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Storm Surge Disaster Caused by Typhoon Jebi, T1821, at Fukae Harbor in Japan

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Abstract

Facts of the storm surge in Fukae Harbor caused by Typhoon Jebi, T1821, on 4 September, 2018 were clarified by the recorded data. The maximum tidal level (TL) occurred between 14:16 and 14:18, and was estimated to be 305 cm. The maximum deviation of the TL from the predicted TL was 254 cm. The main factor in the storm surge was the wind effect of the southerly. The outside maximum water level in Fukae Harbor was 336 cm, and was 36 cm higher than the TL of the time due to wind waves generated by local winds. The flooding was produced not only by the overflow caused by the storm surge but also by waves overtopping. If the storm surge had occurred at the maximum TL of the year, flooding would have produced by the overflow alone. The hazard maps of inundation by flooding from rivers and of inundation inside levees very nearly express the inundation area resulting from the storm surge. Overlaying evaluation of hazard maps of similar disasters is important in a perspective of risk detection. As the present seawalls may not be able to prevent the greatest storm surge, both tsunamis and storm surges should be considered in coastal disaster prevention.

Keywords : Storm surge, Typhoon Jebi, Overflow, Waves overtopping, Hazard map

1. OBJECTIVES

Typhoon Jebi, T1821, hit Japan on 4 September, 2018, passing over Awaji Island and Honshu (the main island of Japan) on the west side of Osaka Bay, as shown in Fig.1¹. The track was similar to that of the Daini Muroto Typhoon on 16 September, 1961, which recorded the maximum tidal level (TL) (2.2 m in the port of Kobe). A storm surge warning was issued, and the record was broken in the coastal zone of Osaka Bay. The storm surge and high waves inflicted enormous damage, such as flooding at Kansai International Airport in the coastal area². Investigations, field surveys and reports about damages were conducted by Kinki Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), who established the Storm Surge Committee for Osaka Bay (hereinafter referred to as the committee)², and by the Japan Society of Civil Engineers³.

The ground floor of building outside the seawall in the harbor of Fukae Campus of Kobe University (hereinafter referred to as Fukae Harbor) was flooded as the sea went over the seawall. The storm surge reached the upstream of Takahashi River, adjacent to Fukae Harbor, and the river basin was flooded. The storm surge in Fukae Harbor was recorded in detail digitally such as tide gauge data and imaging data.

Although these data are useful and important for coastal disaster prevention, they have not been reflected in any of investigation conducted by MLIT, Japan Society of Civil Engineer and so on. This paper is intended to clarify the facts of the storm surge in Fukae Harbor based on these data, and coastal hazard is discussed.

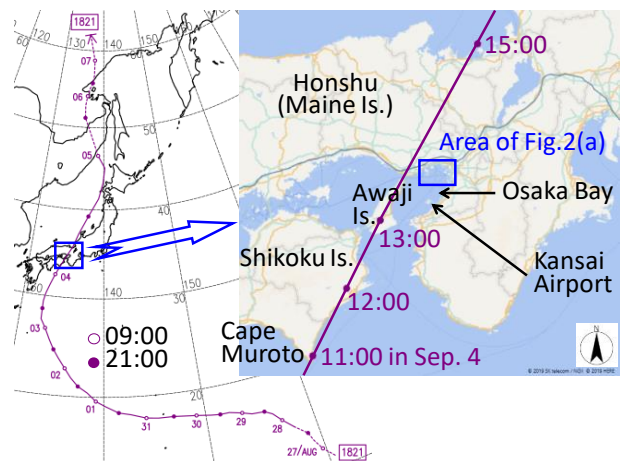


Fig.1 Track of Typhoon Jebi. The enlarged track was illustrated based on the location table¹.

2. RECORD OF STORM SURGE

Figure 2 shows enlarged illustrations of the inner part of Osaka Bay (a), Fukae Harbor and Takahashi River basin in the Higashinada region of Kobe City (b), and Fukae Harbor (c). Fukae Harbor is located at the back of a waterway between

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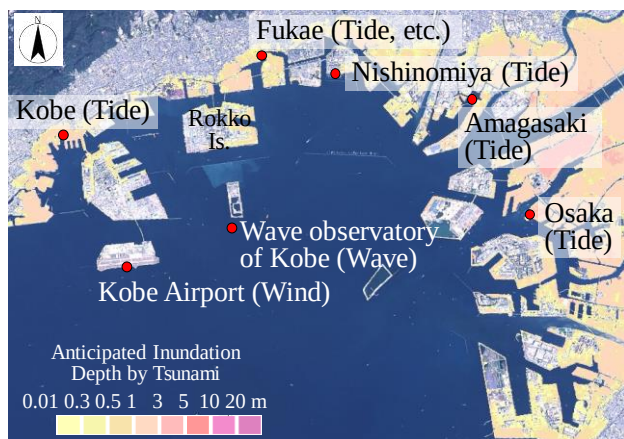
reclaimed land in the inner part of Osaka Bay. The mouth of Takahashi River is on the east side of Fukae Harbor, which is surrounded by seawalls and has two tide gates. The training ship, Fukae Maru, is moored in the harbor.

