Building Damage Mapping of the 2003 Bam, Iran, Earthquake Using Envisat/ASAR Intensity Imagery

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A strong earthquake occurred beneath the city of Bam, Iran, on 26 December 2003. High-resolution optical satellite images, such as Ikonos and QuickBird, obtained after the earthquake indicate that severely damaged areas were widely distributed in the city. A European radar satellite, Envisat, also captured the hard-hit areas on 07 January 2004. This paper introduces an automated damage detection technique that was developed based on the data set of the 1995 Kobe, Japan, earthquake and applied to Envisat/ASAR images of Bam. A detailed investigation of the characteristics of the areas damaged due to the Bam earthquake in terms of the differences in the backscattering coefficient and the correlation coefficient of the pre- and post-event Envisat/ASAR images was conducted in order to raise the precision of damage detection. Finally, the damage-mapping scheme was revised to present the distribution of damaged areas in Bam. [DOI: 10.1193/1.2101027]

INTRODUCTION

Recent earthquakes like the 1994 Northridge and the 1995 Kobe earthquakes, have reminded us how important it is to understand damage information as quickly as possible following an earthquake so that normal activities may resume and restoration planning begin. Synthetic aperture radar (SAR) has a remarkable capability to record the physical contours of the earth's surface, regardless of weather conditions or the amount of sunlight. SAR interferometric analyses that use phase information, successfully provide a quantitative relative ground displacement level due to natural disasters (Massonnet 1993) and an inventory of the built environment (Eguchi et al. 2000). Complex coherence obtained from the interferometric analysis enables building damage due to earthquakes to be evaluated (Matsuoka and Yamazaki 2000). However, complex coherence is sensitive to parameters, such as satellite geometry, acquisition duration, and radar wavelength (Zebker and Villasenor 1992). The backscattering coefficient of the earth's surface with amplitude information (intensity) is less dependent on the above-mentioned conditions (Yonezawa and Takeuchi 2001). Hence, the backscattering coefficient derived from SAR intensity images can be used to develop a universal method for identifying damaged areas in disasters such as earthquakes, forest fires, and floods. The 1995 Kobe earthquake provided both detailed ground truth data with building damage

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and the opportunity to investigate the relationship between the backscattering property and the degree of damage. From this analysis, a method for detecting areas with building damage was developed (Matsuoka and Yamazaki 2004).

Recently, the authors had the opportunity to capture images of hard-hit areas due to earthquakes by high-resolution optical satellites and were able to compare SAR intensity images with these satellite images. Advanced SAR system (ASAR) onboard satellite, Envisat, which can capture the earth's surface with approximately 30-meter resolution, observed the hard-hit areas on 07 January 2004. High-resolution satellites, Ikonos and QuickBird, successfully observed the damaged areas for this earthquake. High-resolution optical satellite images indicated that severely damaged areas were widely distributed in Bam. This paper presents the results of an investigation of the characteristics of damaged areas in the SAR images and an automated damage detection technique developed by the present authors applied to the SAR images.

APPLICATION OF A DAMAGE DETECTION METHOD TO BAM EARTHQUAKE

The backscattered strength of microwaves reflects the roughness of the surface, the moisture level, and the incident angle of the microwaves and its wavelength. Typically, man-made structures show relatively high reflections due to spectral characteristics called the "cardinal effect of structures and ground." Open spaces or damaged buildings have relatively low reflectances, since microwaves are scattered in different directions. Based on the above characteristics (Figure 1), the authors previously developed an automated method for detecting areas with severely damaged buildings using the time-series SAR data sets for the Kobe earthquake (Matsuoka and Yamazaki 2004). This empirical method is described in the next paragraph.

First, two multi-looked intensity images taken before and after an earthquake were prepared. It is desirable that the acquisition dates are as close as possible to the day of the earthquake and that the observation conditions are similar. However, the method was successful in damage detection for the Kobe example, although the image pair had vastly different observation orbits before and after the earthquake. After co-registering the pre- and post-event images, each image was filtered using a Lee filter (Lee 1980) with a 21×21 pixel window. The difference in the backscattering coefficient d in Equation 1 and the correlation coefficient r in Equation 2 are derived from the two filtered images. Then, the discriminant score z_0 is obtained by Equation 3.

