An earthquake occurred in the Mediterranean coast of Algeria on May 21, 2003. RADARSAT with the fine-beam mode and ERS-2 observed the damaged area after the event. On December 26, 2003, another strong earthquake occurred beneath the city of Bam, Iran. Severely damaged areas were found to be widely distributed in the city from high-resolution optical satellite images obtained after the earthquake. ENVISAT also captured the hard-hit areas on January 7, 2004. In this paper, we investigated the characteristics of damaged areas in these SAR images by visual interpretation and clarified the effect of spatial resolution for the detection of building damage. Then, we introduced our automated damage detection technique which was developed based on the data set of the 1995 Kobe, Japan earthquake and showed the examples of detected damage areas in case of the Kobe, the 1999 Turkey, and the 2001 India earthquakes. Finally, we extracted the damaged areas due to the 2003 Algeria and Iran earthquakes by this method.

1. INTRODUCTION

The recent earthquakes such as the 1994 Northridge and the 1995 Kobe earthquakes, realized us the importance of grasping damage information of built-up areas at an early stage for recovery activities and restoration planning. Synthetic aperture radar (SAR) is remarkable for its capability to record the physical value of the earth's surface, regardless of weather condition or sun illumination. SAR interferometric analyses using the phase information successfully provided the quantitation of the relative ground displacement level due to natural disasters [1], as well as the inventory of built environment [2]. The complex coherence obtained from the interferometric analysis enables us to evaluate building areas with slight damage due to earthquakes [3]. But it is sensitive to parameters, such as the satellite geometry, acquisition duration and wavelength of radar [4]. The backscattering coefficient of the earth's surface, having amplitude information (intensity), is less dependent on the above-mentioned conditions [5]. Hence, the backscattering coefficient derived from SAR intensity images may be used for developing a universal method to identify damaged areas in disasters such as earthquakes, forest fires and floods. Detailed ground truth data with building damage due to the 1995 Kobe earthquake provided us the opportunity to investigate the relationship between the backscattering property and the degree of damage. From this analysis, we have already developed a method to detect areas of building damage [6].

Recently, we have an opportunity to capture images of hard-hit areas due to earthquakes by high-resolution optical images, such as IKONOS and QuickBird, and to compare them with SAR intensity images. An earthquake occurred in the Mediterranean coast of Algeria on May 21, 2003. The cities of Boumerdes and Zemmouri were the most extensively damaged areas. Canadian SAR satellite, RADARSAT, observed the Boumerdes area by the fine-beam mode, on 4 days after the event. European SAR satellite, ERS-2, also observed the same area on June 7, 2003. On December 26, 2003, another strong earthquake occurred beneath the city of Bam, Iran. ENVISAT also captured the hard-hit areas on January 7, 2004. High-resolution satellites, IKONOS and QuickBird, successfully observed damaged areas for both earthquakes. Severely damaged areas were found to be widely distributed in the city of Bam from high-resolution optical satellite images obtained after the event. In this paper, the characteristics of damaged areas in these SAR images were investigated by visual interpretation and the effect of spatial resolution for the detection of damaged buildings was clarified. Then, the automated damage detection technique developed by the present authors was applied to the SAR images of Algeria and Iran. ENVISAT also captured the hard-hit areas on January 7, 2004. High-resolution satellites, IKONOS and QuickBird, successfully observed damaged areas for both earthquakes. Severely damaged areas were found to be widely distributed in the city of Bam from high-resolution optical satellite images obtained after the event. In this paper, the characteristics of damaged areas in these SAR images were investigated by visual interpretation and the effect of spatial resolution for the detection of damaged buildings was clarified. Then, the automated damage detection technique developed by the present authors was applied to the SAR images of Algeria and Iran. Furthermore, the accuracy of the proposed method is examined by comparing the result of the analysis with the identified damaged buildings from the QuickBird images.

2. CHARACTERISTICS OF SAR IMAGES

2.1 The 2003 Algeria and Iran Earthquakes

A moment magnitude 6.8 earthquake shook the Mediterranean coast of Algeria on May 21, 2003. The epicenter is located offshore of the province of Boumerdes. Approximate numbers of collapsed and heavily damaged buildings were 7,400 and 7,000,
respectively. Four days after the event, RADARSAT observed the Boumerdes area by the fine-beam-mode, which captures the earth surface with approximately 8-meter resolution. ERS-2, whose resolution is approximately 30 meters, also observed the hard-hit area including Zemmouri city on June 7, 2003. The both systems transmit the same C-band microwave signal and receive its reflection back to the sensors or antennas. However significant differences of the two SAR systems are the specifications of spatial resolution, incidence angle, and polarization.

The historic city of Bam, Iran, was strongly shaken by a magnitude 6.6 earthquake whose epicenter is located very close to the city, at 5:26 am on December 26, 2003. More than 49,000 traditional mud-brick and clay houses were collapsed and more than 43,000 people, about one third of the population before the earthquake, were killed by this early morning attack. After the earthquake, ENVISAT observed Bam and Baravat cities on January 7, 2004. SAR system specifications of ENVISAT used in this study are almost same as those of ERS.

