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Geo-Disaster Report

Levee damage and bridge scour by 2019 typhoon Hagibis in Kanto Region, Japan

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Abstract

Typhoon Hagibis made landfall in Japan at 19:00 JST on 12th October 2019. The heavy rainfall caused by the typhoon was mostly concentrated within a 24-hour period; it brought devastating damage to eastern Japan. This report focuses on the flood-induced levee damage and bridge scour generated by the typhoon in the Kanto region. The levee breaches occurred mainly in the northern part of the region. They were concentrated along the Kuji and Naka Rivers and tributaries of the Tone and Arakawa Rivers. In most breached locations, the cause of the damage was the landward overtopping of the river water. Surface erosion on the slope of the protected side and/or slope failure on the protected side due to seepage-induced instability were the main causes of the levee breaches. Apart from the flooding induced by the inundation of the river water, inland flooding was also found. Damage to a river bridge due to local scour revealed the importance of considering the movement of sandbars in river channels, i.e., changes in the river flow conditions, when assessing the risks of bridge scour.

Keywords: Typhoon Hagibis; Levee breach; Overtopping; Inland flooding; Bridge scour

1. Introduction

Typhoon Hagibis, also known as the Reiwa 1st year East Japan Typhoon or Typhoon No. 19, made landfall in Japan at 19:00 JST on 12th October 2019. This caused heavy rainfall and brought devastating damage to eastern Japan (Japan Meteorological Agency, 2019). Many geotechnical structures and natural slopes were damaged by the typhoon. This report focuses on the flood-induced levee damage and bridge scour generated by the typhoon in the Kanto region. The Kanto region includes the Greater Tokyo Area. The population in this region is about 43 million, which is one-third of the total population of Japan. The Kanto Plain forms half of the land area of this region and the majority of the levee damage addressed in this report occurred on the flood plain.

The total amount of rainfall in the Kanto region over four days, including the period of the typhoon landfall, is shown in Fig. 1. The data were obtained from the database maintained by the Japan Meteorological Agency (2020). It

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should be noted that the total amount of rainfall during this four-day period exceeded the October mean (around 200 mm in this area) at many of the weather stations and was very large considering the fact that the average annual total amount of rainfall in Japan is around 1,700 mm. The heavy rainfall caused by the typhoon was mostly concentrated within a 24-hour period (Takemi and Unuma, 2020) on 12th October 2019.

Due to this heavy rainfall, the water level exceeded the maximum water level in the past at many of the water level observatories in the Kanto region (Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2020), leading to the breach of levees. Table 1 summarises the flood damage in the Kanto region brought about by the typhoon. The data were obtained from the MLIT (2020a). In the table, overtopping means that there was a flow of river water over the levee, while overflow means that there was a flow at a location where there was no levee. In the Kanto region, levee breaches occurred at 11 locations along four rivers in three river systems in sections managed by the national government, while levee breaches occurred at 35 locations along 19 rivers in four river systems in sections managed by local governments. Apart from the levee breaches, overtopping, overflow, and inland flooding also happened in many places. The locations of the levee breaches in the Kanto region are indicated in Fig. 2. The location of the Hino Bridge, where bridge scour was found, is also indicated in the figure. The levee breaches caused by the typhoon were mainly found in the northern part of the region. They were concentrated along the Kuji and Naka Rivers and tributaries of the Tone and Arakawa Rivers.

To provide an overview of the levee breaches brought about by the typhoon, a summary of the breaches of the levees managed by the national government in the Kanto region is tabulated in Table 2. Details of the breaches and the soils comprising the embankments and foundations were obtained from the report by the Investigation Committee for the Levee Breach by the 2019 Typhoon Hagibis in the Kanto Region (2020), while the other information was obtained from the Geospatial Information Authority of Japan (2020). The relative height of the breached levees, i.e., the elevation of the levee crest to the protected land elevation, was small (≤ 5 m). In most breached locations, the cause of the damage was the landward overtopping of river water. Although the breached levees on the Kuji and Naka Rivers were mainly made of sandy or gravelly soil, and were built on relatively permeable foundations, no obvious traces of backward erosion piping or sand boils were found. This suggests that surface erosion on the slopes of the protected side and/or slope failures on the protected side due to seepage-induced instability were the main causes of the levee breaches. In the following sections, details of the damage to the levees and a description of the bridge scour at the Hino Bridge are provided.

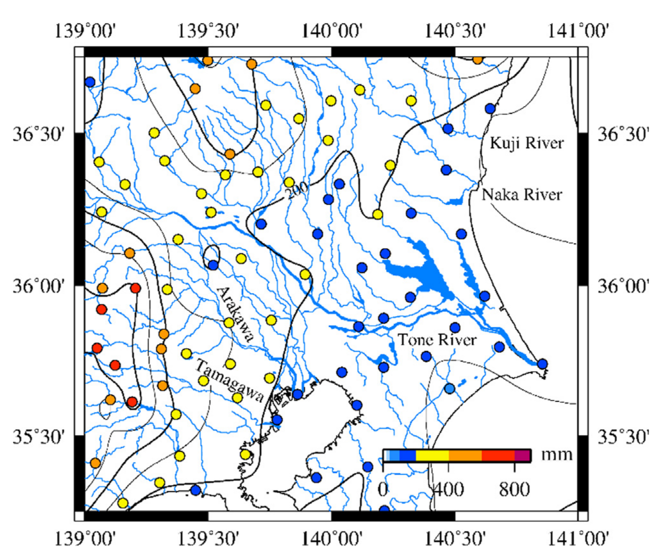


Fig. 1. Accumulated rainfall amount (mm) in Kanto region during period from 00:00 JST on 10 October to 24:00 JST on 13 October 2019. The circles indicate the locations of the weather stations.

2. Levee breaches in Arakawa river system

2.1. Overview of rainfall and river level in tributaries with levee breaches

The Arakawa River, a major river in the Kanto region, originates at Mount Kobushigadake. It flows through the centre of Saitama Prefecture down the lowlands of eastern Tokyo to Tokyo Bay. Fig. 3 shows the elevation distribution of the upper and middle reaches of the Arakawa River system and the locations of the observation stations. Six levees in the Arakawa River system were breached due to the flood caused by the typhoon. These breaches occurred along the Tokigawa, Oppegawa, and Shinegawa Rivers, all of which are tributaries of the Arakawa River, at the locations indicated by the red circles in Fig. 3. The source of these rivers is the Soto-Chichibu Mountains, which is around 800 m above sea level. The typhoon resulted in more than 500 mm of cumulative rainfall in the Soto-Chichibu area, with 300–400 mm of rainfall being recorded in the basin; this was the highest amount of rainfall (or close to it) ever recorded here. Fig. 4 shows hydrographs for the observatory near the breached points in the Arakawa River system. The red line in each graph indicates the design high water level. The river levels rose with the rainfall in each river basin, with the highest rise in water level being recorded from late at night on 12th October 2019 to early morning on 13th October 2019. The water levels at the observatories at Nomoto along the Tokigawa River and at the Takasaka and Ochiai Bridges on the Oppegawa River exceeded the design high water levels; in fact, they were the highest levels ever recorded. The hydrograph for the Karako Bridge shows that the water level of the river repeatedly rose and fell around the design high water level; this was attributed to three breaches in the upper stream of the observatory.

Table 1
Summary of flood damage in Kanto region.

