

ACCURACY VERIFICATION OF A REAL-TIME PREDICTION SYSTEM FOR WAVE RUNUP HEIGHTS

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A real-time wave runup heights prediction system for about 500 coastal points in Japan was developed to take precautions and evacuate from flooding caused by wave overtopping. Accuracy verification of the system for recent wave overtopping events shows that actual conditions during the events can be adequately forecasted with the use of appropriate formulae on wave runup. The verification also indicates that the system can predict disaster risk from storm surges and high waves with enough time for flood prevention measures and evacuation.

Keywords: storm surge; high wave; wave runup; wave overtopping; real-time prediction system

INTRODUCTION

Situated in the northwestern Pacific Ocean, Japan has suffered extensive coastal damage from storm surges and high waves caused by typhoons and winter storms. In particular, coastal areas around ‘three major bays’ in Japan consisting of Tokyo, Osaka and Ise Bays are at high risk of storm surge flooding, including hinterlands below sea level, and have been repeatedly suffered extensive damage. For example, storm surge induced by the Typhoon Vera in 1959 left more than 5,000 people dead or missing along the coast of Ise Bay. Even in recent years, wave overtopping has often caused flood damage all over the country, such as giant swell around Toyama Bay in February 2008 (Ranasinghe et al. (2010)) and flood damage in Ashiya City, Hyogo Prefecture and other areas due to Typhoon Jebi in September 2018 (Mori et al. (2018)).

To mitigate flood damage caused by storm surges and high waves in Japan, administrative systems have been developed based on storm surge warnings and the designation of inundation zones expected for the highest possible storm surge, in addition to development of coastal protection facilities such as coastal dikes. Most of coastlines in urban areas in Japan are protected by dikes or revetments, which total approximately 4,000 km and 6,000 km, respectively. The height of coastal dikes and revetments is being reviewed, taking into account the effects of climate change on sea levels and storm surges (Kato et al. (2023)). Nevertheless, the current storm surge warning in Japan only considers tidal rise caused by storm surges, but not waves, as shown in Table 1, so it does not indicate when wave overtopping will occur in the coastal area. In order to ensure reliable and safe flood prevention measures and rapid evacuation of the residents from the damage caused by wave overtopping, it is necessary to introduce storm surge forecasting that includes the height of wave runup on the coastal dikes and revetments.

Systems to predict wave runup height have been introduced in the world. For example, the USGS (U.S. Geological Survey) predicts ‘total water level’ (tide level plus the wave runup height) along 4,700 km of U.S. Atlantic and Gulf of Mexico sandy coastline published as the Total Water Level and Coastal Change Forecast Viewer. This viewer can provide guidance on potential coastal erosion and flooding based on waves. Because this system is designed to deal with wave overtopping on sand dunes, it is difficult to apply this system to Japan's coasts, where dikes and revetments of complex shapes have been constructed.

Japan’s Ministry of Land, Infrastructure, Transport and Tourism developed a real-time wave runup height prediction system (WRPS) for Japan’s coasts, which began test operation in 2007. WRPS is currently in operation at approximately 500 coastal points nationwide to take precautions and evacuate from flooding caused by wave overtopping. It can consider shapes of coastal dikes and revetments, and bathymetry around the target point. The prediction accuracy of WRPS has been verified at some locations (Kato et al. (2010, 2020)), but it has not yet been comprehensively verified.

This paper shows an overview of the WRPS, and accuracy verification of the WRPS in predicting wave runup heights based on a case study of actual wave overtopping events that have occurred in recent years. Unlike previous verifications by quantitative comparisons between observed and predicted values of wave runup height at a limited number of points, we conduct qualitative verification on hazard prediction by confirming the relationship between predicted wave runup heights and the crest heights of the dikes and revetments for major cases where wave overtopping was actually observed.

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Table 1 - Current status of warning levels and storm surge information in Japan.

