A STUDY ON POSSIBLE CRITICAL STORM SURGE UNDER PRESENT CLIMATE CONDITIONS IN THE ARIAKE SEA, JAPAN

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A STUDY ON POSSIBLE CRITICL STORM SURGE UNDER PRESENT CLIMATE CONDITIONS IN THE ARIAKE SEA, JAPAN

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In this study, to understand the characteristics of storm surges along the coast of innermost area in the Ariake Sea, the tidal changes at three points along the embankments were measured for about three months in the summer of 2012. In addition, several storm surge simulations were conducted by using the parameters of an actual Typhoon No.16 (T1216) to investigate the possible large storm surge in the Ariake Sea under the present climate conditions. The observational results show that the storm surge amplifies remarkably in the innermost area in particular. Furthermore the numerical simulation results imply that there is the risk of serious storm surge disaster in the Ariake Sea under even the present climate condition.

Keywords: the Ariake Sea, storm surge; tidal observation; numerical simulation

INTRODUCTION

Recently, due to global warming, there are growing concerns about possible tremendous storm surge disasters which might be caused by furious typhoons in the future (Yasuda et al. 2014). However, even in the present climate conditions, there were some typhoons which might be able to cause severe disasters if it had passed the worst course. Typhoon Haiyan, for example, caused severe storm surge disasters in the Philippines in November 2013 (Tajima et al. 2014). In Japan, Typhoon 1216 (hereafter T1216) which passed on the western sea of the Kyushu Island in September 2012 was actually such a dangerous typhoon.

The Ariake Sea located in Kyushu Island is one of the sea areas that have a high risk of severe storm surges caused by typhoons in Japan. Especially, the innermost area of the Ariake Sea has large lowlands behind the coastlines. Therefore, once severe storm surge occurs at the innermost area of the Ariake Sea, its damage might be very serious.

In this study, to understand the characteristics of storm surges along the coast of innermost area in the Ariake Sea, the tidal changes in front of embankments along three different areas were measured for about three months in the summer of 2012. During the tidal change measurements, the storm surge caused by the above-mentioned typhoon T1216 was observed. Then, in addition to the investigation on the storm surge characteristics of the Ariake Sea, we conducted several storm surge simulations with the parameters of the T1216 by assuming several different typhoon tracks including the worst track. The results show that the maximum storm tide would exceed the existing design level even in the present climate conditions if it had passed in the worst track.

THE ARIAKE SEA

The Ariake Sea is located in Kyushu Island, west part of Japan. The sea opens to the East China Sea and connects to the Yatsushiro Sea with three straits as shown in Fig 1. The area and the average depth of the sea are approximately 1,700km^2 and 20m respectively. The sea has vast tidal flats in the innermost area. The maximum tidal range during the spring tide reaches 6m at the innermost area. The Ariake Sea is known as one of the sea areas that have highly risk of the storm surge in Japan because the sea area had been damaged by the storm surges caused by typhoons in the past (Hiyajo et al. 2011). Figure 2 shows an example of the storm surge disasters occurred in the Ariake Sea in the past. In 1999, a storm surge disaster occurred in the Yatsushiro Sea neighboring to the Ariake Sea and 12 persons were killed by the storm surge (Takikawa 2001). Currently, the coastlines are protected with the large embankments as shown in Fig.3. The crown height of the embankments is 7.5m above T.P. (Tokyo Peil, a standard sea level in Japan). However, the serious concerns that severe storm surge disasters would be caused by the powerful typhoons due to the global warming are increasing. Especially, since

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the innermost area of the Ariake Sea has large lowlands behind the coastlines, once severe storm surge occurs at the area, its damage might be very serious.

