The 2011 Tohoku (Japan) Tsunami Inundation and Liquefaction Investigated Through Optical, Thermal, and SAR Data

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Abstract—We studied the disastrous effects of the tsunami triggered by the Mw 9.0 earthquake that occurred on March 11, 2011, offshore the Honshu island (Japan). The tsunami caused a huge amount of casualties and severe damage along most of the eastern coastline of the island. The data set used is composed of images from ASTER, visible and thermal, and ENVISAT SAR sensors. The processing and the analysis of data from different sources were performed in order to obtain the tsunami inundation map of the Sendai coastal area, to analyze inland factors driving the tsunami inundation, and to detect the liquefaction effects in the Chiba bay area as well. The obtained inundation line, with a maximum value of about 6 km, has been jointly analyzed with digital elevation model providing the run-up values, which are generally below 21 m in the ca. 60-km-long study area of Sendai. Moreover, from SAR coherence and intensity correlation, a wide area of subsidence is mapped at Chiba bay, which is reasonably related to strong ground shaking and pervasive liquefaction.

Index Terms—Liquefaction, optical and thermal data, SAR, wave inundation, 2011 Japan tsunami.

I. INTRODUCTION

The Mw 9.0 Tohoku earthquake occurred on March 11, 2011, near the northeastern coast of the Japanese island of Honshu (Tohoku region), and ruptured the undersea megathrust fault along which the Pacific plate underthrusts Honshu (i.e., [1] and reference therein) triggering a destructive tsunami that hit the coastal communities of Honshu. Damage and inundation maps and reports of the numerous tsunami surveys were made immediately and lasted for months to cover the wide extent of the struck area. On a general note, the tsunami wave exceeded 10 m in height, and the inundations on land spread out across the Tohoku region and, particularly in the Sendai plain in the Miyagi Prefecture, reached up to 5 km inland from the coastline; the run-up heights of tsunami have been up to 40 m with maximum values reached at the Miyagi and South Iwate coasts [2].

An exceptional amount of high-quality satellite data was available shortly after the Tohoku event and turned out to be extremely useful. The optical and SAR data are successfully used, as this tsunami event, for detecting the presence of water, damage, and, more in general, land cover changes in disastrous natural events [3]–[5].

SAR data are particularly valuable for their all-weather capability and for their specific sensitivity to different kinds of surface changes. In the case of the tsunami inundation, land cover class changes occur with damages of man-made buildings, flooded areas, stressed vegetation, and so on. We have many different SAR backscattering behaviors that can be classified: 1) low radar return from smooth open water bodies that act as specular reflectors; 2) the double-bounce mechanism involving the water surface beneath the vegetation and stems or trunks enhances backscattering, so that flooded vegetation may appear very bright in a SAR image; and 3) a decreasing of the backscattering in urbanized damaged area, where the double-bounce facade soil is lacking [3], [6]–[8]. Indeed, the effectiveness of using pre- and postevent SAR backscattering data for detecting wide uplifted and subsided areas, large modifications of the coastline, and the detection of different levels of damaged areas as well was already proven for the Indonesian earthquake of 2004 [9], [10]. For this latter event, many optical satellite data with medium and high geometrical resolutions were used for identifying changes that occurred on the surface [11], [12]. In particular, ASTER data were used for the identification of the inundation distance after the 2004 Indonesian tsunami [13], for detecting its effects, [14] and for monitoring flood events as well [15].

In this letter, we performed a remote survey of the wave inundation based on Visible and Near Infrared (VNIR), Thermal Infrared (TIR), and SAR data, along with a digital elevation model (DEM), centered in the Sendai coastal area. Our main goals are to obtain an inundation map, to estimate the run-up values, and also to identify inland factors affecting these estimates. We will also show and discuss significant effects on site recorded at Chiba bay from SAR data.

II. DATA SET

The data set is composed of 15m resolution VNIR (24/02/2011 and 19/03/2011) and 90m resolution TIR (23/01/2011, 12/03/2011 and 19/03/2011) images from the ASTER satellite, while the 20m resolution C-band SAR data (21/11/2010, 19/02/2011 and 21/03/2011) are from the ENVISAT mission. All of the data were acquired on different dates, with different spatial coverage and different geometrical resolution. The different spatial coverage hampers the analysis of the flood evolution even if we have different postevent acquisitions, whereas the availability of sensors with different characteristics allows us to extract useful information for our study.

