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Paper:

Numerical Simulations of Storm-Surge Inundation Along Innermost Coast of Ariake Sea Based on Past Violent Typhoons

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The Ariake Sea has Japan's largest tidal range – up to six meters. Given previous Ariake Sea disasters caused by storm surges and high waves, it is considered highly likely that the bay's innermost coast will be damaged by typhoon-triggered storm surges. Concern with increased storm-surge-related disasters is associated with rising sea levels and increasing typhoon intensity due to global warming. As increasingly more potentially disastrous typhoons cross the area, preventing coastal disasters has become increasingly important. The first step toward doing so is damage prediction, which requires numerical simulation. Our study considers the tracks of typhoons considerably influencing the Ariake Sea. To examine storm-surge risk related to both inundation area and process, we calculated storm surges inundating the Sea's innermost coastal area using an improved ocean-flow finite-volume coastal ocean model. Results showed that enhanced storm surges were to be anticipated and that inundation areas could be extensive where typhoons followed a route from west to northeast across the Sea. We also found that even under current climatic conditions, typhoons able to cause significant storm-surge and inundation disasters could adversely affect the Bay's innermost coastal area. Our analysis of this area and process indicated that the inundation extent around the bay's innermost coast varies with the typhoon, confirming the importance of determining typhoon routes triggering the potentially greatest inundation damage.

Keywords: Ariake Sea, storm surge, inundation, numerical simulation

1. Introduction

Typhoon-triggered storm-surge disasters are increasingly occurring around the world. Examples include Hurricane Katrina, which hit the southeastern US in 2005; Cyclone Sidr, which hit Bangladesh in 2007; Cyclone Nargis, which hit Myanmar in 2008; and Typhoon Haiyan, which hit the Philippines in 2013. These events caused large-scale disasters costing many lives and forcing large-scale evacuations. Storm-surge disasters in Korea, such as Typhoon Maemi in 2003 and Typhoon Sanba in 2012, also caused considerable damage.

After Typhoon Vera – known as the Ise Bay Typhoon in Japan – struck Japan in 1959, coastal and river levees and other appropriate defensive structures were developed. Since then, no human casualties related to storm-surge disasters have been reported in Japan, except during Typhoon Bart – T9918) in 1999.[1]

Japan has many densely populated areas below sea level whose geographical features make them susceptible to storm surges. The population and the infrastructure have become increasingly vulnerable to storm-surge disasters because of land subsidence, urban expansion into areas below sea level, an increase in core functions and use of underground spaces in metropolitan areas with a high risk of flooding, and a reduced awareness of the risk of such areas among citizens due to the low recent occurrence of disasters.

The Ariake Sea extends north to south and opens to the west and has Japan's largest tidal range – up to six meters. Given the history of storm-surge and wave-triggered disasters in the Ariake Sea, it is considered highly likely that the sea's innermost coastal area, which is particularly low-lying, will suffer damage in storm surges accompanying typhoons. Concerns also arise due to rising sea levels and increasing typhoon intensity caused by global warming.

Researchers studying Ariake Sea storm surges have found numerical simulation to be useful in predicting and assessing risk related to storm-surge disasters. Based on field observations and numerical analysis, Yamashiro et al. [1] highlighted the risk of storm-surge amplification in the innermost Ariake Sea bay area. By estimating storm surges based on climate projections related to global-warming scenarios, Hashimoto et al. [2] demonstrated the possibility of large storm-surge anomalies exceeding the defense level currently planned for the innermost Ariake

1. "Bart" is the name given to the typhoon by a group of related countries. Japan uses a numbering system for typhoons, so T9918 means typhoon no. 18 in the year 1999.

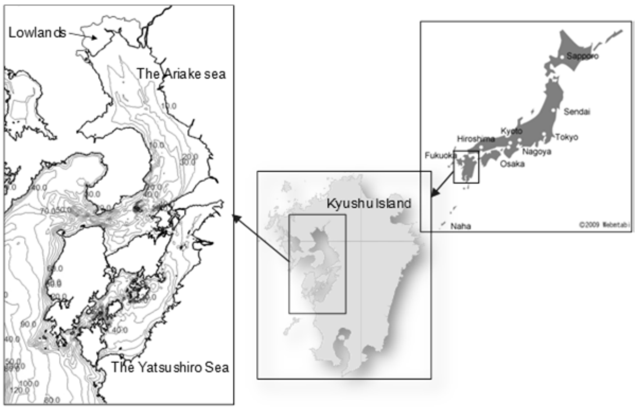

Fig. 1. Location, shape and bathymetric features of the Ariake Sea.