2. 1 Image data

Photographs were taken intermittently from Fukae Maru from 13:35 to 15:36. The time series of the extracted photographs is shown in Fig.3 for each shooting direction, shown in Fig.2(c). Videos were also taken intermittently at the times listed in Table 1. Some videos were broadcast by a news program of SUN-TV that was uploaded to YouTube⁴⁾. Here, we explain the transitions in the situation mainly based on the videos, because the photographs provide only snapshots.

The wind and rain blew in from Fukae Maru side to the

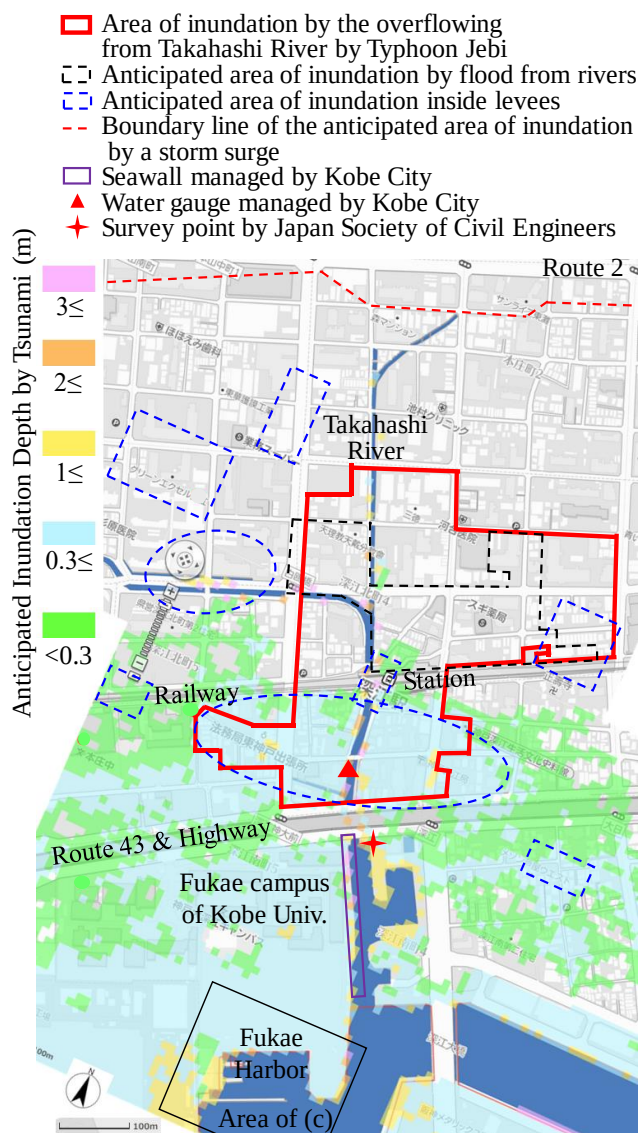
inside of the harbor at 13:22, became stronger until 13:41, and weakened at 13:48. The wind direction changed from northerly to southerly. Waves overtopping the pier were not observed at 13:48, but were seen at 13:55. The average water level (WL) at 13:55 did not reach the elevation of the pier, but the WL went over the pier at 13:57. Waves overtopping the seawall were not observed at 14:02. They began at the mooring pier at 14:04, and occurred intermittently on the northern seawall at 14:05 and on the southern seawall at 14:07. The step in the northern seawall, which is mentioned in the discussion, was visible at this time. Waves overtopping the seawalls occurred continually at the mooring pier at 14:11 and at the northern pier at 14:13. The step in the northern seawall was not visible at this time. The wind weakened at 14:16. The WL decreased until 14:19. Waves overtopping the seawalls occurred at 14:24, but were



(a) Fukae and other tide stations, and the wind and the wave observatories in the inner part of Osaka Bay. Color on the land indicates the anticipated inundation depth by the greatest tsunami¹⁵⁾.



(c) Seawall, survey points and so on around Fukae harbor. In means the inner part of the harbor, Hd means heading ward of Fukae Maru and En means entrance ward of harbor in shooting direction of photo shown in Fig.3.



(b) Area of inundation of Takahashi River basin and Fukae Harbor, and level measurement positions¹²⁾¹⁵⁾¹⁷⁾.

Fig.2 Locations in the study area.