$$d = 10 \cdot \log_{10} \bar{I}a_i - 10 \cdot \log_{10} \bar{I}b_i \quad (1)$$

$$r = \frac{N\sum_{i=1}^{N} Ia_i Ib_i - \sum_{i=1}^{N} Ia_i \sum_{i=1}^{N} Ib_i}{\sqrt{\left(N\sum_{i=1}^{N} Ia_i^2 - \left(\sum_{i=1}^{N} Ia_i\right)^2\right) \cdot \left(N\sum_{i=1}^{N} Ib_i^2 - \left(\sum_{i=1}^{N} Ib_i\right)^2\right)}} \quad (2)$$

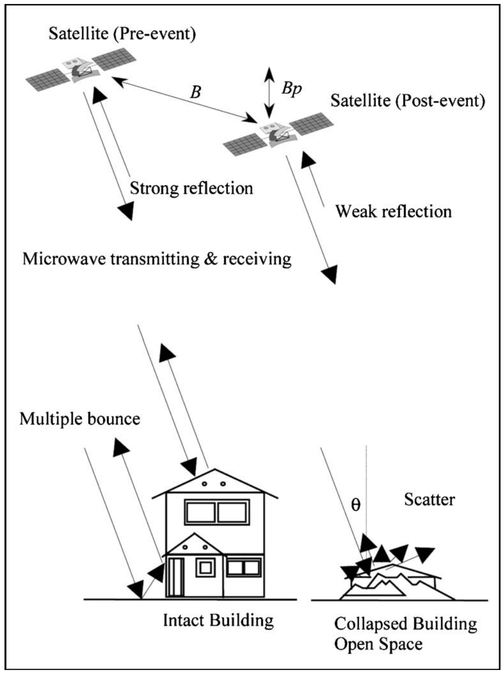

Figure 1. Schematic figure of the repeat pass satellite observation geometry and backscattering characteristics of buildings.

$$z_0 = -2.140d - 12.465r + 4.183 \quad (3)$$

where i is the sample number, and Ia_i and Ib_i are the digital numbers of the post- and pre-images, respectively. $\bar{I}a_i$ and $\bar{I}b_i$ are the corresponding averaged digital numbers over the surroundings of pixel i within a 13×13 pixel window and the total number of pixels N within this window is 169 to compute the two indices. A pixel with a high z_0 value is assigned as a severely damaged area (Figure 2). Focusing on urbanized areas to detect building damage, the pixels with backscattering coefficients smaller than the assigned threshold value around −6 dB are masked in the value z_0 distribution.

Using the above procedure, the discriminant score z_0 and the estimated damage distribution for the cities of Bam and Baravat were calculated using pre- and post-event Envisat images (Figure 3). An image acquired on 03 December 2003 was used as data for pre-event conditions. Comparing to the visual interpretation results from aerial photographs (National Cartographic Center of Iran 2004), severely damaged areas were clearly detected in central Bam, including downtown and Arg-e-Bam, but not much damage information could be detected in other damaged areas, such as the southeastern part of the city.

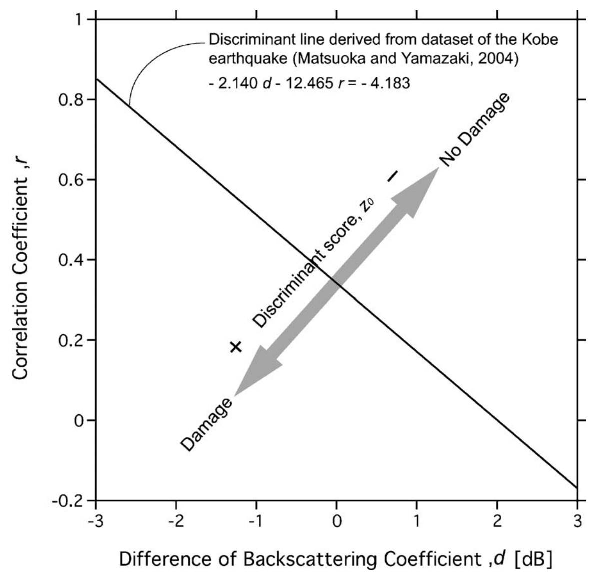

Figure 2. Schematic figure for estimating the severely damaged area using two indices, the difference in the backscattering coefficient and the correlation coefficient calculated from pre- and post-earthquake SAR intensity images.

