USING ALTIMETRY AND REMOTE SENSING IMAGERIES TO OBSERVE LAND VERTICAL MOTION ASSOCIATED WITH 2004 INDIAN OCEAN EARTHQUAKE

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ABSTRACT: A great Indian Ocean earthquake occurred in 2004 had caused uplift and subsidence with various rates in Sumatra and Indonesia. The post-seismic land vertical motion apparently changed land formation and coastal topography. However, it's usually difficult to quantify how coastline has changed after an event in a short time and with low cost. In this study, we utilize historical Landsat images in this region to first compose an inundation chance model along the coastal zone. This model is then converted into digital elevation model by giving height references (upper and lower boundaries) from NAO.99b tide model. The vertical motion in a range of few tens of centimeters can be seen in several tidal flats potentially caused by this megathrust earthquake.

1. INTRODUCTION

Indonesia is located in the "ring of fire" created by the movement of tectonic plate. The plate is continuously and slowly moving until forming the earth's crust under the sea. It is also formed by lava that runs out from sea mountains and hardens as cooled down by seawater (Ashat et al, 2012). In addition, the plate encounters natural geological process as it moves. There are three primary possibilities forming this geologically active area (Condie, 1997): (1) the plate moves away from each other and provide a space for new seabed, (2) plate was subducted by each other and one of them goes down, (3) the edge of plate is sliding without stopping. All possibilities can trigger natural disasters, such as volcanic eruptions, landslides and earthquake even tsunami as well.

Indian ocean earthquake that happened on 26 December 2004 was caused by the subduction of Burma microplate into Indian plate. It had triggered a series of devastating tsunami along the coast of Sumatera island (Curray, 2005). This earthquake occurred at 00:58:53 UTC or 07:58:53 WIB local time on 26 December, when many people went out for regular activities without warning to the upcoming disaster. At that time, they felt the earth shake strongly and the seawater was receding, after few minutes the big wave coming from the middle of the ocean and hit the settlement which killed 230,000 people in 14 counties. It was one of the most devastating natural disaster that ever recorded in the history. Indonesia had the hardest-hit countries, followed India, Thailand, and Sri Lanka.

Simeuleu Island is one of the island close to the epicenter, where the distance is only about 60 km. It is located in 2°35'N 96°05'E with an area of 2,310 km^2. It has a population about 82,100 people. However, victims of that earthquake was only 6 people, because their ancient has learned how to manage natural disasters. In 1907, Simeuleu island had experienced earthquake that triggered tsunami and killed a number of local residents. Since that disaster, their ancient studied about natural disaster that will be happened again in the future. Once the earthquake attack, they will observe the sea profile and animal nature, if sea is receding and animal running toward to the mountain which mean the tsunami will come. Resident who live close to sea will announce that tsunami will come and they should evacuate to the secured place at higher elevation. Therefore, it was one of reason why Simeuleu has less people died even the island is the closest one.S

Even so, this earthquake has caused uplift in the north of Simeuleu island and subsidence in the southern edge (Meltzner et al, 2004). Previous study found that the actual uplift could range between 150 cm and 50 cm (Figure 1) by measuring the coral's height in that place by a validation of 160 locations in Simeuleu island. They also apply optical remote sensing imagery, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard Terra, to observe the coral reef and Porites microatoll. The post-seismic affect also can be investigated with geodetic measurement to see the slip at that time (Chileh et al, 2007).

