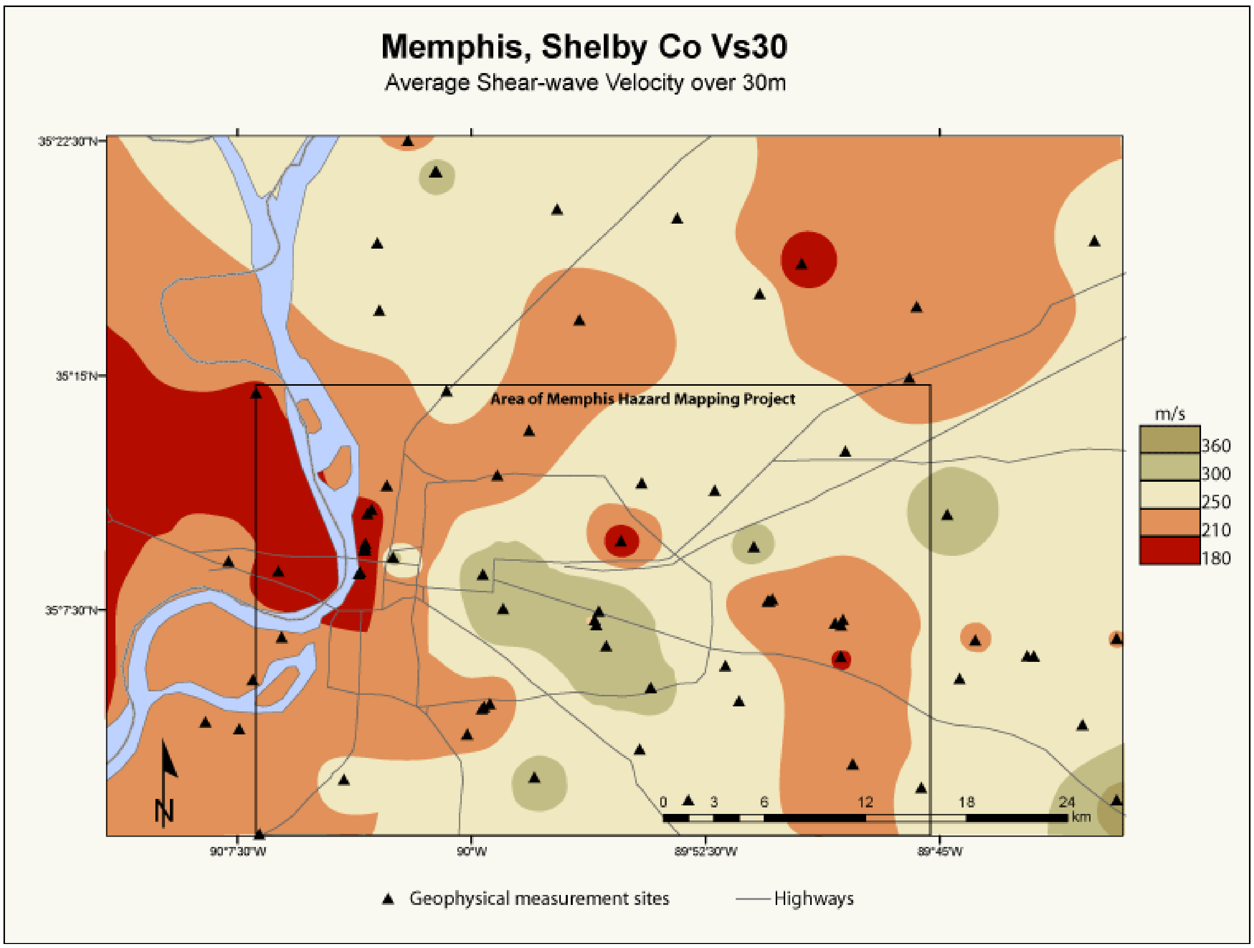


Figure 9. Memphis shear wave velocities (USGS, Chris Cramer).

