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Integrated Approach to Assess the Impact of Tsunami Disaster

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ABSTRACT : The authors propose a research framework in developing a method to search and detect the impact of tsunami disaster by integrating numerical modeling, remote sensing and GIS technologies, which consist of four damage mapping efforts, 1) Regional hazard/damage mapping effort to search the potential impacted region , 2) Damage estimation effort using the numerical modeling of tsunami inundation and fragility function for structural damage, 3)Regional damage detection effort using SAR imagery, 4) Local damage mapping effort using the analysis of high-resolution optical satellite imagery to detect the extent of tsunami inundation zone and the structural damage. The method is implemented to the recent tsunami event, the 2007 Solomon Islands earthquake tsunami, to identify the structural damage probabilities within the inundation zone, combined with the post-tsunami survey data.

1 INTRODUCTION

During the 2004 Indian Ocean tsunami disaster, we have experienced the difficulty to comprehend the overall impact of tsunami. The tsunami propagated entire Indian Ocean and caused extensive damage to 12 countries. Because of the devastating damage on infrastructure and local/regional/international communication network and the failure of the system for emergency response, the impacted regions/countries and overall damage could not be addressed for months. Thus, the importance of developing technologies to detect the regional impact of great tsunami disaster has been raised. However, the extensive scale of catastrophic tsunami makes it difficult to comprehend overall impact of tsunami in the entire Ocean, and also may disable to prioritize how the limited resources for detecting damage and emergency response should be deployed in such limited amount of time and information.

Recent development of remote sensing technologies defeats the above problems and leads to detecting the detailed features of tsunami damage. In the present study, the authors propose a research perspective in developing a method to search and detect the impact of tsunami disaster by integrating numerical modeling, remote sensing, and GIS technologies. Part of the method is implemented to the recent tsunami event (the 2007 Solomon island earthquake tsunami) to search the impacted area and detect the structural damage, using the numerical modeling and the analysis of high-resolution optical satellite imagery.

2 METHODS

2.1 *Exploring the potential impacted region*

Figure 1 indicates the structure of the method proposed in this study, which consists of four damage mapping efforts. The first phase is the regional hazard/damage mapping effort. Mapping the potential tsunami hazard in macro or regional scale is based on the numerical modeling of tsunami propagation and bathymetry/topography database. The numerical model for regional scale is based on the finite difference method of shallow-water theories in spherical or cartesian co-ordinate systems. As the initial condition, we assume instantaneous displacement of the sea surface identical to the vertical sea floor displacement (Okada, 1985, and Mansinha & Smilie, 1971) by using fault parameters such as CMT (Centroid Moment Tensor) solutions of USGS (U.S. Geological Survey), which can be obtained immediately after the event occurs.

In order to address the tsunami impact along the coast, the author introduces PTE (the Potential Tsunami Exposure by Koshimura et al., 2005, and Takashima et al., 2006), as a measure of the population exposed against the potential tsunami hazard. PTE is obtained by the GIS analysis integrating the numerical model results and the world population database, e.g. LandScan^{TM} (Dobson et. al, 2000).

