POST-DISASTER BRIDGE DAMAGE ASSESSMENT USING REMOTELY-SENSED IMAGES

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ABSTRACT
In extreme events, such as natural disasters and terrorist attacks, the performance of critical transportation elements is a major concern. Serious damage to these components can have far reaching implications, including the impedance of critical emergency response actions, and ultimately, the loss of human life. In answer to the need for effective incident response and recovery efforts, remote sensing technologies offer near-real post-disaster damage assessment. This paper documents the methodological development of preliminary damage detection algorithms for highway bridges. *Bridge Hunter* tracks down bridges of interest in remote sensing coverage, while *Bridge Doctor* diagnoses their damage state after a major disaster. The algorithms are used to distinguish between damage scenarios of highway bridges that: (a) collapsed and (b) recorded no damage following the 1994 Northridge earthquake. Following a terrorist attack or natural disaster, these damage detection algorithms would enable rapid damage assessment of numerous bridges across a wide geographic area.

INTRODUCTION
In extreme events, such as natural disasters and terrorist attacks, the performance of critical transportation elements is a major concern. With some 500,000 bridges and 4 million miles of road at risk in the U.S. (Williamson et al., 2002), effective incident response and recovery efforts demand near real-time post-disaster damage assessment. Remote sensing technologies offer a solution. Airborne- and satellite-based sensors present a high-resolution, synoptic overview of the highway system, which can be used to monitor its structural integrity, and assess the degree of damage following an event.

This paper provides an overview of a two-phase methodological procedure used to develop preliminary damage detection algorithms for highway bridges (see also Imagecat 2002a, 2002b). The first task is locating bridges of interest on remote sensing coverage. The second step involves assessing the damage state of these structures, in terms the spectral change between a temporal sequence of images. The 1994 Northridge earthquake is employed as a useful test bed for model development, in view of the widespread damage that was sustained by the transportation network when the 6.7 magnitude event struck Los Angeles on January, 17, 1994.

METHODOLOGICAL APPROACH

The following section provides an overview of the damage detection methodology. A data collection effort was initially undertaken to compile geospatial data for the sample of bridges affected by the 1994 Northridge earthquake. These datasets can be classified into two main types: (1) raster-based remotely-sensed data; and (2) vector data that are either geographic information systems (GIS) based, or can be spatially located and compared with the remote sensing imagery. Table 1 summarizes spectral, spatial and temporal characteristics of the optical and synthetic aperture radar (SAR) coverage that was acquired for the event. Bridge and highway network databases were obtained from the Federal Highway Administration (FHWA) and CALTRANS. These included: the National Bridge Inventory (NBI), which includes a comprehensive listing of highway bridges; the National Highway Planning Network (NHPN), which was used to determine bridge location; the Highway Performance Monitoring System (HPMS), which provided additional attributes for the NHPN; and the CALTRANS Northridge bridge damage database, which was used to calibrate bridge damage levels. The contents of these databases were linked together using CALTRANS identification numbers.

Table 1. Summary of Sensor Type, Spatial and Temporal Properties of Optical and SAR Remote Sensing Imagery Examined Using Bridge Hunter.

PLATFORM	SENSOR TYPE	DATE ACQUIRED	SPATIAL RESOLUTION	TIMESCALE
USGS DOQS	Panchromatic airborne	5/31/94	1m	Post-earthquake
JERS	SAR	4/30/93 7/27/93 7/14/94	18m	Pre-earthquake Pre-earthquake Post-earthquake
SPOT	Multispectral	12/5/93 1/20/94	20m	Pre-earthquake Post-earthquake
	Panchromatic	11/9/93 1/20/94	10m	Pre-earthquake Post-earthquake
SRTM	Interferometric SAR	2/12/00	30m	Post-earthquake
Intermap	SAR	1997	2.5m	Post-earthquake
Landsat	Multispectral	9/20/99	30m	Post-earthquake
	Panchromatic	9/20/99	15m	Post-earthquake

The first phase of the damage detection process involved compiling a comprehensive catalog of images for the 944 bridge structures within the present study area, using an automatic data integration and image processing algorithm referred to as *'Bridge Hunter'*. As the name suggests, Bridge Hunter tracks down bridges of interest in a multitemporal sequence of remote sensing data froma range of airborne and zatellite sensors. As summarized in Figure 1, the algorithm employs database management programs, customized image processing techniques and batch processing to locate bridges from the National Bridge Inventory (NBI) database through dynamic segmentation, subset images with these locations, and then register them through template matching.