Sea coast. Dundu et al. [3] estimated storm surges for the Saga lowlands using the MIKE 3 Flow Model flexible mesh, developed by the Denmark Hydraulic Institute, to examine 2004 and 2005 typhoons hitting Japan. Kiri et al. [4] predicted storm-surge height in the Ariake Sea using a stochastic typhoon model and climate-change projections.

Despite concerns that global warming will intensify typhoons, this has already become an issue along the Ariake Sea's innermost coastal areas.

Based on past typhoon tracks, we consider typhoon routes considerably influencing the area. To examine disaster risk related to both inundation area and process, we calculated storm-surge inundations on the innermost coastal area using the improved ocean-flow finite-volume coastal ocean model (FVCOM) developed by Chen et al. [5] of the University of Massachusetts.

2. Ariake Sea

The Ariake Sea is an inner bay 96 km long in the north-south direction, an average 18 km wide, with an area of 1700 km^2. The water depth at the mouth of the bay is 50 m, although the bay has a relatively shallow average depth of 20 m and a wide tideland along its coast. It is enclosed, with a 4-km-wide opening at the south end (**Fig. 1**).

Because of the lowlands along the innermost coast, huge embankments with a crown height of TP+7.5 m (TP: Tokyo peil; standard sea level measure in Japan) and a relative height difference from the land of 6–8 m, have been constructed to protect the area from storm surges. Devastating damage would result if large storm surges inundated the lowlands, however, so these areas are considered highly vulnerable.

3. Typhoons

Typhoon Sanba (T1216), which struck Japan in 2012, caused storm surges in the Ariake Sea. Typhoon Maemi (T0314) in 2003 turned to the west away from the Ariake Sea was equivalent in strength to T1216, so we chose T0314 and T1216 for this study. The tracks of these two typhoons and three other major typhoons passing through the Ariake Sea are shown in **Fig. 2** and detailed in **Table 1** for comparison.

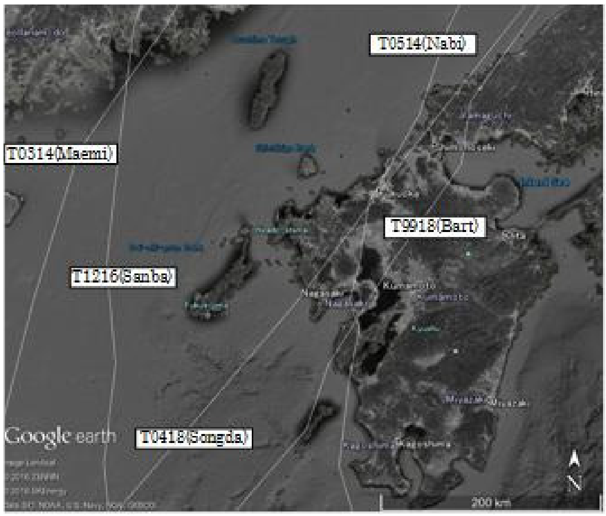

Fig. 2. Tracks of typhoons that have passed the Ariake Sea.

Table 1. Lowest central pressures and maximum wind speeds of past typhoons.

Typhoon No.	Lowest central pressure (hPa)	Maximum wind speed (m/s)	During closest approach to the Ariake Sea	
			Central pressure (hPa)	Wind speed (m/s)
T0314(Maemi)	**910**	**55**	**935**	**45**
T1216 (Sanba)	**900**	**55**	**940**	**45**
T9918 (Bart)	930	45	945	40
T0418(Songda)	925	50	945	40
T0514 (Nabi)	925	50	960	35