Traffic Analysis Zone and Origin and Destination data are closely related to one another. A TAZ is a geographical region used by planning organizations to track auto and freight traffic. The borders of a TAZ can be defined by census boundaries, streets, railroads, or bodies of water. The TAZ and OD data for this study were given to us by the Memphis Metropolitan Planning Organization (Memphis MPO). The TAZ data comes in a Shapefile designating the boundaries of each zone (Figure #). The OD data comes in matrix that essentially tallies the number of trips taken between any two TAZ's. The data was broken down into several categories resulting in 24 different data sets. There are four time windows for the data; 6 a.m. to 9 a.m. (AM), 9 a.m. to 2 p.m. (MD), 2 p.m. to 6 p.m. (PM), and 6 p.m. to 6 a.m. (OP). There are five types of vehicle classes, single occupancy vehicle (SOV), high occupancy vehicle (HOV), combination unit truck (CU), light truck (LT) and single unit truck (SU). The last designation is where the trips are coming from and going to. The first option is internal to external (IE), which is a trip that has originated from within the study area but whose final destination is outside the study region. The second option is internal to internal (II), which is a trip whose origin and destination is within the study region. The third option is external to external (EE), which is a trip that is just passing through the study region. They will be SOV auto traffic, and CU freight traffic (4 or more axels, representing tractor trailers). All sets will be in the AM time window, the auto traffic will be II trips, and the freight traffic will be EE, EI, and II trips.

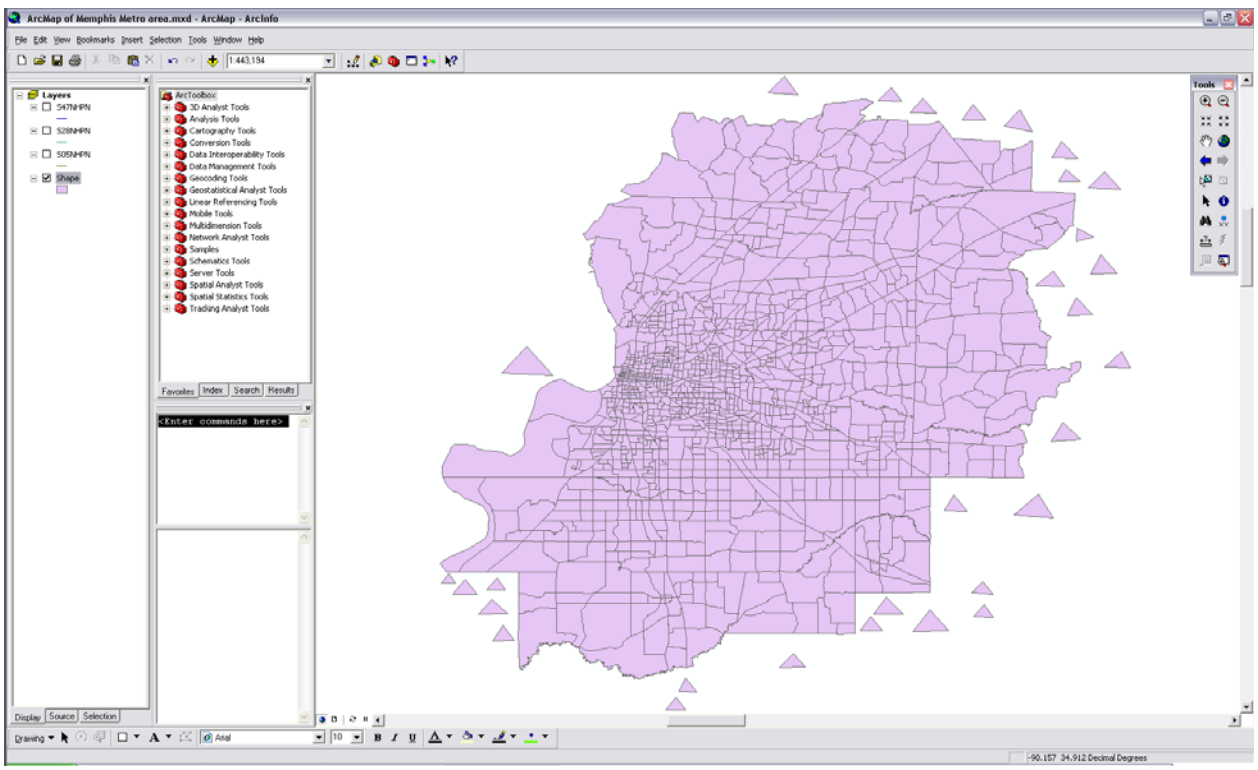


Figure 10. Memphis Traffic Analysis Zones.