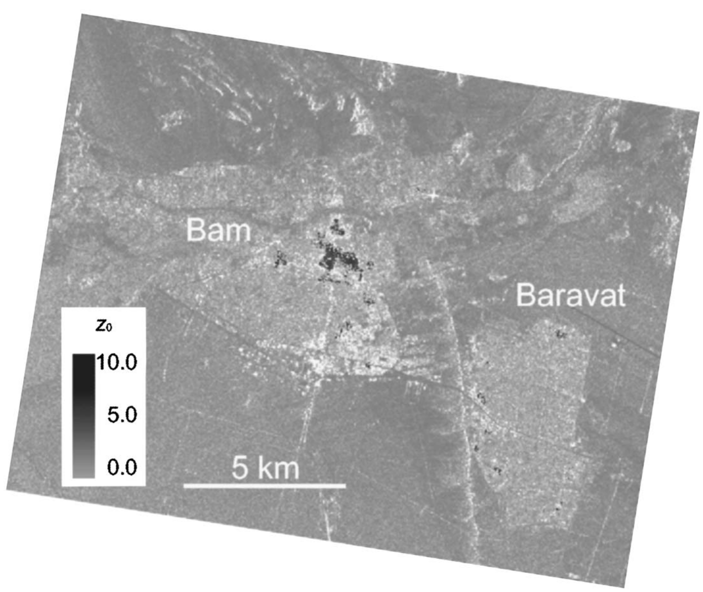

Figure 3. Distribution of the z_0 value, which is derived from a damage detection method (Matsuoka and Yamazaki 2004), using Envisat images taken before (03 December 2003) and after (07 January 2004) the 2003 Bam, Iran earthquake.

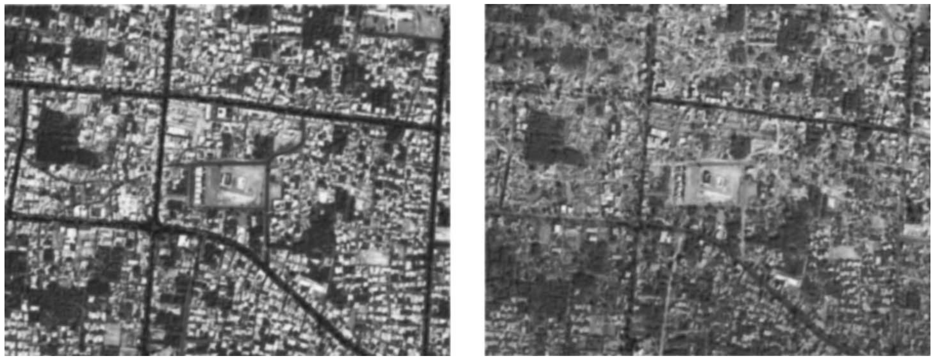

Figure 4. QuickBird images of downtown Bam taken before (30 September 2003, left) and after (03 January 2004, right) the earthquake.

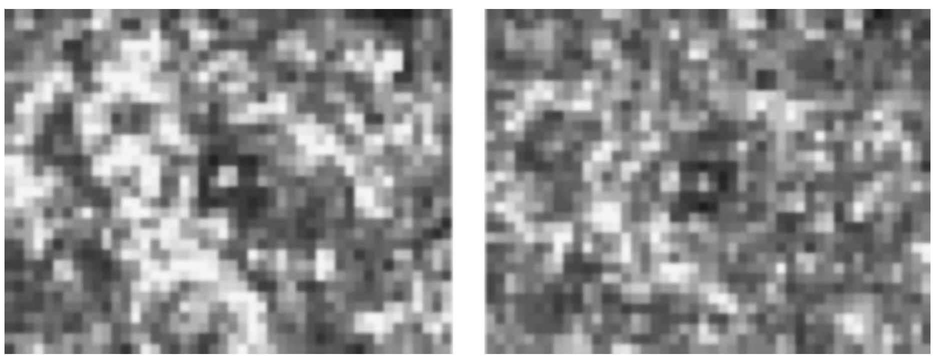

Figure 5. Envisat images of downtown Bam taken before (03 December 2003, left) and after (07 January 2004, right) the earthquake.

BACKSCATTERING CHARACTERISTICS OF DAMAGE AREAS IN BAM

The typical situation (Figure 1) was observed in the backscattering characteristics in the area with numerous collapsed buildings in downtown Bam. Figures 4 and 5 show the pre- and post-earthquake images of the area by QuickBird and Envisat, respectively. The backscattered echoes by severely damaged areas decreased in the post-image of Envisat. However, it also found that a reverse characteristic dominated in some severely damaged areas in southeastern Bam (Figures 6 and 7). Prior to the earthquake, orderly houses with flat roofs were densely located, but the earthquake damaged most of them. According to the Envisat images, the backscattered echoes became stronger in the post-earthquake image. When uniform buildings stand very close to each other, spectral bounces on the flat roofs cause weak reflections. If an earthquake causes some of the buildings located in the near-range of a satellite to collapse, then the cardinal effect against other buildings can cause strong reflections. The debris from the collapsed build-

Figure 6. QuickBird images of southwestern Bam taken before (30 September 2003, left) and after (03 January 2004, right) the earthquake.