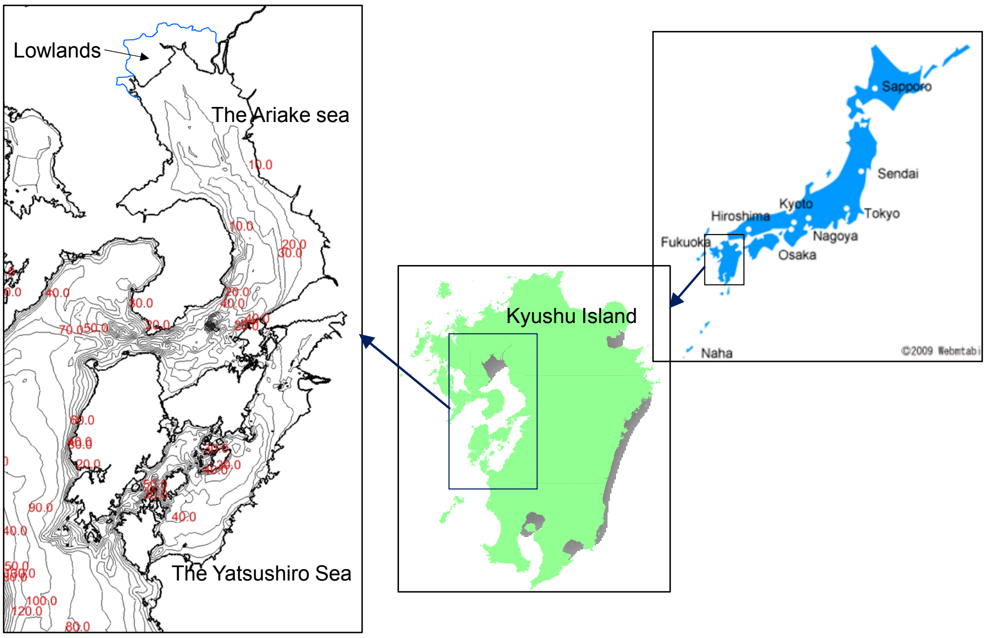

Figure 1. Location of the Ariake Sea.

Figure 2. An example of the storm surge disasters occurred in the Ariake Sea in the past. http://www.k-keikaku.or.jp/xc/modules/pc_ktech/index.php?content_id=1791

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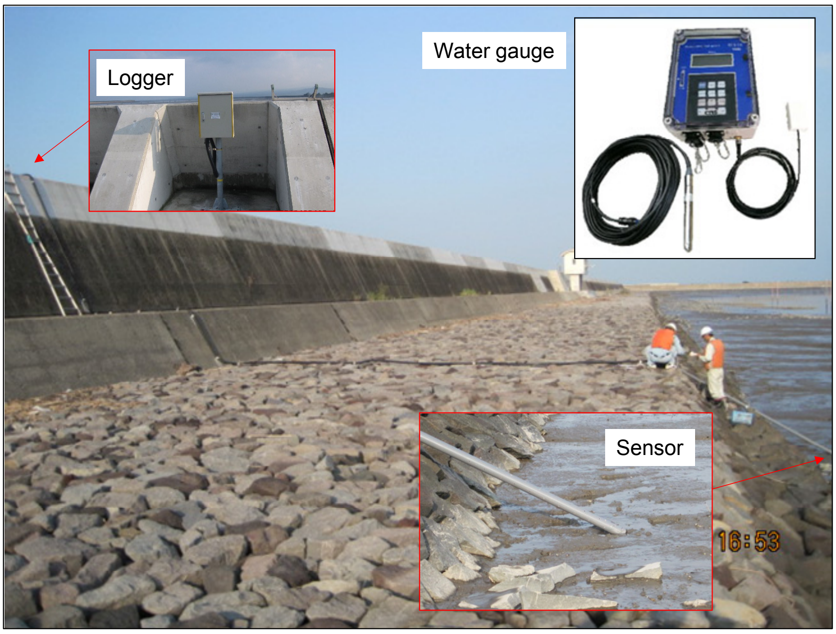

Figure 3. An example of the embankments along the coastline of the Ariake Sea and installation of a water gauge.

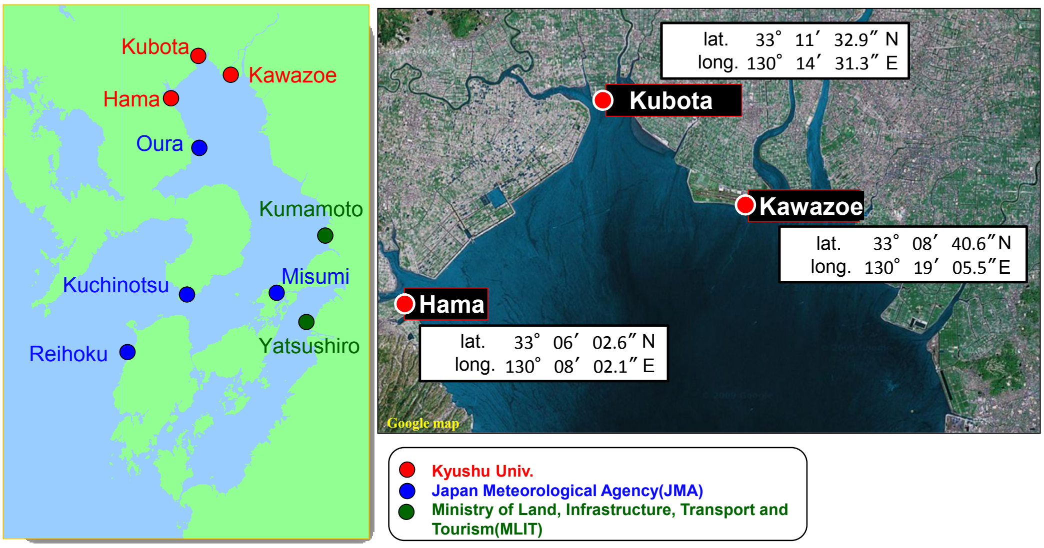

Figure 4. Locations of tidal observation points.