Warning Level	Storm Surge Information	Action to be taken
Equivalent to Alert Level 5	Storm Surge Inundation Information Index : tidal level Presenting Body : Prefecture	Life-threatening situation, ensure safety immediately
Equivalent to Alert Level 4	Storm surge Warning Index : tidal level Presenting Body : JMA(Japan Meteorological agency)	All residents should evacuate from affected areas
Equivalent to Alert Level 3	Storm surge advisory that mentions the possibility of switching to storm surge warning Index : tidal level Presenting Body : JMA	Elderly people, those with disabilities, and others who may need more time to evacuate should evacuate from affected areas
Alert Level 2	Storm surge advisory Index : tidal level Presenting Body : JMA	Confirm your evacuation actions

METHOD TO PREDICT WAVE RUNUP HEIGHT

Input wave and tide prediction data for WRPS

As shown in Figure 1, input wave data for wave runup prediction are the output values of the Coastal Wave Model or the Shallow-water Wave Model operated by the Japan Meteorological Agency (JMA). The Coastal Wave Model predicts coastal waves around Japan with a spatial resolution of 3 minutes, using the output of the Global Wave Model as boundary conditions (Table 2). The Shallow-water Wave Model predicts waves in 17 sea areas around Japan (Figure 2) with a spatial resolution of 1 minute, using the output of the Coastal Wave Model as boundary conditions. When WRPS needs to take into account local topography in the vicinity of the prediction point, such as channels and islands, wave transformation calculation is performed by using a table of wave height ratios in the vicinity of the prediction point, which have been calculated in advance using the energy balance equation for various offshore wave conditions (wave height: in 1 m increments; period: in seconds; wave direction: in 10 degrees increments). We use the wave transformation table when the output of the Coast Wave Model is used as input data for wave runup calculation because of its large grid sizes. The input tide levels used for the prediction are the predicted areal astronomical tide levels plus the output of the JMA storm surge model. As shown in Table 3, the domain of the Storm Surge Model covers the whole of Japan. The JMA wave forecasts are issued every six hours and the storm surge forecasts are issued every three hours. As well as wave and storm surge predictions, which are highly dependent on the track of the typhoon, wave runup heights are predicted for five points (center, fastest, rightmost, slowest and leftmost (Figure 3)) based on the typhoon forecast circle, in which the typhoon is expected to move with a 70% probability.

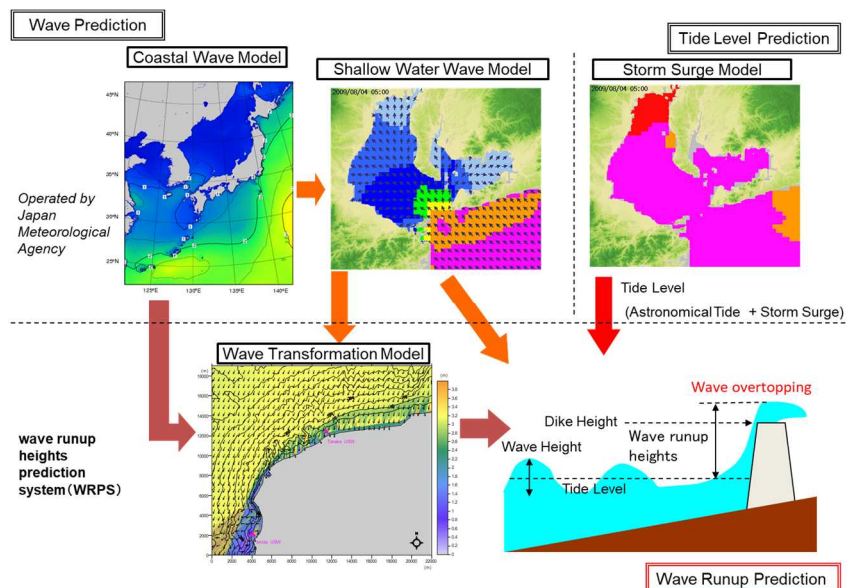
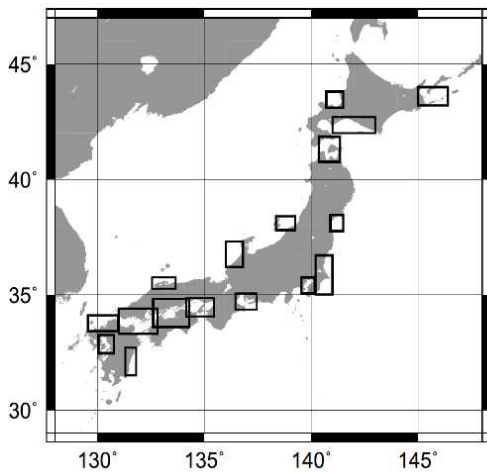