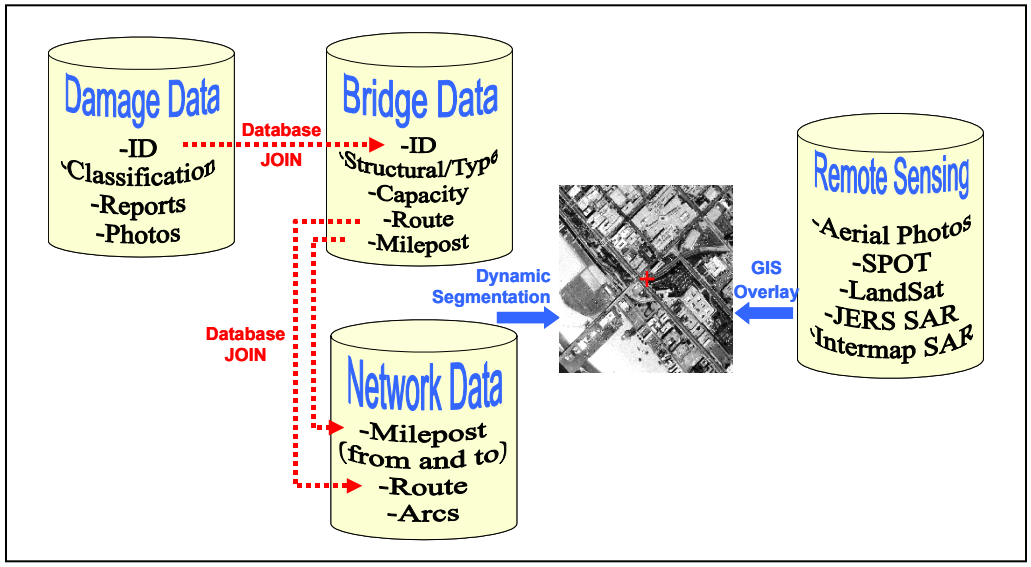


Figure 1. Schematic Representation of Methodological Procedures Employed by *Bridge Hunter* to Locate Bridges of Interest and Output a Catalog of Remotely-Sensed Images.

The second phase of the methodology ascertains whether a bridge has sustained damage, by comparing its spectral characteristics on remote sensing data acquired 'before' and 'after' an earthquake event or terrorist attack. The change detection algorithm, which is referred to as *'Bridge Doctor'*, is represented schematically in Figure 2. Changes between scenes are identified in terms of difference and correlation values. Difference was computed on a per pixel basis, and correlation using a 5x5 pixel sample window, according to Equation 1. Although correlation values are more mathematically sound for larger windows, given the limited width of the bridge and highway features, the present window size achieves a reasonable compromise.

$$\text{Correlation } (I_1, I_2) = \frac{\text{Covariance}(I_1, I_2)}{\sqrt{\text{Standard deviation}(I_1) \cdot \text{Standard deviation}(I_2)}} \qquad (1)$$

The indices of change were sampled at regular intervals along a central transect, which as shown in Figure 2, runs along the highway and across the bridge of interest. Initial tests indicated that two key methodological refinements were in order, because small errors in registration caused anomalous (non-damage related) changes to be registered, and the inclusion mixed pixels proved to be a significant source of error. The refinements involved fine manual tuning of the image-to-image registration, and the use of a mask (shown in red) to exclude spurious non-highway/bridge pixels.

The resulting difference and correlation values were used to produce damage profiles for the sample of bridges in Figure 3, comprising: (1) the full set of *collapsed* structures, where part of the deck fell or was displaced; and to act as a control (2) a subset of examples where zero damage was sustained - the null or *none* case. In general, it may be hypothesized that for collapsed bridges, there will be substantial changes between spectral characteristics on the 'before' and 'after' images. However, in the case of no damage, spectral change should be minimal.