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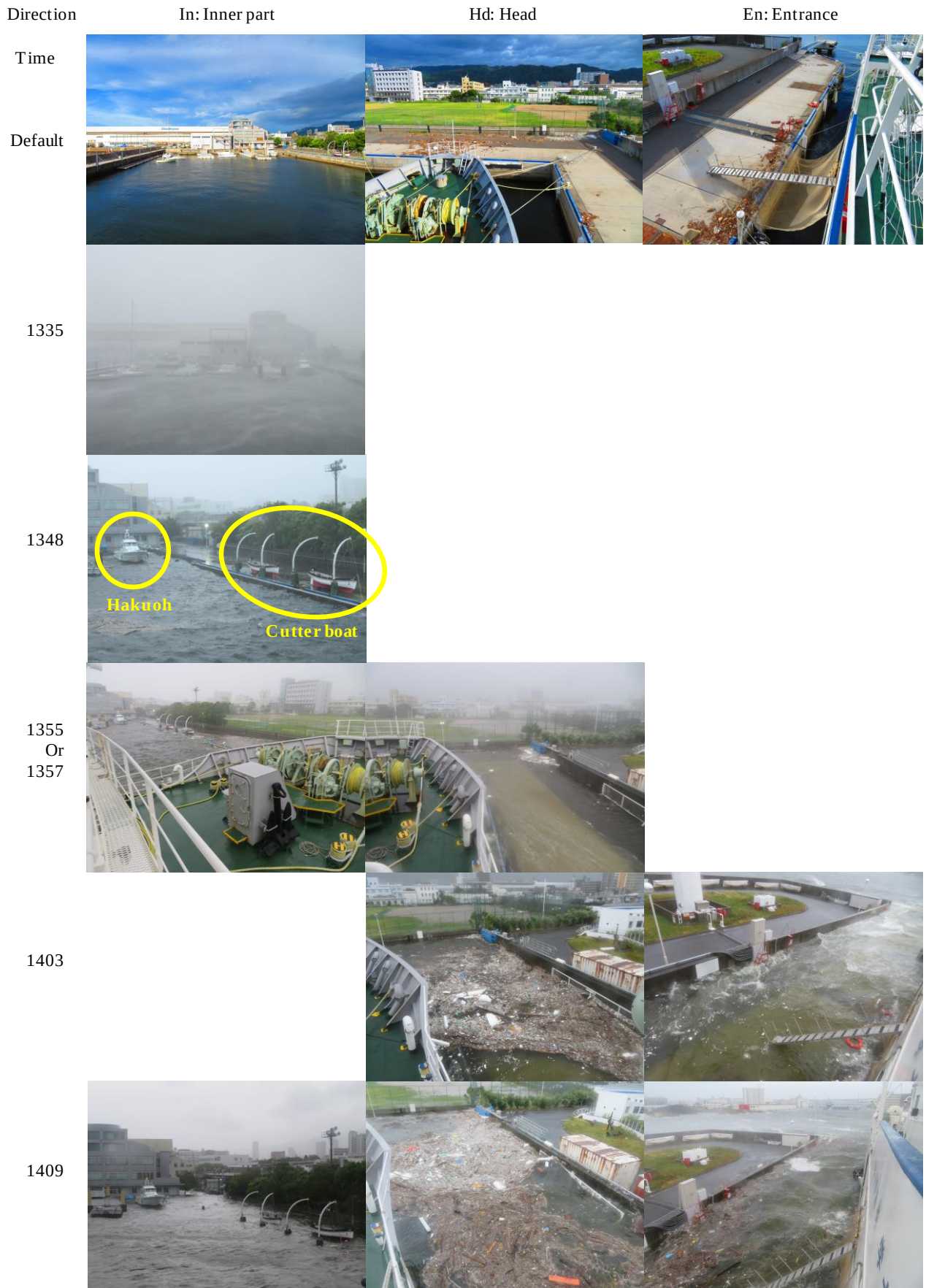


Fig.3 Transition of situations in Fukae Harbor in 4 September by photographs. Shooting directions are shown in Fig.2(c). A-E means the measurement points of cope level shown in Fig.2(c).

Direction	In: Inner part	Hd: Head	En: Entrance
Time			
1414			
1418			
1425 or 1426			
1441			
1457			
1535 Or 1536			

Fig.3 (Continued)

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not observed at 14:31. The average WL at 14:44 was below the elevation of the pier. Water overflowing on the pier was observed at 14:57, but is not seen in the photographs at 15:35.

2.2 Numerical Data

The major factors of a storm surge are strong surface wind

stress that moves water to the downwind shore and low atmospheric pressure that causes water levels to rise. In addition, the wave set-up due to radiation stress, the natural frequency of the bay, the continental shelf waves, etc. also contribute ⁵⁾⁶⁾. High waves also occur during a typhoon due to the addition of ocean waves to storm surges. Various

Table 1 Transition of situation taken by videos, and tidal level (TL) observed in Fukae Harbor in 4 September.

Time	Inside	Northern part	Mooring pier	Southern seawall	Offshore part	TL (cm)
13:22	Wind & Rain to inside.	No data	No data	No data	Small swell	81
13:35	Heavy wind & Rain to inside.	No data	No data	No data	Small swell from offshore.	117
13:41	Heavy wind & Rain to the inside. Can not go to outside.	No data	No data	No data	No data	133
13:48	Weak wind & Rain. Lower WL than ground.	No data	No data	No data	Not visible wave.	155
13:55	No data	No data	Overtopping waves to pier.	No overtopping waves to wall.	Strong wind, Wave, Spray & Swell from offshore. Intermittently visible dolphin.	178
13:57	Hakuoh will touch to pier.	WL over pier.	WL over pier & The fender rolls over the pier.	No overtopping waves to the wall.	Swell & Strong wind from offshore. Not visible dolphin, but crush wave.	209
14:02	Hakuoh will be stranded on pier.	WL over pier & Floating boat. No overtopping waves to the wall & Visible step of wall.	WL over pier & The fender rolls over the pier.	No overtopping waves to the wall.	Swell & Strong wind from offshore. Not visible dolphin.	250
14:04	No data	No data	Intermittently overtopping waves to the wall. Floating fender & Overturned wood box.	No overtopping waves to the wall.	Strong wind from offshore & Spray. Not visible dolphin.	260
14:05	Drifting boats. Wind wave from inside of harbor.	Intermittently overtopping waves to the wall. Floating boat.	No overtopping wave to the wall.	No overtopping waves to the wall.	Not visible dolphin. Swell, Weak wind & Spray.	265
14:07	No data	Intermittently overtopping waves to the wall, but Visible step of wall. Floating boat.	No overtopping wave to the wall.	Intermittent overtopping waves to the wall.	Not visible dolphin. Swell, Wind & Spray.	267
14:11	No data	No data	Continuous overtopping waves to the seawalls.	Intermittent overtopping waves to the wall.	Swell & Spray.	296
14:13	No data	Continuous overtopping waves to the seawalls & Not visible step of wall.	Close to capacity & continuous overtopping waves to the seawalls.	Intermittent overtopping waves to the wall.	Visible handrail of bridge to dolphin & Overtopping waves. Strong wind & spray.	296
14:16	WL reaches below window. Weak wind & Complex sea surface.	Close to capacity, big wave & Continuous overtopping waves to the seawalls.	Close to capacity more than 14:13, Big wave & Continuous overtopping waves to the seawalls.	No overtopping waves to the wall.	Wave & Bare visible handrail of bridge.	305