Figure 1 - Outline of the wave runup height prediction system (WRPS).



five points based on the typhoon forecast circle

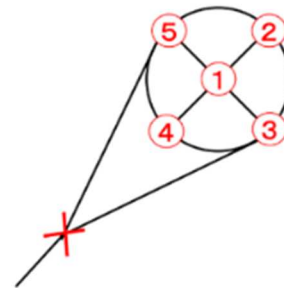


Figure 2 - Calculation areas for the Shallow-water Wave Model.

Figure 3 - Typhoon forecast circle.

Table 2 - Specifications of Global Wave Model, Coastal Wave Model and Shallow-water Wave Model (modified from the source: Japan Meteorological Agency 2024).

Model name	Global Wave Model	Coastal Wave Model	Shallow-water Wave Model
Type of Wave Model	spectral model (third-generation wave model, MRI-III)		spectral model (third-generation wave model, WAM)
Areas	global 75°N – 75°S 180°W – 0° – 180°E	coastal sea of Japan 50°N – 20°N 120°E – 150°E	Areas shown in Figure 2.
Grid size	0.25°×0.25°	0.05°×0.05°	1'×1' (1/60°×1/60°)
Time Step (advection term) (source term)	5 minutes 15 minutes	1 minute 3 minutes	1 minute 1 minute
Forecast range (initial time)	132 hours(06 and 18 UTC) 264 hours(00 and 12 UTC)	132 hours (00,06,12 and 18 UTC)	39 hours (03,09,15 and 21 UTC)
Spectral component	900 components 25 frequencies from 0.0375 to 0.3 Hz 36 directions		1260 components 35 frequencies from 0.0418 to 1.1 Hz 36 directions
Initial condition	Analysis by Optimal Interpolation		Coastal Wave Model
Boundary condition	-	Global Wave Model	Coastal Wave Model
Wind Fields	Global Spectral Model (GSM) Fujita (1957) 's empirical formula and a corresponding gradient wind for a typhoon		Meso-Scale Model (MSM)

Table 3 - Specifications of Japan-area Storm Surge Model (modified from the source: Japan Meteorological Agency 2024).

Model	two-dimensional model
Grid	Lat-Lon Arakawa-C grid
Region	20°N - 50°N, 117.4°E - 150°E
Resolution	approximately 1, 2, 4, 8, 16 km (Adaptive mesh)
Boundary conditions	Modified radiation condition at open boundaries and zero normal flows at coastal boundaries
Time step	4 seconds
Initial time	00, 03, 06, 09, 12, 15, 18, 21 (UTC)
Forecast time	78 hours (00, 12 UTC) and 39 hours (03,06,09,15,18,21 UTC)
Member	TC case: 6 members (MSM+5 typhoon bogus) no TC case: 1 member (MSM)

Wave runup calculation in WRPS

Wave runup calculation in WRPS is based on the diagram in Nakamura et al. (1972), which is widely used in the design of coastal dikes in Japan. This diagram was developed based on the results of hydraulic model experiments with regular waves in a wave channel. As shown in Figures 4 and 5, wave runup heights from the tidal level are calculated with ‘revised imaginary slope’, average slope from the breaking point to the runup point, considering a complex beach and coastal dike profile. Tamada et al. (2009) pointed out that runup heights of regular waves calculated with Nakamura et al. (1972)’s diagram are approximately the median runup heights of irregular waves.