TIDAL OBSERVATION

Measurement of Tidal Change

Field observations were conducted from July through October 2012. Water gauges were set in front of the embankments at three different points in the innermost area: Kawazoe, Kubota, and Hama. The observation points are shown as red circles in Fig.4. Water level changes at the points were measured continually with sampling frequency of 1Hz. In Fig.3, the installation work of the water gauge is shown. Blue and green circles in Fig.4 mean the observation points by the Japan Meteorological Agency(JMA) and the Ministry of Land, Infrastructure, Transport and Tourism(MLIT), respectively. The observational data measured by the public institutions were used in the discussion of amplification characteristics of the storm surge in the Ariake Sea below.

Typhoons that Passed near the Ariake Sea during the Observation

Four typhoons passed through the west sea area of the Kyushu Island during the observation. The tracks of the typhoons are shown in Fig.5. Above all, T1216 was a powerful typhoon compared to the typhoons which caused storm surge in the Ariake Sea in the past. Table 1 compares the lowest central pressures and maximum wind speeds between T1216 and the past typhoons. Note that the maximum wind speeds in the table means the maximum 10-minute average wind speed. Although T1216 caused flooding at some places, the typhoon didn't cause serious damage in the Ariake Sea since its track was away from the sea area fortunately.

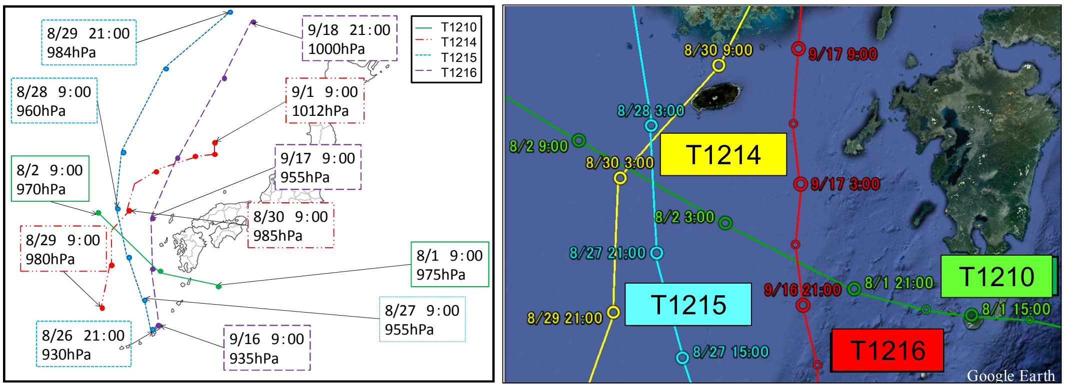

Figure 5. Tracks of typhoons which passed through the west sea area of the Kyushu Island during the observation.

Table 1. Lowest central pressures and maximum wind speeds of T1216 and past typhoons.		
Typhoon No.	Lowest central pressure (hPa)	Maximum wind speed (m/s)
T1216	900.0	55.0
Typhoons that struck the Ariake Sea in the past		
Typhoon No.	Lowest central pressure (hPa)	Maximum wind speed (m/s)
T9918	930.0	45.0
T0418	925.0	50.0
T0514	925.0	50.0

Observational Results

Figure 6 shows the observational data of the tidal changes. Tide level in the figures means the sea level above T.P. Since large tidal flats appear during the ebb tide, the lower tide level was not measured. The periods which typhoons were passing near the Kyushu Island are shown in the figure. From Fig.6, it can be seen that the peak of the water level appeared when T1216 passed. Figure 7 shows the storm tide, which is the sea level departure from astronomical tide, calculated from the observational data shown in Fig.6. The figure clearly shows that T1216 caused the storm tide of 1m or more was caused at the coastline in the innermost area of the Ariake Sea.

