NUMERICAL ANALYSIS OF TSUNAMIS GENERATED BY SEA BOTTOM ERUPTIONS OF THE SAKURAJIMA VOLCANO

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Responding to the devastating damage caused by the Great East Japan Earthquake, coastal researchers and practitioners start to investigate the possible reactions towards supposed maximum tsunamis throughout Japan. In Kagoshima prefecture, caution should be paid on not only seismic tsunamis along plate boundaries, but also volcanic tsunamis caused by sea bottom eruptions near the Sakurajima Island. Since the energy of tsunamis occurred in the domain north of Sakurajima Island is confined in the closed basin, the fluctuating motions are possibly totally different from those in open sea areas. The present study conducts numerical analyses on the tsunami propagations by varying the source points and sea bottom deformations, and investigates the characteristics of the tsunamis inherent to the closed water basins.

Keywords: Sea bottom eruption; Closed basin; Multiple reflection; Volcanic tsunamis

BACKGROUND

After the 2011 off the Pacific coast of Tohoku tsunami, requirements to estimate possible huge tsunamis have rapidly increased throughout Japan. Because tsunami characteristics are usually different from site to site, it is very important to predict behaviors of site-specific tsunami. In Kagoshima prefecture, two types of tsunami are prospected: One is seismic tsunami occurring along plate boundaries, and the other is volcanic tsunami generated by a sea bottom eruption.

The water basin in the present study is northern part of Kagoshima bay bordered by Sakurajima Island (Fig.1). The basin is mostly closed, which only opens at the west end of the Sakurajima Island by around 4 km. The bathymetry of the whole bay is deep as 140 m in average and 200 m at the maximum because the bay was formed by intrusion of the sea water into a caldera generated by a huge eruption 25 thousands years ago. When Sakurajima caused another big eruption in 1914, the east end of the island was connected to the Osumi peninsula by the erupted deposit.

The Sakurajima volcano is an active volcano located in the central of Kagoshima Bay and in the front of Kagoshima city. Historically it raised big eruptions at the sea bottom during 1780-1781 called An-ei eruption (Imura, 1998; Kobayashi, 1989). An ancient document recorded that 15 drowning victims were found by the associated tsunami occurred at 18 March, 1781. The document also described the tsunami behavior as that big waves were running up with the magnitude of 12.6 to 14.4 m around 10 times at Koike beach. Tsuji (1997) inferred that the magnitude would not be a vertical height, but a horizontal length. If the recorded magnitude is horizontal length and the topographic gradient at Koike coast (around 1/17) keep the same now and then, the estimated tsunami height would be 74-85 cm.

Referring these historical tsunami events caused by volcanic eruptions, we should prepare the possible tsunami disaster in this water basin. Once a big tsunami is generated in a closed basin, multi-

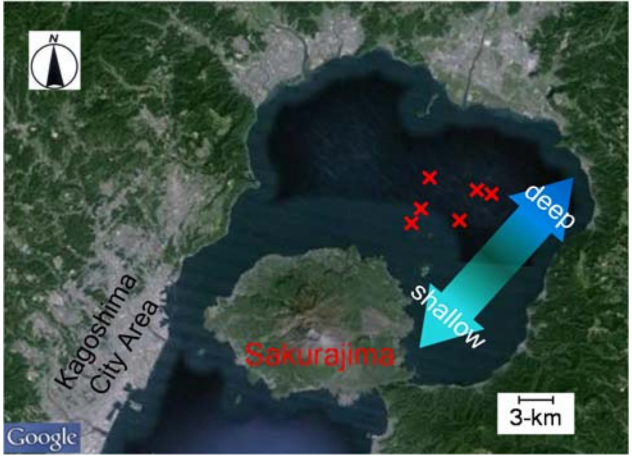

Figure 1. Points of An-ei eruption

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ple reflections along the coast will occur. At 1983 Central Japan Sea tsunami, reflected tsunamis from Korea peninsula and Russian coast attacked Japan coast again and induced additional damages(Tanimoto et al., 1983). Also at 1883 Krakatau tsunami which was caused by a sea bottom volcanic eruption, the properties of the generated tsunamis were found to be much governed by the surrounding topography including Sumatra and Java Islands (Kawamata et al., 1992). Therefore, for our study site; mostly closed and deep water basin, the behavior of the prospected tsunami is much governed by the topographic properties. This study aims to investigate the inherent characteristics of the tsunami behaviors by numerical analysis.