Ancillary data like the ASTER Global DEM 2 (GDEM2) were used as a base map and as a support for our image analysis.
be discriminated. From the five ASTER TIR channels, ranging from 8 to 11 μm, the one centered at 10.657 μm was selected. In this channel, the mean radiance values of the water classes are similar, i.e., 6.6, 6.83, and 6.85 for the river, flood, and sea, respectively, while the flooded regions in the pre-event image reach a mean value of 5.5, making the discrimination between flooded and nonflooded regions possible by a thresholding algorithm. The maps obtained in the three different days of acquisitions are shown in Fig. 2. It is possible to note [Fig. 2(a)], just as in the preinundation map, that only ocean and the main rivers are visible. The second image shows the map of inundated area relative to the day after the event [Fig. 2(b)], while the water retreat is pointed out in Fig. 2(c). The comparison with high-resolution SAR images in overlapping regions [see Fig. 2(d)] made possible to extract maximum inundation limit in the whole investigated area.

The VNIR ASTER radiance images were analyzed in order to characterize the surface tsunami effects. We have applied an unsupervised algorithm with an input set of two images, one pre-event and one postevent [17]. For each image, we have four bands, three VNIR channels plus the normalized difference vegetation index, for total inputs of eight bands. A $k$-means classifier was used, setting 30 different classes, namely, change and no-change classes. In order to obtain information on the tsunami inundation, we labeled the six classes that reflect the wave effects on land, by visual inspection of very high resolution optical images from Google Earth, i.e., flooding, debris, building damage, mud, and stressed and nonstressed vegetation classes [see Fig. 5(b)–(d)].

In order to retrieve the SAR backscattering for the two dates before and one after the event, the images were multilooked (five looks in azimuth and one look in range), coregistered, calibrated, and geocoded on a common cartographic system with 20-m pixel spacing, using the SRTM DEM [18]. The resulting three backscattering maps were also filtered using the Lee filter [19]. This filter was used for removing high-frequency noise (speckle) while preserving high-frequency features (edges). In Fig. 2(d), we have a detail of red (R)–green (G)–blue (B) (RGB) color composition using preseismic (February 19, 2011; red channel) and postseismic (March 21, 2011; blue and green channels) images. It is worth to note how the regions of changes in cyan and red show a good agreement with flood map from ASTER TIR data. The red regions are related to zones where the open water is still present, characterized by low backscattering in the postevent image, while the cyan ones represent where the backscattering is higher in the postseismic image. This latter behavior could be linked with many different phenomena such as the increase in the moisture of the soil, the presence of debris on the surface, or an increase of the roughness, all elements that show that a change occurred [7]. The comparison between the SAR and the TIR map in the common region allows us to set the thresholds on the image difference for identifying in the whole Sendai plain the inundation between the pre- and postevent backscatterings (Fig. 3). We can validate the resulting inundation line distance (red line in Fig. 3) with the one from the Geospatial Information Authority of Japan (GSI) based on field survey [20] and with others based on different SAR sensors, such as TerraSAR-X.

III. DATA ANALYSIS AND INTERPRETATION

A. Tsunami Inundation and Run-Up at Sendai Coastal Area

In order to retrieve the flooding map using the three ASTER TIR night imageries, we considered the principle of different thermal inertia between water and “Earth,” which is the property of the material that measures the reaction to the delivery of a certain amount of energy with a temperature variation [16]. During the day, the solar radiation is absorbed and stored by surfaces according to thermal conductivity of the materials, while in the night, they cool at a different rate, allowing them to

Fig. 1. RGB color composite of two SAR backscattering images [(R) February 19, 2011; (G) March 21, 2011; (B) March 21, 2011] of the investigated area. The areas of changes are highlighted in red and cyan. Superimposed is (colored lines and capital letters) the spatial coverage of the data: A. ASTER TIR March 12, 2011. Red capital letter is positioned within the covered area; B. ASTER TIR March 19, 2011. Green capital letter is positioned within the covered area; C. ASTER VNIR March 19, 2011; and D. ASTER thermal January 23, 2011, and ASTER VNIR February 24, 2011. The yellow dotted box represents the area shown in Fig. 2.

The largest spatial coverage of the tsunami struck area is from the SAR data (Fig. 1), while the TIR data are the closest in time to the event (few hours after) although covering a small portion of the hit region. Then, the idea was to try to use the TIR data acquired on March 12, as a “training input” for the SAR ones in order to produce the inundation map using images acquired ten days after the event. This is the case of ENVISAT data, where the effects of the partially retracted flood could still be detected. Moreover, we extracted the information about the stressed vegetation and damaged buildings and infrastructures by VNIR ASTER data, providing critical information for understanding the inundation behavior. The entire procedure is explained in detail in Section III-A.