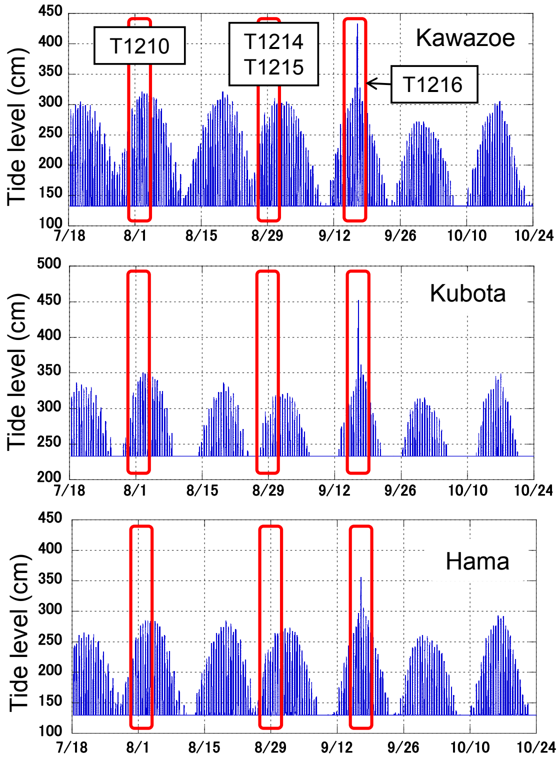

Figure 6. Observational data of the tidal changes.

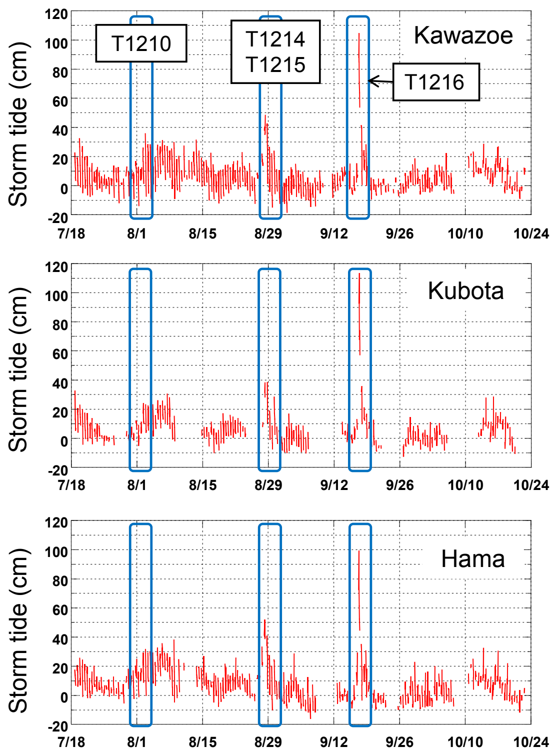

Figure 7 Storm tide changes.

Amplification Characteristics of the Storm Surge

Ordinarily, the spatial distribution of storm tide in an inner bay is drastically changed depending on the typhoon's property, e.g. size, intensity, path, etc. In the case of T1216, the highest storm tide of about 1.2m occurred at Kubota which is the deepest location of the Ariake Sea. Typhoons moving northward on the west sea area of the Ariak Sea like T1216 can cause large storm tides in the innermost area of the sea. Figure 8 shows the amplification factor of the storm tide caused by T1216. The figure includes the observational data measured by the Japan Meteorological Agency(JMA) and the Ministry of Land, Infrastructure, Transport and Tourism(MLIT). The amplification factor means the ratio of the storm tide at each measurement point in the Ariake Sea to the storm tide at Reihoku, outside of the sea. The horizontal axis indicates the approximate distance from Reihoku to each measurement point. From the figure, it is clear that the amplification factor of the storm tide increase as the distance from Reihoku increases. In the case of T1216, the storm tide at the coast in the innermost area reached about three times as high as the storm tide at the mouth of the bay.

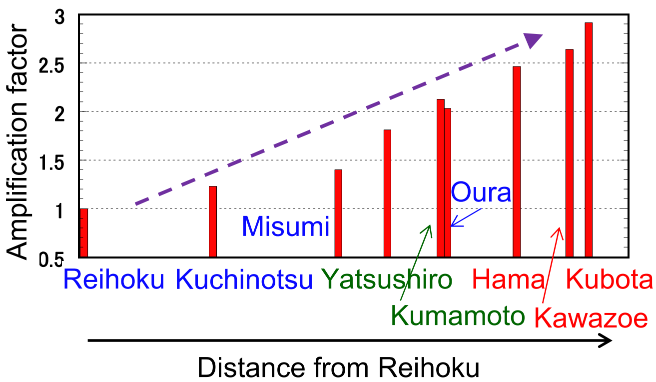

Figure 8. Amplification factor of the storm tide caused by T1216: The amplification factor means the ratio of the storm tide at each measurement point in the Ariake Sea to the storm tide at Reihoku, outside of the sea.