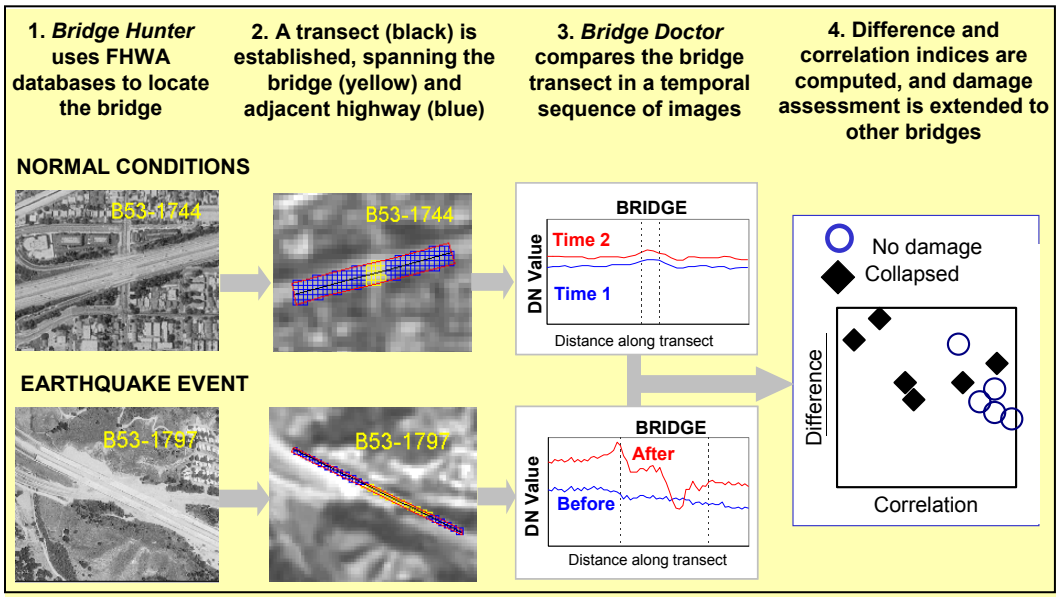


Figure 2. Schematic Representation of the Change Detection Methodology *'Bridge Doctor'*.

Scatter plots were also generated based on difference and correlation values for the entirety of each bridge. A mask was used to distinguish between relevant pixels (see, for example, the yellow delineated pixels in Figure 2), and those falling on the adjacent highway (blue delineation). The average and standard deviation of difference and correlation were then computed for each structure.

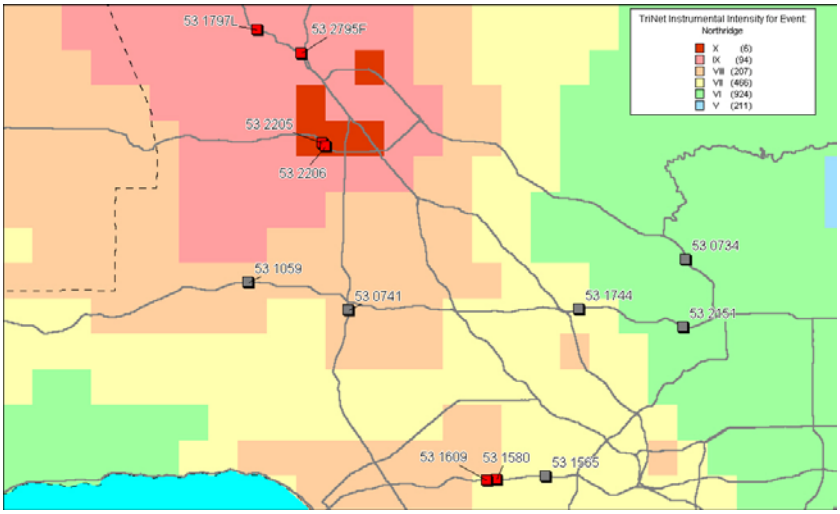
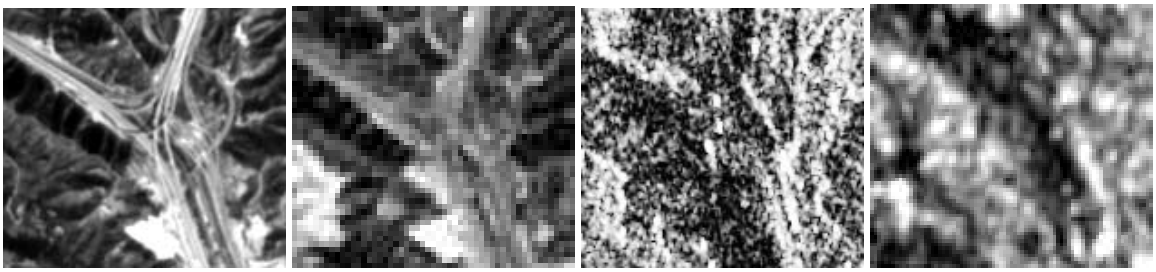