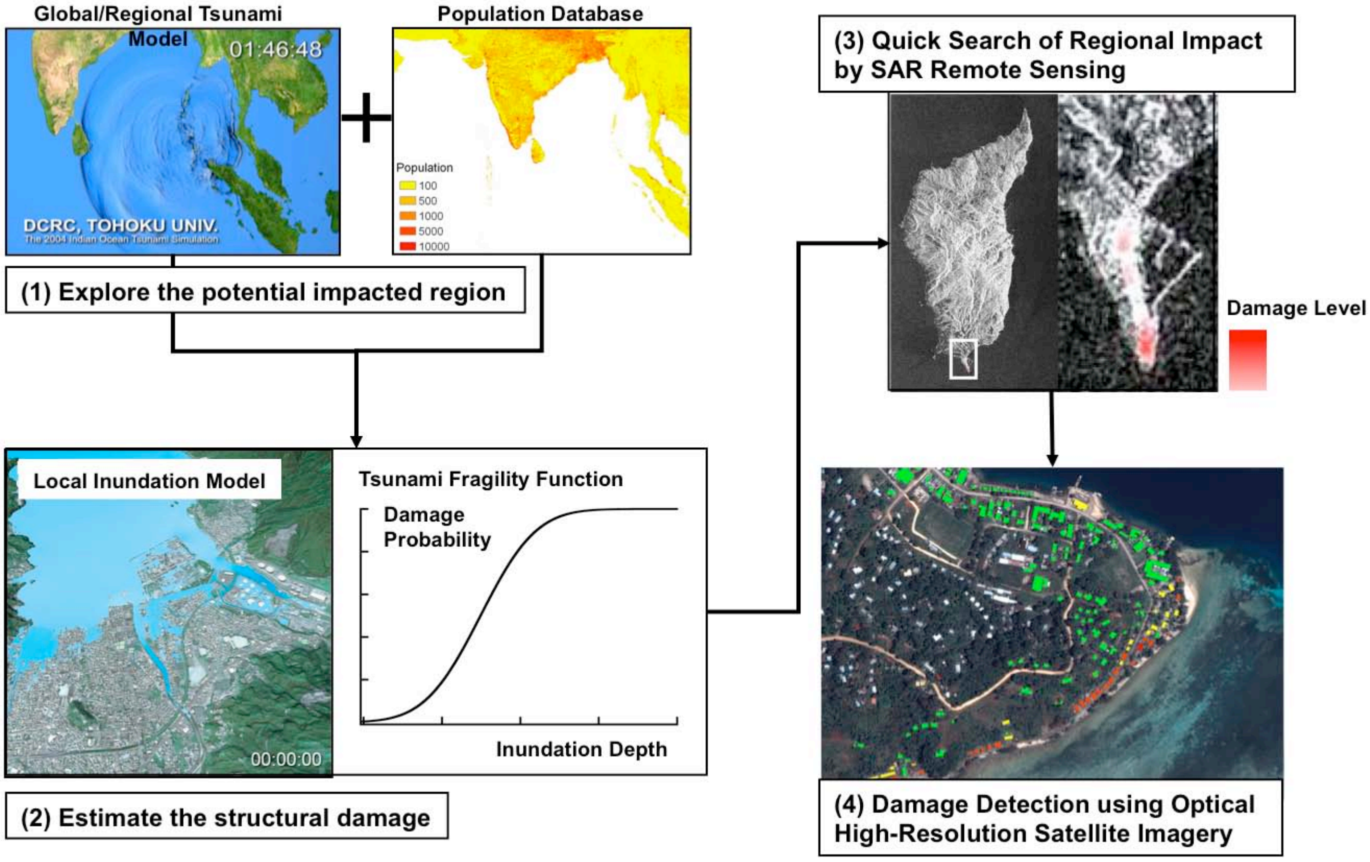

Figure 1. Structure of the present study.

2.2 *Estimating structural damage*

After the potential impacted region is estimated, the analysis moves on to the phase of estimating local damage due to the coastal inundation of tsunami. It requires the integrated approach of inundation modeling with local bathymetry/topography grid and fragility functions to convert the estimated potential tsunami hazard into the qualitative estimation of damaged houses or casualties. Koshimura et al. (2007) proposed the procedure to develop a tsunami fragility function for estimating structural damage, by using the integrated approach of tsunami inundation modeling and structural damage mapping using high-resolution satellite imagery.

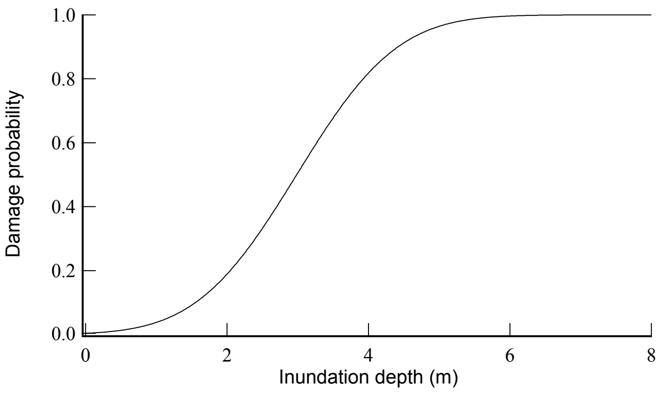

Figure 2. Fragility function for structural damage.