NUMERICAL SIMULATIONS

As mentioned above, although T1216 was a powerful typhoon, the typhoon did not cause the severe storm surge disaster in the Ariake Sea since the typhoon passed on the sea area more than 200km west of the Ariake Sea. It was fortunate that the track of T1216 was far away from the Ariake Sea. Meanwhile, it is not difficult to imagine that T1216 could cause a severe storm surge disaster in the Ariake Sea if its track had been closer to the Ariake Sea. In this study, to investigate how large storm tide could occur in the innermost area of the Ariake Sea if T1216 had passed near the Ariake Sea, numerical storm surge simulations were conducted with the parameters of T1216 but assuming several different typhoon tracks.

Numerical Simulation Models

Numerical storm surge simulations were conducted by using FVCOM(Finite Volume Coastal Ocean Model) developed by Chen et al. (2003). FVCOM employs an unstructured grid system so as to accurately compute tidal currents in complicated inner bays. The spatial-temporal change of atmospheric pressure and wind velocity, which are input data for the storm surge simulations, were calculated by using a conventional typhoon model in which the atmospheric pressure field is calculated by Myers pressure formula. The best track data of T1216 by the Japan Meteorological Agency(JMA) was used as the input typhoon parameters for the typhoon model: location of the center of typhoon and central pressure. Although the radius of maximum wind is also needed as one of the input data, it is not included in the best track data. We therefore determined the appropriate radius so as to make the calculated pressure fields fit the observed pressure fields.

Computational Conditions

A domain for the numerical simulations is shown in Fig.9. The numerical domain was determined taking the tracks of T1216 into consideration. The maximum grid size near open boundaries of the domain is about 17km and the smallest grid size is about 0.8km in inside of the Ariake Sea. Tidal level was fixed to mean water level in all simulations. Thus, numerical results of storm surge signify storm tides which is sea level departures from normal level. The duration of the simulations was set 45 hours, from 0:00, September 16 to 21:00, September 17, 2012 Japan time. Other conditions are shown in Table 2.

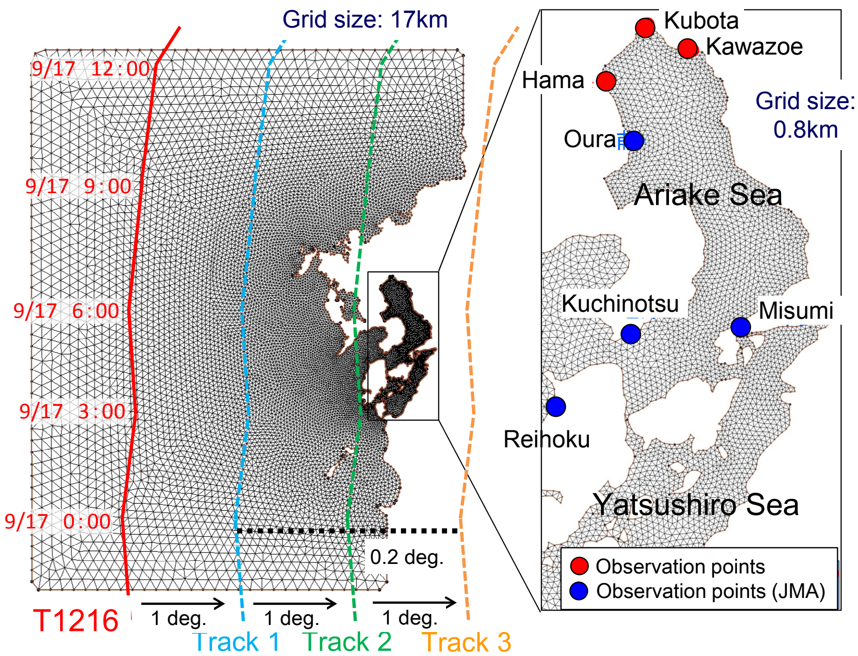

Figure 9. Numerical domain for storm surge simulations and the assumed typhoon tracks.