Once all the required data have been input into REDARS2, a study region can be created. The primary purpose of REDARS2 is to predict damage to highway systems in the event of a future earthquake. This can be done in the program by two ways, simulating a single earthquake (deterministic model), or simulating 10,000 years of earthquakes and essentially averaging the results (probabilistic model). Because this program is relatively new and not widely used, it currently uses attenuation relationships that apply only the seismic regions in the Western United States. Because the geologic conditions and fault structure of the New Madrid seismic zone is vastly different than in California or other western states, REDARS2 cannot currently be used as a pre earthquake planning tool for the Memphis metropolitan area. In the version of the software that is currently being developed, Memphis is supposed to be included in the testing of the program, so hopefully the appropriate attenuation relationships will be available for future use in REDARS2.

REDARS2 in its current state could potentially be used for a post-earthquake disaster management tool, assuming that the data needed to create a study region could be compiled and reformatted as necessary. There are two functions, along with several display options within the model that could be used to plan freight routes that are affected by damaged bridges, and generalize the response of the regional highway system. The first function is called “Routes” and is found under the Analysis tab. This function allows the user to select road links along a particular route, and the program gives the travel times along that route from before the earthquake, and after the earthquake at user defined time intervals (the default is 7 days, 60 days, and 150 days). Multiple routes can be created and saved. The second function is called “Shortest Path” and is also found under the Analysis tab. This function allows the user to select any two nodes in the system and find the best path (defined as least travel time) between the two nodes. A node is defined as an intersection of 2 roads, or the endpoints of bridges. This can be performed for the same times as the “Routes” function (before and after earthquake). This can only be performed between 1 pair of nodes at a time, and node combinations and results cannot be saved.

These functions have been tested with a scenario in REDARS2. The program came with all of the necessary FHWA and traffic data to run a scenario in the San Francisco Bay Area. The following scenario is a deterministic analysis of a Magnitude 7.2 centered underneath the Bay Bridge at -122.348° Longitude and 37.818° Latitude. A summary of the results of the test is shown in Figure 11. 99 out of 269 bridges were damaged; 49 received slight damage, 39 with moderate damage, 10 with extensive damage, and 1 experienced collapse. Descriptions of bridge damage states can be found in Table 1, and Table 2. The colors on the map represent the damage status of bridges and roadways. The legend is in the top left of the map. Other measures of damage include a system wide 5% increase in travel time 7 days after the event, and a 3% increase after 60 days. Losses associated with the highway transportation system are estimated to be 185 million dollars.