4. Numerical Simulation

4.1. Simulation Models

In storm-surge calculation, wind and atmospheric pressure fields are first calculated as external force, i.e., input values, based on typhoon models. These are empirical models expressing wind fields based on atmospheric-pressure distribution using the Myers formula and empirical reduction coefficients. Typhoon atmospheric-pressure and wind fields, calculated at 1-km intervals based on meteorological data sets (best track data), were from the Regional Specialized Meteorological Centre (RSMC).[2] Given these external forces, we calculated storm-surge using ocean-flow FVCOM version 2.7. This ocean-flow model uses unstructured grids and a three-dimensional fi-

2. http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html

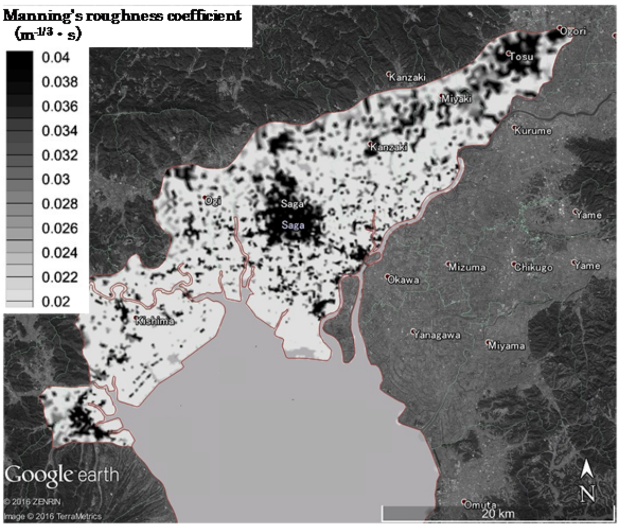

Fig. 3. Distribution of Manning's roughness coefficient in Saga lowlands.

Table 2. Manning's roughness coefficient (Kotani et al. [6]).

Land use	n
Smooth ground	0.020
Shallow water area /natural beach	0.025
Vegetated area	0.030
Populated area (low density)	0.040

nite volume, enabling complex coastlines difficult to express using structured grids to be expressed in detail, which, in turn, enables accurate calculation. Because these models handle submergence and drying and because mid-bay storm surges and land area inundation are calculated simultaneously, we used these models to calculate storm-surge inundation for specific land area settings (constant atmospheric pressure: 1013 hPa, wind speed: 0 m/s) while excluding suction effects due to atmospheric pressure drops and wind-induced drift effects. In calculating inundation, the bottom friction Cd drag coefficient (Eq. (1)) changed from the value in Eq. (2) to the value in Eq. (3) to account for land-use classification.

$$\text{Bottom stress: } (\tau_{bx}, \tau_{by}) = C_d\sqrt{u^2+v^2}(u,v) \quad . \quad (1)$$

Drag coefficient on sea bottom :

$$C_d = \max\left(k^2 \Big/ \ln(\frac{z}{z_0})^2, 0.0025\right) \quad . \quad . \quad . \quad (2)$$

$$\text{Drag coefficient on land: } C_d = \rho_w g n^2 \Big/ H^{\frac{1}{3}} \quad . \quad (3)$$

τ_{bx}, τ_{by} is bottom friction in the x and y directions. u and v are flow velocities in the x and y directions. C_d is the drag coefficient. $k = 0.4$ (the Karman constant). z_0 is the roughness length. ρ_w is seawater density. g is acceleration due to gravity. n is the Manning roughness coefficient. H is water depth.

For distribution of Manning's roughness coefficients and lowland-use classification in the innermost bay coast (**Fig. 3**), we used the land-use classification proposed by