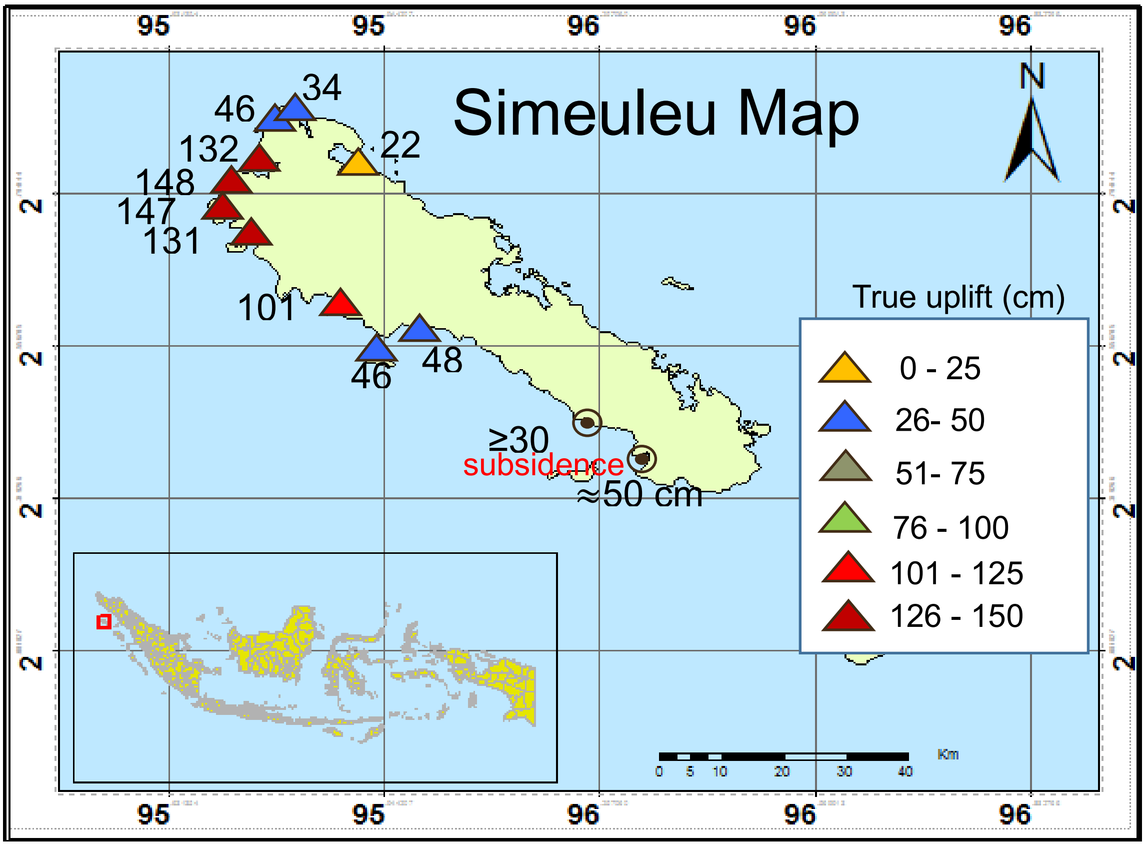

Figure 1. Simeuleu map (Meltzner et al, 2006)

In this study, we investigate land vertical motion in the north of Simeuleu island to observe land deformation and changes in coastal topography. However, it is difficult to quantify coastline after a massive earthquake with sudden changes. Hence, we want to see land vertical motion before and after earthquake by collecting Landsat image to build inundation chance map and convert the map into a digital elevation model (DEM). After that, we also analyze sea level trend from satellite altimetry observation before 2004 and after.

2. METHODOLOGY

In general, to observe land vertical motion by optical imagery is quite difficult owing to the nadir looking angle. We used Landsat images as our dataset, beside it is free, it also suitable for analyzing water cover since its spatial resolution 30 m. By collecting Landsat series images (Table 1) we will calculate water index with green and MIR band (Xu, 2006).

Table 1. List of Landsat images used in this study

Landsat 5	Landsat 7	Landsat 8
1987 – 2011	1999 – present	2013 – present
Band 2 and band 5	Band 2 and Band 5	Band 3 and Band 6
17 images	50 images	54 images

Each satellite in Landsat series has different specification of bands. Landsat 5 and 7 has the similar band used to compute water index: the green band is band-2 while MIR band is band-5. Landsat 8 is little bit different, the green band is band-3 while MIR is band-6. The water body has stronger reflection in green band than the other bands and stronger absorption in infrared (MIR) band, so we can apply this spectral characteristic to analyze the change of coastal zone in Simeuleu island associated with Indian ocean earthquake 2004.

$$MNDWI = \frac{Green-MIR}{Green+MIR} \tag{1}$$

In this equation, Green band has higher reflectance for water and middle infrared band experiences stronger absorption, so the water with MNDWI>0 can be identified clearly from other pixels and the coastline can be further delineated. We calculate water index for images from Landsat and set a threshold to divide in two class, water and non-water. In the north of Simeuleu island we set the threshold equal to 0.4, which means that if the value equal or larger than this value it will be assigned as 1. Otherwise, it will be 0. Therefore, we obtain water and non-water in each pixel of Landsat images.

Next, to sum up all pixel in a sequence of Landsat images with the following equation (Tseng et al., 2017) and divide by the number of images in the dataset, we can obtain the inundation chance of each pixel. This map indicates relative elevation in the intertidal zone.

$$\sum_{k=1}^{N} \frac{L_k(i,j)}{N} \text{ x } 100\ \% \tag{2}$$

Which means "i,j" is row of water index images, N is total number of Landsat images that we use in our study.