Table 1 (Continued)

Time	Inside	Northern part	Mooring pier	Southern seawall	Offshore part	TL (cm)
14:19	Lower WL than 14:19.	Intermittently overtopping waves to the wall & Visible step of wall.	Continuous overtopping waves to the seawalls.	Intermittently overtopping waves to the wall.	Visible handrail of bridge. Wave. Weak wind & No spray.	303
14:24	No data	Intermittently overtopping waves to the wall & Floating boat.	Continuous overtopping waves to the seawalls.	No overtopping waves to the wall.	Visible handrail of dolphin. bridge. Wave. Weak wind & No spray.	285
14:31	No data	No data	No overtopping waves to the seawalls.	No data	No data	242
14:36	No data	No data	WL over pier & The fender rolls over the pier.	No overtopping waves to the wall.	Visible dolphin. Westerly wind & Weak wind wave.	228
14:44	Hakuoh is floating on the sea.	Close to capacity & Intermittently overtopping waves to the seawalls. Not floating boat.	Close to capacity & Intermittently overtopping waves to the seawalls. Disorganized rubble.	No overtopping waves to the wall.	Visible dolphin. bridge. Weak wind & wave.	211

frequencies are mixed in ocean waves. Wind waves are generated and affected directly by local winds and have a relatively short period. Swells that have been generated elsewhere propagate via long fetch after the energy supply from wind disappears, and have a relatively long period. When waves crash into structures such as seawalls, swashes occur. The river discharge is related to storm surges that occur in the upstream reaches of the river. The TLs and WLs in this study are based on the mean sea level of Tokyo Bay (Tokyo Peil; T.P.), namely, the elevation.

We measured the TL in the tide well using a digital Fuess-type tide gauge and the sea surface atmospheric pressure every minute at Fukae Tide Station (Fig.2(c)). The outside WL was measured by a level gauge installed below the sea surface every 5 minutes. Japan Meteorological Agency measures wind direction and wind speed using an Automated Meteorological Data Acquisition System (AMeDAS) at Kobe Airport (Fig.2(a)), and data measured every 10 minutes are available from the Japan Meteorological Agency website⁷⁾. The MLIT measures wave height at the observatory of Kobe ((Fig.2(a)) every 20 minute as part of Nationwide Ocean Wave Information Network for Ports and Harbors (NOWPHAS), but the definitive data for 2018 have not yet been released⁸⁾. Therefore, the significant wave height was read from the figure shown in the report of the committee⁹⁾.

The difference between observations and predictions, namely the deviation in TL (= observation – prediction), in Fukae Harbor on 4 September was large for the period 10:00–18:00, and the variances of other phenomena are also remarkable. Figure 4 shows the time series of the period 10:00–18:00; the observed and predicted TL (a); the deviation of TL and the atmospheric pressure (b); the outside WL, the

difference between the outside WL and the observed TL, (namely the difference between the outside and the inside), and the wave height (c); and the average and the maximum instantaneous wind direction and wind speed (d). The atmospheric pressure decreased and wind speed increased from around 10:50. The wind direction began to change clockwise from ENE and the TL soared from around 13:30. The wind speed increased suddenly from 13:40, and the maximum recorded average wind speed of 34.5 m/s (wind direction is SSW) and instantaneous wind speed of 44.3 m/s (wind direction is SSW) occurred at 14:00. The minimum atmospheric pressure of 960.2 hPa was recorded at 13:58. Subsequently, the atmospheric pressure increased and the wind weakened, but the TL rose. The TL was constant at 301 cm from 14:16 to 14:22, which was likely to be due to overflow from the tide well. The TL might have reached its maximum during this period. The maximum WL, 336 cm, was recorded at 14:15. The TL and wind speed decreased with fluctuations. The wind direction was almost constant from the WSW, from 14:20.

The WL difference between the inside and the outside fluctuated for a short period, then began to increase from 13:30, and continued to increase until reaching the maximum TL. Wave heights increased suddenly at 14:00 and a maximum height of 4.72 m with a period of 6.2 sec was recorded at 14:00.