Figure 3. Map Showing the Location of Selected Collapsed (Red Symbols) and Non-Damaged Bridges (Grey Symbols) for Assessing Model Performance. TRINET Intensity Data is shown in the Background.

RESULTS

A sample of output images from *Bridge Hunter* was examined to determine the optimal datasets for damage detection. From the USGS aerial images captured approximately 6 months after the event, it was usually evident where damage had been sustained, from repairs that were being made. This 1m data is of lower resolution than Quickbird (0.61 m) and comparable to the IKONOS satellite imagery available today. Although these datasets will probably be used to detect damage arising from future earthquakes, together with STRM imagery, they were unavailable on appropriate pre- and post-Northridge timescales. Upon inspection, it became apparent that the SAR JERS and optical Landsat coverage would not suffice for visualizing bridges. By comparing the amount of detail depicted by the various sensors in Plate 1, it is evident that highway features are difficult to discern. Subsequent phases of the change detection process therefore focused on SPOT panchromatic, as the highest resolution dataset available.



(a) (b) (c) (d)

Plate 1. Comparison of Output from *Bridge Hunter* for Collapsed Bridge B53-1960 (I5/I14 Intersection): (a) SPOT Panchromatic; (b) Landsat Multi-spectral; (c) JERS Intensity; (d) SRTM Intensity.

From the graphical representation in Figure 4, basic reflectance characteristics for the non-damaged bridges are highly consistent, following a similar pattern along each transect. Although the magnitude of values often increases around the bridge deck (see, for example, Figure 4d), this change is mirrored in both the 'before' and 'after' scene, and is likely to arise from a fundamental difference between the reflectance characteristics of contrasting road surface materials. DN values in the 'after' images are consistently higher than 'before', with the offset of –20 <DN< -10 in the corresponding difference plots attributable to varied illumination conditions at the time of imaging.

Compared with the non-damaged scenario, results for the collapsed structures in Figure 5 reveal substantial spectral changes between the 'before' and 'after' scenes. Around the collapsed bridge B53-1580 on the I10 at Fairfax-Washington (Figure 5a), the damage profiles no longer show a similar trend. The abrupt divergence in response around the collapsed structure is highlighted by the difference plot, which deviates from the non-damage levels of change (-20 <DN< -10) to negative values approaching DN~ -30. The damage description from CALTRANS (1994) indicates that this divergence corresponds with the collapse of an entire span. Outside the damaged area, spectral responses return to a typical value of DN ~ -10, indicating that other than illumination differences, little further change has occurred.