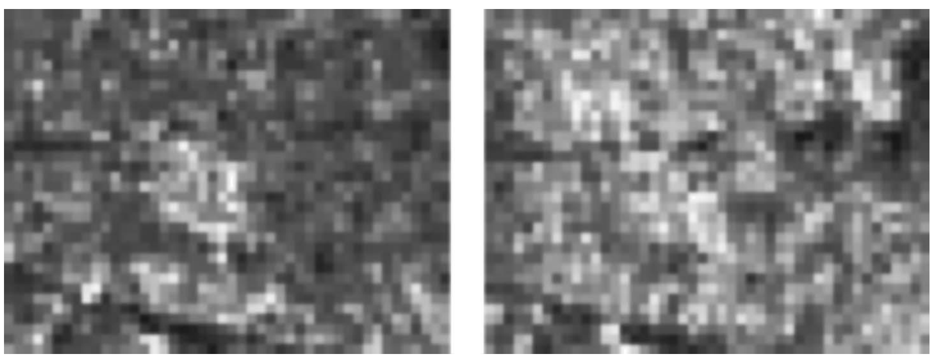

Figure 7. Envisat images of southwestern Bam taken before (03 December 2003, left) and after (07 January 2004, right) the earthquake.

ings could also create a relatively higher reflectance of microwaves than smooth/flat roof surfaces, which is schematically depicted in Figure 8. In order to revise the model based on the above experience, a more thorough examination of the backscattering characteristics in the damaged and non-damaged areas is described below.

REVISED METHOD FOR DAMAGE MAPPING AND ITS APPLICATION

Using the visual damage interpretation result from the QuickBird images (Yamazaki et al. 2005), the damage ratio of buildings, D, on a city-block level was calculated as the ratio between the number of buildings classified as Grade 5 (destruction) in the European Macroseismic Scale, EMS-98 (European Seismological Commission 1998), and the total number of buildings in each block. Then the pixels that correspond to the two groups with less damaged ($D < 1\%$) and severely damaged ($D > 80\%$) areas were selected in order to examine the difference in the pre- and post-backscattering coefficient

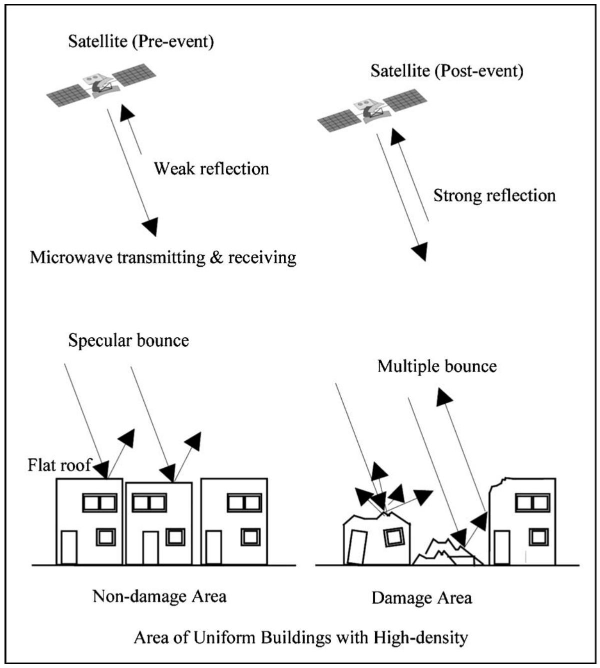

Figure 8. Schematic figure of the backscattering characteristics of orderly uniform buildings with flat roofs and their damages.

and the correlation coefficient of post- and pre-earthquake images. Figure 9 shows that the severely damaged group has two subgroups, A and B. Subgroup A, which consists of the pixels mainly in the area of central Bam, can almost be distinguished from the group in the less damage area by the linear discriminant line derived from the data set of the Kobe earthquake. Some of the damaged areas in Subgroup A were successfully extracted using the discriminant score, z_0, of Equation 3. On the other hand, it is difficult to extract the damaged areas in Subgroup-B, which is like the situation shown in Figure 8, by this discriminant line. Therefore, this study introduced another line (the dotted line in Figure 9) to extract this subgroup. The coefficient value of d in Equation 3 was changed to a positive number as follows.