While the wind direction varied from ENE to WSW via south, a remarkable increase in TL occurred. The maximum TL occurred approximately 20 minutes after the minimum atmospheric pressure and the maximum wind speed occurred. Thus, the main factor in the Jebi storm surge was the wind effect of the southerly wind on the inner part of Osaka Bay. The

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committee suggested the same opinion¹⁰⁾.

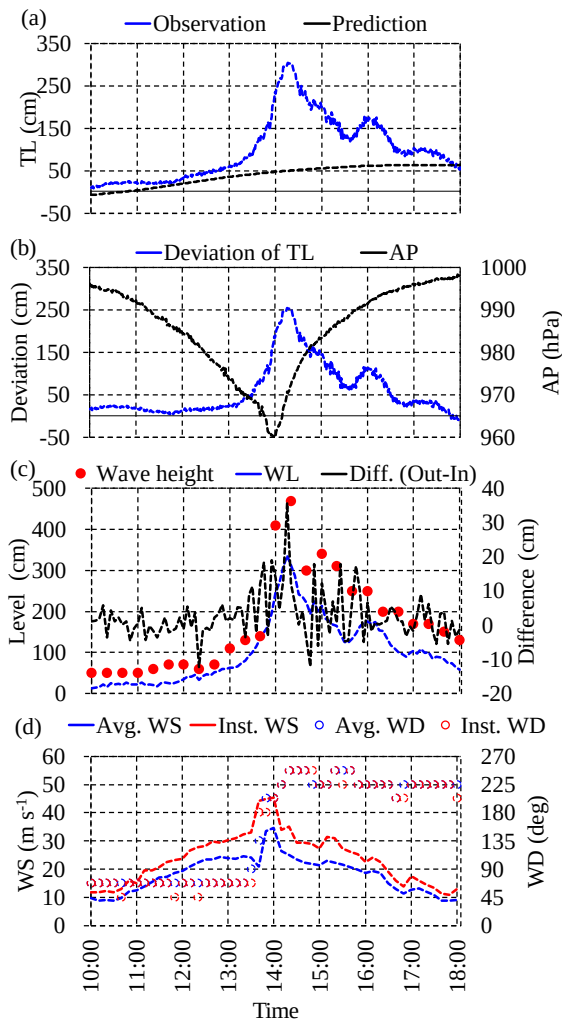


Fig.4 Time series of the observed and the predicted tidal level (a), the deviation of tidal level (observation – prediction and the atmospheric pressure (b), the outside water level, the difference between the outside and the inside (water level – tidal level), and the wave height (c), the average and the maximum instantaneous wind direction and speed (d) for 10:00-18:00 on 4 September

2. 3 Survey Data and Damages

The measured or estimated levels and heights in the following discussions are summarized in Fig.5. We conducted a survey and examined the damage in Fukae Harbor on the day after the storm surge. Figure 6 shows the inside of the Fukae Tide Station (a) and the rear of the tide well (b) on 5 September. Equipment placed near the floor was disorganized. A chair in the front room and a large wooden box in the inner room were overturned. Mud was present in the tide station, but no trace of mud was found in other rooms of this building. The storm surge left several traces in the room. It was confirmed that the maximum TL was 73 cm from the floor based on measurements of the traces. The top surface of the tide well

was 71 cm from the floor. The elevation of the top surface was determined to be 303 cm, based on the survey, which is 2 cm lower than the maximum TL. Thus, the maximum TL was estimated to be 305 cm. This is 4 cm higher than the maximum record from the tide gauge. These findings suggest that the seawater not only flooded in from the door but also overflowed from the tide well, which contained mud.

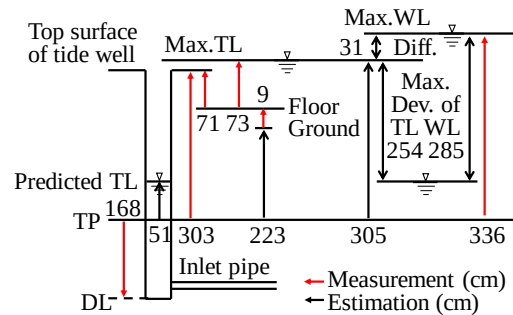


Fig. 5 Measured or estimated levels, heights, differences, and deviations

Figure 7 shows the area around the eastern tide gate (a), the building and its entrance (b), and the sea surface in front of the building and the boathouse (c) three days after the storm surge. Flotsam had accumulated in the corner and some was still floating. The glass door of the building had been broken, and a trace of the storm surge was confirmed. Boats placed in front of the building and cutter boats in the boathouse seemed to have floated off their trestles. The shutter of the boathouse was distorted outward, probably due to backwash.