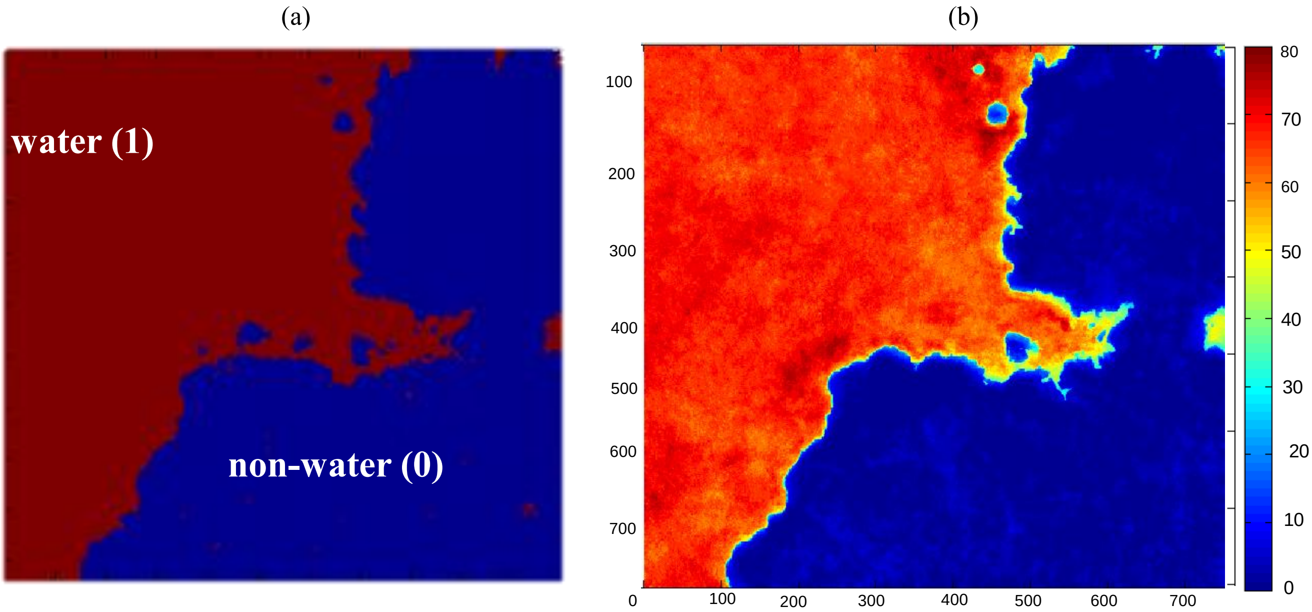

Figure 2. North of Simeuleu island (a) water index images (b) the inundation chance

Figure 2(a) is a typical classified image that contains water and non-water pixels. Then we apply the inundation chance equation to see the chance of coastline as shown figure 2(b). The darker blue area to the right indicates high elevation while the darker red to the left denotes lower elevation.

Finally, we use Japan's National Atmospheric Observatory (NAO.99b) global tide model as height reference to convert inundation chance into actual elevation. This tide model is assimilation from 5 years of TOPEX/Poseidon satellite and has spatial resolution 0.5°, with an accuracy at about 2 – 4 cm (Matsumoto et al., 2000). We run NAO.99b global tide model to obtain mean higher high water (MHHW) and mean lower low water (MLLW) then put as our height reference (upper and lower boundaries), MHHW = -19.59 cm and MLLW = 20.53 cm (Figure 3). By these two variables our inundation chance will be converted to digital elevation model with MHHW and MLLW as the height reference. We also provide two DEMs, before and after 2004, to quantify how large land vertical motion in Simeuleu island and we found that some area is uplift (Figure 3). Finally, we exploit satellite altimetry to see the changes sea level trend before and after the earthquake.

3. RESULT

There are some places in the north of Simeuleu island encountered uplift and subsidence because of this earthquake at about few tens of centimeters. During earthquake, the intertidal zone had raised into supratidal zone, where tidal waves cannot reach these areas anymore. By comparing DEM before and after earthquake, we can see clearly that coastline changes far away in between. Altimetry observation also shows that the sea level trend has a little bit altered owing to the change of bathymetry.

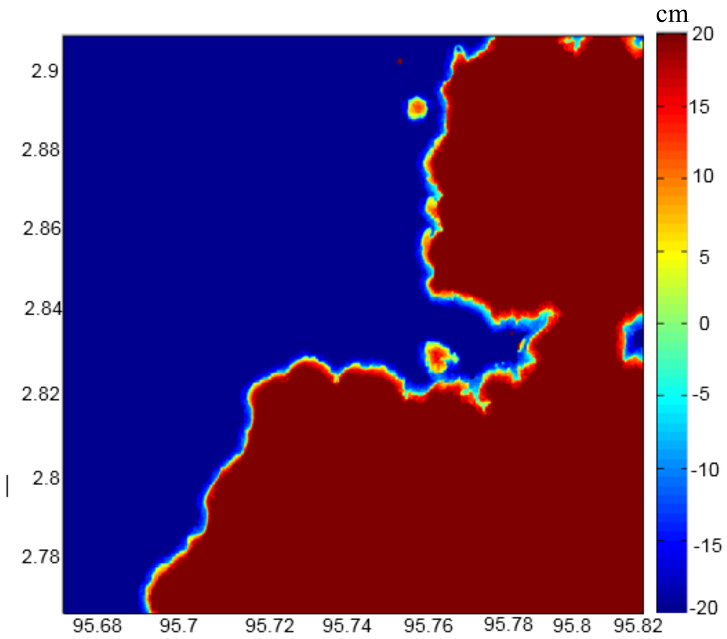

Figure 3. Overall DEM from 1987 - 2017

4. CONCLUSION

In this study, we demonstrate how optical imagery can be used to observe land vertical motion and use NAO.99b global tide model to obtain MHHW and MLLW from 1999 to 2017. These two terms are used as height reference in the reconstructed digital elevation model to define the intertidal zone between high tide and low tide marks. Finally, we also identified digital elevation models before and after the earthquake to quantify post-seismic land vertical motion at Simeuleu island.

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