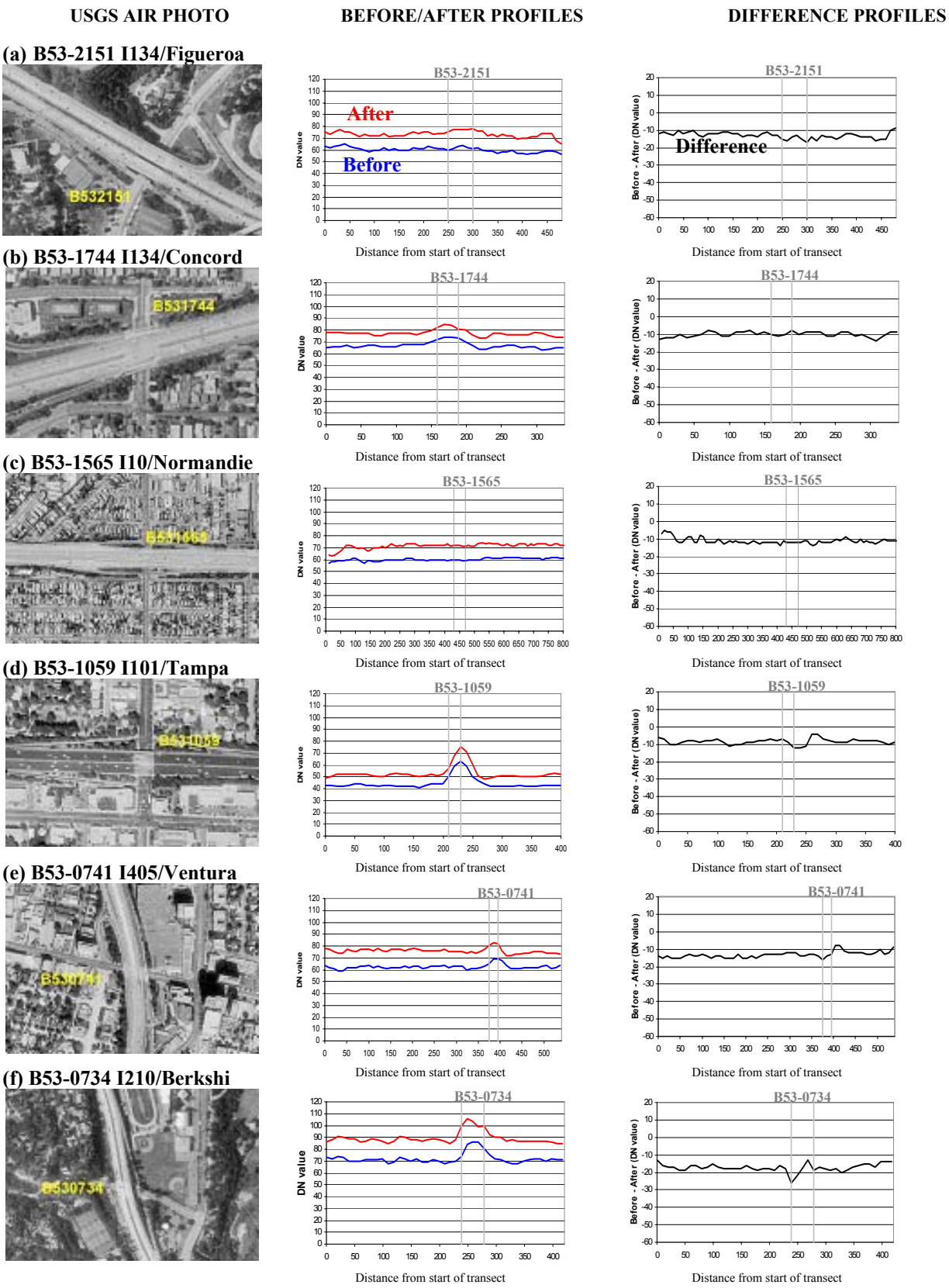


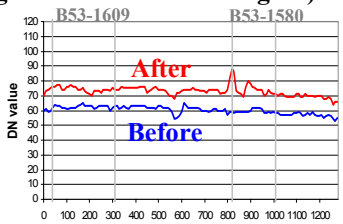
Figure 4. SPOT Damage Profiles showing Reflectance Characteristics and Difference Values along the Central Transect of Bridges/Highways Recording 'No Damage' During the Northridge Earthquake.

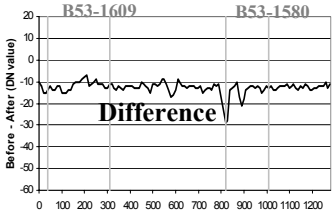
DAMAGE DESCRIPTION	USGS AIR PHOTO	BEFORE/AFTER PROFILES	DIFFERENCE PROFILES

(a) B53-1609 and B53-1580 (I10 - La Cienega and Fairfax/Washington)

B53-1580: One span collapsed.