The cope level, heights of the seawall, from the ground was measured in five places, labeled A–E, in Fig.2(c). The elevation of the ground is necessary to obtain the cope level, based on T.P. As the step between the floor and the ground of the tide station is 9 cm, the elevation of the ground is 223 cm (= 303 – 71 – 9). This corresponds to an elevation of 2.2 m in Digital Japan Basic Map (Map Information) issued by Geospatial Information Authority of Japan¹¹⁾. It must be noted that the notation of the map is in 0.1 m units. The TL measurements when videos were shot are shown in Table 1, and the average elevations of each location, the cope level from the ground, and the heights of the seawall in reserve in relation to the storm surge at points A–E are shown in Table 2. The elevation of the ground of Fukae Harbor has a range of 1.9–2.3 m according to the map, and decreases from the building to the mooring pier and southward from the pier. The elevation of the mooring pier is 200 cm. The TL reached this elevation at 13:56, and was completely below this elevation at 15:03 according to the tide gauge data. The heights of the seawall in reserve are determined from the differences between cope level and TL. When the WL was constant at 14:16, the WL was about 40–60 cm below the cope level. These levels are in agreement with

what can be seen in the images.

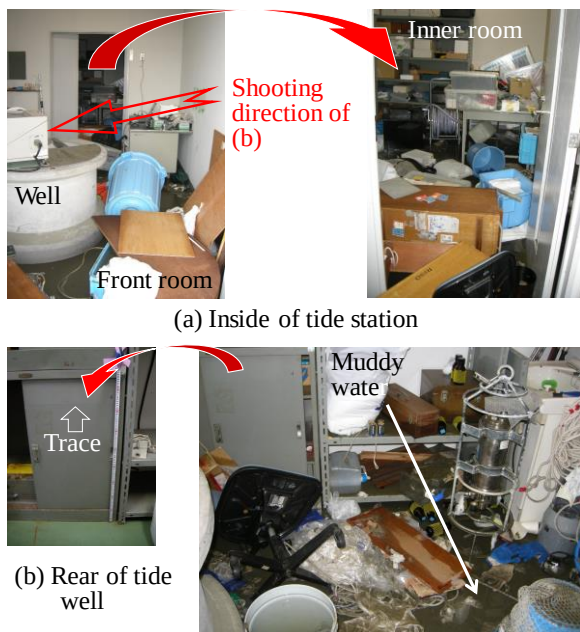


Fig.6 Inside of the Fukae Tide Station after storm surge

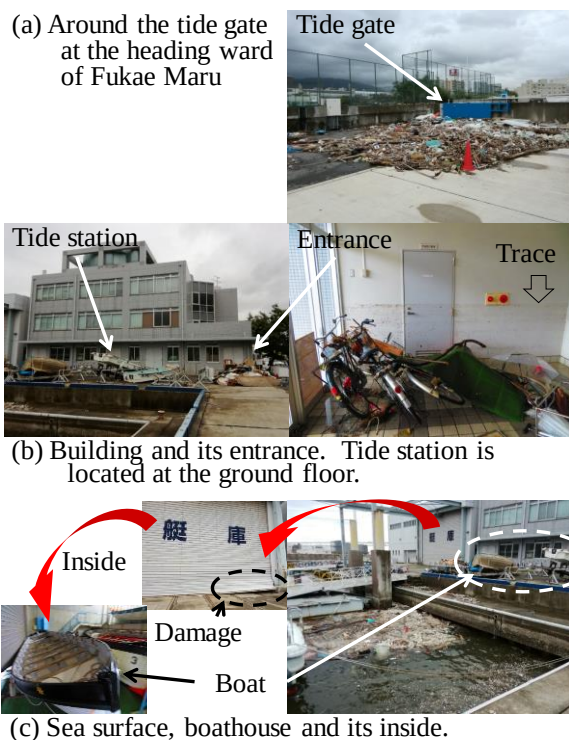


Fig.7 Fukae Harbor after storm surge

The seawalls were consolidated in 1996 and were designed based on Kobe Peil (the datum line of the port of Kobe; K.P.) + 5.1 m in the southern part that faces the offshore sea (aspect of A) and at K.P. + 4.6 m inside Fukae Harbor and along Takahashi River. The elevation of A is 4.21 m and B–E are at

3.71 m since K.P. = T.P. – 0.89. The differences between the design and the actual levels are shown in Table 2. There is one section that is ≥ 20 cm lower than the design. On the other hand, part of the seawall along Takahashi River shown in Fig.2(b) is managed by Kobe City, and was raised during 2014–2016 as a storm surge precaution in the port of Kobe. The seawall was designed at K.P. + 4.8 m (the elevation is 3.91 m) when the prediction of the Nankai Trough earthquake tsunami was revised by Japanese government after the Tohoku Region Pacific Coast Earthquake was considered, as well as subsidence. The seawall is 0.3 m lower than the part consolidated in 1996, and a gap of 68 cm exists. These data suggest that seawall design varies based on when and by whom it is maintained.

Table 2 Various level at A-E on the seawall

Point	E	D	C	B	A
Location	Inside	Northern pier	Mooring pier	Mooring pier	Southern seawall
Elevation of ground (m)	2.2	2.1	2.0	2.0	2.0
CL from ground (cm)	143	141	147	163	210
Height in reserve of seawall (cm)	58	46	42	58	105
Diff. from design level (cm)	-8	-20	-24	-8	-11

Table 3 Maximum tide with Typhoon Jebi recorded at Tide Stations in the inner part of Osaka Bay

Tide Station	Maximum Tide			Remarks
	Time	Level (cm)	Dev. (cm)	
Kobe	14:09	233	181	Mean for 3 min.
Fukae	14:16	305	258	Record every min.
Nishinomiya	14:15	324	272	Mean for 20 min.
Amagasaki	14:15	353	302	Mean for 10 min.
Osaka	14:18	329	277	Mean for 3 min.