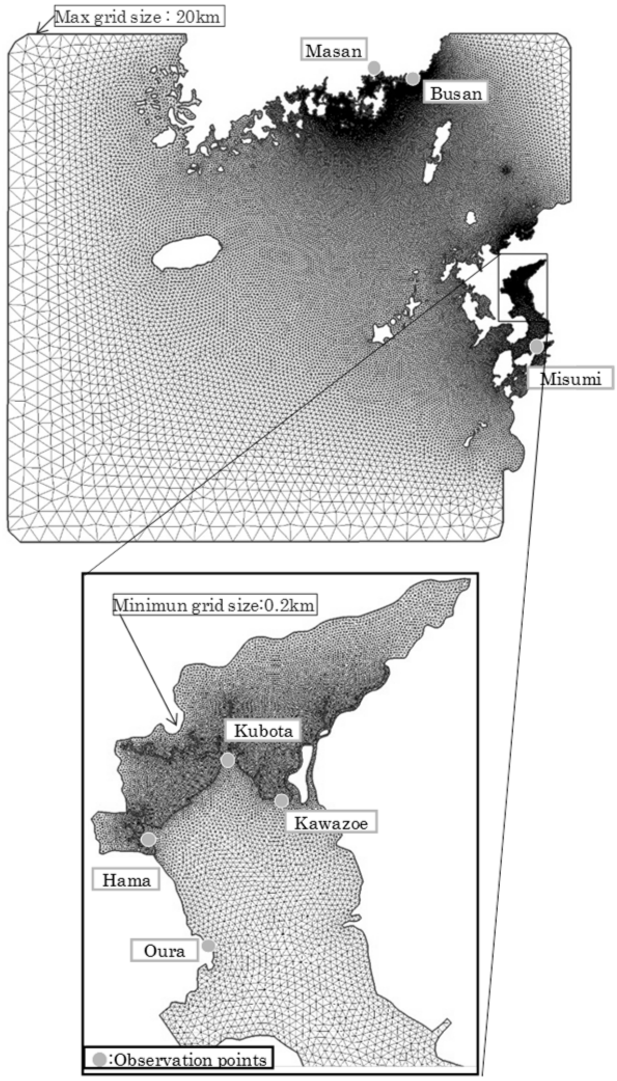

Fig. 4. Computational domains for storm-surge simulations.

Kotani et al. [6] (**Table 2**). Land-use classification was based on data from the Geospatial Information Authority of Japan.[3]

4.2. Verification of Storm-Surge Simulation

To verify the accuracy of our storm-surge calculation models, we calculated storm-surge height for previous violent typhoons T0314 and T1216.

The calculation domains and grids we used for calculation are shown in **Fig. 4**. Using unstructured grids, we set the domain around the open boundary with the largest grid interval of 20 km. We set innermost Ariake coastal lowlands and inner Masan bay in Korea, where significant storm-surge anomalies occur, at the smallest interval of 0.2 km. For the coastline, we used data from the National Land Numerical Information download service[4] and the National Oceanic and Atmospheric Administration[5]. Sea-bottom topographic data was derived from in-

3. http://nlftp.mlit.go.jp/ksj/jpgis/datalist/KsjTmplt-L03-b.html
4. http://nlftp.mlit.go.jp/ksj-e/index.html
5. http://www.ngdc.noaa.gov/mgg/shorelines/shorelines.html

Table 3. Computational conditions.

Grid size	0.2–20 km
Number of layers	4
Seawater density	Constant (20°, 30 psu)
Open boundary condition	Water level due to low Atmospheric pressure (without tide)
Time interval	1.0 s

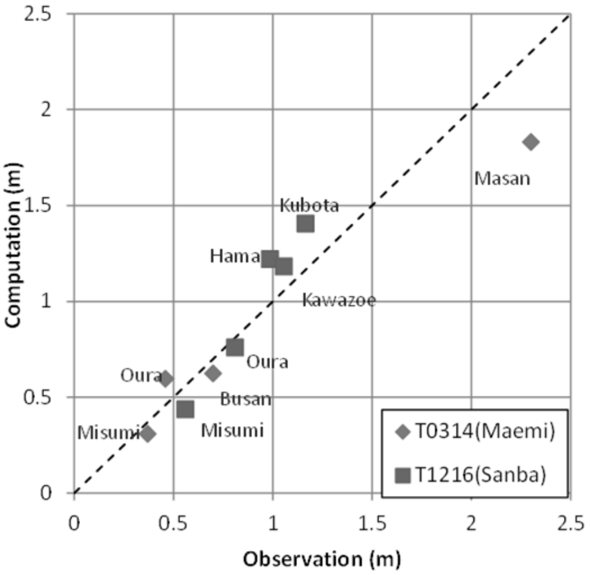

Fig. 5. Comparison of the maximum storm-surge anomalies due to T0314 and T1216 between the computational and observational results.

terpolating individual grid points based on data from the Japan Hydrographic Association[6] and the Japan Oceanographic Data Center[7]. For lowland heights above sea level on the innermost Ariake coastal area, we used digital elevation model data from the Geospatial Information Authority of Japan[8]. Water depth was divided into four layers using the sigma coordinate.