In EurOtop (2018), which is an overtopping manual largely based on European research, for example, gives the wave runup height as $R_{u2\%}$, which is the wave runup height, measured vertically from the tide level that is exceeded by 2% of the number of incident waves and the USACE (2002) does the same. However, most of the coastal dikes in Japan are covered with concrete not only on the seaward slope but also on the crest and the landward slope to withstand some wave overtopping (Figure 6). For this reason, the height of the coastal dikes is determined using the wave runup height of regular waves, rather than the representative wave runup height of irregular waves such as the wave runup height exceeded by 2%.

As shown in Table 4, WRPS uses different wave runup equations depending on seabed slope which is defined as slope between the toe of the dike and the point of wave breaking. This is because the diagram and formula in Nakamura et al. (1972) are generally based on seabed slopes steeper than 1/30. Kato et al. (2010) developed the equation for a seabed slope of 1/100 with numerical experiments, which was confirmed to agree with the experimental results of Nakamura et al. (1972) with seabed slope of around 1/30. The equation for a seabed slope of 1/100 is given by:

$$R/H'_0 = 12.570(\cot \beta)^{-0.6788} \text{ for } H'_0/L_0 = 0.006 \quad (1-1)$$

$$R/H'_0 = 8.5351(\cot \beta)^{-0.5935} \text{ for } H'_0/L_0 = 0.008 \quad (1-2)$$

$$R/H'_0 = 10.350(\cot \beta)^{-0.6839} \text{ for } H'_0/L_0 = 0.010 \quad (1-3)$$

$$R/H'_0 = 15.076(\cot \beta)^{-0.8908} \text{ for } H'_0/L_0 = 0.020 \quad (1-4)$$

$$R/H'_0 = 20.188(\cot \beta)^{-1.0146} \text{ for } H'_0/L_0 = 0.040 \quad (1-5)$$

where R is wave runup height, H'_0 is the equivalent deep water wave significant height, L_0 is deep water wave length, β is revised imaginary slope (Figure 4). H'_0 is obtained by dividing the wave height at a given depth, determined by the Shallow-water Wave Model or wave transformation table, by the shoaling coefficient K_s . The scope of this equation is $15 < \cot \beta < 60$.

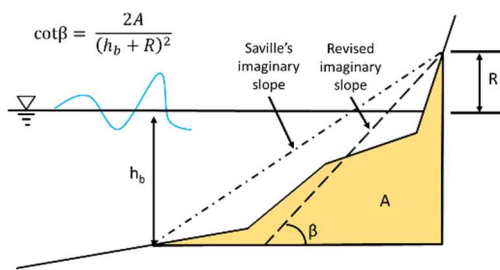


Figure 4 - Revised imaginary slope in Nakamura et al. (1972). h_b represents the breaking wave depth.

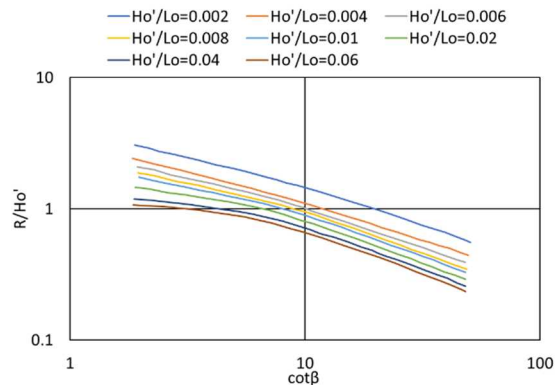


Figure 5 - The calculation diagram of Nakamura et al. (1972). where R , H'_0 , L_0 and β are same as Kato et al. (2010).

Table 4 - The equations of wave runup heights in WRPS.