NUMERICAL_ANALYSIS

The computational domain shown in Fig.1 is divided into a 150 m mesh. The following shallow water equations are used for the computation of water surface fluctuations. The staggered leap-frog scheme is adopted for the discretization.

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \qquad (1)$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}+A\frac{\partial^2 M}{\partial x^2}+A\frac{\partial^2 M}{\partial y^2}-\frac{KM\sqrt{M^2+N^2}}{d^2} \qquad (2)$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}+A\frac{\partial^2 N}{\partial x^2}+A\frac{\partial^2 N}{\partial y^2}-\frac{KN\sqrt{M^2+N^2}}{d^2} \qquad (3)$$

Here, each symbol denotes as follows:

u, v: horizontal velocity of x- y- direction
h: total depth ($h = \eta + d$ η: water level fluctuation, d: depth)
M, N: flow flux ($M = uh$, $N = vh$)
$H = z_b + h$ (z_b: sea bottom elevation)
g: acceleration of gravity
K: coefficient of sea bottom friction
A: horizontal diffusion coefficient (assumed to be 100m^2/s)

Tsunami Source Model

The characteristics of generated volcanic tsunamis are investigated by altering shapes of the sea bottom deformations. Two types of the sea bottom deformations models are considered based on studies on presumed magma intrusions at the events of the An-ei eruption (Imura 1998, Kobayashi 2001). Model Type1 is a 900 m square column immediately rises to a height of 15 m (Fig.2), and Model Type2 is a conic deformation with a radius of 700 m immediately rise to height of 15 m (Fig.3). The initial water surface deformation is assumed to be exactly same as that of sea bottom deformation.

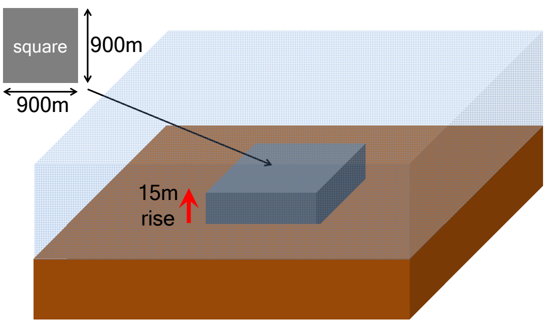

Figure 2. Tsunami source model (Type1)

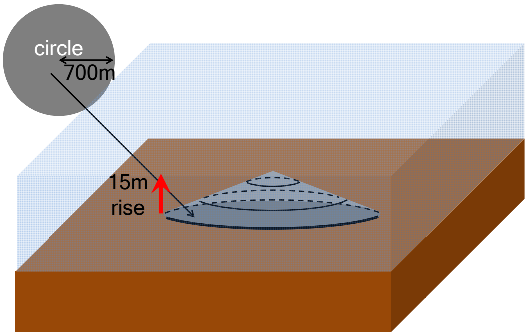

Figure 3. Tsunami source model (Type2)