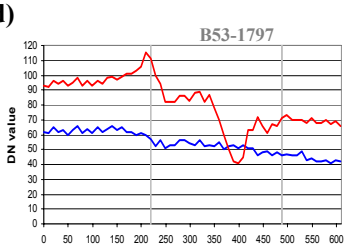
B53-1609: One collapsed span. Most columns buckled.

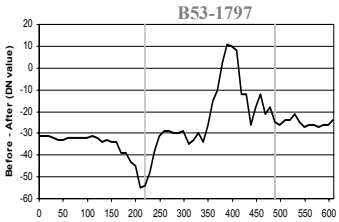




(b) B53-1797 (I5 - Gavin Canyon eastbound)

Spans 2 & 4 collapsed.





(c) B53-1797 (I5 - Gavin Canyon westbound)

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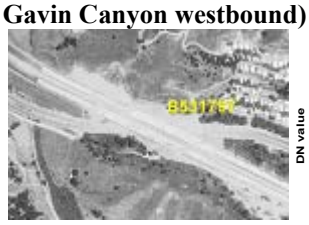
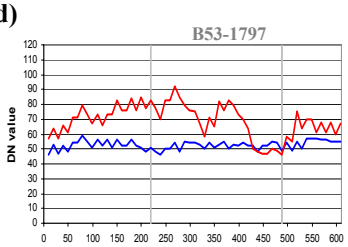
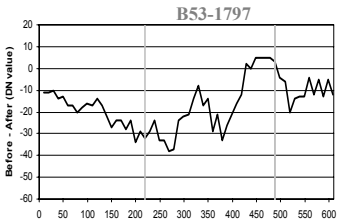
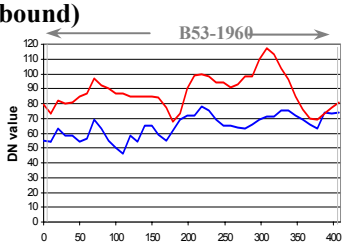


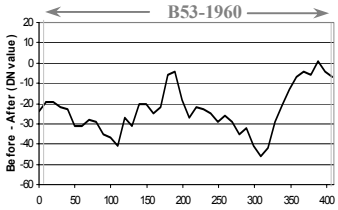




(d) B53-1960 (I5 southbound and I14 southbound)

Spans 1 & 2 collapsed

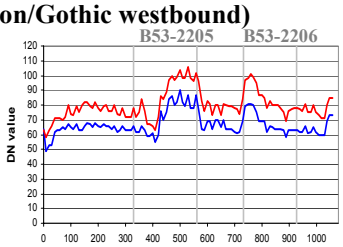


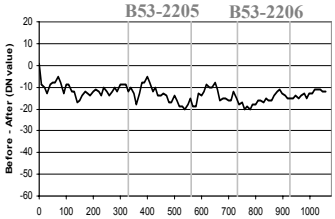


(e) B53-2205 and B53-2206 (Hwy 118 - Mission/Gothic westbound)

B53-2205: Westbound structure damaged (2 ft sag)

B53-2206: All columns failed. Some poking through deck

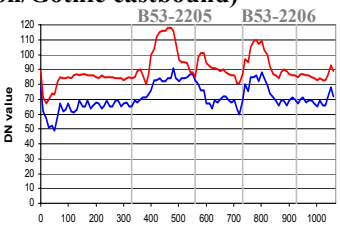




(f) B53-2205 and B53-2206 (Hwy 118 - Mission/Gothic eastbound)

B53-2205: Eastbound structure collapsed.

B53-2206: Structure partially collapsed



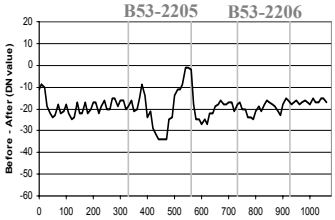


Figure 5. SPOT Damage Profiles showing Reflectance Characteristics and Difference Values along the Central Transect of Bridges that Collapsed During the Northridge Earthquake.

