Application of a Methodology for Detecting Building-Damage Area to Recent Earthquakes Using SAR Intensity Imageries

Masashi MATSUOKA and Fumio YAMAZAKI
Earthquake Disaster Mitigation Research Center (EDM), NIED
2465-1 Mikiyama Fukui, Miki, Hyogo 673-0433, Japan.
Email: matsuoka@edm.bosai.go.jp

Abstract

One of the remarkable characteristics of synthetic aperture radar (SAR) is to record a physical value called the backscattering coefficient of the earth's surface not depending on weather conditions and sun illumination. Therefore, SAR could be a powerful tool and be used to develop a universal method for grasping damaged areas by disasters such as earthquakes, forest fires and floods. Detailed ground truth data for building damage due to the 1995 Kobe earthquake provided us the opportunity to investigate the relationship between the backscattering property from SAR images and the degree of damage. From the above analysis we have already developed a method to detect areas of building damage. In this paper, we applied this method to the images taken over the area hit by the 1999 Kocaeli, Turkey, the 2001 Gujarat, India, and the 1993 Hokkaido Nansei-Oki, Japan earthquakes, and then the accuracy of the proposed method was examined by comparing the results of the analyses with those from the damage surveys.

INTRODUCTION

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 a parameter sensitive to 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. In this paper, we briefly introduce the automated damage detection method and apply this method to the images taken over the areas hit by the 1999 Kocaeli, Turkey, the 2001 Gujarat, India, and the 1993 Hokkaido Nansei-Oki, Japan earthquakes, and then the validity of the technique is demonstrated from the comparison with the damage survey data.

THE METHOD OF AUTOMATED DAMAGE DETECTION

The backscattered strength of microwave reflects the roughness of the surface, the moisture level of the area, and the incident angle of the microwave and its wavelength. Generally, man-made structures show comparatively high reflection due to specular characteristics called the "cardinal effect of structures and ground." Open spaces or damaged buildings have comparatively low reflectance because microwaves are scattered in different directions (see Fig. 1). Based on the above characteristics, we have already developed an automated method to detect the areas with severely damaged buildings using the time-series SAR datasets for the Kobe earthquake [6].

In this empirical method, we 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 the both observation conditions are similar. However, the method was successful in the damage detection for the Kobe example, even in the case that the image pair (ERS: 1994/10/12, 1995/05/23) having 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 x 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, we calculate the discriminant score z obtained by Eq. (3). The pixel whose value z is high is assigned as a severely damage area.

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

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

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

where i is the sample number, Ia_i and Ib_i are the digital numbers of the post- and pre-images, $\hat{I}a_i$ and $\hat{I}b_i$ are the corresponding averaged digital numbers over the surroundings of pixel i within a 13 x 13 pixel window, and the total number of pixels N within this window is 169 to compute the two indices [6]. Focusing on urbanized areas to detect building damage, the pixels whose backscattering coefficients are smaller than the assigned threshold value are masked in the vale z distribution.

SAR DATASET OF RECENT EARTHQUAKES

Satellite SAR observed the stricken areas by the recent earthquakes as well as the Kobe event. We selected three destructive earthquakes, the 1999 Kocaeli, Turkey, the 2001 Gujarat, India, and the 1993 Hokkaido Nansei-Oki, Japan, which generated a large number of collapsed buildings and human causalities in the large areas, for demonstrating the validity of the method.

On August 17, 1999, a moment magnitude (Mw) 7.4 earthquake shook the northwestern region (Kocaeli) of Turkey. Series of radar observations by ERS-1 and ERS-2 were conducted 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 *Bp* is approximately 30 m, this pair is also perfectly suitable for an interferometric study. One and half years later, the Gurarat earthquake (Mw=7.5) devastated the western part of India on January 26, 2001. Canadian satellite RADARSAT with the fine-beam mode whose ground (pixel) 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 *Bp* of the two acquisitions are more than 400 days and 6 km, respectively.