Figure 2 shows an example of the fragility function for structural damage in Banda Aceh, Indonesia during the 2004 Indian Ocean tsunami disaster. The tsunami fragility function proposed by the authors is the form of damage probability of houses/structures as a function of tsunami inundation depth or current velocity. And it enables to estimate tsunami-induced damage qualitatively, if the hydrodynamic features of tsunami inundation flow, such as inundation depth and current velocity, and the exact position/number of exposed houses and structures are known. However, note that the local tsunami inundation modeling requires detailed features of local bathymetry and land topography.

2.3 *Searching regional impact by SAR remote sensing*

The estimation phase described above moves on to the "detection" phase, using the remote sensing technologies. To detect the impacted area in regional scale, the authors use the significant capability of SAR (Synthetic Aperture Radar) which records the physical counters of the earth's surface, regardless of the weather conditions or sun lights (Matsuoka & Yamazaki, 2002, and Matsuoka & Yamazaki, 2004). In general, SAR imagery has the spectral characteristics of microwaves, i.e. strong reflection to artificial structures such as buildings and houses, while open spaces and damaged structures indicate relatively low-reflection and strong scattering. Matsuoka & Yamazaki (2002) focused on the differences of backscattering coefficient of pre and post-event SAR imageries and developed discriminant score to identify the impacted area from a set of pre and post event SAR imageries, as shown in Figure 3. Their method has a significant capability to search the impacted area in regional scale, regardless of the climate condition. However, note that the SAR remote sensing does not have adequate resolution in space to identify the individual damage on structures, and also has difficulty in detecting the damaged area with relatively small extent in space.

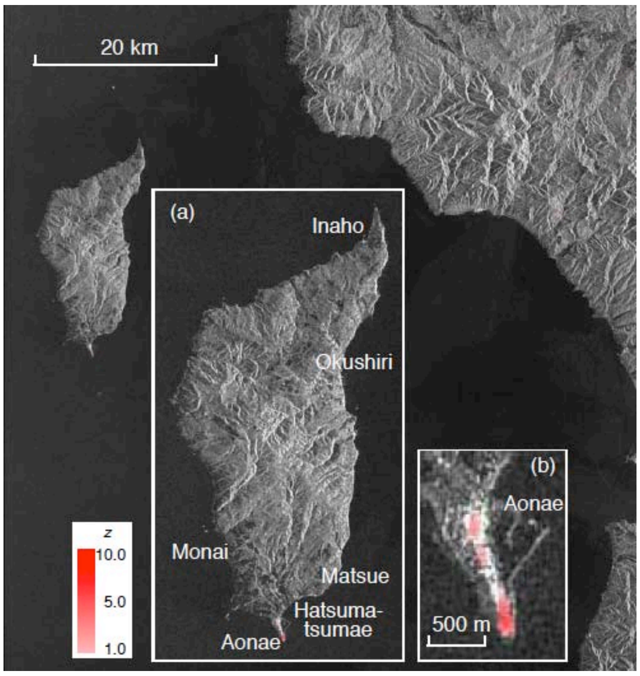

Figure 3. Tsunami impacted area detected by the analysis of SAR data (JERS: 1993/07/08 - 1993/08/21, Matsuoka & Yamazaki, 2002).

2.4 *Tsunami damage detection using optical high-resolution satellite imagery*

Recent advances of remote sensing technologies expand capabilities of detecting spatial extent of tsunami affected areas and damage on structures. The highest spatial resolution of optical imageries from commercial satellites is up to 60–70 centimeters (QuickBird owned by DigitalGlobe, Inc.) or 1 meter (IKONOS operated by GeoEye). Since the 2004 Sumatra-Andaman earthquake tsunami, these satellites have captured the images of tsunami affected areas and were used for disaster management activities including emergency response and recovery. For instance, Vu et al. (2007) developed a framework to integrate optical satellite imageries and digital elevation data in mapping tsunami affected areas. And Miura et al. (2006) visually interpreted the structural damage using IKONOS imageries of pre and post–tsunami in Sri Lanka.