Managed by	River system	Breach	Overtopping/Overflow*	Inland flood
National gov.	Kuji	3	0/2	0
	Naka	3	3/11	5
	Tone	0	0/9	20
	Arakawa	5	0/7	0
	Tamagawa	0	0/1	1
	Sub total	11	3/30	26
Local governments	Okitagawa	0	0/1	0
	Kuji	4	2/0	0
	Naka	11	11/10	0
	Tone	18	17/57	0
	Arakawa	2	5/42	1
	Tamagawa	0	0/5	0
	Sakaigawa	0	0/1	0
	Hikiji	0	0/1	0
	Sagami	0	0/2	0
	Hayakawa	0	0/2	0
	Fuji	0	0/4	1
	Sub total	35	35/125	2
Total		46	38/155	28

* Overtopping means that there was a flow of river water over the levee, while overflow means that there was a flow at a location where there was no levee.

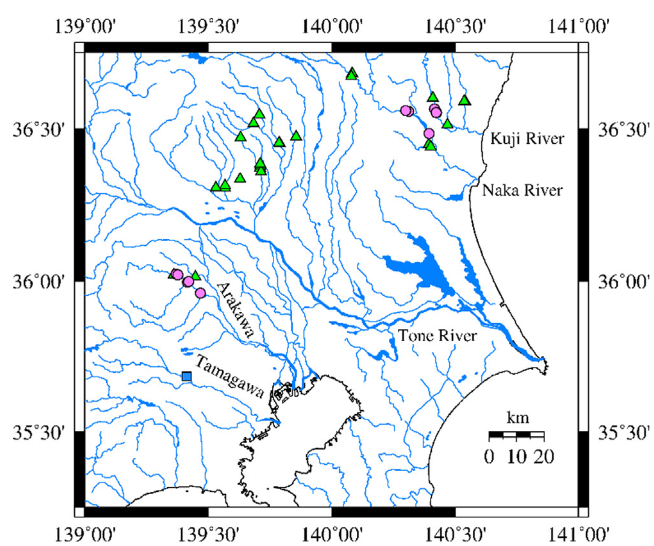


Fig. 2. Locations of levee breaches and bridge scour in Kanto region. The circles indicate the levees managed by the national government, while the triangles indicate those managed by local governments. The square indicates the Hino Bridge at which the scour was found.

2.2. Levee breaches at L7.6 k on Oppegawa River and R0.4 k on Tokigawa River

The breaches at 7.6 k on the left levee of the Oppegawa River and at 0.4 k on the right levee of the Tokigawa River are located near the inflow of the Tokigawa River into the Oppegawa River, as shown in Fig. 5. The breached point at L7.6 k is at the corner directly upstream of the floodgate of the Tsukumogawa River, which joins the Oppegawa River, and it extends for around 40 m to the left levee of the Tsukumogawa River. The breached point at R0.4 k is located on the outer levee of a gentle bend in the Tokigawa River near its confluence with the Oppegawa River, and it extends for around 90 m. This area is surrounded by levees and terraces of the Tokigawa and Oppegawa Rivers, and around 160 ha of this area was inundated by levee breaches and overflows.

Fig. 6 presents a drone image taken by the MLIT around the L7.6 k breached area of the Oppegawa River. The image shows the flood traces of the Tsukumogawa River; the water level is estimated to have been higher than the current levee height in the breached area. Fig. 7 presents a drone image taken by the MLIT around the R0.4 k breached area of the Tokigawa River. The width of this levee is narrower than that of the upstream and downstream levees in this section, and there are many trees in this area of the river. Fig. 8 shows the cross-section of the breached levee at R0.4 k and grain size distributions for the soils taken from the points shown in the figure. The soils at Points C–E were placed over the old levee (Points A and B) to widen and raise the levee. The levee was mainly made of silty soil, and its foundation was made of soft alluvial clay. Sandy soil and gravelly soil were used for widening and raising the levee. No sand erosion or leakage was found near the toe of the slope on the protected side in either the upstream or downstream areas of the breached section, and no clear evidence of erosion was found on the riverside slope or flood channel. The water level of the overflow was investigated by surveying the levee height and floodplain, and it was confirmed to be more than 0.9 m higher than the current levee height at 0.0–0.6 k on the right levee, including the breached section. Furthermore, no leakage or erosion damage was found at 7.6 k on the left levee of the Oppegawa River.

The failure in these two areas is attributed to overtopping due to scouring on the protected side by overflow

Table 2
Summary of breaches of levees managed by national government in Kanto region.

River	Location			h_r (m)	Soil		L_b (m)	h_o (m)	OD	d_s (m)
	River km *3	N LAT	E LNG		Embankment	Foundation				
Oppegawa *1	L 7.6 k	35.99473	139.41683	5.2	ML/MH	ML	40	>0.4	LW	0.0
Oppegawa *1	R 0 k	35.95911	139.46846	4.7	ML	MH	70	>0.4	LW	2.0
Tokigawa *1	L 6.5 k	36.02339	139.37121	2.8	ML/GM	GM/SM	30	>0.25	LW	0.8
Tokigawa *1	R 0.4 k	35.99770	139.42220	4.3	ML	MH	90	>0.9	LW	>0
Tokigawa *1	R 5.9 k	36.01953	139.37711	3.0	CL	1 m ML on SM	20	0.15	LW	1.5
Naka	L 40 k	36.55771	140.31223	3.2	SM/GM	3 m SM on GW	200	>0.6	LW	6.2
Naka	R 28.6 k	36.48552	140.39566	3.2	GM	1 m MH on GW	250	0.4	LW	2.3
Naka	R 41.2 k	36.56039	140.30039	2.7	GM	2 m SM on GW	250	>0.9	LW	2.7
Kuji	L 25.5 k	36.55340	140.42643	3.1	SM/ML	2 m CH on GW	100	0.3	LW	1.0
Kuji	L 27 k	36.56547	140.41746	2.7	SM	1 m SM on GW	64	0.55	LW	4.6
Kuji	L 34 k *4	36.60089	140.40947	3.5	GW	1 m GM on GW	60	0.4	LW	3.0
Kuji	R 25.5 k	36.55298	140.42330	2.5	MH	1 m ML on GW	40	0.2	RW	1.6
Asakawa, *2	R 0.6 k *4	36.51038	140.47398	4.2	SM/ML	1 m ML on GW	60	–	RW	5.5
Asakawa, *2	R 1.5 k *4	36.51504	140.47045	1.8	SM/ML	CH	40	–	RW	2.0

*1 Arakawa River System; *2 Kuji River System; *3 L indicates left levee, while R indicates right levee; *4 Levee is managed by local government, but restoration was undertaken by national government; h_r: Relative levee height; L_b: Breach length; h_o: Overflow depth; OD: Overtopping direction; LW: Landward; RW: Riverward; and d_s: Maximum scour depth.