On July 12, 1993, the Hokkaido Nansei-Oki earthquake of Mw=7.7 occurred with the hypocenter at

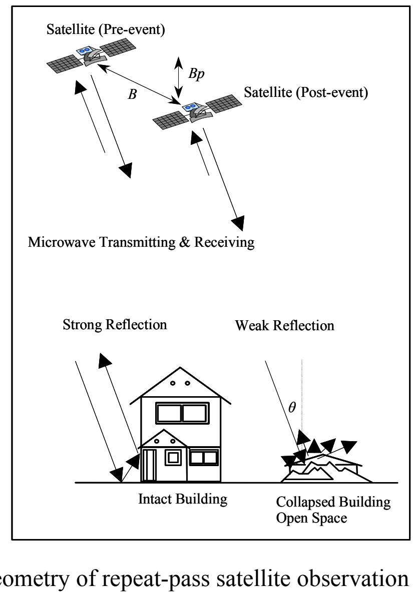

Figure 1. Schematic figure of the geometry of repeat-pass satellite observation and backscattering characteristics of objects on the earth's surface.

Table 1. The mean and standard deviation of difference in backscattering coefficient, correlation, and discriminant score for the damage level

Earthquakes and analized areas	Number of pixels	Mean and standard deviation d [dB]	r	z
The 1995 Kobe, Japan earthquake				
Hanshin district (severe damage ratio [%])				
0 ~ 6.25	2000	-0.29 (0.35)	0.54 (0.14)	-1.96 (2.02)
6.25 ~ 12.5	2000	-0.37 (0.43)	0.50 (0.15)	-1.24 (2.30)
12.5 ~ 25	2000	-0.54 (0.47)	0.48 (0.16)	-0.60 (2.44)
25 ~ 50	2000	-0.71 (0.60)	0.43 (0.17)	0.32 (2.85)
50 ~ 100	2000	-0.95 (0.79)	0.36 (0.18)	1.70 (3.41)
The 1999 Kocaeli, Turkey earthquake				
Golcuk (collapse damage ratio [%])[9]				
0 ~ 6.25	363	-0.36 (0.30)	0.44 (0.14)	-0.55 (1.74)
6.25 ~ 12.5	117	-0.13 (0.30)	0.40 (0.21)	-0.54 (2.66)
12.5 ~ 25	140	-0.49 (0.47)	0.41 (0.16)	0.13 (2.21)
25 ~ 50	218	-0.69 (0.27)	0.36 (0.15)	1.21 (1.85)
50 ~ 100	24	-1.01 (0.07)	0.33 (0.13)	2.18 (1.61)
Adapazari (ratio of heavy damage or collapse [%])[10]				
0 ~ 5	666	0.07 (0.29)	0.46 (0.21)	-1.65 (2.38)
5 ~ 15	589	-0.01 (0.19)	0.46 (0.14)	-1.49 (1.81)
15 ~ 30	2967	-0.04 (0.27)	0.43 (0.14)	-1.07 (1.77)
30 ~ 45	2799	-0.30 (0.29)	0.33 (0.13)	0.74 (1.68)
45 ~ 100	1102	-0.40 (0.28)	0.32 (0.10)	1.07 (1.30)
Adapazari (damage level)[11]				
No to slight damage	13	-0.10 (0.20)	0.46 (0.12)	-1.30 (1.63)
Moderate to Heavy damage	25	-0.16 (0.36)	0.40 (0.10)	-0.43 (1.64)
Catastrophic damage	10	-0.53 (0.20)	0.28 (0.06)	1.81 (1.01)
The 2001 Gujarat, India earthquake				
Bhuj (building damage level)[14]				
Areas without extensive or complete damage	6743	-0.17 (0.91)	0.32 (0.14)	0.58 (2.52)
Extensive damage	1011	-0.80 (0.91)	0.30 (0.11)	2.13 (2.69)
Complete damage	738	-0.92 (0.78)	0.28 (0.11)	2.66 (2.43)
The 1993 Hokkaido Nansei-Oki, Japan earthquake				
Aonae, Hatsumatsumae, Matsue, Monai, Okushiri and Inaho (building damage level)				
No damage	279	0.31 (0.87)	0.71 (0.15)	-5.27 (2.98)
Complete damage	328	-2.04 (1.43)	0.34 (0.24)	4.26 (5.52)

northern part of Okushiri Island, Hokkaido; many houses, ships and port facilities were severely damaged. In Okushiri Island, many houses built along the coast were washed away by great tsunamis. For this earthquake, the JERS (ground resolution and pixel size is 18 m) observed the damaged area on August 21, 1993. The major difference between JERS and ERS or RADARSAT is that JERS's microwave frequency is L band, or it has a rather long wavelength of approximately 23 cm. Theoretically, even though short wavelength microwaves used by the ERS and the RADARSAT are more sensitive to the ground surface variations, it is confirmed that the influence due to difference of the wavelength is rather small when they are used to detect rather large variations on the ground surface such as collapsed buildings [6]. As a pre-event image of this earthquake, we selected an image observed on July 8, 1993. The distance between satellites Bp of two acquisitions is approximately 220 m and they make a good pair to obtain sufficient phase interference.