2.2 Backscattering Characteristics in Damage Areas

Figs. 1 and 2 show the zoom-up images of pre- and post-event by RADARSAT and ERS-2, respectively, for a typical area in Boumerdes city, where totally collapsed buildings are identified in an image taken by Quickbird satellite two days after the earthquake, as shown in Fig.3. The images acquired on February 20, 1998 by RADARSAT and July 27, 2002 by ERS-2 were used for the data prior to the event. The locations of collapsed buildings determined by visual inspection using the QuickBird image are marked as small circles in these figures. As seen in Fig.1, it is found that the backscattering intensity of buildings circled by small solid line in the post-event image is smaller than that in the pre-event image. Generally, man-made structures show comparatively high reflection due to the cardinal effect of structures and ground. Open spaces or damaged buildings have comparatively low reflectance because microwaves are scattered in different directions (see in Fig. 4).

Buildings may be reduced to debris by an earthquake, and in some cases, the debris of buildings may be removed, leaving the ground exposed. Thus, the backscattering coefficient determined after collapse is likely to be lowered compared to that obtained prior to the event. However, the reverse situations are occurred for the buildings marked by dot circles in Fig. 1. According to these appearances in high-resolution SAR images, several reasons are considered such as the relationship among the illumination direction of microwave transmitted from the satellite, the longitudinal direction of buildings, and the built-up density of buildings. The area of refugee tents temporary placed in an open space in the post-event image shows brighter than that in the pre-event image. These kinds of complicated characteristics of backscattering echo were identified in the high-resolution SAR images. Therefore, in order to detect damage areas by an image analysis, we might need to use aggregate information such as an average, texture, and correlation from a local window. Since the resolution of ERS-2 images shown in Fig. 2 is fairly coarse, it is relatively difficult to identify the backscattering characteristics of individual buildings.

Regarding the SAR images of Bam, Iran earthquake, the typical situation (see in Fig. 4) was found in the backscattering characteristics of the area of many collapsed buildings in the downtown of Bam city. Figs. 5 and 6 show the area of pre- and post-earthquake images by QuickBird and ENVISAT, respectively. The pre-event ENVISAT image was acquired on December 3, 2003. The backscattering echoes by severely damaged areas were decreased in the post-image of ENVISAT. However, we also found that the above-mentioned reverse
characteristics are dominant in some severely damaged areas in the southeast of Bam city (see in Figs. 7 and 8). Many orderly houses with flat roof were densely located prior to the earthquake, but the most of them were damaged by the earthquake. According to the ENVISAT images, the backscattered echoes became stronger in the post-earthquake image. When uniform buildings stand very close each other, specular bounces on the flat roofs cause the weak reflection. Then, if some buildings located in the near-range to a satellite were collapsed due to an earthquake, the cardinal effect against other buildings could cause strong reflection. The debris of collapsed buildings could also create relatively higher reflectance of microwave than the smooth/flat roof surfaces. A schematic figure is shown in Fig. 9.

3. AUTOMATED DAMAGE DETECTION METHOD

As we have mentioned in the previous section, man-made structures show comparatively high reflection due to the cardinal effect of structures and ground (Fig. 4). Based on this characteristic, we have developed an automated method to detect the areas with severely damaged buildings using the time-series SAR dataset for the Kobe earthquake [6]. In this empirical method, we need to prepare two multi-looked intensity images taken before and after an earthquake. It is desirable that the acquisition dates are close, as much as possible, to the earthquake occurrence day and that the both observation conditions are similar. However, the method was successful in damage...
detection for the Kobe example shown later, even though the image pair has quite different observation orbits before and after the earthquake. After co-registration for the pre- and post-event images, each image is filtered using Lee filter \[7\] with 21 × 21 pixel window. The difference in the backscattering coefficient \(d\) in Eq. 1 and the correlation coefficient \(r\) in Eq. 2 are derived from the two filtered images. Then, the discriminant score \(z_i\) is obtained by Eq. 3.

\[
d = 10 \cdot \log_{10} \frac{\bar{I}_a - \bar{I}_b}{N \sum_{i=1}^{N} I_a - \sum_{i=1}^{N} \bar{I}_a \sum_{i=1}^{N} I_b} - 10 \cdot \log_{10} \frac{\bar{I}_a - \bar{I}_b}{N \sum_{i=1}^{N} I_a - \sum_{i=1}^{N} \bar{I}_a \sum_{i=1}^{N} I_b}
\]

\[
r = \frac{N \sum_{i=1}^{N} I_a I_b - \sum_{i=1}^{N} I_a \sum_{i=1}^{N} I_b}{\sqrt{\left(N \sum_{i=1}^{N} I_a^2 - \left(\sum_{i=1}^{N} I_a\right)^2\right) \cdot \left(N \sum_{i=1}^{N} I_b^2 - \left(\sum_{i=1}^{N} I_b\right)^2\right)}}
\]

\[
z_i = -2.140 d - 12.465 r + 4.183
\]

as where \(i\) is the sample number, \(I_a\) and \(I_b\) are the digital numbers of the post- and pre-images, \(\bar{I}_a\) and \(\bar{I}_b\) 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 \[6\].