Our primary calculation conditions are shown in **Table 3**. Periods for calculating storm surges were set to 53 h from 2003/9/11 10:00 to 2003/9/13 15:00 and 44 h from 2012/9/16 01:00 to 2012/9/17 21:00 for T0314 and T1216, considering spin-up calculation. Note that only storm-surge anomaly from the average sea level were calculated, without considering astronomical tides.

Figure 5 compares maximum storm-surge anomalies between calculation and observation for T0314 and T1216. Anomalies at Masan and Busan are based on tide field-measurement records reported by Kawai et al. [6]. Values observed at Oura were measured by a Japan Meteorological Agency tide gauge. Field observations reported by Yamashiro et al. [1] were used for three points at the innermost bay (Kubota, Hama, and Kawazoe). Although T0314 calculation values are relatively small in Masan

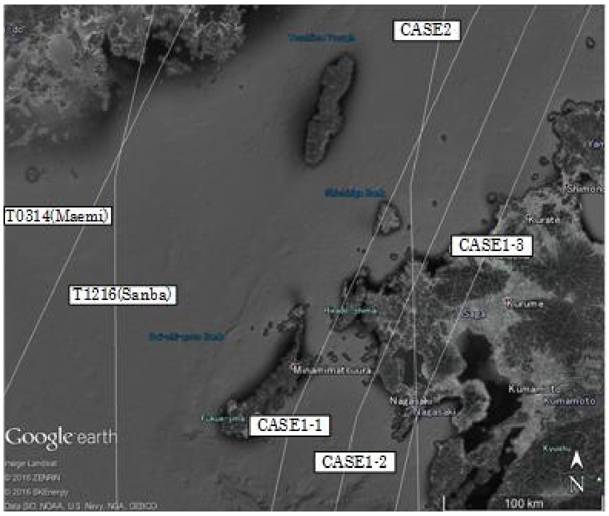

Fig. 6. Assumed typhoon tracks.

Table 4. Computational conditions.

Grid size	0.2–20 km
Number of layers	4
Sea water density	Constant (20°, 30 psu)
Open boundary	H.W.L (T.P. + 2.72 m) + Water level due to low atmospheric pressure (without tide)
Time interval	0.2 s

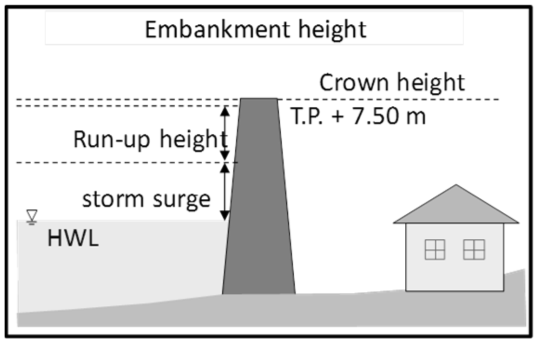

Fig. 7. Embankment height.

while T1216 values are relatively large, results generally reproduced well. No inundation damage was reported in the observed area for the two target typhoons, no land-area inundation was simulated in calculations.

4.3. Storm Surge and Inundation Simulation

Although T0314 and T1216 were powerful, neither caused severe storm surges at Ariake because their tracks were comparatively far away. Had they been closer, however, they could have caused severe damage and/or injury. To assess such risk, we simulated storm surge inundations assuming that past typhoons had been closer.