Seabed slope	Equations
Steeper than 1/30	The diagram and formula for wave runup in Nakamura et al. (1972)
Milder than 1/30	The formula for wave runup in Kato et al. (2010)

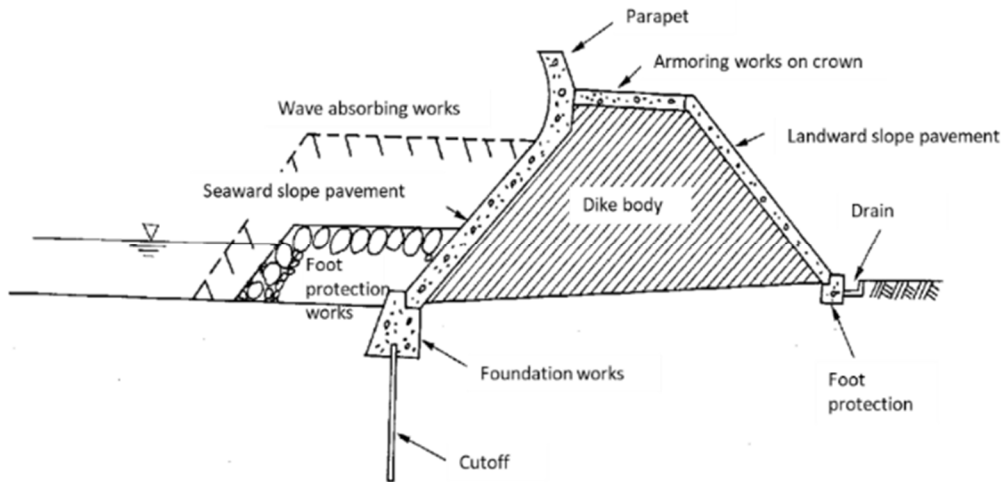


Figure 6 - Conceptual diagram of the coastal dike in Japan, modified from Technical Standard for Coastal Protection Facilities and its Commentary (2018)

WRPS Display Content

WRPS displays wave runup prediction results for about 500 coastal points in Japan, as shown in Figure 7. WRPS predicts wave runup height (tide level + wave runup from the tide level) up to 39 hours in advance, taking into account the bathymetry of the target point and the shape of the dike. The predicted wave runup heights are updated according to the JMA's distribution of tide and wave forecasts (tide: every 3 hours; waves: every 6 hours). As the height of coastal dikes is determined by adding the required height for the design wave to the design high tide level, the WRPS is designed to visually indicate when and how long significant wave overtopping would occur, as shown in Figure 8. The predicted point at which wave runup height exceeds the crest height of the dike within the prediction period can be checked on the map.



Figure 7 - The prediction points are distributed across Japan, totaling about 500 locations.

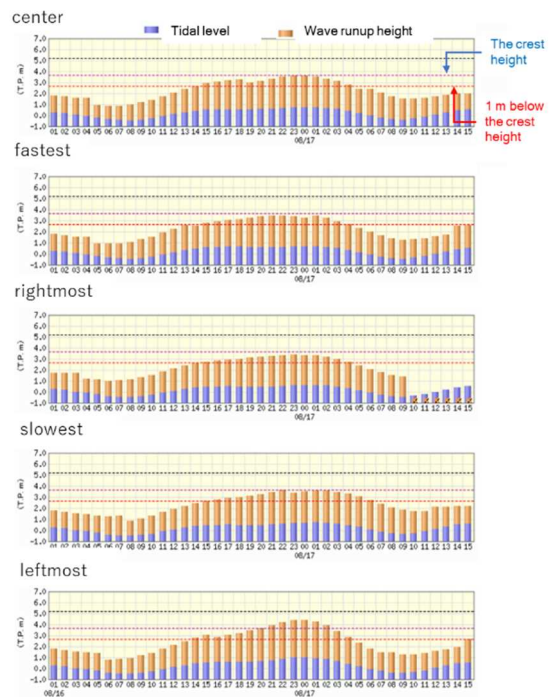


Figure 8 - Examples of the predicted wave runup height (tide level + wave runup from the tide level) from WRPS for five courses.

Differences between the Total Water Level and Coastal Change Prediction Viewer and the WRPS.

The USGS Total Water Level and Coastal Change Prediction Viewer (USGS Viewer) is similar to the WRPS, so this section summarises the differences between the two systems.