$$z_1 = 2.140\ d - 12.465\ r + 4.183 \tag{4}$$

To extract the overall damage areas, the z value was calculated as

$$z = \max(z_0, z_1) \tag{5}$$

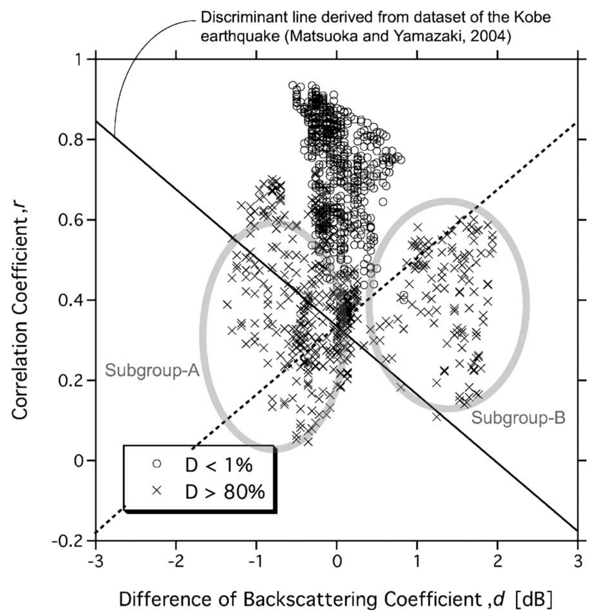

Figure 9. Difference in the backscattering coefficient and correlation coefficient of a less damaged area where the ratio of Grade 5 damaged buildings (*D*) is less than 1%, and a severely damage area where the *D* is more than 80%. The solid line indicates the discriminant line from the data set of the 1995 Kobe earthquake (Matsuoka and Yamazaki 2004). The dotted line is another line that is assumed to distinguish the less damaged area and Subgroup B in the severely damage areas.

Figure 10 shows the distribution of z value using the pre- and post-event Envisat images. The damaged areas, which are widely detected in Bam, correspond with the interpretation using aerial photographs (National Cartographic Center of Iran 2004), QuickBird images (Adams et al. 2004; Yamazaki et al. 2004) and a field survey (Hisada et al. 2005).

CONCLUSION

This paper visually and quantitatively evaluates the backscattering information of damaged areas due to the 2003 Bam, Iran earthquake using pre- and post-earthquake Envisat/ASAR intensity images. An automated technique is introduced for detecting areas with building damage, which was developed by the experiences from the 1995 Kobe, Japan earthquake, and revised according to the backscattering characteristics in the city of Bam. The revised method was then used to map damage from a pair of Envisat images. Consequently, the damaged areas, which were detected based on the compound variable that used the difference value and correlation coefficient of the backscattering

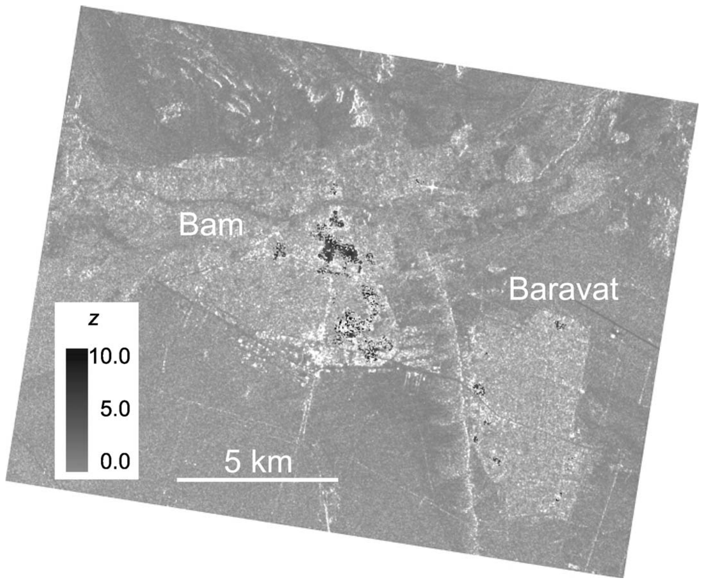

Figure 10. Distribution of the *z* value, which is derived from a revised method using the pair of Envisat images.

coefficient as explanatory variables, roughly correspond to the distribution of severely damaged areas obtained from a field survey and visual interpretation of high-resolution optical satellite images.

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