Specifically, for T0314, we assumed parallel routes 2, 2.4 and 2.8 degrees east of the actual route. Yamashiro et

6. http://www.jha.or.jp/en/jha/
7. http://jdoss1.jodc.go.jp/vpage/depth500_file_j.html
8. http://fgd.gsi.go.jp/download/

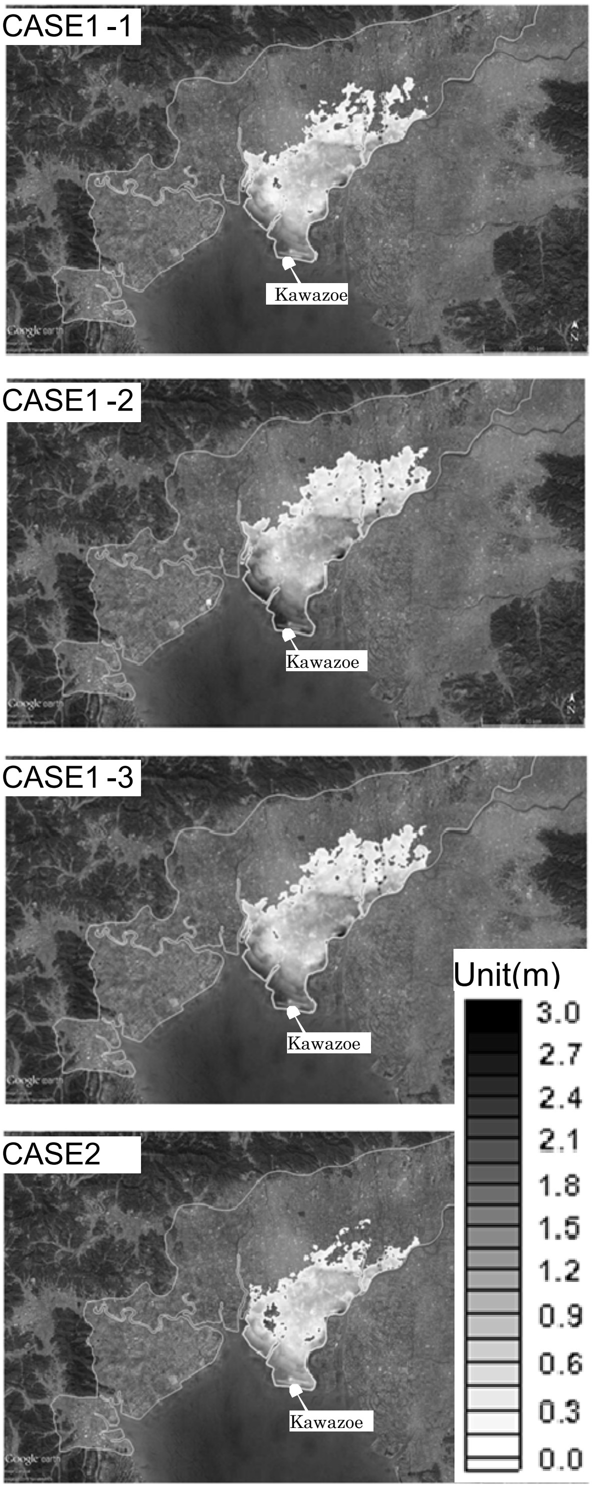

Fig. 8. Spatial distributions of maximum inundation depth.