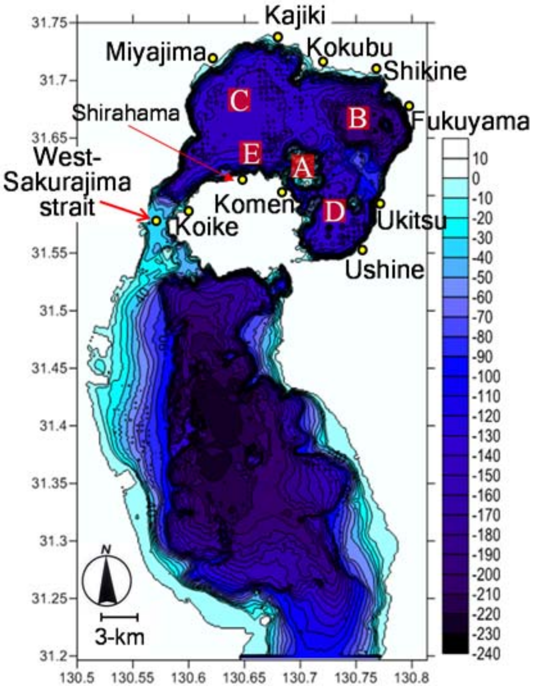

Figure 4. Wave source points(A-E) and monitoring points

The wave source is set at five points (Fig.4, Point A-E) to investigate how the generated tsunami waves are affected by the source points. The tsunami induced water surface fluctuations are monitored at 11 points of the coast. (Fig.4).

RESULTS

CASE1: Square column source is set at point A

Figure 5 illustrates the tsunami propagations with 1 min intervals when the square column source is uprifted 15 m suddenly at point-A(this coincides to the volcanic eruption on 6th July, 1780, An-ei period). The water depth at point A is relatively shallow around 50-60 m. At the begining (the first figure of Fig.5 after 1 min from the eruption), the water surface elevation looks almost point shape, then propagates over the basin as time passes. After reaching the eastern border, the reflected fluctuations travel to the north coast and reflected again there. After 7 to 8 min., the fluctuations are multi-reflected and the resultant water surface paterns becomes complex. A part of the fluctuating energy in the water basin outflows through the west-Sakurajima strate, and resultantly the fluctuating heights are slowly attenuated as time passes.

Figure 6 shows the time histroy of the water surface elevations at several points along the coast. It is found that the tsunami arrival times are generally very short. For example, 1-2 minutes result at Komen point; the closest point to the source point, even the longest, only 10 minutes are obtained at Koike point. It is also found that the fluctuations last for a long time due to the multiple reflection at the coast. This is considered the inherent property of tsunamis generated in a closed basin.

The maximum height (= total amplitude) records at Komen around 5 m. The fluctuating period is around 130 s. At Kokubu and Shikine points, the tsunami heights reach to around 3 m. The fluctuating period at Kokubu is approximately 220 s. The results att Koike point show that the maximum amplitude is 1 m and more than 10 fluctuations continue. Note that these quantities roughly coincide with those of the description in the ancient documents.