Exaggerated spectral differences were also recorded for bridges: B53-1797 on the I5 at Gavin Canyon (Figure 5b-c); bridge B53-1960 at the I5/I14 intersection (Figure 5d); and bridge B53-2205 on Hwy 118 at Mission Gothic (Figure 5e-f). In each case, there is the characteristic divergence in spectral response around the bridge span, with difference values reaching a maximum of DN~ -55. The difference profiles also record positive values, associated with a reversal in the relative intensity of before and after scenes. This appears to be a unique characteristic of collapsed structures.

The spectral characteristics for bridge B53-2206 suggest a non-damage state. However, the CALTRANS (1994) database instead reports that this structure collapsed. An explanation for both this discrepancy, and the absence of a damage signature for bridge B53-1960 at La Cienega (see Figure 5a), may lie with the nature of collapse. In the latter case, bridge collapse was manifest as a comparatively small vertical slump, accompanied by a series of wide cracks. Given the 10m resolution of SPOT panchromatic coverage, it is likely that the weak spectral signature of these cracks evaded detection.

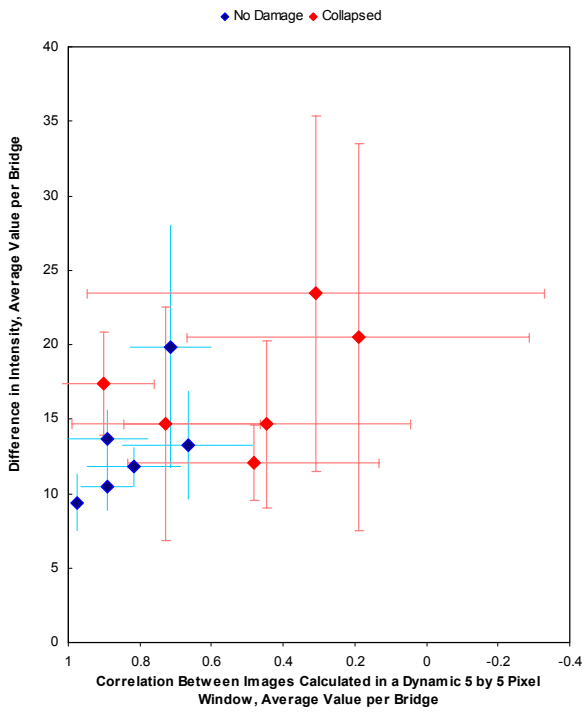


Figure 6. Graphical Representation of Mean Correlation and Difference Values Recorded on SPOT Imagery, for the Subset of Collapsed and Non-Damage Bridges.

The bi-variate scatter plot in Figure 6 provides a useful comparison between the damage indices for collapsed and non-damaged bridges. The results indicate that collapsed bridges record considerably lower levels of correlation than their non-damaged counterpart, while the difference between 'before' and 'after' scenes tends to be greater. From standard deviation readings, the range of difference and correlation values is also higher for collapsed bridges. Scatter about these trends may arise from: (1) anomalous changes due to congestion associated with detour traffic; and (2) collapsed bridges 'slumping' in a manner that appears undamaged when imaged from above.

CONCLUSIONS

- Bridge and highway features are readily detected on SPOT panchromatic data, and visual inspection of a subset of collapsed structures suggested that damage was present following the Northridge earthquake. With imagery available 'before' and 'after' the event, this dataset became the focus of change detection efforts. Due to issues of spatial and temporal resolution, Landsat, SPOT multispectral, and JERS-SAR data were unsuitable for this change detection algorithm.

- *Bridge Hunter* and *Bridge Doctor* damage detection algorithms successfully distinguish between cases of bridges that collapsed and recorded no damage following the 1994 Northridge earthquake. The spectral characteristics of highway bridges are consistent where no damage has been sustained, yet exhibit pronounced divergence where part of the deck has fallen.

- Damage profiles and bi-variate bridge scatter plots are useful tools for monitoring the structural integrity of highway bridges. Bridges sustaining no obvious damage consistently exhibit smaller spectral differences and higher correlation values between before and after images than collapsed structures.

- Following a terrorist attack or natural disaster, the Bridge Hunter/Bridge Doctor damage detection algorithms would enable rapid damage assessment of numerous bridges across a wide geographic area.

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