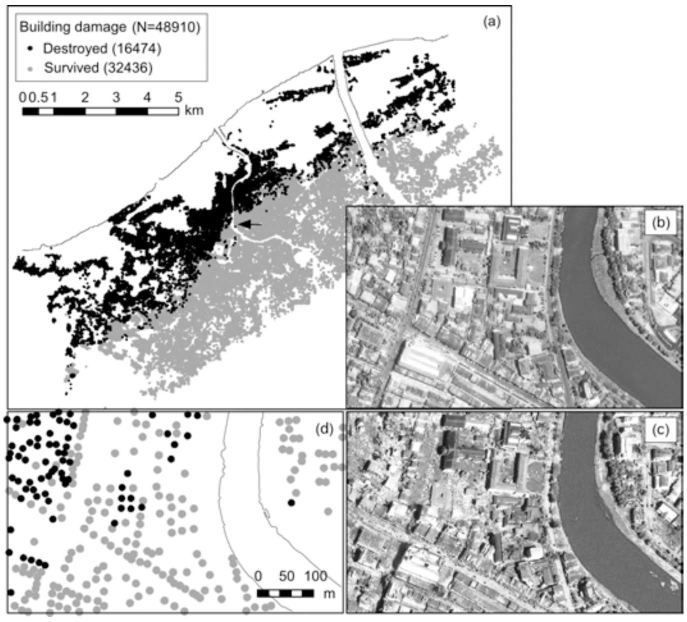

Figure 4. Spatial distribution of structural damage interpreted from the post–tsunami satellite imagery (IKONOS).

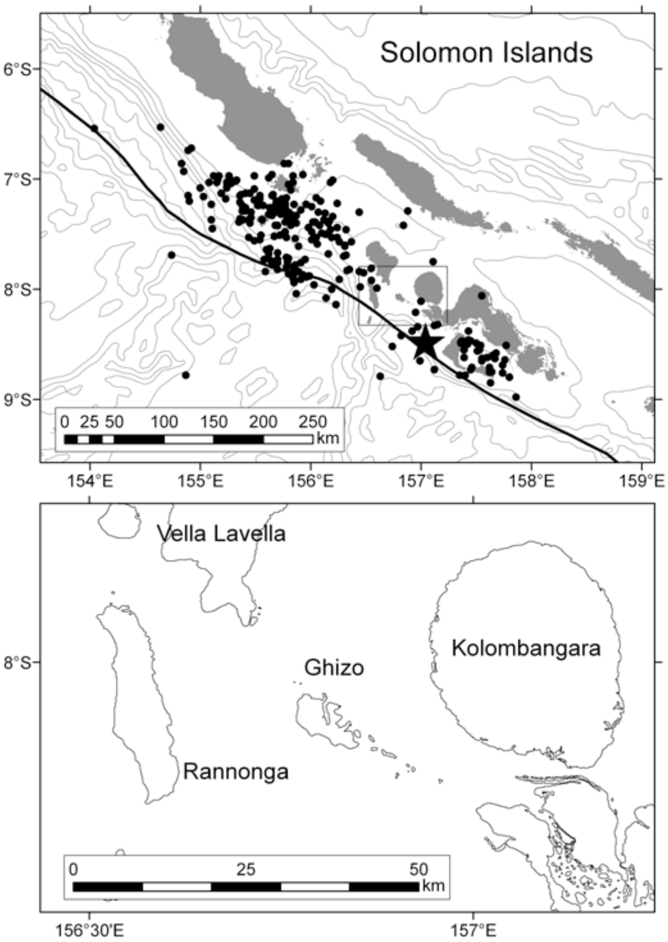

Figure 5 Study area of the 2007 Solomon earthquake tsunami.

Figure 4 indicates an example of the detection of structural damage using IKONOS satellite imageries of pre and post tsunami event of the 2004 Sumatra-Andaman earthquake tsunami disaster (Koshimura et al., 2007). As indicated from the figure, the high-resolution optical satellite imagery has capability to detect the damage of each house/structure by inspecting pre and post-event imageries.