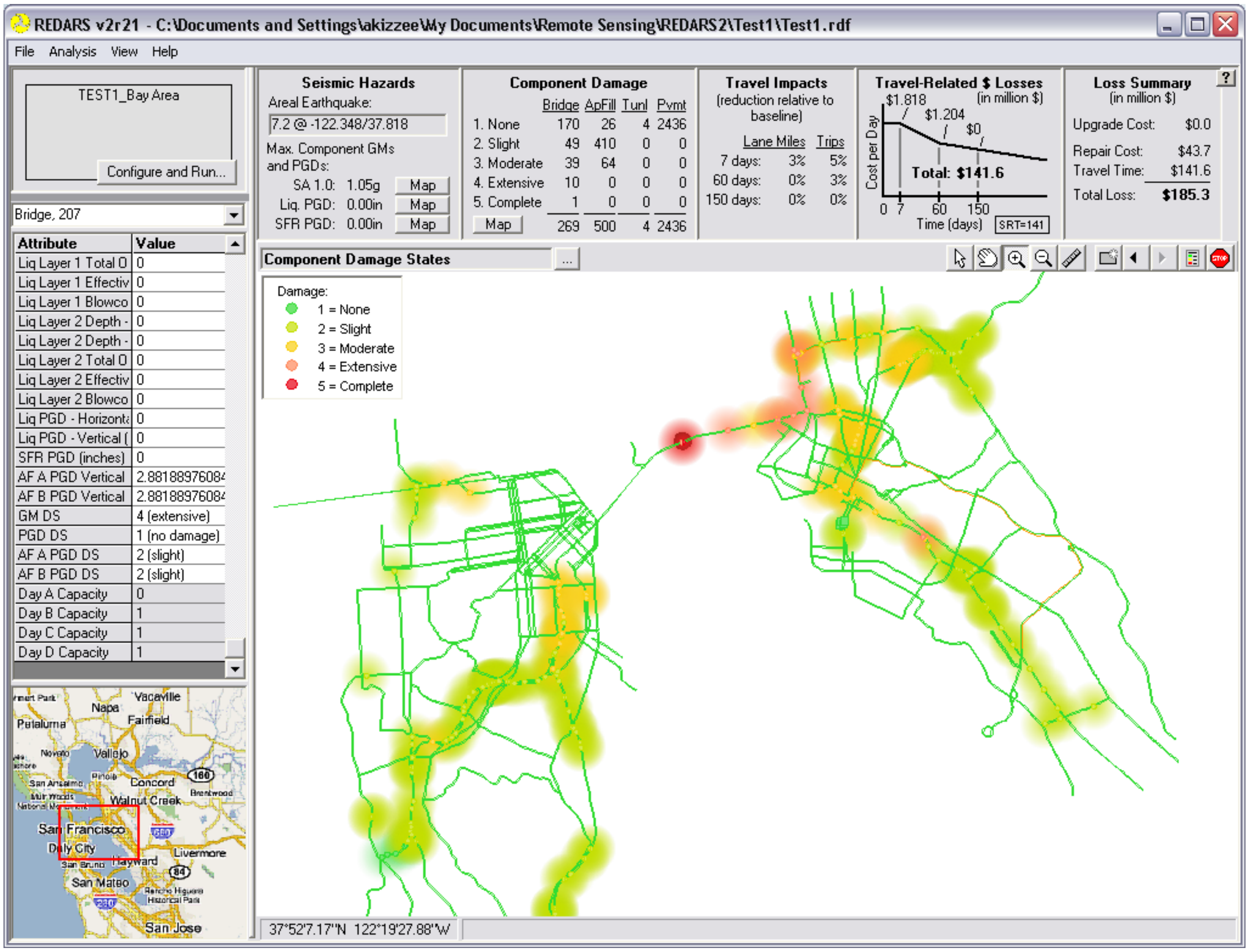


Figure 11. Mag. 7.2 Scenario in San Francisco Bay.

The following sections will display the capabilities of the "Route" and "Shortest Path" functions. The selected route is between Broadway and 7th Street in Downtown Oakland, near the Nimitz Freeway (I-880), to the intersection of Hegenberger Expressway (73rd Ave) and International Boulevard (E 14th). The pre-event route suggested by REDARS2 is along I-880 Freeway southeast to Hegneberger. The route is 7.9 miles long and is estimated to take 9.8 minutes. It is shown in a map view in Figure 12, and in the REDARS2 output in Figure 13. In the REDARS view, the route is shown in highlighted orange lines. In the simulation of the Magnitude 7.2 earthquake predicts that several of the Bridges on I-880 will be damaged along this route, with one bridge having "Extensive" damage. So the suggested post earthquake route is north on Broadway, east on Grand, then taking I-580 east toward the destination. This post earthquake route it about 1 mile longer and take 14 minutes. The REDARS2 screen shots in Figure 12 and Figure 13 show the route and travel times from before and after the earthquake, respectively.