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Fig. 2. Region included in the yellow dotted box of Fig. 1, where pre- and postevent TIR images were available. In (a), (b), and (c), the radiance \([W/(m^2 \cdot sr \cdot \mu m)]\) and its values are shown. (a) TIR image taken on January 23, 2011, where the water is due to the presence of the river flow and sea. (b) TIR image taken on March 12, 2011, where the flooded areas are in dark and light blue. (c) TIR image taken on March 19, 2011, shows the presence of still flooded areas in dark and light blue. (d) RGB color composite of two SAR backscattering images [(R) February 19, 2011; (G) March 21, 2011; (B) March 21, 2011]. The red and cyan highlight the areas of changes. From the comparison with the TIR data in the three different days, it is possible to recognize four different backscattering behaviors in the panel (d): (Black areas) Presence of steady water in all TIR acquisitions, principally the river flow; (white areas) undamaged built-up areas; (red areas) the presence of water on March 19 or damaged buildings; (cyan areas) the water recedes on March 19, but an increase of the soil moisture or an increase of the roughness of the surface due to the presence of the debris is detected by the SAR data.

Fig. 3. Shaded relief of the Sendai plain from ASTER DEM. The red line is the inundation limit from this study. The white line represents five differently oriented segments approximating the coast. The blue box represents the area shown in Fig. 5(b)–(d), while the purple box is the area shown in Fig. 5(a). A, B, C, and D are the locations of the inundation minima in the Sendai plain.

We represented the entire 60-km-long Sendai coastline with five segments, trying to approximate the real one (Fig. 3), and we calculated the distance of the inundation limit (Fig. 4) with the same sampling of the GDEM2 (30 m). A maximum value of inundation, about 6 km, is found in the central portion of the Sendai plain, and the distance tapers to about 1 km at the edges of the plain (Figs. 3 and 4); an average value of 4.3 km is registered for the whole data set. The general trend of the inundation distance profile is well represented by a smoothed symmetric bell shape, although few local minima can be seen (A, B, C, and D in Figs. 3 and 4). The values of run-up at the maximum inundation limit, which represent the difference between the elevation of maximum tsunami penetration (inundation line) and the sea level at the time of the tsunami [24], were extracted using the GDEM2 (elevation error of 6.5 m and horizontal error of 6 m) [25]. The run-up values are below 12 m with an average of 6 m, except for a local peak of 16.6 m, within the ca. 40-km-long flat coastal plain of Sendai (central sector of blue line in Fig. 4). Slightly higher values have been measured at the borders, not exceeding 21 m, except for a local peak of 34 m at the southern portion (blue line in Fig. 4). The run-up distribution from this study is in agreement with those reported in the literature [26], [27]. As shown in Fig. 4, the inundation distance and run-up general trends are both “parabolic” with opposite convexity, highlighting an anticorrelation of the two distributions. The two trends of the inundation limit and the run-up were plotted along
the average strike of the coastline simplified (top of Fig. 4). A clear correlation of the inundation distance with the coastal topography is observable. As a matter of fact, the southern and northern coastal topographies that are characterized by high-relief record the lowest inundation penetration (Figs. 3 and 4), while within the plain, the waves entered inland for at least 4 km.

Moreover, we investigated the slope values of the inundation limit along the entire study area extracted from the GDEM2 (Fig. 4). For this purpose, the mean value of the terrain slope was analyzed along the five coastline sections shown in Fig. 4. The inundation limit shows higher average slope values of 2° and 2.7° in the northern (strike 347°) and southern (strike 54°) coastline segments, respectively, where a prominent topography is present close to the shoreline. On the other hand, within the Sendai plain, coincident with the three central coastal segments (Fig. 4), the average slope values range between 0.8° and 1.0°, suggesting that the slope could be considered as a characteristic parameter potentially constraining tsunami inland wave penetration in wide open fields, while when the coastal topography is rapidly increasing, the inundation limit is uncorrelated with the slope.

We did not observe any significant direct influence of the vegetation cover on the water penetration along the whole investigated area. Similarly, taking into account the epicentral location and the tsunami wave path, the five sections of the coastline displaying a different strike up to about 70° do not play an important role in the inland water penetration (Fig. 4).