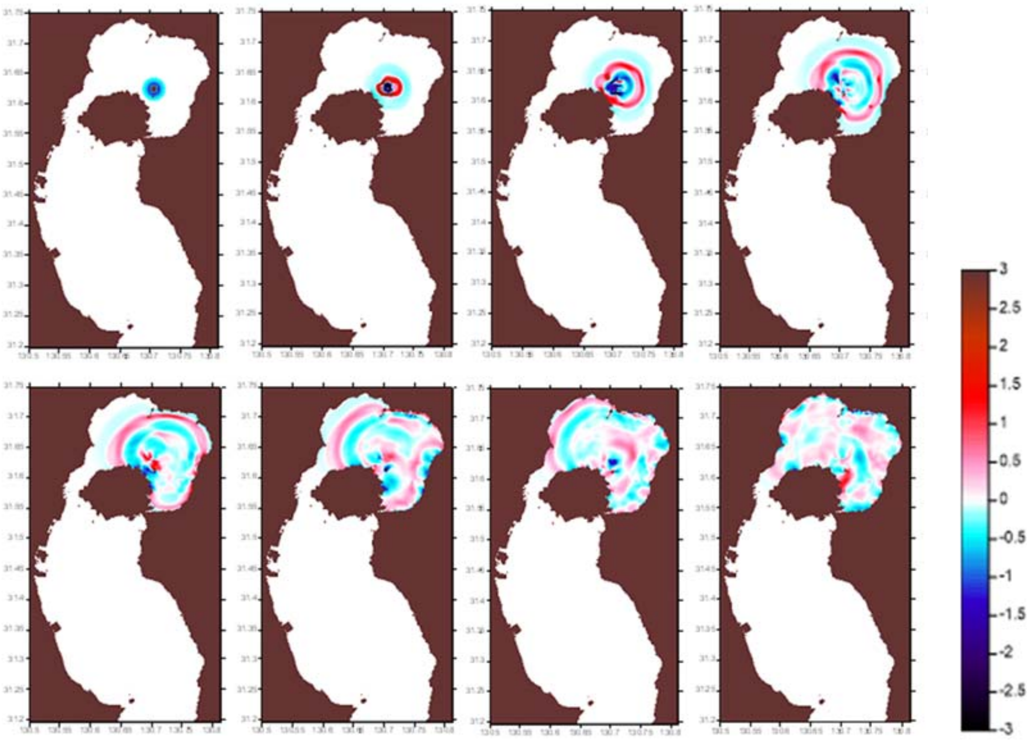

Figure 5. Tsunami propagations (CASE1)

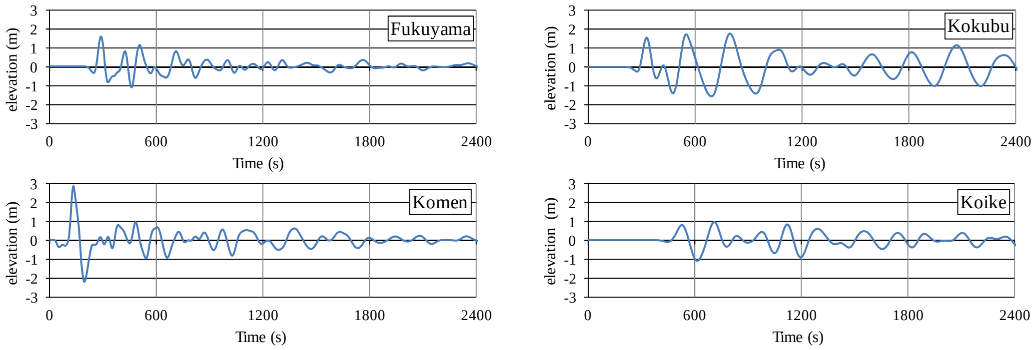

Figure 6. Time series of the water surface fluctuation (CASE1)

CASE2: Square column source is at point B

Figure 7 illustrates the tsunami propagations every 1 min for the case that the wave source is set at point B. The water depth there is around 200 m which is deeper than CASE1. After 4-6 minutes, the tsunami wave reached at Kokubu, Shikine and Fukuyama, then reflected and propagated towards the north and west part of the basin. The time histories of the water surface fluctuations indicate that the maximum amplitude reachs to 3.5-4 m at Shikine and Fukuyama which are located near the source points. At Komen point, however, the water surface fluctuation becomes small, because the surrounding area is shallow and the incoming tsunami may dissipated by the breaking. In our calculations, the non-linear shallow water equations are adopted, which can express the breaking dissipation through the bore type dissipation caused by non-linear terms (Kobayashi et al.,1989). The results yield that tsunami fluctuating period becomes around 120 s at Kokubu and approximately 80 s for other points.

Comparison of these results and those of CASE-1 reveals that the water surface fluctuations of CASE2 are generally bigger than those of CASE1 except the north points of Sakurajima. The results of fluctuating period of CASE2 are, in general, shorter than those of CASE1. They can be explained that the depth of point B is deeper than that of point A.