In this study, we assumed and introduced a value \(z_2\) to extract another type of damaged areas which are likely to be the situation shown in Fig. 9. The coefficient value of \(d\) is just changed to positive number as following.

\[
z_2 = 2.140 d - 12.465 r + 4.183
\]

The \(z\) value is calculated as

\[
z = \max(z_1, z_2)
\]

The pixel whose value \(z\) is high is assigned as a severely damage area. Then, focusing on urbanized areas to detect building damage, the pixels whose backscattering coefficient is smaller than the assigned threshold value around –6 dB is masked in the value \(z\) distribution. Following the above procedure for detecting damage areas, the distribution of value \(z\) overlaid on the SAR original intensity image is depicted in Fig. 10 by using an image pair (ERS-1: 1994/10/12, 1995/05/23) obtained before and after the 1995 Kobe, Japan earthquake. In this figure, the red-colored area constitutes a belt that is similar to the hard-hit zone based on a field survey after the earthquake \[8\].

For validation of the method, we have applied it to the 1999 Kocaeli, Turkey and the 2001 Gujarat, India earthquakes. On August 17, 1999, an earthquake shook the northwestern region (Kocaeli) of Turkey. Series of radar observations by ERS-1 and ERS-2 were conducted

Fig. 10. Distribution of the \(z\) value using ERS-1 images taken before (1994/10/12) and after (1995/05/23) the 1995 Kobe, Japan earthquake

Fig. 11. Distribution of the \(z\) value using ERS images taken before (1999/08/13) and after (1999/09/17) the 1999 Kocaeli, Turkey earthquake
over the affected area before and after the event. The image taken on August 13 and September 17, 1999 were used for the pre- and post-earthquake images, respectively. Because the perpendicular separation of the two satellites, called the baseline $B_p$, is approximately 30 m, this pair is also perfectly suitable for an interferometric study. Fig. 11 shows the distribution of $z$ value of this event. Damaged areas shown in red color are widely detected in Golcuk and Adapazari and not in other cities around Izmit Bay. This distribution is in good agreement with the damage statistics of buildings [9, 10].

One and half years later, the Gujarat, India earthquake devastated the western part of India on January 26, 2001. RADARSAT with the fine-beam mode whose ground resolution and incident angle are 8 m and 46 degrees, respectively, flew over around Bhuj city on February 11, 2001. We used the image taken on December 31, 1999 for the data before the Gujarat earthquake. Using this pair, the damage detection by the coherence of phase information cannot be expected since the time interval and $B_p$ of the two acquisitions are more than 400 days and 6 km, respectively. The result of applying the automated detection method to RADARSAT/Fine images is shown in Fig. 12. The damaged areas, which are locally extracted in some villages between Bhuj and Anjar and both cities, well correspond to those interpreted by aerial photographs [11] and Landsat images [12].

In addition, from the results of three earthquakes, the situation shown in Fig. 9 was not appeared significantly. Because the damage distributions extracted by the proposed procedure are very similar to those of our previous trials [13] which took into account of the only $z_1$ value.

4. DAMAGE DETECTION OF THE 2003 ALGERIA AND IRAN EARTHQUAKES

Using the above-mentioned procedure and the SAR images, we calculated the discriminant score $z$ and estimated the damage distribution for the two earthquakes occurred in 2003. In the result of the RADARSAT images of Boumerdes city, Algeria, it is difficult to extract any wide distribution of building damage. According to the visual inspection of building damage in Boumerdes city using QuickBird imagery, the maximum value of the collapsed building ratio is not so high (approx. 14%) [14]. By our above examinations for the 1995 Kobe, the 1999 Turkey, and the 2003 India earthquakes, the distribution
of heavily damaged zone, the area where the collapsed building ratio is more than approximately 25% in our experience, should be detected [13]. Therefore, this result for Boumerdes city shows good agreement with our experiences for the other earthquakes. By using ERS-2 images of the Algeria earthquake, damaged areas are clearly detected in the city of Zemmouri and not in other areas (see in Fig. 13).

For the cities of Bam and Baravat by the Iran earthquake, the distribution of $z$ value using the pre- and post-event ENVISAT images is shown in Fig. 14. The damaged areas, which are widely detected in Bam city, well correspond to those interpreted by aerial photographs [15] and QuickBird images [16].

5. CONCLUSIONS

This paper reported on visual and quantitative evaluation on the backscattering characteristics of damaged areas due to the 2003 Algeria and Iran earthquakes using SAR intensity images. We introduced an automated technique for detecting areas with building damage, which was developed from the experiences from the 1995 Kobe, Japan earthquake. The examples of detected damage areas in case of the Kobe, the 1999 Kocaeli, Turkey, and the 2001 Gujarat, India earthquakes were shown to examine the accuracy of the proposed method by comparing with the field survey data. Then, we applied the automated technique for damage detection to the pre- and post-event images of the 2003 Algeria and Iran earthquakes. As a result, the damaged areas detected based on the compound variable that uses the difference value and correlation coefficient of the backscattering coefficient as explanatory variables roughly corresponded to the distribution of severely damaged areas obtained by visual interpretation of high-resolution optical satellite images.

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