COMPARISON BETWEEN THE ESTIMATED AND ACTUAL DAMAGE DISTRIBUTIONS

Using the above-mentioned procedure and the SAR images, the distribution of the discriminant score z was formed for each earthquake. The threshold value for masking to select built-up areas is -6dB in the backscattering coefficient. The distribution of z value overlaid on the pre-event intensity image was georectified and compared with the GIS-based field survey data.

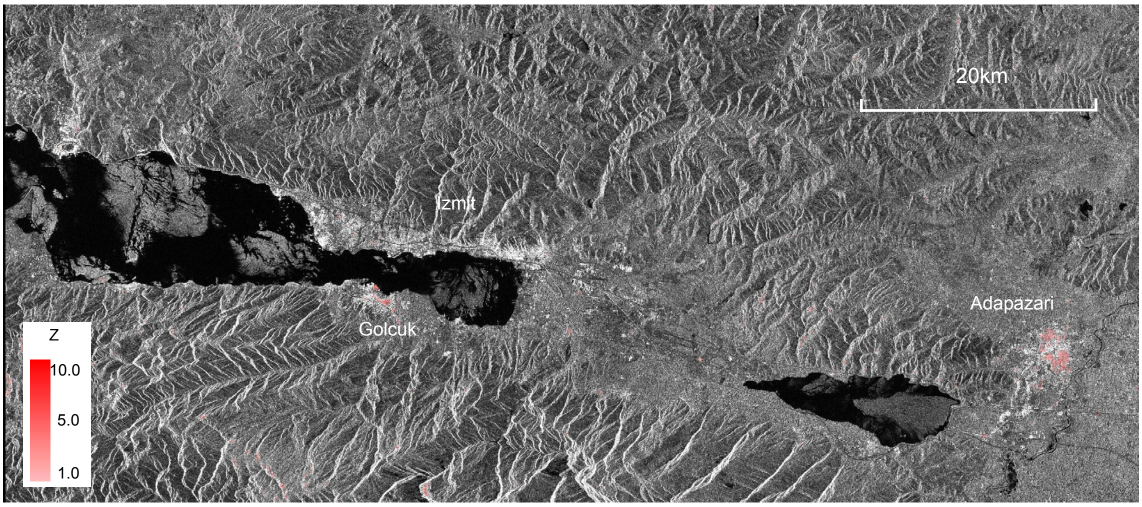

Figure 2. Distribution of the value *z* overlaid on the intensity image taken over the affected area by the Kocaeli, Turkey earthquake

The 1999 Kocaeli, Turkey Earthquake

The distribution of *z* value is shown in Fig. 2. 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 [8]. In Golcuk, a detailed and systematic field survey on building damage was conducted [9]. The collapse ratio of the buildings was calculated and the mean values and standard deviations of *z* for the damage levels are shown in Table 1. As observed in the Kobe study, the *z* value in this case is also seen to increase as the damage level increases. (see Table 1). In Adapazari, comparisons with other field survey data [10][11] were also conducted. Similar tendency between the damage level and z value was revealed.

The 2001 Gujarat, India Earthquake

The result of applying this method to RADARSAT/Fine images is shown in Fig. 3. 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 [12] and Landsat images [13]. IKONOS had an opportunity to observe the surrounding of Bhuj. The relationship between the estimated damage areas from a post-earthquake IKONOS image [14] and calculated *z* value is also listed in Table 1. The *z* value demonstrates the degree of building damage and is relatively close to the result for Golcuk, Turkey. It is considered that the urban district structure and damage pattern of the buildings in India are similar to those of Turkey.