The USGS Viewer shows the risk of dune erosion and flooding by comparing predicted total water level to not only at the dune crest but also at the dune base. In addition, the wave runup heights included in the total water level shown by the USGS viewer are $R_{u2\%}$, which is exceeded by 2% of the number of incident waves, similar to EurOtop (2018) and USACE (2002). On the other hand, WRPS compares wave runup height predicted with regular waves to the dike crest height. These differences are due to the fact that most of the coastal dikes in Japan are covered with concrete not only on the seaward slope but also on the landward slope to withstand some wave overtopping, whereas the main purpose of the USGS viewer is to predict erosion of coastal dunes.

Both systems display prediction result taking into account the uncertainty in wave runup height prediction. WRPS carries out wave runup prediction for five typhoon forecasts, paying particular attention to uncertainty in the typhoon forecast. On the other hand, The USGS Viewer shows provides a prediction range with 95% confidence intervals corresponding to changes in coastal gradient. This is because Stockdon et al. (2023) indicates that the USGS Viewer includes uncertainties in each component of the total water level model (wave height, wave period, tides, storm surge, beach slope, dune topographic elevation and shoreline location) and analyses the prediction errors for each component, concluding that the largest source of uncertainty in the model framework is the static representation of coastal morphology (coastal gradient) in the empirical runup parameterisation. This also indicates the need for WRPS to analyse the error of each component and to consider the uncertainty in the predicted values, taking into account, for example, changes in the sandy beach in front of the coastal dike.

VERIFICATION RESULTS

Verification of prediction accuracy

To confirm consistency between predicted wave runup heights and actual wave overtopping on-site, we verified prediction accuracy for cases of wave overtopping that occurred in the vicinity of the predicted points between 2016 and 2022. The cases of wave overtopping were identified through on-site monitoring, CCTV (Closed Circuit Television) cameras and observing the spread of debris after an overtopping event as shown in Figure 9. From the collected cases of wave overtopping, six events (18 points) with a significant degree of wave overtopping were selected, as shown in Table 5. Because the points shown in Table 5 had not yet been predicted at the time of the wave overtopping events, wave runup heights were recalculated in the same method as WRPS and used recalculated values were used for the verification.

Figure 10 shows whether the peak of the latest recalculated wave runup heights from WRPS exceeded the crest of the dikes. In 14 cases (blue in the graph), the predicted wave runup heights exceeded the crest height of dike and accurately captured the actual overtopping conditions at the site. In five cases (orange in the graph), the predicted heights exceeded the value 1 m below the crest height, indicating an increased risk of wave overtopping. These results prove that WRPS can predict the risk of wave overtopping in most cases.

On the other hand, in two cases (red in the graph), the predicted heights were more than 1 m below the crest height. The formulas used in WRPS to calculate wave runup heights are based on regular waves as mentioned before. However, due to the irregularity of actual waves, wave runup heights in the field can be temporarily higher than the predicted values. For these two cases, the 2% exceedance runup values were calculated using the formula of Mase et al. (2013) for irregular waves. The formula of Mase et al. (2013) is given by:

$$R_{2\%}/H_0' = 2.99 - 2.73 \exp\left(-0.57 \tan \beta / \sqrt{H_0'/L_0}\right) \quad (2)$$

where $R_{2\%}$ is 2% exceedance runup values, H_0' , L_0 and β are same as Kato et al. (2010). $R_{2\%}$ in both cases exceeded the crest height (event B (point 10): 0.04m above crest height, event D (point 15): 4.76m above crest height), indicating that the actual overtopping situation could be reproduced with an appropriate formula.