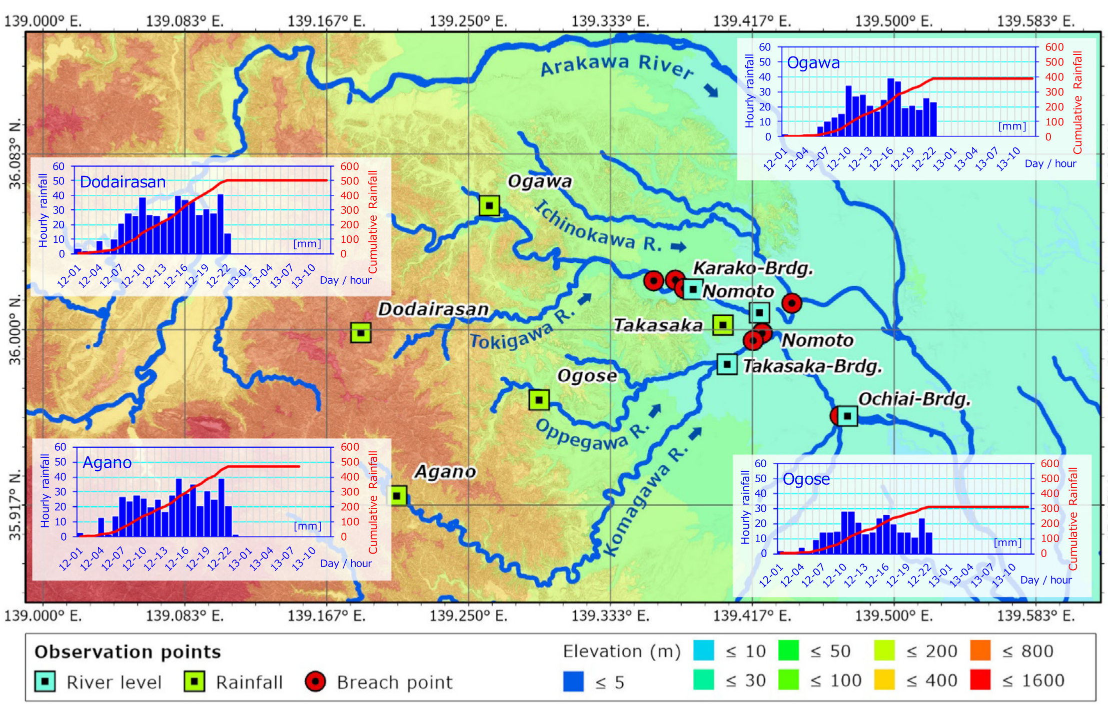


Fig. 3. Locations of breaches in Arakawa River system, and river level and rainfall monitoring stations. Data were obtained from the database maintained by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (http://www1.river.go.jp/). Elevation data were obtained from the base map information of the Geospatial Information Authority of Japan (https://fgd.gsi.go.jp/download/menu.php).

and the presence of drifting objects at the top of the upstream of the failed area.

2.3. Levee breach at L6.5 k on Tokigawa River

The breached point at 6.5 k on the left levee of the Tokigawa River is located at the water-colliding front of the Tokigawa River and near the confluence of the tributaries of the Tokigawa River, as shown in Fig. 9. Near the breached area, breaches also occurred at R5.9 k on the opposite side of the river and at R1.4 k upstream of the Godooh Bridge, which is managed by Saitama Prefecture. These breached levees were temporary ones. Approximately 140 ha of the plain was inundated owing to overtopping in a series of sections. Fig. 10 shows the levee breach at L6.5 k, where the levee was breached for around 30 m. Fig. 11 shows the situation of the slope on the protected side, which is continuous from the breached point. To

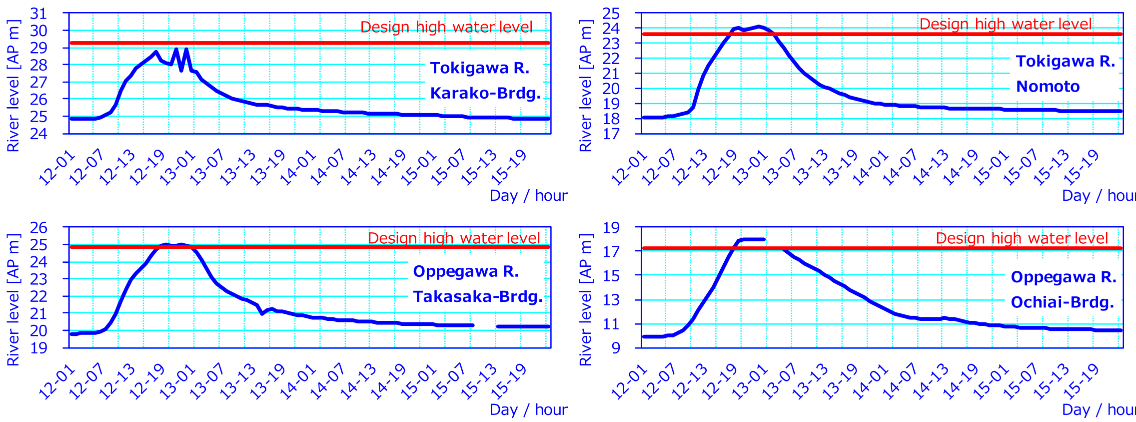


Fig. 4. Hydrographs in vicinity of breaches in Arakawa River system. Data were obtained from the database maintained by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (http://www1.river.go.jp/).

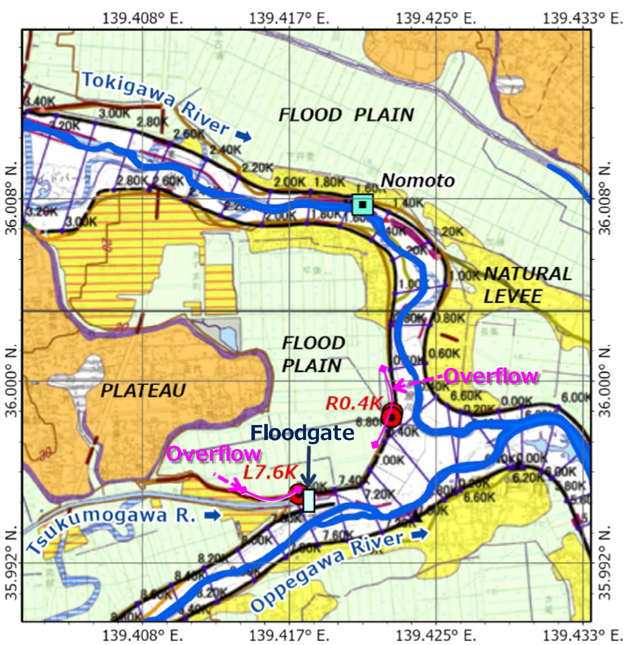


Fig. 5. Landform classification map for flood control in vicinity of breaches. The landform classification map was obtained from the base map information of the Geospatial Information Authority of Japan (https://cyberjapandata.gsi.go.jp/xyz/lcmfc2/12/3634/1608.png).

investigate the mechanism of breach damage at L6.5 k, the MLIT investigated the overflow situation. The water level was found to be higher than the current levee height from 6.0 k to the upstream on the left levee, and the overtopping interval was estimated to be 600 m from 6.0 k to 6.6 k, considering the erosion at the shoulder of slope on the protected side, as shown in Fig. 11. Based on the difference between the water level estimated from the traces and the height of the current levee, the overflow depth was estimated to be more than 0.25 m. No sand erosion or leakage was found near the toe of the slope on the protected side in either the upstream or downstream areas of the breached section, and no clear evidence of erosion was found on the riverside slope or flood channel. The soil composition is similar to that of R0.4 k, as described above, with the

Fig. 6. Breach at 7.6 k on left levee of Oppegawa River. The drone image was obtained from the database maintained by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (https://www.ktr.mlit.go.jp/bousai/index00000051.html).

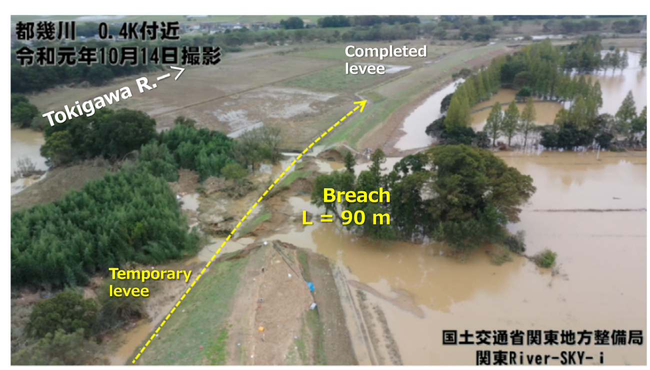


Fig. 7. Breach at 0.4 k on right levee of Tokigawa River. The drone image was obtained from the database maintained by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (https://www.ktr.mlit.go.jp/bousai/index00000051.html).

levee being made of a silt-based clay soil and the foundation ground being made of an alluvial soft clay soil. The cause of the failure was considered to be the erosion of the levee due to overtopping.