The 1993 Hokkaido Nansei-Oki, Japan Earthquake

The result of our damage detection method is shown in Fig. 4. At Aonae and Hatsumatsumae, located on the southern part of Okushiri Island where many houses were washed away by tsunamis, damaged pixels were extracted (See the magnified view of Okushiri Island in Fig. 4(a)). According to the damage survey report [15], the tsunami damage at the tip of the peninsula was especially severe in Aonae area; houses were washed away in the northern part of the area. In the area in between, there exist buildings that were saved from the fire and tsunami damage. Figure 4(b) shows the magnified view of Aonae, where distribution of damage pixels detected by JERS represents the situation almost accurately. Using the damage survey report [15] and pre- and post-event aerial photographs, we interpreted the areas where buildings were washed away, fired and collapsed and the areas without building damage at Aonae, Matsue, Okushiri, Monai and Inaho districts, and overlaid them with *z* distributions.

As a result, as shown in Table 1, the mean value of *z* was 4.3 for damaged areas, while it was approximately -5.3 for no damaged areas. The difference is larger than that of the result from C band satellite as discussed previously. The reason why the value is small in the no damaged areas is that, the L band with long wavelength is rather insensitive to observation conditions and variations of the ground surface and has quite high correlation coefficient of 0.7 for the pre- and post- event images of the earthquake. The larger value of *z* at damage building areas results from the reduced backscattering coefficient of approximately

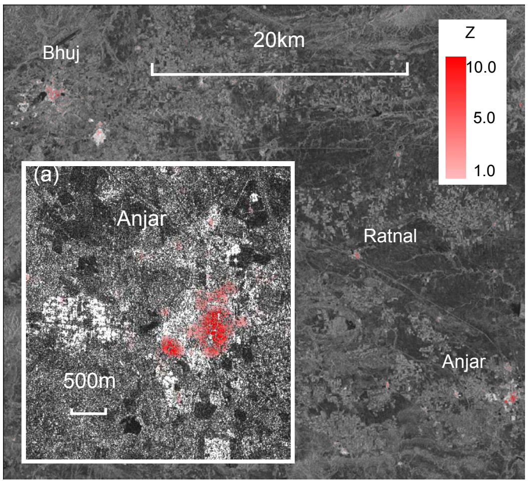

Figure 3. Distribution of the value z overlaid on the intensity image taken over the affected area by the Gujarat, India earthquake

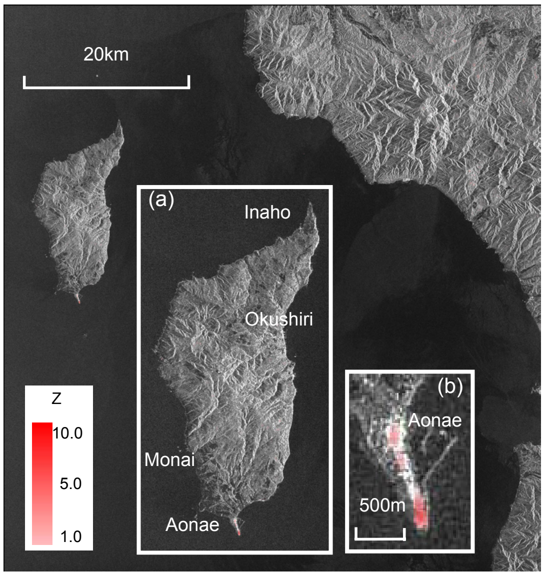

Figure 4. Distribution of the value z overlaid on the intensity image taken over the affected area by the Hokkaido Nansei-Oki, Japan earthquake

-2dB after the earthquake, obtained as a result of the tsunami damage that made the areas almost open space and reduced the cardinal effect significantly.

CONCLUSIONS

We applied an automated technique for detecting areas with building damage, which was developed from the experiences of the 1995 Kobe earthquake using SAR intensity images, to recent destructive earthquakes, the 1999 Kocaeli, Turkey, the 2001 Gujarat, India, and the 1993 Hokkaido Nansei-Oki, Japan earthquakes. The extracted damage distributions were in good agreement with the actual situations investigated by field surveys. In this study, we confirmed that the characteristics of this technique has less dependency on the baseline between the pre- and post-event satellites.