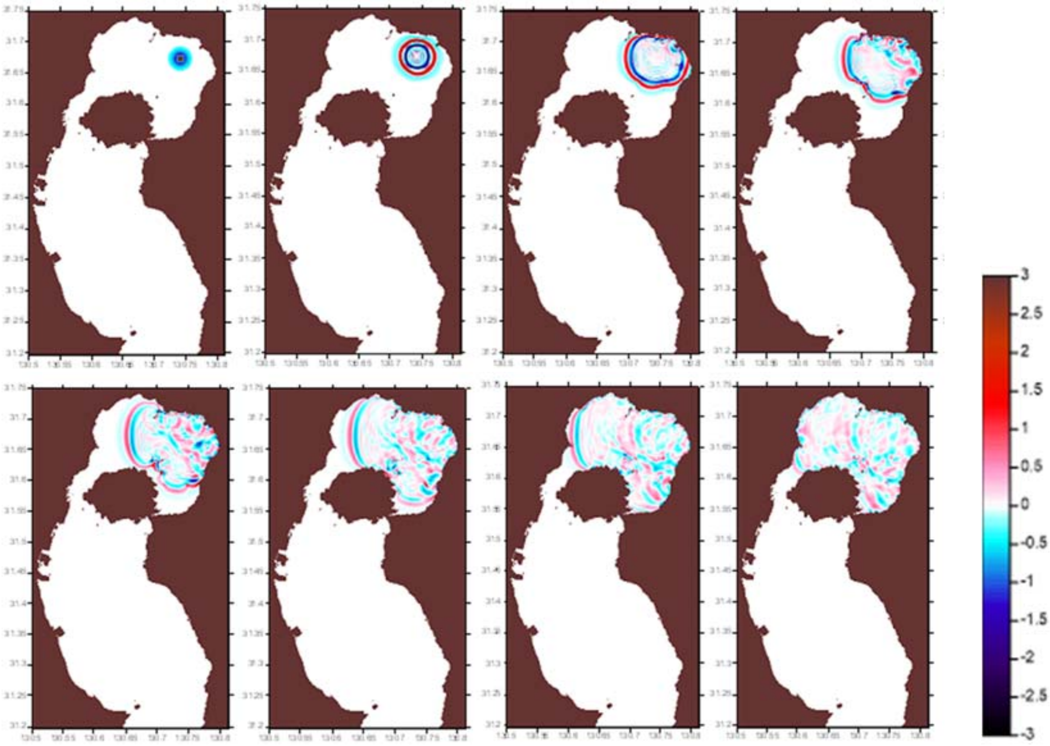

Figure 7. Tsunami propagations (CASE2)

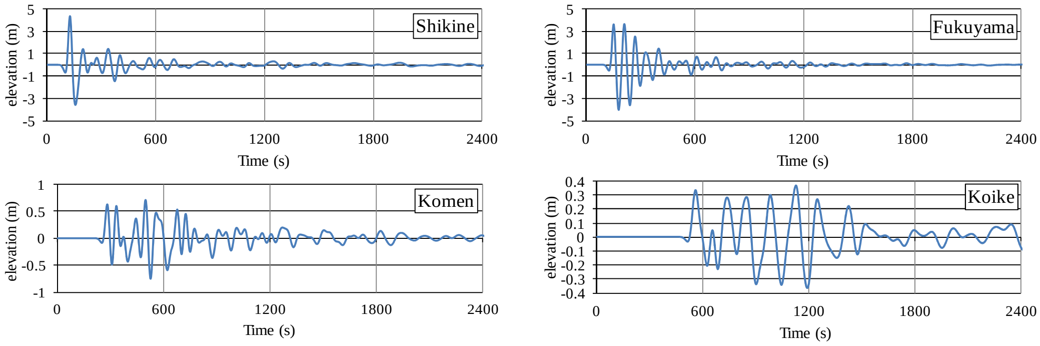

Figure 8. Time series of the water surface fluctuation (CASE2)

As stated above, the gradual dissipation of fluctuation energy is related to energy outflow occuring only through the West-Sakurajima strait. Quantitative estimations on the energy outflow are made using the following equation,

$$E_{rad}(t) = \rho g \int_0^W \int_0^{h(x)} \eta(x,z)\, v(x,z)\, dz dx \qquad (4)$$

, in which, W is the opening width of Sakurajima strait, v is north-south velocity component of tsunami motion based on the fact that the strait runs west-east direction.

The calculated out flow energies E_{rad} are illustrated in Figure 9. All results take negative sign, that indicates that the energy flux is passing through the strait from north to south.