In addition, some slope erosion damage was seen in this section on the slope of the protected side owing to overtopping; however, this did not lead to breaching. As shown in

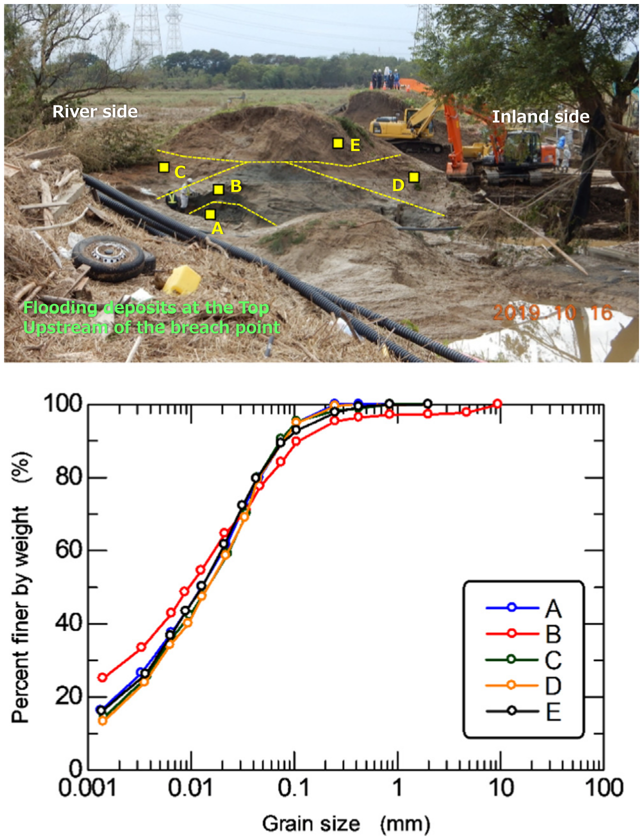


Fig. 8. Cross-section of breached levee at R0.4 k and grain size distribution curves for soils taken from points shown in picture. The data were obtained from the report by the Investigation Committee for the Levee Breach by the 2019 Typhoon Hagibis in the Kanto Region (2020).

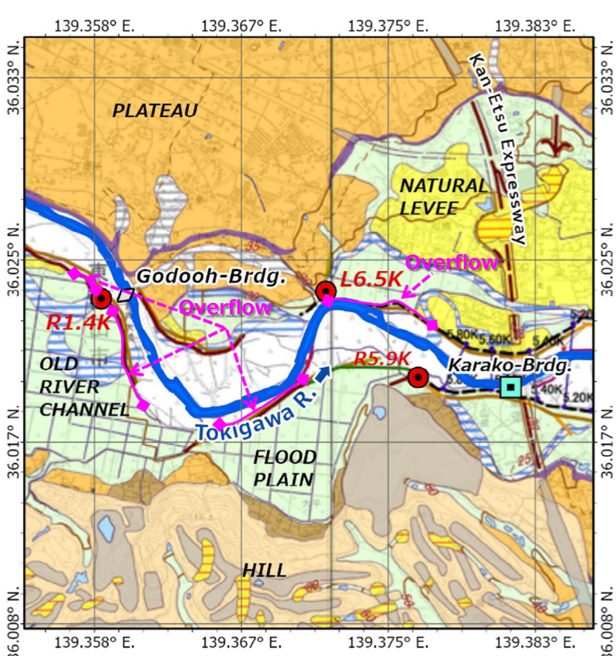


Fig. 9. Landform classification map for flood control in vicinity of breaches. The landform classification map was obtained from the base map information of the Geospatial Information Authority of Japan (https://cyberjapandata.gsi.go.jp/xyz/lcmfc2/13/7267/3216.png).

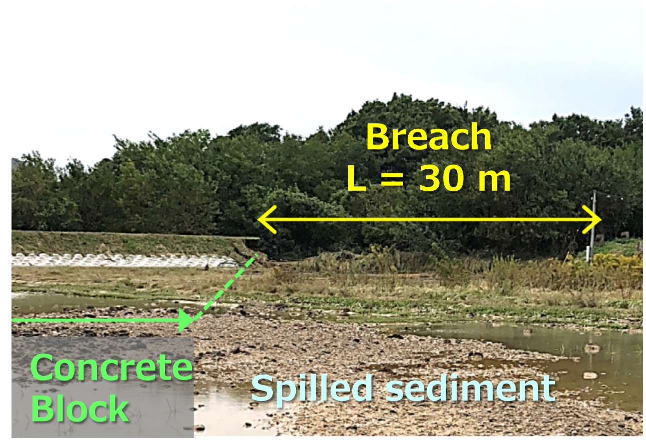


Fig. 10. Breach at 5.6 k on left levee of Tokigawa River.

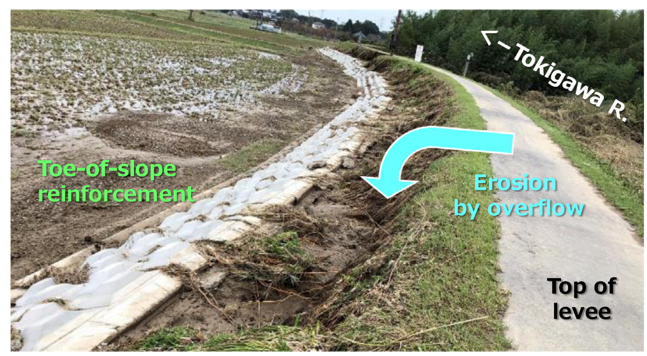


Fig. 11. Levee that survived erosion by overflow.

Figs. 10 and 11, concrete blocks were installed in this section to protect the toe of the levee on the protected side. This is a good example of the measures taken to prevent breaches from occurring due to overtopping in the current flood event that exceeded the capacity of the facility. If a levee is made of clay, the risk of its breaching due to river water overtopping can be reduced by protecting the toe of the slope of the levee with concrete blocks or other such materials.

3. Levee breaches in Tone River System

3.1. Overview of rainfall and levee breaches in tributaries

In Tochigi Prefecture, where tributaries of the Tone and Naka Rivers are located, the passage of the typhoon caused extensive damage over a wide area. Rainfall conditions in Tochigi Prefecture were heavy from 11th to 13th October 2019. The peak of the rainfall was at midnight on 12th October 2019. Heavy rainfall fell mainly in the mountainous areas northwest of Tochigi Prefecture. Fig. 12 shows the precipitation history at Oku-Nikko in the Tone River basin. Precipitation was concentrated on 12th October 2019. The rain gathered in the river systems, and the measured rainfall in each area of Tochigi Prefecture was more than twice the monthly average. In the above-mentioned river systems, several levees were also breached (Fig. 13).