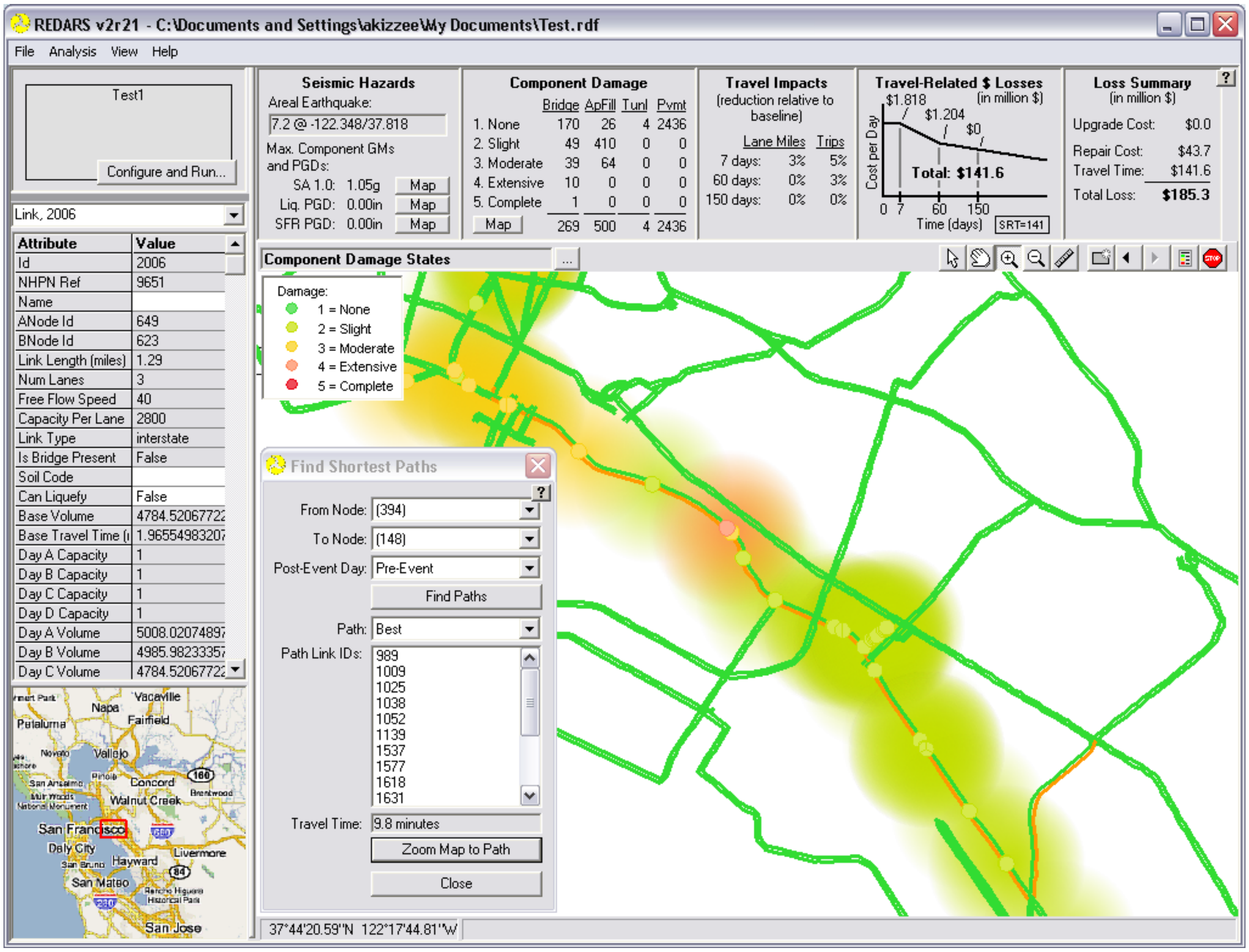


Figure 12. "Shortest Path" route before an earthquake.