3 MODEL IMPLEMENTATION

3.1 *Searching potential impacted area of the 2007 Solomon island earthquake tsunami*

The present method is applied to the 2007 Solomon Island earthquake tsunami, which occurred at 20:39 (UTC), 1 April, 2007, in the vicinity of Solomon Islands (Figure 5). The coseismic deformation as the initial sea surface displacement is calculated by using the CMT solution of USGS. Fault plane (subsurface rupture area) is determined to be consistent with the aftershock distribution. Figure 6 represents the distribution of estimated tsunami height by the present method and exposed population along the coasts of Solomon Islands. The more densely populated region is illustrated by darker gray scale.

From the results, the southern coast of Choiseul Island and Gizho Island are found to be potential impacted area in which significant casualty is expected. The results are consistent with the number of casualties reported by Tsuji et al. (2007), total 42 including 6 in southern Choiseul island and 20 in Ghizo island.

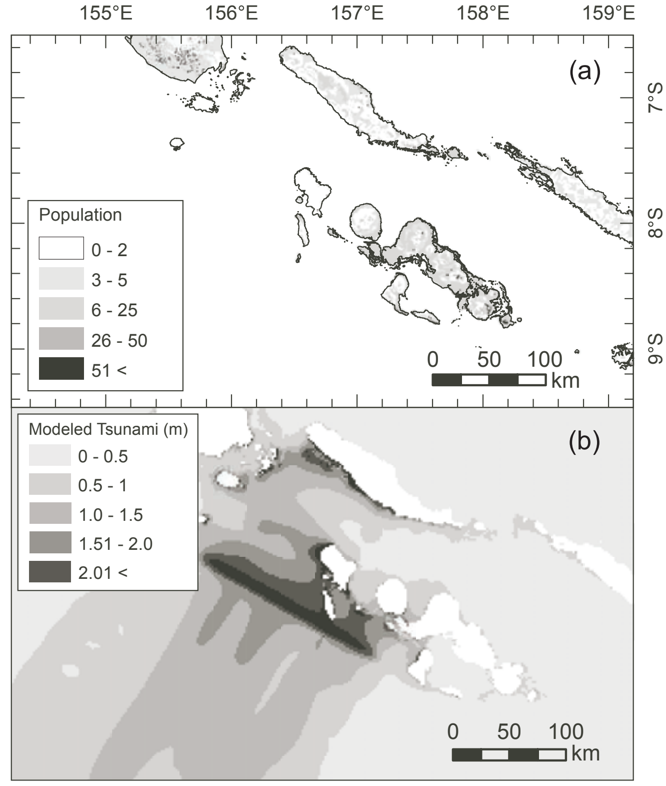

Figure 6. (a) Population density and (b) estimated tsunami height by the numerical model.

3.2 *Structural damage detection using high-resolution satellite imagery*

Through the previous analysis, we focus on the structural/house damage in Ghizo island, caused by the 1 April 2007 Solomon Island earthquake tsunami. First, we acquire the QuickBird pan-sharpened composite imageries of Ghizo Island during pre and post-tsunami (23 September 2003 and 5 April 2007), to build house inventories for visual damage inspection. Figure 7 shows the post-event satellite imagery of QuickBird, acquired on 5 April, 2007. By visual inspection of both pre and post event imageries, we classify the structural damage according to the damage class shown in Figure 8. As a result of structural damage mapping effort, structural damage distribution in each area, e.g. Figure 9 (area II).