3. DISCUSSIONS

3.1 Maximum TL and the Outside WL

As previously described, the maximum TL was 305 cm during the period 14:16–14:22. The recorded WL was higher at 14:15 than at 14:20. Based on the video, the WL was higher at 14:16 than at 14:19. Therefore, it is estimated that the maximum TL in Fukae Harbor occurred between 14:16 and 14:18. As the predicted TL of Fukae Harbor in this period was 51 cm, the maximum deviation of the TL was 254 cm. Tide gauges are installed in the four tide stations shown in Fig.2(a), and the maximum levels are reported⁹⁾ as shown in Table 3. The estimation in Fukae Harbor is reasonable compared to the other tide stations. The deviation was biggest at Amagasaki Tide Station (302 cm) and decreased toward Kobe Tide Station. Fukae Tide Station provided valuable data to fill the gap and to aid understanding of the variation between Nishinomiya and

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Kobe, where damage was heavy. For a quantitative discussion, it is necessary to determine the occurrence time of the maximum TL. Here, we assume 14:16, based on the time at Nishinomiya Tide Station, the station closest to Fukae Tide Station. TLs during the period 14:16-14:22 shown in Fig.4(a) and Table 1, were interpolated using the maximum TL.

Fukae Bridge water gauge in Takahashi River ((Fig.2(b)), established by Kobe City, recorded 330 cm at 14:15¹²⁾. Japan Society of Civil Engineers measured the flood depth in Takahashi River basin and reported 332 cm at the point shown in Fig.2(b)³⁾. The trace of maximum WL in the building shown in Fig.7(b) was measured and is 333 cm. The maximum WL (336 cm) measured in Fukae Harbor (Fig.2(c)) is reasonable compared with these numbers, is 36 cm higher than the TL of the time, and means an amplitude. The cause of the difference is thought to be a wind waves generated by local winds near the harbor. Surging surfs with a period of several seconds were observed in the video. As the inlet pipe of a tide gauge acts as a filter of high frequency waves, the wind waves might not have been recorded in the TL. Therefore, the maximum of wind waves height was almost 70 cm, and is reasonable based on the videos.

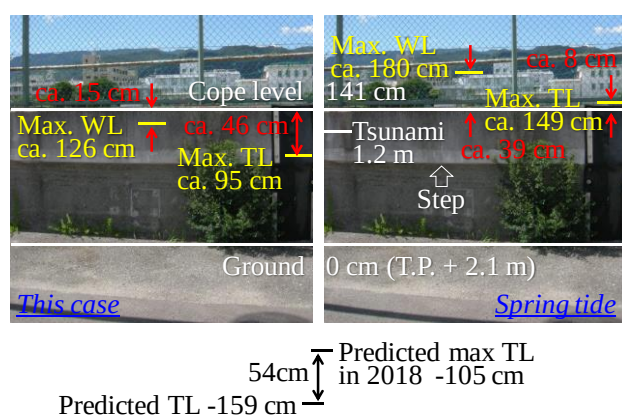


Fig.8 Comparison of levels based on the ground in D of Fig.2(c). Left one shows this case. Right one shows the case that the storm surge occurred under the greatest spring tide in 2018. Tsunami means the anticipated greatest level in Higashinada caused by the Nankai Trough earthquake¹⁶⁾.

A comparison of levels from the ground at point D in Fig.2(c) is shown on the left side of Fig.8. The height in reserve of the seawall is ca. 46 cm against the maximum TL, and it is ca. 15 cm against the outside maximum WL including wind waves. This means that the flooding was produced not only by the overflow caused by the storm surge and the short period wind waves, but also by waves overtopping caused by the high waves formulated by swash, the long period wind waves, and the swells. The videos support these results, and the committee reported that similar situations occurred at many places in the port of Kobe²⁾. Furthermore, this result implies that typhoon

disaster prevention based only on anticipated storm surges is insufficient, even in areas at low risk for high waves, such as the back of a waterway. It is difficult to say whether breakwater effects are considered for seawalls along waterways. There is a step in the northern seawall (aspect of C). The seawall would not probably not be designed to break waves. However, it was confirmed by the video that swashes were bounced by the step. When designing seawalls along waterway, their wave-breaking effect should be considered.

3.2 Potential Risks

Because the mean TL along the Japanese coast is higher in summer and autumn by the expansion of the seawater due to the increasing water temperature, there is a potential risk of typhoon storm surges. Fortunately, 4 September was not a spring tide, and the time of Jebi's passage was not at high tide. The high tide of the day occurred around 17:00. The predicted TL at high tide was 14 cm higher than when the storm surge occurred. If the storm surge had occurred at the same time as high tide, the seawall might not have been high enough with the addition of the wind waves. However, the damage would not have been greatly different as overflowing did not occur. The greatest spring tide in 2018 was on 11 September. The maximum TL would have been 54 cm higher when the storm surge occurred on that date. If the storm surge had occurred at that time, it would have exceeded the seawall by 8 cm, as shown on the right side of Fig.8. Overflowing would have occurred and continued for 8 minutes. Not only the inundation of buildings outside of the seawall but also the damage inside the seawall would have been more serious. The actual cope level at D is ca. 20 cm lower than the design level. If the cope level was in accordance with the design, the seawall would have protected against the storm surge, even at the maximum TL of the year. The cope level should be measured for any time point and should be maintained at a height above the required level.