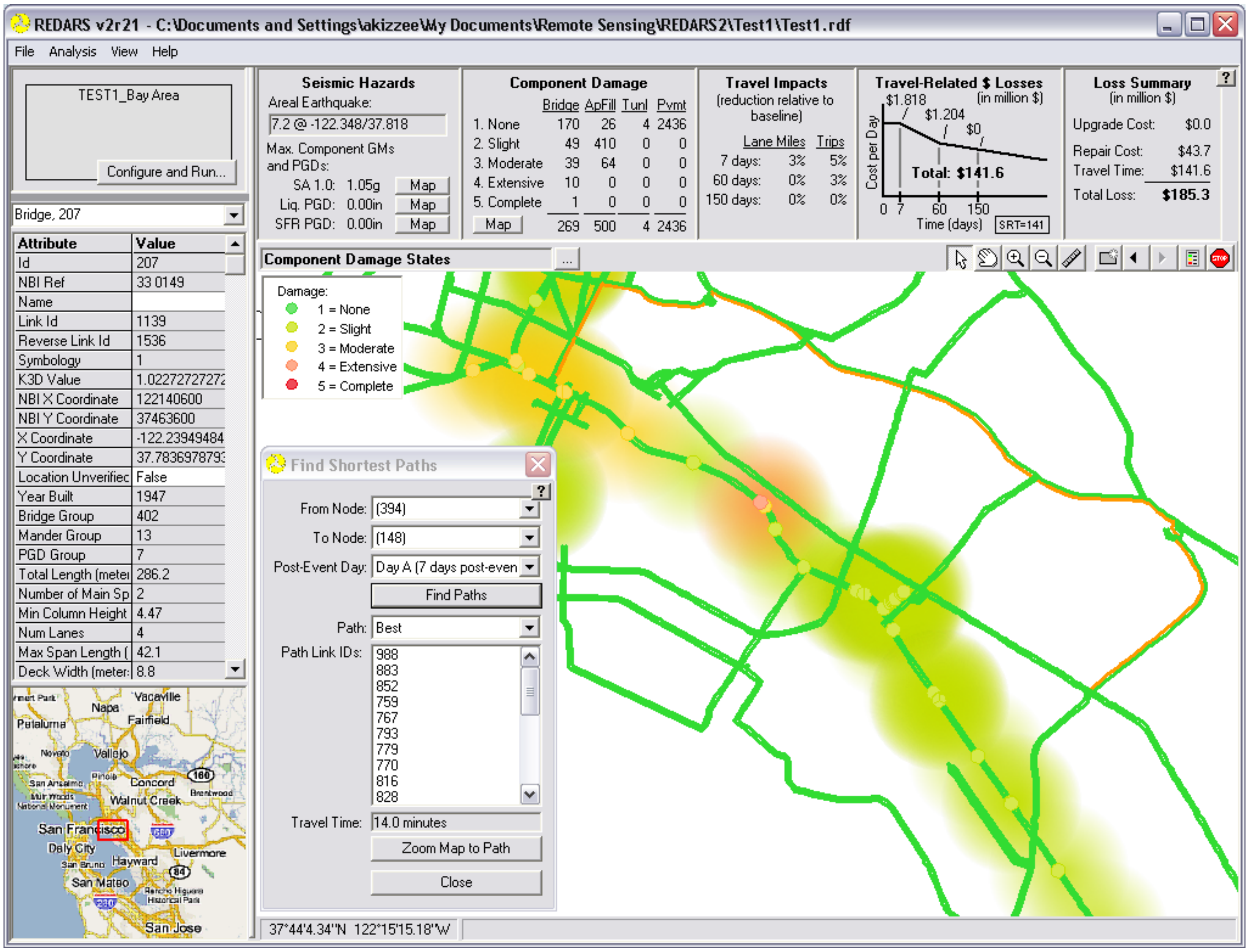


Figure 13. "Shortest Path" route after earthquake.

The "Route" analysis works in a similar way. Instead of designating two point to travel between, the user highlights the portions of road that are included on a particular route. The program automatically calculates how much time this trip will take before and after the earthquake. Figure 14 is the route that represents the portion highway portion of the trip that was described in the "Shortest Path" analysis above. The pre-event time for this trip is 5.72 minutes, and the 7 day post-event time is 16.5 minutes, an increase of 189%. An advantage of the "Route" analysis is that multiple routes can be saved in each scenario, unlike the "Shortest Path" analysis. However, it doesn't display whether any detours were taken on the new route, or if the traffic was slower because of increased traffic or closed lanes. There are several other features that further explain the state of the highway system within REDARS.