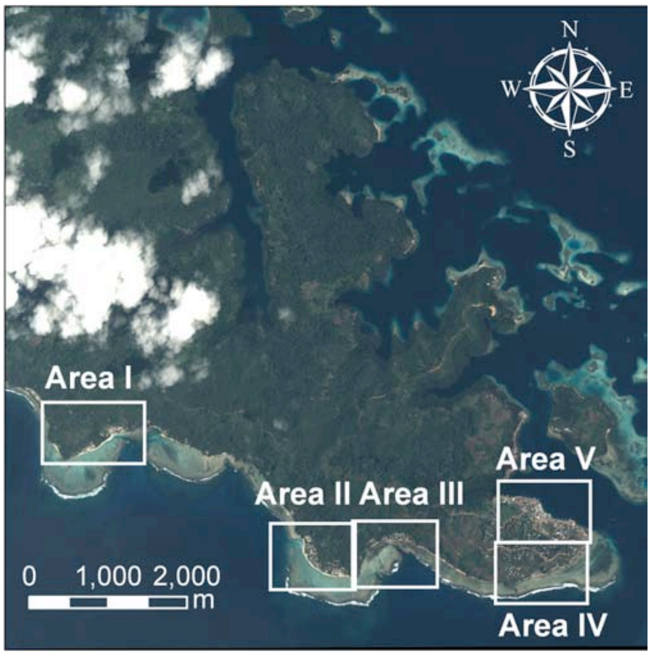

Figure 7. Post event satellite imagery of Ghizo island (QuickBird as of 5 April 2007).

Figure 8. Damage classification from pre and post event imageries.

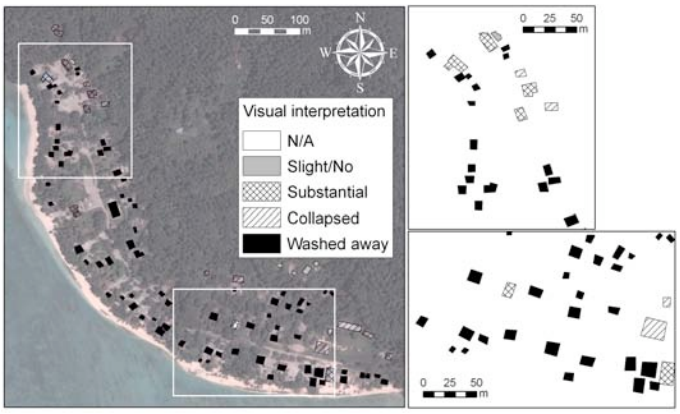

Figure 9. The result of visual damage interpretation (Area II).

3.3 *Detection of tsunami inundation zone*

We define the additional measure of structural damage, i.e. damage probability in the tsunami inundation zone. In order to detect the extent of tsunami inundation zone, we calculate NDVI (Normalized Difference Vegetation Index) from the post-event imagery, focusing on the vegetation change due to the tsunami penetration on land. As shown in Figure 10, QuickBird imagery obviously detects the vegetation change between pre and post tsunami. In the figure, we can see the tsunami debris along the edge of tsunami inundation zone. Focusing on the existence of tsunami debris, we sample 100 points to identify the threshold of NDVI to classify the tsunami inundation zone. As shown in Figure 11, NDVI values are calculated in a range 0.34 ± 0.05. As a result, the extent of tsunami inundation zone is determined by the supervised classification based on NDVI threshold. Figure 12 shows the result of the detection of tsunami inundation zone by applying the threshold value of NDVI, and the result is consistent with the field survey.

Figure 10 Vegetation change found from pre and post event imageries.

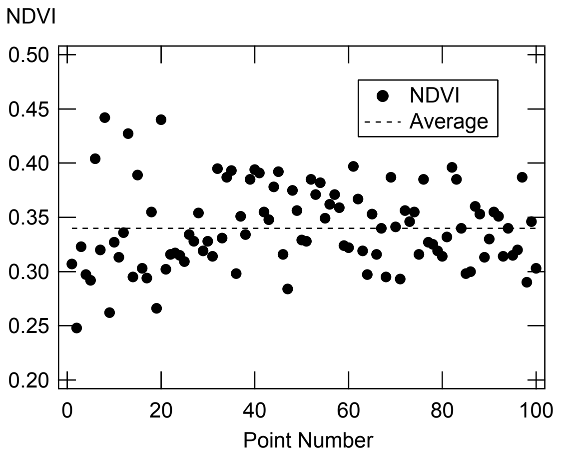

Figure 11 NDVI values calculated along the points on debris line (see Figure 10)

3.4 *Structural damage probability*

Integration of structural damage classification and estimated inundation zone leads to understanding the structural damage probability as shown in Table 1.