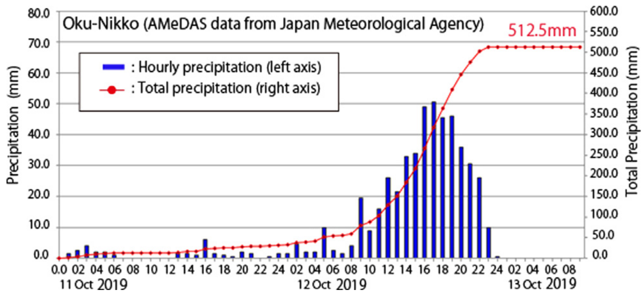


Fig. 12. Example of precipitation in mountainous area of Tochigi Prefecture. Rainfall data in Oku-Nikko. The data were obtained from the AMeDAS database by the Japan Weather Association.

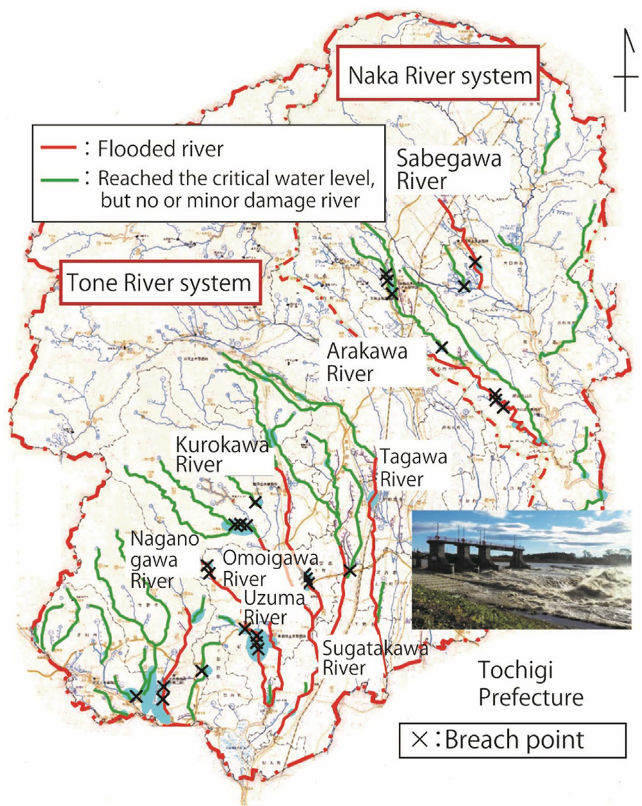


Fig. 13. Locations of Tonegawa River system and Nakagawa River system in Tochigi Prefecture (Map provided by Tochigi Prefectural Office with English translation).

3.2. Omoigawa River

Four levees were breached along the Omoigawa River due to a large amount of water flow (see Fig. 13 for locations). Due to the multiple breaches, about 152 ha of the urban area of the city was flooded and 237 houses were flooded. Fig. 14 shows the situation at the breached points on the Omoigawa River near the Tenman-bashi Bridge in the Kuchiawano and Kuno areas of Kanuma City, and photographs of three out of the four breached levee points on the Omoigawa River. The levee of the Omoigawa River was breached and flooded at a meandering point of the river flow. Most of the levees in the surrounding area are old levees. The water flowed into the urban area from Breach Point A and the residential area was flooded. The inundated water from Breach Point B to the urban area returned to the river from Breach Point C. Fig. 15 shows the time history of the river water levels measured at the Tenman-bashi Bridge Observation Station on the Omoigawa River. Since the observation station was located in the flooded area, the data were lost during the flood.

Fig. 16 shows the repair works laid out by the Tochigi Prefectural Government for the surrounding areas. There is a plan to widen the beds upstream and downstream of the river, in the vicinity of the flooded area, to secure the flow of water and to repair the levees.

4. Levee breaches in Naka River System

4.1. Overview of rainfall and river level in river with levee breaches

The Naka River flows in the northern part of the Kanto region. The river originates at Mt. Nasudake (1917 m above sea level) located at the border of Fukushima and Tochigi Prefectures. It flows through Tochigi and Ibaraki Prefectures until it reaches the Pacific Ocean. The length of the main river channel is about 150 km, the river basin area is about 3270 km^2, and the population of the river basin is about 0.92 million.

The levee breaches along the Naka River took place at five locations because of the flood caused by the typhoon. The locations of representative levee breaches are presented by red crosses in Fig. 17 and black crosses in Fig. 13. The rainfall observed at the Torinoko Observatory located in Ibaraki Prefecture was 268.0 mm for 48 h; this breaks the previous record of rainfall of 151.4 mm for 48 h due to Typhoon No. 6 (Doksuri) in 2012. Fig. 17 also shows a hydrograph for the Noguchi Observatory near the breaches along the Naka River. The blue line shows the river water level and the blue bar shows the rainfall. It can be seen that the river water level rose sharply with the approach of the typhoon starting on the evening of 12th October 2019. The peak of the river water occurred early in the morning on 13th October 2019, which indicates that the duration of the flood was relatively short, although the typhoon brought intense rainfall.

4.2. Levee breach at L40.0 k on Naka River

At Noguchi in Hitachi-ohmiya City, Ibaraki Prefecture, the left levee at 40.0 k was breached for about 200 m. Temporary restoration works for the breached levee were started immediately after the event, as shown in Fig. 18. The original levee section was about 3.0 m in height with a 1:2.0 slope. The crest was covered with asphalt pavement, about 3.0 m in width, as part of the temporary restoration works. The Investigation Committee for the Levee Breach by the 2019 Typhoon Hagibis in the Kanto Region (2020) surveyed the cause of the breach and concluded that over-

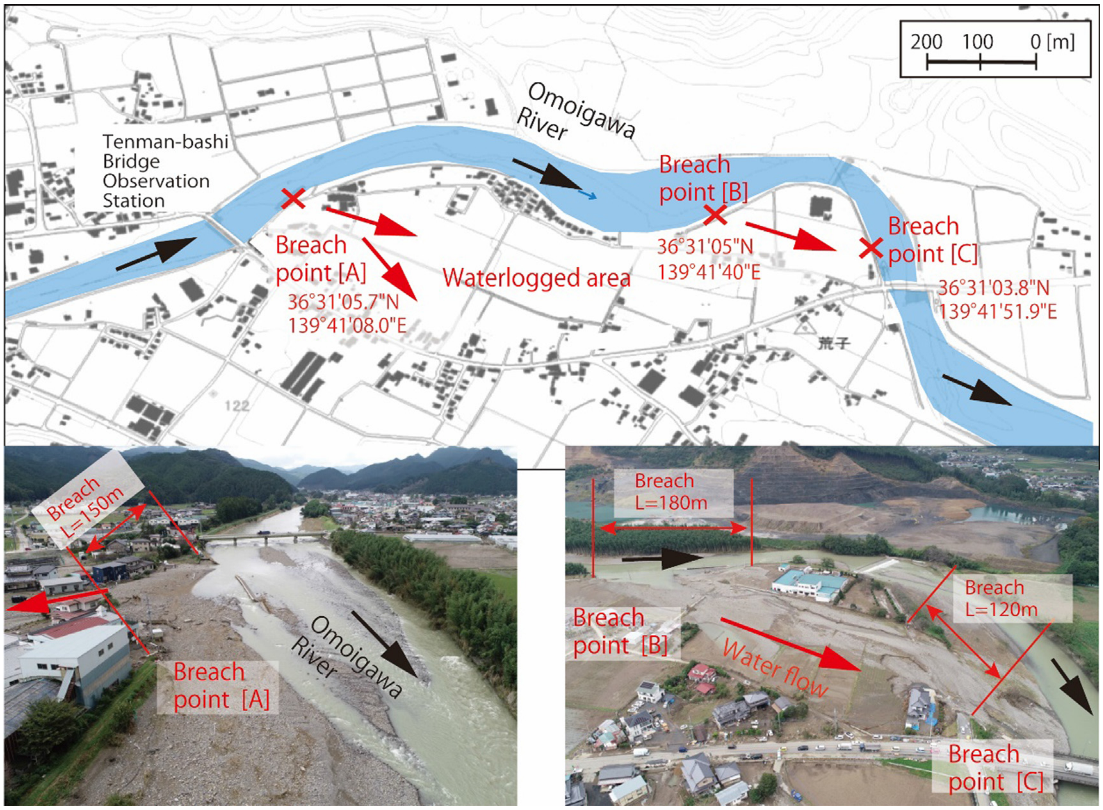


Fig. 14. Locations of breached points on Omoigawa River (in Tone River system) near Tenman-bashi Bridge in Kuchiawano and Kuno areas, Kanuma City, Tochigi Prefecture (Map and photos provided by Tochigi Prefectural Office with English translation).