The possibility of an intensification of typhoon due to global warming has been demonstrated^{13), 14)}. When atmospheric pressure decreases by 1 hPa, the sea surface rises by 1 cm by the hydrostatic equilibrium. So the height of the seawall in reserve for the storm surge shown in Fig.7 is equivalent to the atmospheric pressure drop of 46 hPa. It is 925 hPa when this is subtracted from atmospheric pressure (970.8 hPa) of maximum TL. It is the value recorded on the Pacific Ocean far off the coast around 20N in Fig.1. However, T2010, Haishen kept its intensity at 925 hPa until around 30N. Of course, the atmospheric pressure drop on land will be not enough to produce storm surges with overflows by itself, because an intensity of typhoon decreases when they make landfall. That said, other factors will increase the possibility of storm surge occurrence, the disaster caused by global warming should be consider as imminent.

3.3 Comparison with Hazard Maps

The storm surge hazard map of Kobe City has not been released before the storm surges. Fig.2(b) shows the tsunami hazard map (the anticipated area of inundation resulting from the greatest class of tsunami), and the anticipated areas of inundation by flooding from rivers and of inundation inside levees that reach the limit of their drainage ability are superimposed¹⁵⁾. In addition, the area of inundation from Takahashi River resulting from the Jebi storm surge is also shown¹²⁾. The southern part of the inundation area resulting from the storm surge (the south side of the railway) agreed with the inside inundation area and is included in the tsunami inundation area. The northern part of the inundation area from the storm surge agrees with the inundation area from the river, but is wider. Thus, the hazard map very nearly expresses the inundation area resulting from the storm surge. The reason the inundation area is small may be due to a difference in the flood volume from Takahashi River. Although the predictions differ for each disaster, the source of every inundation is Takahashi River. If inhabitants detect a risk for a particular disaster from a hazard map, they should also identify the risks of a similar disasters. Overlaying evaluation of hazard maps of similar disasters is important in a perspective of risk detection.

The working group of the Port of Kobe Committee reported that, “The tsunami precautions such as the raising or the reinforcement of seawalls exerted beneficial effects on the storm surge”. The greatest predicted tsunami in Higashinada, caused by the Nankai Trough earthquake, is anticipated at 3.3 m by Hyogo prefecture¹⁶⁾, as shown in Fig.8. Other result is based on numerical simulation of more than 4 meters¹⁷⁾. As the storm surge resulting from Jebi was below this level, the tsunami precautions should be effective. On the other hand, the map of inundation area as a result of storm surges was published in September 2019¹⁸⁾, in response to the storm surge from Jebi. Based on the strongest typhoon and the high tide, the maximum TL in Higashinada was estimated to be 5 m. The largest storm surge was anticipated by considering high waves and river flooding in addition to this. As a result, all of the south side of Route 2 in Takahashi River basin (the line shown in Fig. 2b) would be inundated, irrespective of whether seawalls are breached, which is explained that “The greatest storm surge which can be anticipated have a scale which is not prevented with facilities such as a seawall”¹⁹⁾. It indicates the possibility that storm surges in worst scenario resulting from typhoons are cannot be prevented by the present tsunami precautions.

4. CONCLUSIONS

Facts of the storm surge in Fukae Harbor caused by Typhoon Jebi, T1821, on 4 September, 2018 were clarified by the recorded data. The transitions in the situation was explained

by image data taken from Fukae Maru. The image data support the recorded numerical data. The TL reached 200 cm of the elevation of the mooring pier at 13:56, and was completely below this elevation at 15:03. The maximum TL occurred between 14:16 and 14:18, and was estimated to be 305 cm. As the predicted TL of Fukae Harbor in this period was 51 cm, the maximum deviation of the TL was 254 cm. The main factor in the Jebi storm surge was the wind effect of the southerly wind on the inner part of Osaka Bay.

The outside maximum WL in Fukae Harbor was 336 cm, and was 36 cm higher than the TL of the time. The cause of the difference between the outside and the inside is thought to be wind waves generated by local winds near the harbor. The height in reserve of the seawall is ca. 46 cm against the maximum TL, and it is ca. 15 cm against the outside maximum WL including wind waves. The flooding was produced not only by the overflow caused by the storm surge but also by waves overtopping. If the storm surge had occurred at the maximum TL of the year, flooding would have been produced by the overflow alone.

Fukae Tide Station provided valuable data to fill the gap and to aid understanding of the variation between Nishinomiya and Kobe, where damage was heavy. The image data visualized that a design in consideration of a wave-breaking effect was necessary even in the seawall of the back of a waterway. It was presented that these data are useful and important for coastal disaster prevention.

The hazard maps of inundation by flooding from rivers and of inundation inside levees very nearly express the inundation area resulting from the storm surge. Overlaying evaluation of hazard maps of similar disasters is important in a perspective of risk detection. On the other hand, the present facilities such as seawalls may not be able to prevent the greatest storm surge. Both tsunamis and storm surges should be always considered in coastal disaster prevention.

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