When wave source point locates near West-Sakurajima strait, large energy outflow are observed during first 600 seconds (Point A, C, and E). When wave source locates inner part of the bay (Point B), less energy outflow occurs. When wave source locates north of Sakurajima, relatively big energy outflow remains even after 1,200 seconds (Point A, D, and E). It is caused by multiple reflection of the tsunami. The total energy outflow becomes larger as the wave source locates close to the northern coast of Sakurajima (Point A and E). They suggest that persistence of tsunami energy strongly depends on the location of the tsunami source.

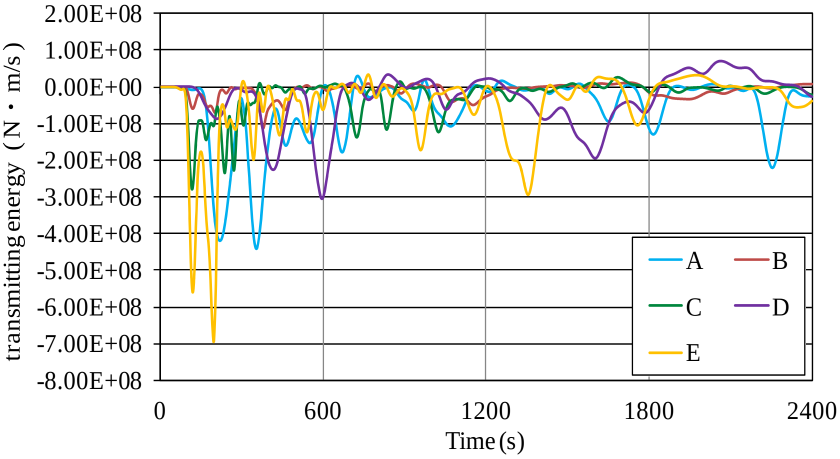

Figure 9. Transmitting energy through the West-Sakurajima strait

CASE3: Conic source is at point B

Whereas the square column model is adopted as the tsunami source in CASE1 and CASE2, in CASE3 the conic source shown in Fig.3 is used. The source is placed at point B same as CASE2. Figure 10 illustrates the tsunami propagations. Figure 10 shows the time histroy of water surface fluctuations. It is found that the first tsunami motions start with landward motions all the monitoring points in CASE3, whereas start with withdraw motions in CASE1 and CASE2. It is also noted that the fluctuating periods are almost same as those of CASE2, but the magnitudes of water surface fluctuation are bigger than those of CASE2 at all the monitoring points. The increase of the fluctuation can be explained that the initial water surface gradient, which coincides the conic source gradient, is greater than that of CASE2 using square column source shape.