The four inundation minima within the plain (marked as A, B, C, and D in Figs. 3 and 4) are likely due to the presence of the three main rivers (A, B, and D) and to the effect of a densely urbanized area at the shoreline that reduced the wave energy (C). In Fig. 5(a), the meander of the Abukuma River, oriented almost parallel to the coastline, appears to influence the inundation distance that is locally reduced to about 2 km, while the minimum B, which occurred close to another river flow, is shown in Fig. 2. The presence of the meander likely lowered the tsunami energy and channeled part of the water, resulting in a less pronounced inland penetration (minima A, B, and D in Figs. 3 and 4). A smaller anomaly can be interpreted as the effect of the important urbanization of Arahama built-up area, within 1 km from the coastline, which has been completely destroyed by the tsunami wave [Fig. 5(b)–(d)].

B. Ground Subsidence Along the Tokyo Bay Coastal Area

The coastline of the Tokyo bay in the Chiba prefecture, about 300 km south of Sendai (inset in Fig. 1), suffered strong earthquake shaking and expanded damages to residential and commercial buildings caused by severe liquefaction occurring in the saturated sandy ground of this reclaimed land [28]. SAR data highlighted a well-defined area of loss of coherence and some localized backscattering changes (Fig. 6). One preseismic map (November 21, 2010–February 19, 2011) and one coseismic map (February 19–March 21, 2011) of coherence and intensity correlation were created. The almost similar values of perpendicular baseline, namely, 223 and 209 m, for the pre- and coseismic images, respectively, let us associate the observed loss of coherence in the coseismic image to temporal decorrelation due to the earthquake and not to spatial decorrelation [3] [Fig. 6(a)]. The area of coherence loss identifies a sharp zone of about 70 km² and coincides with a portion of reclaimed

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**Fig. 5.** (a) Region included in the purple box of Fig. 3. Minimum A in the inundation distance caused by the presence of the river. The red line is the inundation limit from this study. (b) Region included in the blue box of Fig. 3; preseismic ASTER VNIR image. (c) Postseismic ASTER VNIR image. (d) Postseismic ASTER VNIR image with superposed change detection classification where the damaged building class is indicated in purple. Minimum C in the inundation distance is probably due to the presence of the heavy damaged urbanized area along the shoreline. Moreover, it also is possible to see (blue) flooding, (green) stressed vegetation, and (yellow) no-stressed vegetation classes.

**Fig. 6.** Tokyo bay coastal area. (a) RGB color composite of two SAR coherence images [(R) preseismic (November 21, 2010–February 19, 2011); (G) coseismic (February 19–March 21, 2011); (B) coseismic (February 19–March 21, 2011)]. (b) RGB color composite of two SAR intensity correlation images [(R) preseismic (November 21, 2010–February 19, 2011); (G) coseismic (February 19–March 21, 2011); (B) coseismic (February 19–March 21, 2011)]. The blue ellipses represent the decorrelation due to major surface liquefaction effects, which are in accordance with [28]; a zoom of one of these areas is shown in the inset.
land along the coast characterized by “soft ground” prone to both differential compaction and/or liquefaction-induced failure, as observed by several eyewitnesses (e.g., [28]). The aforementioned evidence is likely related to a ground subsidence phenomenon resulting from the strong shaking, where moving away from the satellite between pre- and postacquisi-
sions is detected. In this case, the deformation is higher than half part on the wavelength (2.8 cm) which makes the loss of coherence highlighted in Fig. 6(a). At the same time, the backscattering properties of the surface [Fig. 6(b)] remain similar before and after the event, except for some restricted zone (see blue ellipses), where liquefaction features (e.g., sand blows) were surveyed [28]. In this kind of scenario, the reduction of intensity correlation is observed particularly when the backscattering characteristics of the surface change drastically [3], which is the case of liquefaction phenomenon.

IV. CONCLUSION

Major findings from this study on the 2011 Tohoku (Japan) tsunami inundation in the area of Sendai and liquefaction process at Tokyo bay can be summarized as follows.

1) The coastal topography influences the inundation pro-
cess: High-relief zones record the lowest inundation dis-
tances, while within the plain, the waves entered inland for at least 4 km.

2) The inundation limit slope value within the central plain (open field) shows a characteristic behavior (0.8°–1°): The tsunami wave inundation distance appears strictly related to a specific slope.

3) The vegetation cover does not show significant direct influence on the water inland penetration. Similarly, the changing in strike of the coastline does not have clear consequences in the inundation pattern.

4) SAR data highlighted a well-defined ~70-km²-wide area of loss of coherence at the reclaimed land along the coastline of the Tokyo bay. The analysis of the computed maps of coherence and intensity correlation shows clear features that are likely associated to the ground sub-
dience phenomena, resulting from the strong shaking and the pervasive liquefaction that affected the area. This study would contribute to the definition of the suscepti-
ble levels of coastal region that is devastated by tsunami wave and by shaking-induced ground failures.

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