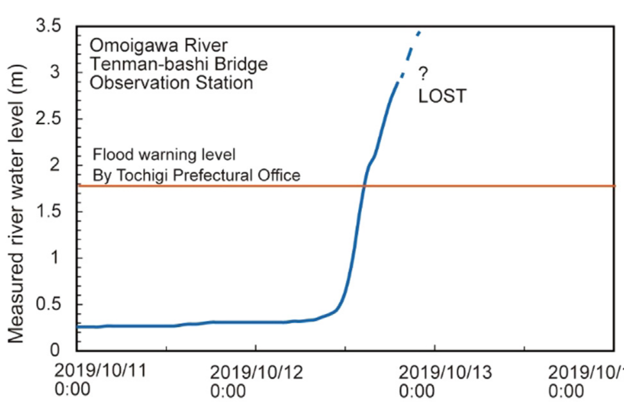


Fig. 15. Time history of river water levels measured at Tenman-bashi Bridge Observation Station on Omoigawa River (Data provided by Professor Yuichi Ikeda, Utsunomiya University, School of Regional Design).

topping was a major cause, but that seepage and erosion also had the potential to be complex causes.

The depth of the overtopping was more than 0.60 m at the section of the levee that breached and became less than 0.60 m at the downstream section of the levee that did not breach. A trace of overtopping could be observed at the downstream section of the levee. From the field survey, the process of erosion by overtopping was classified into the following four steps:

- Step 1: The beginning of vegetation erosion due to overtopping was seen at the shoulder of the levee (Fig. 19a)).
- Step 2: Small grain size soil began to flow out due to the overtopped water (Fig. 19b)).
- Step 3: Then, larger grain size soil was washed away (Fig. 19c)).
- Step 4: The failure of the levee by erosion took place at its shoulder (Fig. 19d)).

4.3. Levee breach at R41.2 k on Naka River

At Shimoisehata in Hitachi-ohmiya City, Ibaraki Prefecture, the failure of the right levee at 41.2 k occurred. The scene of the temporary restoration works is shown in Fig. 20. The collapsed section was about 250 m in length, 4.9 m in slope length, and 3.7 m in crest width. Fig. 21 shows the river-side and land-side slopes adjacent to the collapsed section. The river-side slope had no damage, while marked traces of erosion were found on the land-side slope despite the fact that it has been protected by revetment blocks before the typhoon. According to the construction blueprint by the MLIT, the whole area around the breached section had crest pavements and revetment blocks for the river-side slope, while the land-side slope may have been covered with revetment blocks,

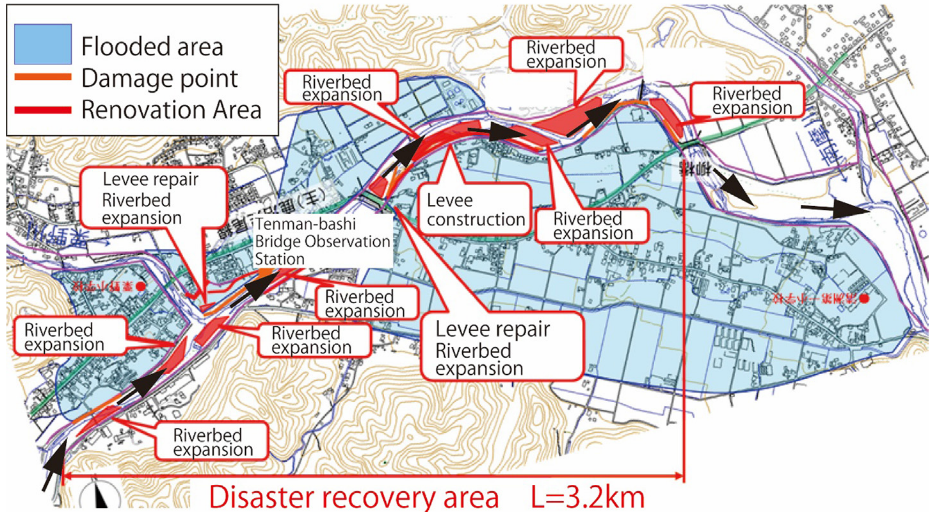


Fig. 16. Overview of plan for restoration and repair services for damaged areas on Omoigawa River (Map provided by Tochigi Prefectural Office with English translation).

about 30 m in length, at the downstream side of the collapsed section which was about 250 m in length. On the other hand, no signs of sand boils or piping were found during the field survey conducted five days after the event. Considering these results, the breach may have been caused by the erosion of the land-side slope, without revetment blocks, brought about by overtopping. In particular, the failure of the section with revetment blocks, with a land-side slope 30 m in length, may have occurred subsequently due to the flow-out of fill materials after the collapse of the section without revetment blocks (i.e., a progressive failure). The breach at this location suggests that the effects of crest pavements and revetment blocks on reducing the overtopping-induced damage to both side slopes are still unclear. Further studies will need to be conducted to clarify these effects in the future.

4.4. Sabigawa River

One part of the left levee of the Sabigawa River was breached due to overtopping (see Fig. 13 for locations). Fig. 22 shows the location of the breach point on the Sabigawa River (in the Naka River system) in Kita-owagu area, Otawara City. The length of the breached section is 150 m. The river water overtopped the levee and inundated the city due to the levee collapse. As a result, 66 ha of rice fields and the city were inundated.

Fig. 23 shows the time history of the river water levels measured at the Sabi-bashi Bridge Observation Station on the Sabigawa River. The observation station is located in the suburbs of the flooded point. Fig. 24 shows the location of the breached point and waterlogged area along the Sabigawa River. The river bends steeply to the right toward the downstream side at the breached point. The levee in that area, including the broken section, is old and was made of dredged sediment from the river. The embankment material is sandy soil, containing a large amount of cobbles the size of a fist. Fig. 25 shows the damaged levee at the breached point. Along with sandy soil, the embankment also contains many boulders. The cross-section of the damaged levee shows that the embankment was made of sandy soil and there was no core made of low-permeability material. Based on the conditions of the breached levee, soil of the embankment, surrounding topography, and river, the flood-induced wetting of the levee presumably made the levee unstable and resulted in its collapse due to external forces, such as increased water pressure. Most of the levees in the surrounding area are also old. As the material of the levees in this area comprise sandy soil with cobbles/boulders, they are prone to collapse depending on the topography and rainfall conditions. The emergency response to this breach was completed in about 10 days and consisted of constructing a temporary water barrier using large sandbags. Repairs to the levee, including the damaged sections, are planned for the future.