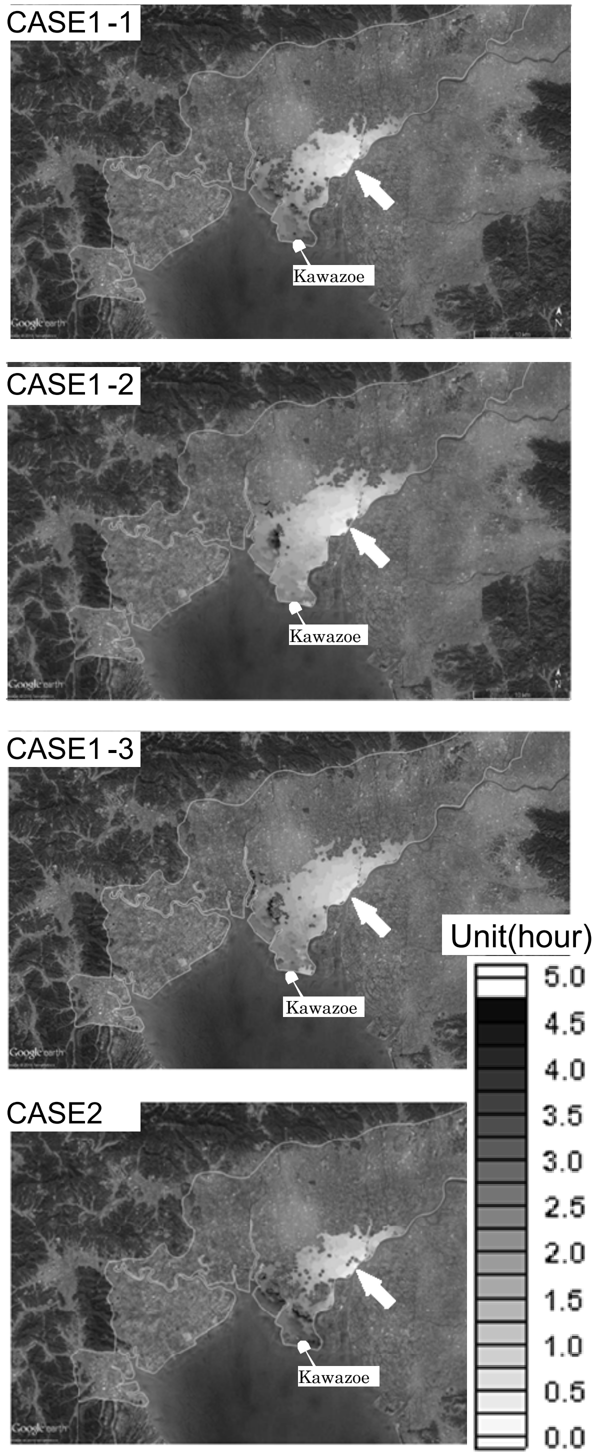

Fig. 9. Spatial distributions of inundation occurrence time.

al. [1] showed that a storm-surge anomaly would have increased had T1216 followed a parallel path 2 degrees east of the actual route. Accordingly, we calculated the T1216 storm-surge inundation route using this typhoon track. **Fig. 6** shows assumed typhoon routes: T0314 track displaced 2 degrees east: case 1-1; 2.4 degrees east: case 1-2; and 2.8 degrees east: case 1-3. Other calculation conditions are shown in **Table 4**. The initial tide level was set at TP+2.72 m, i.e., the high water level (HWL) of the innermost bay area. As shown in **Fig. 7**, models did not consider sea waves, but the embankment crown height was set at the actual crown height, i.e., TP+7.50 m, which includes the wave run up height of 2.32 m.

Figure 8 shows maximum spatial inundation depth distributions for individual cases, confirming that inundation occurred over a wide area in all cases. The maximum inundation depth of 3 m shows that coastal areas are extremely vulnerable to storm surges.

Figure 9 shows spatial distributions of inundation occurrences for individual cases. Inundations occur from the start of inundation on land to the start of inundation in each grid. Spatial distribution occurrence shows that inundation begins from river embankments (white arrows in the figure), followed by rapid expansion of inundation areas.

An examination of case 1-2, where T0314 runs parallel 2.4 degrees to the east, which shows the greatest inundation depth, showed that areas with an inundation depth of 3 m spread broadly across the Kawazoe region within a short inundation occurrence. This in turn suggests that evacuation would be extremely difficult in these coastal areas even if inundation began from river embankments away from coastal areas. Total areas of inundation and maximum depth differ case by case, so it is important to determine the typhoon route that causes the greatest inundation damage in each area – even more so because spatial inundation distributions in different areas vary with the typhoon track.

5. Conclusions

We have examined the inundation process and scale on the innermost coastal Ariake Sea coast using storm-surge inundation calculations in which data from typhoons T0314 and T1216 were used as external force. Results indicated that disastrous storm surges could be anticipated in typhoons following routes running from the west to the northeast. When a typhoon on the scale of T0314 followed the route of case 1-2, the area of inundation damage could expand considerably. This indicates that under current climatic conditions, the innermost coastal areas of the bay could be hit by typhoons that would cause significant storm-surge inundation damage. An analysis of how the typhoon route influenced the inundation process indicated that the spatial distribution of inundation varied with the area depending on the assumed route. This underlines the importance of determining typhoon routes that would cause the most disastrous inundation damage when assessing storm-surge risk. These findings should prove useful in helping to prevent coastal disasters in innermost Ariake Sea coastal areas.

Acknowledgements

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