Table 2. Computational conditions.	
Grid size	0.8 ~ 17 km
Number of Layers	10
Sea water density	Constant (20°, 30psu)
Open boundary condition	Water level due to the low atmospheric pressure (without tide)
Time interval	1.0s

First, the storm surge caused by T1216 was reproduced to verify the accuracy of the numerical simulation. Next, three different tracks, Track 1, Track 2 and Track 3, shown in Fig.9 were assumed. The tracks were moved eastward in parallel with the interval of one degree in longitude. Furthermore, eight tracks more were assumed with the interval of 0.2 degree in longitude between Track1 and Track 3. Consequently, eleven virtual track cases in total were set. In all virtual track cases, only tracks was modified, but other typhoon parameters, i.e. central pressures and radius of maximum wind, were the same as T1216.

Verification of Storm Surge Simulation

Figure 10 shows the comparison of the maximum storm tide due to T1216 between computational results and the observational results. On the whole, the computational results agree well with the observational results. It, however, can be seen that the numerical simulation overestimates the maximum storm tide at Kubota in the innermost area. Figure 11 shows the distribution of the maximum storm tide along the coast of the innermost area. As seen in the figure, the numerical simulation overestimates the maximum storm tide only around Kubota. Then, we decided to correct the computational results by dividing the maximum storm tide around Kubota by the ratio of computational result (st_c) to observational result (st_o) at Kubota. Note that st_c and st_o were defined as the differences from the computational result at Oura so as to not change the computational result at Oura. The corrected storm tide distribution shows better agreement with the observational results as shown in Fig.11. On the basis of this, the computational results in all cases with virtual tracks, which will be described below, were corrected in the same way.

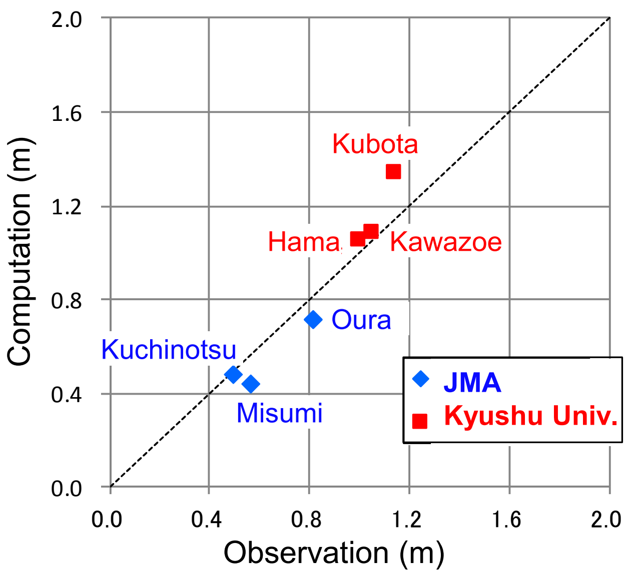

Figure 10. Comparison of the maximum storm tide due to T1216 between computational results and the observational results.

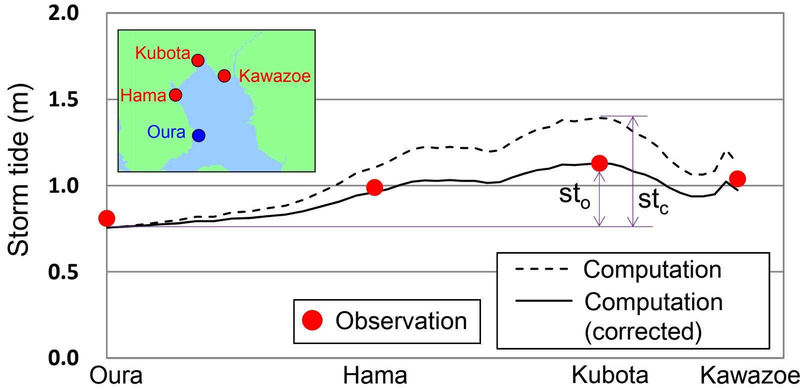

Figure 11. Distribution of the maximum storm tide due to T1216 along the coast of the innermost area.

Change of Storm Tide in the Ariake Sea depending on Typhoon Tracks

Figure 12 shows the spatial distributions of the maximum storm tide. The maximum storm surges in Track1 and Track2 cases are definitely larger than the actual storm tide caused by T1216. Especially, in Track 2, the storm tide in innermost area amplifies remarkably. Therefore, it can be said that the typhoon track of this case is extremely dangerous for the innermost area. On the contrary, in Track 3, the storm tide became smaller and its distribution pattern changed markedly because the typhoon passed on the land, east side of the Ariake Sea.