5. Levee breach in Kuji River System

5.1. Overview of rainfall and river level in river and its tributaries with levee breaches

The Kuji River also flows in the northern part of the Kanto region from north of the Naka River. The Kuji River originates at Mt. Yamizosan (1022 m above sea level) located at the border of Fukushima and Ibaraki Prefectures. It flows through Ibaraki Prefecture to the Pacific Ocean. The length of the main river channel is about 124 km, the river basin area is about 1490 km^2, and the population of the river basin is 0.19 million.

The levee breaches on the Kuji River system took place at 10 locations due to the flood caused by the typhoon. These breaches occurred along the Kuji River and its tribu-

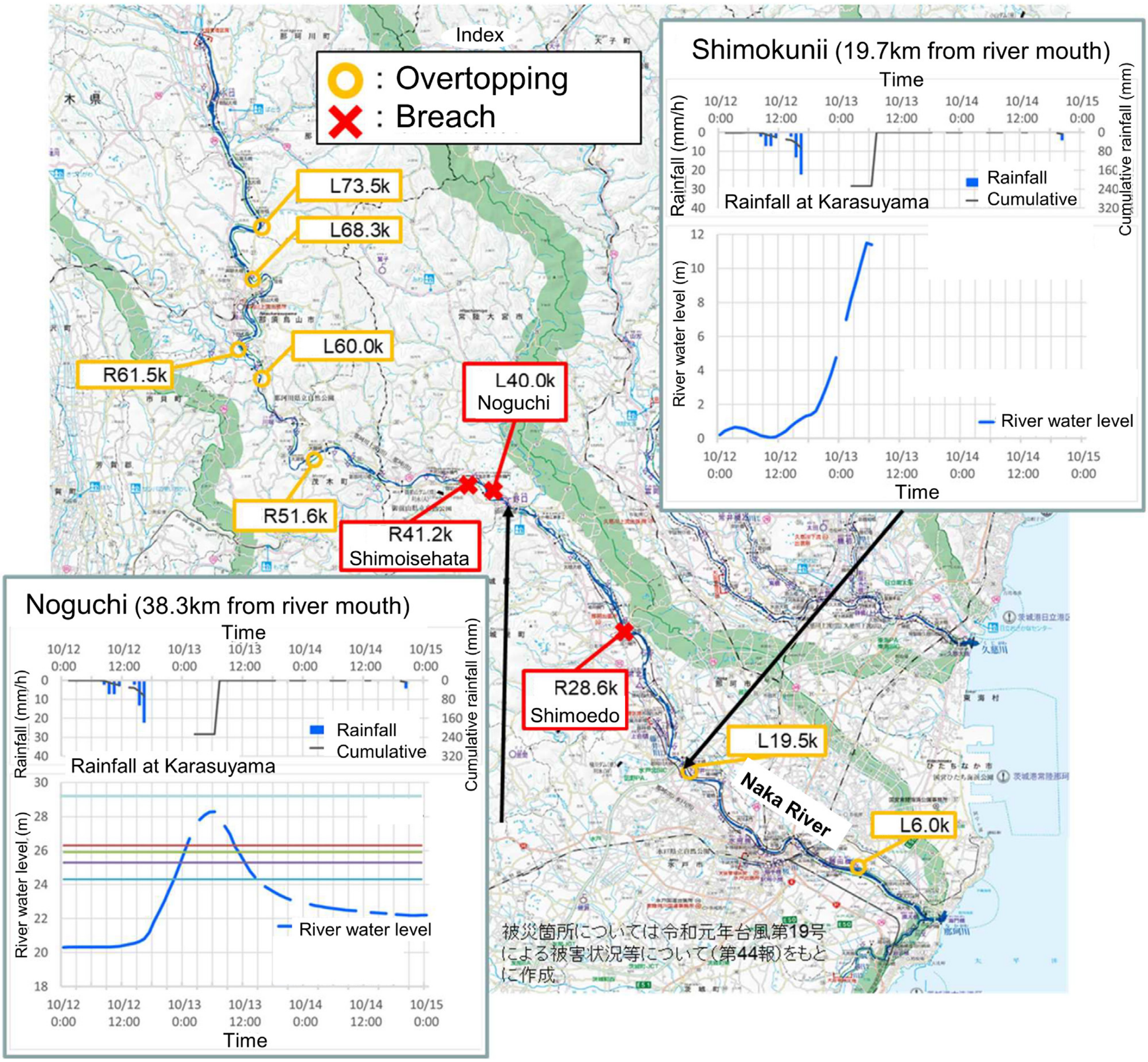


Fig. 17. Locations of some breaches in Naka River system and hydrographs (Investigation Committee for the Levee Breach by the 2019 Typhoon Hagibis in the Kanto Region (2020) with English translation).

taries, such as the Sato River and the Asakawa River. The representative breached locations are indicated by the red and grey crosses in Fig. 26. The rainfall observed at Kegano Observatory, located at the upstream side of the breaches, was 207 mm for 48 h. This amount of rainfall is record-breaking as compared with the previous record of 185 mm for 48 h due to Typhoon No. 10 in 1986. Fig. 26 also shows the hydrograph for the Tomioka Observatory near the breaches in the Kuji River system. The blue line shows the river water level and the blue bar shows the rainfall. The river water level rose sharply with the approach of the typhoon starting on the evening of 12th October 2019. The peak of the river water occurred early in the morning of 13th October 2019, which indicates that the flood trend was similar to that of the Naka River system.

5.2. Levee breach at L34.0 k on Kuji River

At Onuki in Hitachi-ohmiya City, Ibaraki Prefecture, the failure of the left levee at 34.0 k occurred at a length of about 60 m. The slope length of the collapsed section was about 5 m. As shown in Fig. 27, large sandbags were placed on the levee toe in the temporary restoration works. Considering the facts that (1) no traces of sand boils or piping were found in the field investigations conducted about two weeks after the event and (2) soils were deposited behind the collapsed section, as shown in Fig. 27, the

Fig. 18. Temporary restoration works of left levee at 40.0 k of Naka River.

breach might have been caused by the erosion of the land-side slope due to overtopping. As seen in Fig. 28, both side surfaces of the undamaged levee that was adjacent to the breached section has been covered with crest pavements and revetment blocks. According to the aerial photograph, most of the breached section had also been covered with the pavements and blocks prior to the typhoon. As mentioned earlier (i.e., the right levee of 41.2 k on the Naka River), the effects of the crest pavements and revetment blocks for both side slopes on reducing overtopping-induced damage are still unclear.

5.3. Sato River

At Jyofukuji-Cho and Chinone-Cho in Hitachi-ohta City, Ibaraki Prefecture, the breaches along the Sato River levee took place at several locations due possibly to the sharp curves of the river channel, as shown in Fig. 29. As mentioned previously, the Sato River is a tributary of the Kuji River. The breach at each location is summarised in the following.

At Point C, indicated in Fig. 29, the failure of the upstream and downstream sections of the right levee

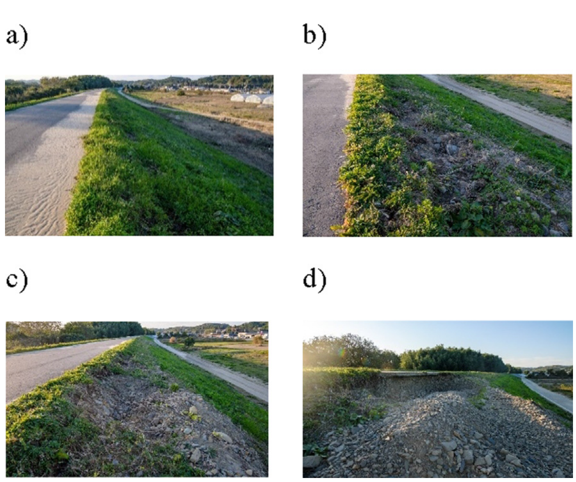


Fig. 19. Process of erosion of land-side slope by overtopping: (a) Step 1, (b) Step 2, (c) Step 3, and (d) Step 4.