Also, combined with the result of the post-tsunami survey, the fragility function (fragility curve) is determined through the regression analysis (Figure 13) assuming that it is expressed as the cumulative probability P_D of occurrence of the damage ;

$$P_D = \Phi\left[\frac{x-\mu}{\sigma}\right] \tag{1}$$

, where Φ is the standard normal distribution function, x is the measured tsunami height, and μ and σ are the mean and standard deviation of x.

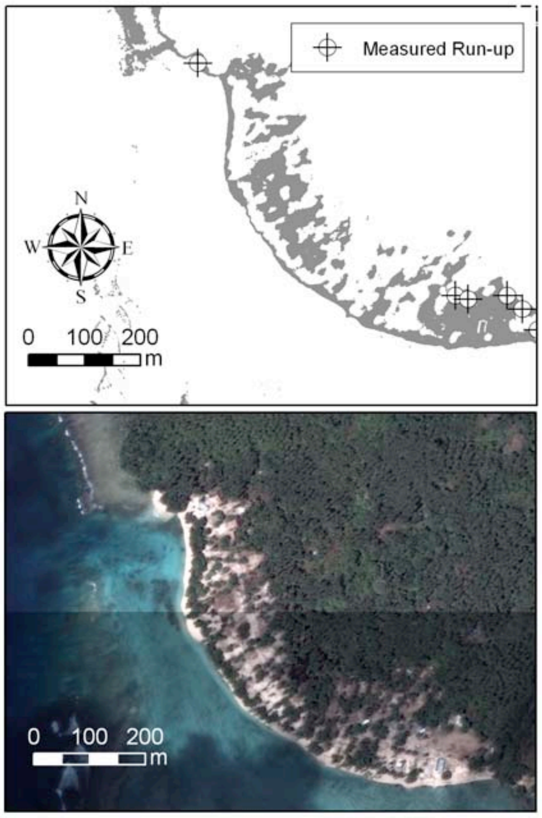

Figure 12 Extent of tsunami inundation zone estimated from the NDVI classification (Area II).

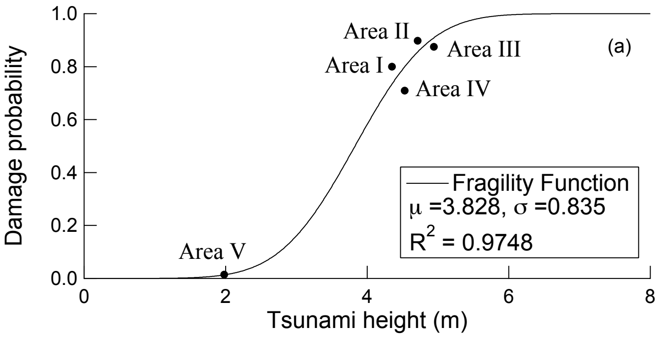

Figure 13. Fragility function of structural damage obtained from Ghizo island.

Table 1. Structural damage probability obtained from the visual damage classification and NDVI analysis detecting the inundation zone.

Area	N_0	N_D	P_D	H_{max}
Area I	85	68	0.8	4.1
Area II	98	88	0.9	2.95
Area III	40	35	0.86	2.48
Area IV	62	44	0.71	1.88
Area V	134	2	0.01	1.09

N_0 : Number of structures within the inundation zone, N_D : Number of structures classified as G4 and G3, P_D : Damage probability, H_{max} : Measured maximum tsunami height (m) in each area

4 CONCRUDING REMARKS

Integrating the numerical model of tsunami propagation/inundation, GIS analysis, and the remote sensing technologies with use of modern computing power has possibility to expand the capability in detecting the impact of tsunami disaster. The present research is still underway in developing automatic damage detection algorithms, real-time tsunami inundation modeling to estimate the structural damage in a quantitative manner, developing house and structure inventory database, and high-resolution merged bathymetry and topography data. Especially, the global deployment of developing fragility functions including damage mapping with satellite imagery is one of the most significant issues. Also, another significant barrier to overcome is developing the database of high-resolution bathymetry and topography grid in world-wide scale.

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