Table 5 - The selected wave overtopping events.

event	climate disturbance	Number of points
A	Typhoon LIONROCK (2016)	4
B	Typhoon LAN (2017)	7
C	Typhoon JEBI (2018)	2
D	Typhoon HAGIBIS (2019)	5
E	winter storm in January 2021	1
F	winter storm in December 2022	2

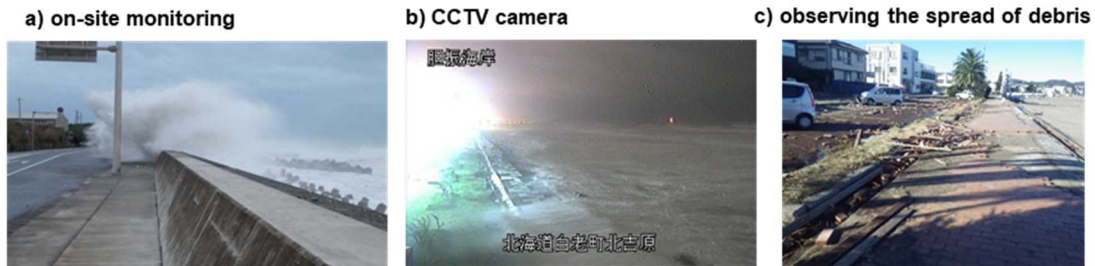


Figure 9 - Example of on-site monitoring(a) , CCTV cameras(b) and by observing the spread of debris after an overtopping event(c).

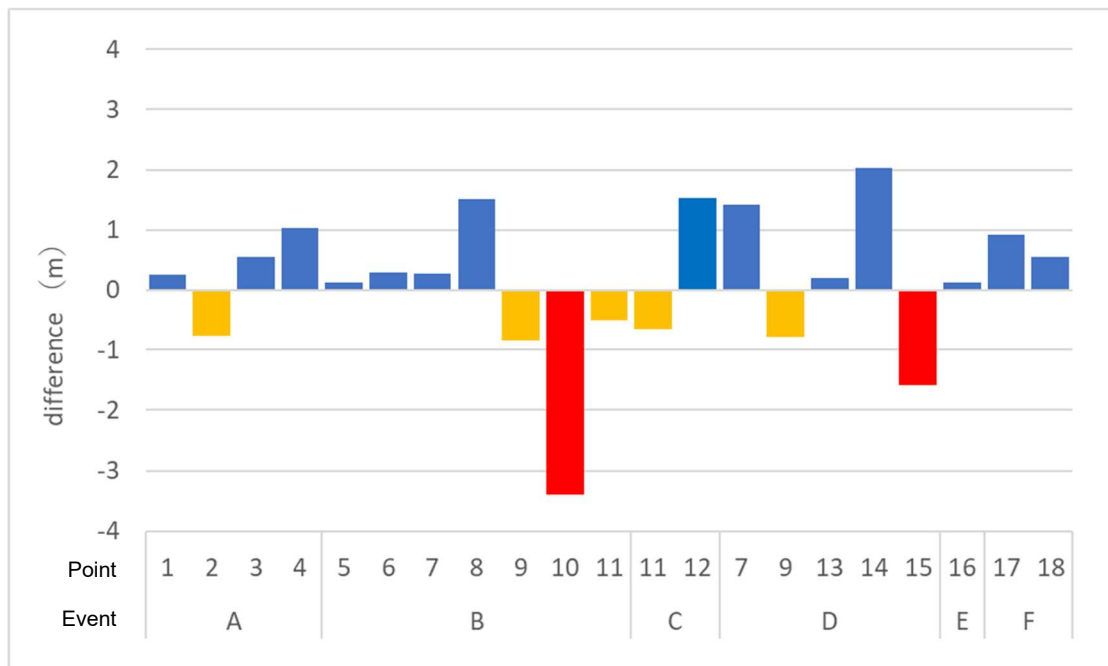


Figure 10 - The differences between the maximum predicted wave runup heights and the crest heights. The same point number of points shown on the horizontal axis of the graph represent results for the same predicted point.

Verification of how far in advance in the event of significant flooding

Disaster preparedness for wave overtopping needs to predict when wave runup heights exceed the crest height of coastal dike. Therefore, we verified how far in advance wave runup height could be predicted to be exceed the crest height for event C (point 12), flooding in Ashiya City, Hyogo Prefecture and other areas due to Typhoon Jebi in September 2018.