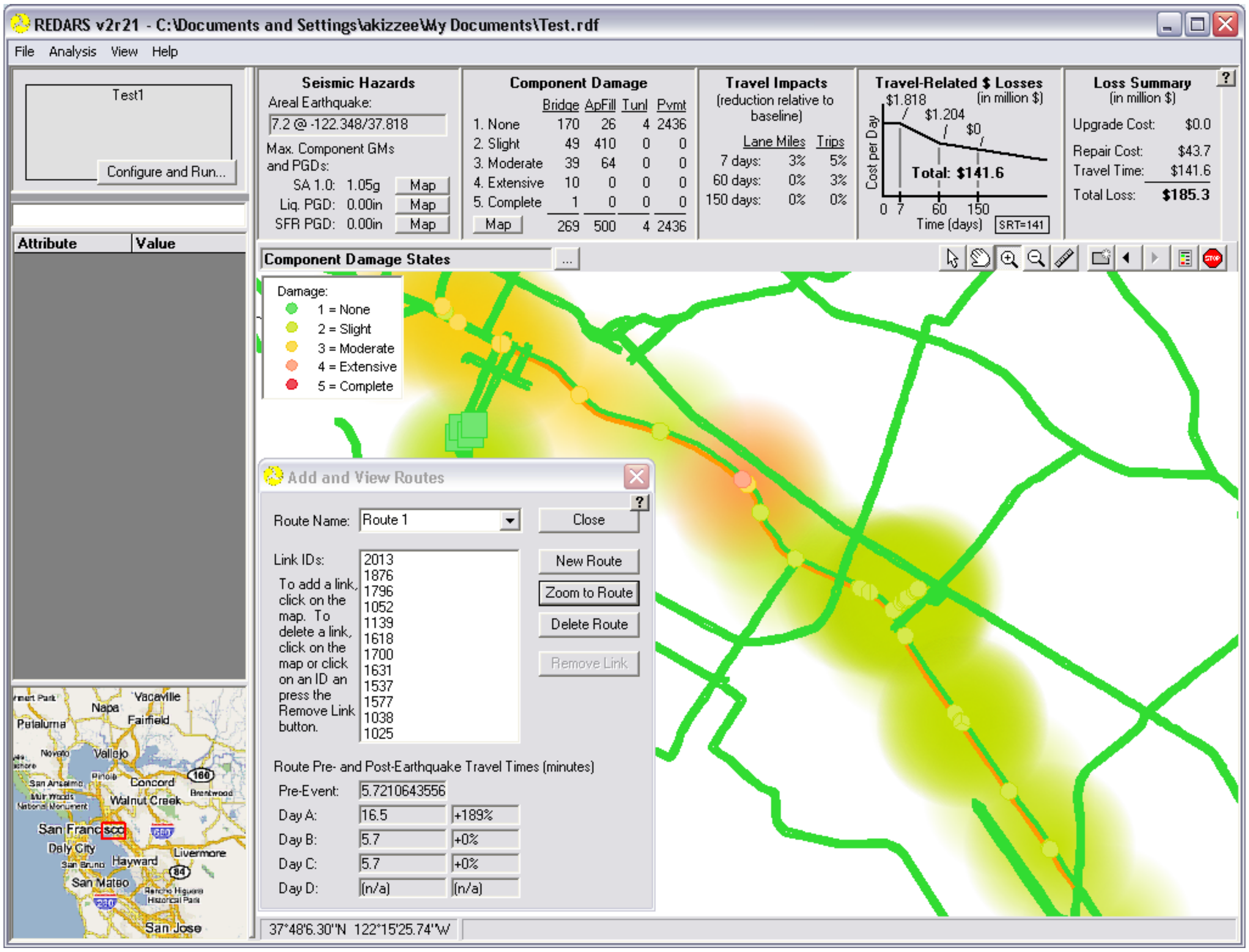


Figure 14. "Route" analysis after earthquake.

All of the following features are displayed in the map viewer, and can be changed in the box above the left corner of the map. "Component Damage State" has already been shown in Figure 14, and it displays the damage status of the bridges and tunnels in the model. As described earlier, there are five levels of bridge damage. "System State" displays the % of lanes open on all road segments. There are 5 levels of the system state; 100% open, 75% to 99% open, 26% to 74% open, 1% to 25% open, and 0% open. The map color scheme for the system state is the same as the bridge damage color scale. "Traffic Volume" displays the traffic volume of all road segments compared to pre-event traffic volume. Factors that effect this value are bridge closures/damage, detours, and forgone trips because of increased travel time. There are 7 levels of "Traffic Volume" displayed on the map; no base volume, closed, 1% to 33% of pre-event volume, 34% to 66% of pre-event volume, 67% to 99% of pre-event volume, 100% of pre-event volume, and over 100% of pre-event volume. "Travel Time Increases" can be displayed for auto and freight traffic, and differentiate between egress and access times for each TAZ. And finally "Trip Reductions" can be displayed for auto and freight traffic, and differentiate between production and attraction for each TAZ. All of the above display options are for the standard three time intervals post-event (7 day, 60 day, and 150 day).

Because the program was designed for primary use as a planning tool, no route analysis capabilities or traffic modeling is possible until a scenario is run. Therefore, the user should create the smallest earthquake possible (moment magnitude 5) in a location that is very far from Memphis (at least 100 km). This will enable the “Route” and “Shortest Path” analysis features to run. To make these functions applicable in a post disaster scenario, the actual damage state of bridges must be input into REDARS. This can be done simply by selecting a bridge and changing the damage state on the “Attributes Table”. However, manually changing the damage status makes the program not be able to perform the “Route” or “Shortest Path” functions, or display any of the affects that the closure has on the highway system. This is an error in the program that will hopefully be corrected for the next release. Another aspect of the program that is not ideal is the inability to view the data in tabular format. All of the traffic volume, lane closure, and bridge damage information is displayed graphically in the map window. Information about a specific road link or bridge can be viewed 1 at a time in the “Attributes” window, but there does not seem to be a way to easily access this information for the entire system. A feature like this would make REDARS2 much more applicable in a post-disaster scenario.

Because the all of the Memphis data currently is not formatted correctly, and because of the limited technical support that is available to us from the distributors of the software, it is currently unknown if REDARS2 in its current state will actually serve th The issue of figuring out what and how much damage has been sustained to any given area after a natural disaster or terrorist attack has been problematic for some time. Since the 9/11 attack on the United States and the mishandling of Hurricane Katrina, emergency management has become a key field of study and highly funded. When a natural disaster or terrorist attack happens, it is the job of emergency management personnel to assess the situation and disseminate key information to all interested parties as soon as possible to increase awareness and contribute to public safety.