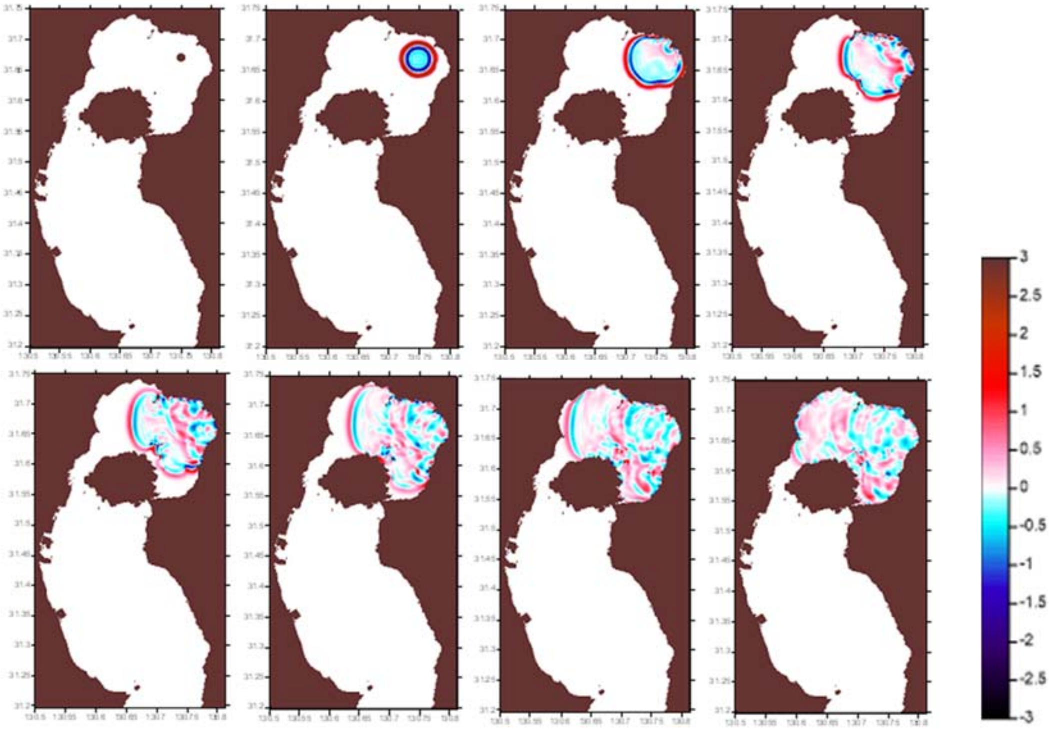

Figure 10. Tsunami propagations (CASE3)

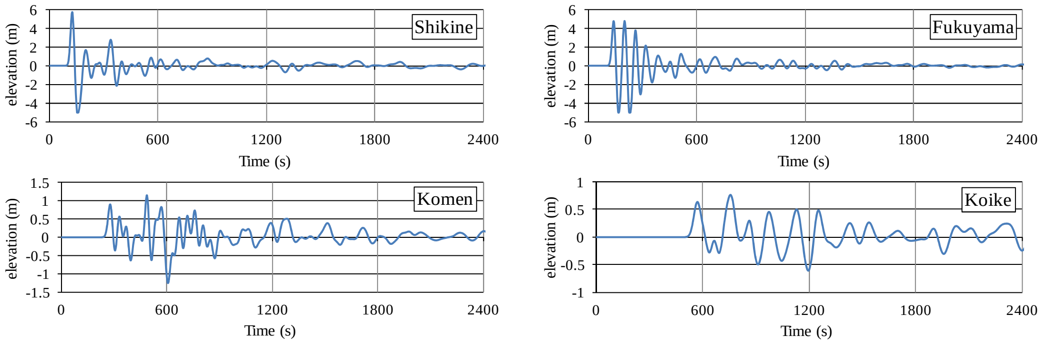

Figure 11. Time series of the water surface fluctuation (CASE3)

CONCLUSIONS

This study has conducted numerical calculations on the volcanic action induced tsunamis by varying the source point position and shape of deformation. The inherent characteristics to the closed water basin are obtained. The main findings are as follows:

- The tsunami waves arrive at the coast in very short time, at the latest within 10 minutes because the study area is a small and relatively deep basin.
- The generated fluctuations persist for a long time by multiple reflections at the coast.
- The tsunami wave heights described in the ancient documents at An-ei eruption are found to be nearly reproduced.
- When wave source is set at deeper point, the fluctuating amplitudes become greater and periods shorter.
- The generated tsunami wave height becomes greater when a conic shape is adopted as the source than that a square column shape is provided, because the gradient of initial water surface becomes greater.
- Outflow of the tsunami energy is restricted only by passing through the West-Sakurajima strait. The energy outflow becomes larger as the wave source locates close to the northern coast of Sakurajima (Point A and E).
- The present numerical simulations revealed that large tsunami wave heights occurs along the northern coast of the basin like Kokubu, Shikine and Fukuyama, therefore more tsunami precaution should be paid for these area.

The following subjects are remained for the future study.

In this study, the initial water level deformation is assumed to be exactly same as that of sea bottom deformation. As the next step, more realistic initial water surface disturbance responding to the vertical sea bottom movement should be considered in the numerical study.

The water surface fluctuations in the closed basin are possibly governed by the eigen frequency motions determined by the topographic condition. Persistent water fluctuations affected by multiple reflection along the coast should be considered from this aspect.

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