According to the Hyogo Prefectural Government (2018), the flooded area in Ashiya City was 26 ha, with a flood depth of 0.2 m - 0.67 m. In this event, there were 17 houses were flooded above ground level. Therefore, knowing in advance when wave overtopping would occur could lead to appropriate, reliable and safe flood prevention measures and rapid evacuation of residents from the damage. The timeline of the flood is shown in Table 6.

Figure 11 shows the superposition of the calculated wave runup heights and the dike crest height for 13:00-18:00 on 4 September for each initial time of prediction. Wave runup heights predicted at the initial times of 06:00 and 12:00 on 4 September exceeded the crest height at 14:00-15:00 on 4 September when inundation occurred. WRPS displayed the results of the calculation approximately three hours after the initial times of the prediction, showing that the system predicted the time at which the wave runup height would exceed the crest height approximately five hours before the inundation. In addition, even if the initial time of prediction was 18:00 on 3 September, the wave runup heights would be expected to exceed the crest height at 15:00 on 4 September, meaning that the risk of flooding could be identified approximately one day in advance.

Time	Event
14:05	Starts of inundation
14:20-14:50	Maximum inundation time
15:30	End of inundation

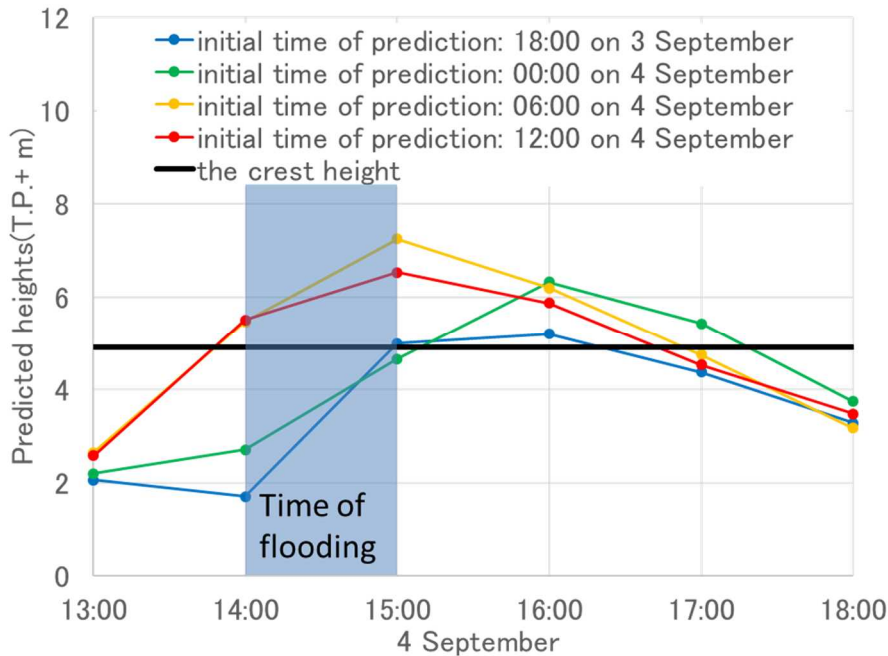


Figure 11 - Comparison of predicted wave runup heights for each initial time of prediction and the crest height.

CONCLUSIONS AND FUTURE WORKS

Accuracy verification of the real-time wave runup heights prediction system (WRPS) of recent wave overtopping events in Japan shows that the actual wave overtopping conditions can be adequately reproduced with the use of appropriate formulae on wave runup heights. The verification also indicates that disaster risk from storm surges and high waves can be predicted with enough time for flood prevention measures and evacuation.

The results of this verification are still qualitative. Nationwide quantitative verification on wave runup heights requires the development of low-cost technology for wave height observation using LiDAR, etc. In addition, the quantitative verification requires verification of the predicted waves and tidal levels, the accuracy of the wave runup formula, and the effects of changes in the bathymetry around the coastal dike on the predicted values. Field observations of wave runup heights will be carried out to verify the accuracy of the prediction, taking into account the degree of influence of the components on the prediction. These efforts will promote more accurate and reliable prediction of wave runup heights.

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