ACKNOWLEDGEMENT

Discussions with Mr. R. T. Eguchi, Mr. C. K. Huyck, and Mr. B. Mansouri of ImageCat, Inc. were helpful for our study. Prof. N. Nojima of Gifu University kindly provided us with the information on descriminant analysis. Mr. H. Aoki of Kiso-Jiban Consultants co., ltd., helped us to convert the data of Okushiri Island damaged areas into GIS. A part of this study is funded by the Grant-in-Aid for Scientific Research (Grant No.:10333577). We would like to express our gratitude to the organization concerned. JERS is owned by the Ministry of Economy, Trade and Industry and National Space Development Agency of Japan; ERS is owned by European Space Agency; and RADARSAT is owned by Canadian Space Agency.

REFERENCES

[1] D. Massonnet, M. Rossi, C. Carmona, F. Adragna, G. Peltzer, K. Fiegl, and T. Rabaute, "The displacement field of the Landars earthquake mapped by radar interferometry," *Nature*, Vol.364, pp.138-142, 1993.

[2] R. T. Eguchi, C. K. Huyck, B. Houshmand, D. M. Tralli, and M. Shinozuka, "A new application for remotely sensed data: Construction of building inventories using synthetic aperture radar technology," *Proc. 2nd Multi-lateral Workshop on Development of Earthquake and Tsunami Disaster Mitigation Technologies and Their Integration for the Asia-Pacific Region*, pp.217-228, 2000.

[3] M. Matsuoka and F. Yamazaki, "Use of interferometric satellite SAR for earthquake damage detection," *Proc. 6th International Conference on Seismic Zonation*, EERI, CD-ROM, 2000.

[4] H. A. Zebker, and J. Villasenor, "Decorrelation in interferometric radar echoes," *IEEE Trans. Geoscience and Remote Sensing*, Vol.30, No.5, pp.950-959, 1992.

[5] C. Yonezawa, and S. Takeuchi, "Decorrelation of SAR data by urban damages caused by the 1995

Hyogoken-nanbu earthquake," *International Journal of Remote Sensing*, Vol.22, No.8, pp.1585-1600, 2001.

[6] M. Matsuoka and F. Yamazaki, "Image processing for building damage detection due to disasters using SAR intensity images," *Proc. of 31st Conference of the Remote Sensing Society of Japan*, pp.269-270, 2001 (in Japanese).

[7] J. S. Lee, "Digital image enhancement and noise filtering by use of local statistics," *IEEE Trans. Pattern Analysis and Machine Intelligence*, Vol.2, No.2, pp.165-168, 1980.

[8] L. A. Johnson, A. Coburn, and M. Rahnama, "Damage survey approach to estimating insurance losses," *Earthquake Spectra, 1999 Kocaeli, Turkey Earthquake Reconnaissance Report*, pp.281-293, 2000.

[9] AIJ reconnaissance team, T. Kabeyasawa et al. "Progress report on damage investigation after Kocaeli earthquake by Architectural Institute of Japan," *Proc. ITU-IAHS International Conference on the Kocaeli Earthquake 17 August 1999*, pp.300-305, 2001.

[10] J. D. Bray, and J. P. Stewart, "Damage pattern and foundation performance in Adapazari," *Earthquake Spectra, 1999 Kocaeli, Turkey Earthquake Reconnaissance Report*, pp.163-189, 2000.

[11] R. T. Eguchi, C. K. Huyck, B. Houshmand, B. Mansouri, M. Shinozuka, F. Yamazaki, M. Matsuoka, and S. Ulgen, "The Marmara earthquake: A view from space, the Marmara Turkey earthquake of August 17, 1999," *Reconnaissance Report, Technical Report MCEER-00-0001*, pp.151-169, 2000.

[12] Indian Inst. Tech. and Earthquake Disaster Mitigation Res. Ctr., The Bhuj earthquake of January 26, 2001. Consequences and future challenges, 2001.

[13] Y. Yusuf, M. Matsuoka, and F. Yamazaki, "Damage detection from Landsat-7 satellite images for the 2001 Gujarat, India earthquake," *Proc. 22nd Asian Conference on Remote Sensing*, Vol.1, pp.300-305, 2001.

[14] L. Chiroiu, and G. Andre, "Damage assessment using high resolution satellite imagery: Application to 2001 Bhuj, India, earthquake," *Proc. 7th National Conference on Earthquake Engineering*, EERI, CD-ROM, 2002.

[15] Architectural Institute of Japan, "Report on the Damage Investigation of the 1993 off Kushiro Earthquake and the South-West off Hokkaido Earthquake", 1995 (in Japanese).