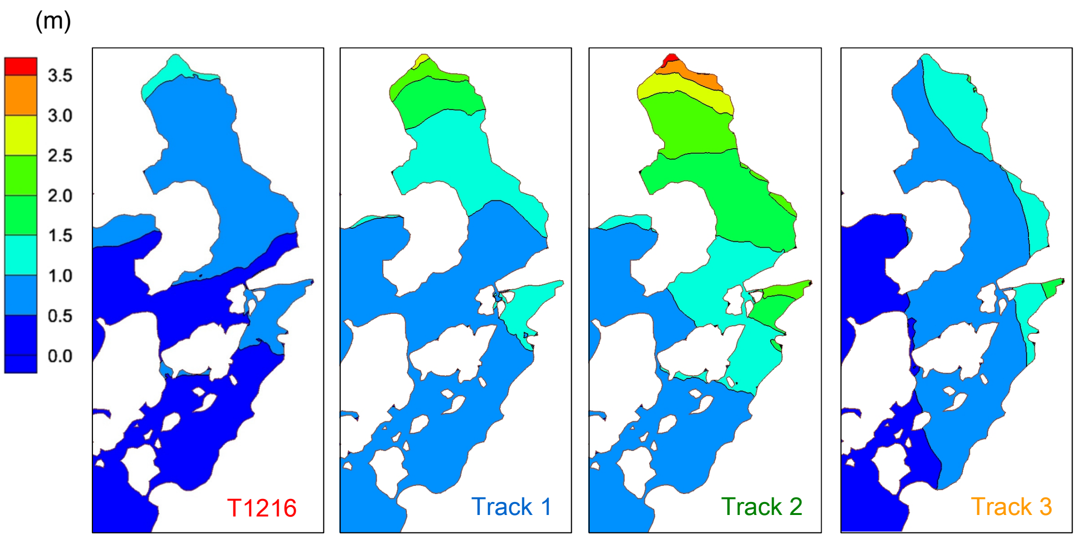

Figure 12. Spatial distributions of the maximum storm tide in the Ariake Sea.

Figure 13 shows the distributions of the maximum storm tide along the coast of innermost area. The design level of storm tide for embankments along the coast in the Ariake Sea is also shown in the figure. As mentioned above, the crown height of the embankments is 7.5m above T.P. In the current design of the crown height, the design storm tide is estimated at 2.36m. The design crown height includes the mean monthly-highest water level of 2.66m, the run-up height of 2.32m and the freeboard of 0.16m as well. From this figure, it is understood that the storm surge at Kubota reached to 3m and the simulated storm surge exceeds the design storm tide in the long range of the coast in the case of Track 2.

Figure 14 shows the changes of the maximum storm tides dependent on the typhoon tracks at five places. The horizontal axis indicates the variation of the typhoon tracks in longitude: the parallel shift of the typhoon's tracks in computation cases from the original track of T1216. The design storm tide is shown as well. This figure shows that the maximum storm tide in the Ariake Sea, especially in the innermost area i.e. Kubota and Kawazoe, increases remarkably as the typhoon's track comes close to the Ariake Sea from the original track of T1216. Furthermore, it is also understood that the worst track of the typhoon is slightly different depending on the place in the Ariake Sea. The duration in which the storm tide exceeds the design storm tide at three places in the innermost area is shown in Fig 15. From this figure, it can be seen that the storm tide in the innermost area could exceed the design storm tide for several hours if the T1216 had passed through near the Ariake Sea. These results imply that there is the risk of serious storm surge disaster in the Ariake Sea under even the present climate condition.

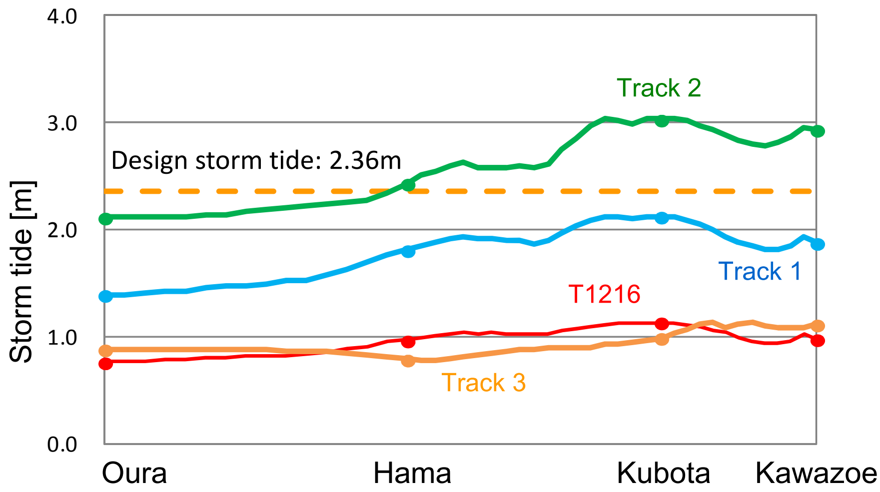

Figure 13. Comparison of the distributions of the maximum storm tide along the coast of innermost area.