Since Memphis and Shelby County are situated directly on top of the second largest fault zone in the United States, responding to a disaster such as these has become an area of much interest. Memphis is a large shipping hub for goods throughout the world with a large independent parcel delivery service and an interstate highway that stretches from coast to coast passing through the city. If Memphis’s transportation infrastructure were to be destroyed or even damaged by one of these incidents, the effects would ripple throughout the country and world. This research is important to Memphis and Shelby County so that we can make a timely assessment of the infrastructure damage in the event of an earthquake.

DISCUSSION

The Hybrid Method was able to distinguish between damaged and undamaged bridges, except in the case of the very short (30m) bridge. This method may be detecting one of several changes due to bridge damage: a downed bridge that reveals the land or water below, a damaged bridge surface, or deposition on the bridge from a nearby landslide. Since an undamaged bridge section with a large vehicle on it can look quite different from one without a vehicle, it can be interpreted as damaged using automated methods. Taking a moving average of 10m bridge sections allowed us to distinguish damaged bridges from undamaged bridges with a truck on them.

Since China has recently experienced substantial economic development, it has increased and updated its transportation infrastructure. Some of the bridges in this study area have been remodeled/refinished during the three year span of time between images. Even with these intentional changes between image dates, the Hybrid Method was able to distinguish well between damaged and undamaged bridges, regardless of whether or not the bridge had undergone remodeling or refinishing (however the Taff Method was not able to distinguish between them).

This research shows that it may be possible to automatically detect damaged bridges on a large scale from satellite images instead of through on-the-ground survey techniques or by using helicopter flyovers. This method may also be useful for detecting bridge damage in other disaster events (extreme weather, fires, floods, terrorist or other attacks). The method may both save a lot of money and allow for quicker damage assessment than available through other methods.

LIMITATIONS

If one or both images taken before and after the earthquake are taken at a time when there is heavy traffic on bridges, this method may be less accurate. Since our test site did not have substantial traffic, it uncertain what effects heavy traffic may have on the results. It is possible that if heavy traffic were present during *both* the pre- and post-earthquake image, this method may still give decent results, however, if only one of the images is taken during a heavy traffic period, it is expected that the results would be less accurate.

China has been growing economically for almost three decades now, which has also contributed to their infrastructural growth. The infrastructure in our study area experienced development. We know that the town of Yingxiu has modified some of its bridges and roads. The area has two bridges that have been removed since the 2005 imagery, several streets have been paved, and a few of the study bridges may have gone alterations. Even in the face of this limitation, our results were quite good.

The developed method detects bridge damage once the outline of the bridge is demarcated in both the pre- and post- earthquake images. This method is referred to by Eguchi (2004) as the “Bridge Doctor” portion of the analysis. However, determining the coordinates of the bridge edges was done by hand in this analysis – this phase is referred to as the “Bridge Hunter” phase by Eguchi (2004) and an automated method still needs to be developed. With future funding, we plan to use an object-oriented classification approach to locate the bridges. An object-oriented approach finds sets of adjacent pixels that have similar spectral values – which will ideally demarcate the bridges from the surrounding landscape, even in the case of damaged bridges. We plan to “seed” the objected-oriented approach by giving approximate coordinates of the bridges, available from other data sources, and then having software find the exact borders of the bridges in the imagery.

NOTES

The location of our research sites were carefully chosen. Other sites may be useful for further research, as long as there was a documented destructive event, a transportation infrastructure (i.e., in an area not too rural), and availability of high spatial resolution imagery. The site for research must have both damaged bridges and documented information about the damaged bridges. The imagery that we used was purchased through a consortium of research and educational professionals, Sichuan Earthquake Data Consortium. We were able to obtain open source information about bridge damage in the study area through the internet, by MicroSoft, EPICentre, MCEER, EERI, EPSRC, EEFIT, and ImageCat, Inc. Several of the team members in these organizations traveled to the site of our research to document the effects of the earthquake and there observations were published in a website titled "Virtual Disaster Viewer (VDV)" (http://www.virtualdisasterviewer.com/vdv/select_event.php).

For these analyses, we used the following software: ERDAS Imagine, ESRI ArcGIS, Hawth's Tools, and Microsoft Excel.

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