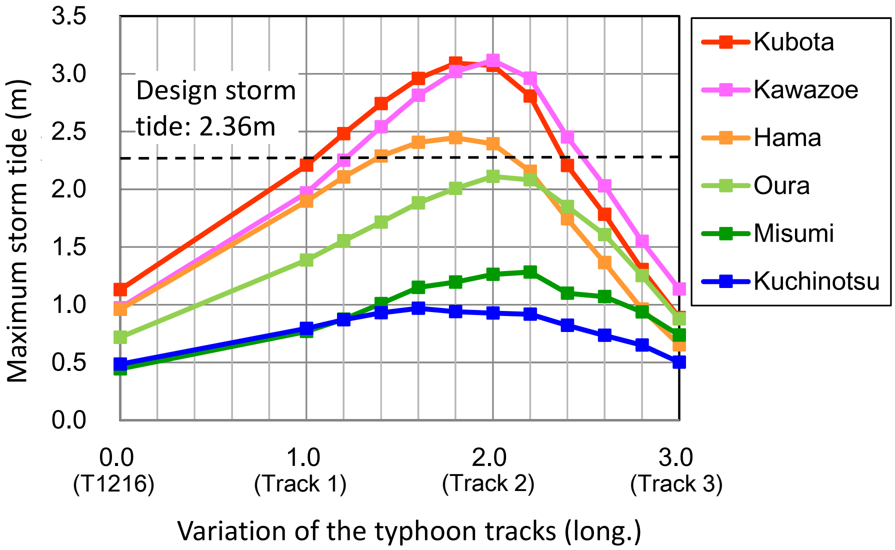

Figure 14. Changes of the maximum storm tides dependent on the typhoon tracks.

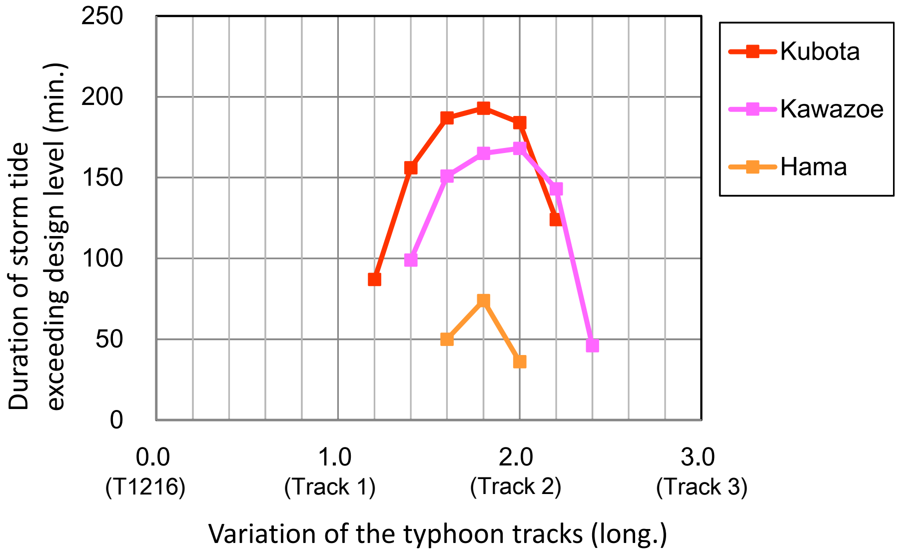

Figure 15. Changes of the duration in which the storm tide exceeds the design storm tide dependent on the typhoon tracks.

CONCLUSIONS

In this study, to understand the characteristics of storm surges along the coast of innermost area in the Ariake Sea, the tidal changes at three points along the embankments were measured for about three months in the summer of 2012. In addition, several storm surge simulations were conducted by using the parameters of an actual typhoon T1216 to investigate the possible large storm surge in the Ariake Sea under the present climate conditions. Main findings are as follows:

1. The observational results of storm surge due to T1216 shows that the maximum storm surge at the coast around innermost area increased up to 3times of the maximum storm surge near the mouth of the bay. The storm surge amplifies remarkably in the innermost area in particular.
2. The numerical simulation results show that the storm tide would exceed the existing design storm tide if T1216 had passed through the worst track. This implies that there is the risk of serious storm surge disaster under the present climate condition.

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