Fig. 20. Temporary restoration works of right levee at 41.2 k of Naka River.

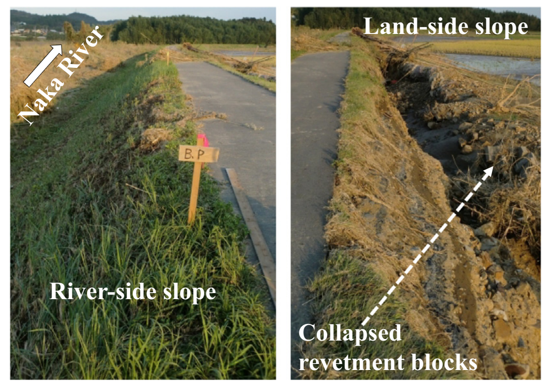
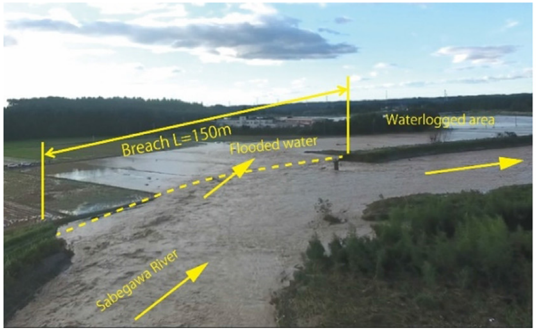


Fig. 21. River-side and land-side slopes adjacent to collapsed section at 41.2 k of Naka River.

occurred across the Akasu Bridge, as shown in Fig. 30. These two damaged sections were about 80 and 120 m in length, respectively, 2–3 m in slope length, and 4–4.5 m in crest width. As seen in Fig. 31, the Akasu Bridge has six spans in spite of its short length. According to photos taken by a neighbourhood resident, the bridge girder and piers caught driftwood generated by this flood, suggesting that the rise in the river was accelerated locally by the trapped driftwood and might have led to the breach attributed to the erosion of the land-side slope caused by overtopping.

On the upstream side, about 400 m from Point C (i.e., at Point D in Fig. 29), the failure of the left levee occurred at a length of about 55 m (Fig. 32). The slope length and crest width of the collapsed section were about 4.5 and 3 m, respectively. Large sandbags were used to temporarily fill in the breached section as part of the restoration works.

At Point B, indicated in Fig. 29, which corresponds to the downstream side from Point C, the failure of the left levee took place at a length of about 35 m, as shown in Fig. 33. The slope length and crest width of the collapsed section were about 2.5 and 3.5 m, respectively. The main cause of the breach at Point B might have been the erosion of the land-side slope caused by the overtopping attributed to the sharp curve of the river channel (see Fig. 29). As demonstrated by this case, a sharp curve in a river channel can be one of the most important factors causing overtopping-induced damage to a levee.



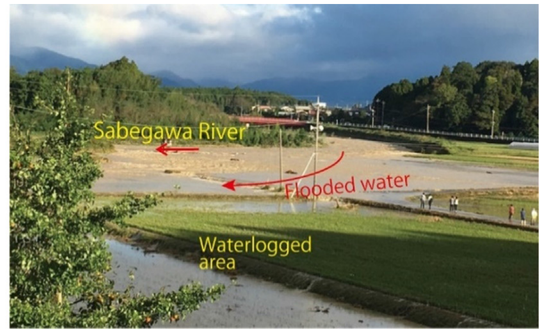


Fig. 22. Breached point on Sabigawa River (in Naka River system) in Kita-owagu area, Otawara City, Tochigi Prefecture. Left photo: View from upstream side, Right photo: View from left levee (Photos provided by Tochigi Prefectural Office with English translation).

At the downstream side, about 500 m from Point B (i.e., at Point A in Fig. 29), the failure of the right levee, about 20 m in length, 4 m in slope length, and 3.5 m in crest width, occurred as shown in Fig. 34. The foundation of the water level observatory, constructed on the river-side shoulder and located on the downstream side about 16 m from the breached area, shown in Fig. 34, was severely damaged by scour. On the downstream side of the observatory, traces of the erosion of the river-side shoulder were found at a length of 22 m, as shown in Fig. 35. Moreover, as seen in Figs. 34 and 35, bamboo bushes on the river-side shoulder were inclined toward the river-side. When considering these factors, the possible process of the breach could be explained as follows.

(1) The overtopping occurred possibly due to the sharp curve of the river channel (Fig. 29).
(2) The river water flowed back to the river channel after overtopping.
(3) The backwater, whose water level on the protected side was higher than that in the river channel, caused the erosion of the river-side slope. The cross-section of the levee was gradually reduced, and finally, the breach occurred.

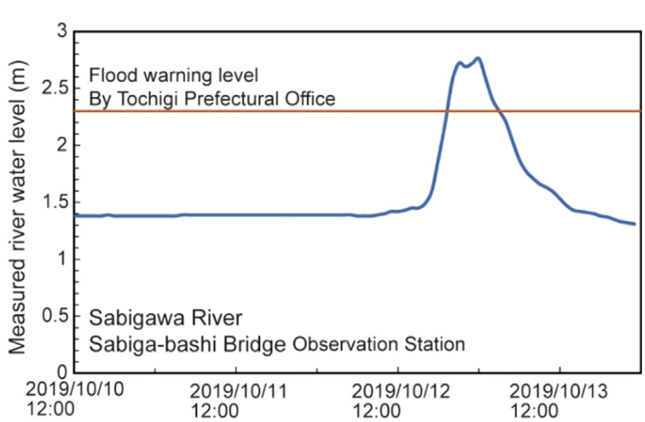


Fig. 23. Time history of river water levels measured at Sabi-bashi Bridge Observation Station on Sabigawa River (Data provided by Professor Yuichi Ikeda, Utsunomiya University, School of Regional Design).

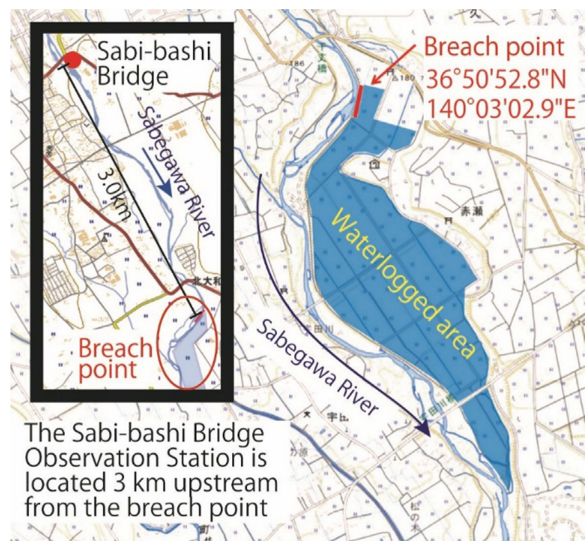


Fig. 24. Location of breached point and waterlogged area in Sabigawa River (Map provided by Tochigi Prefectural Office with English translation).

This type of breach may have occurred at three more sites in Ibaraki Prefecture, as reported by the Investigation Committee for the Levee Breach by the 2019 Typhoon Hagibis in the Kanto Region (2020). Due attention should also be paid to this failure pattern.

5.4. Soil properties of fill materials retrieved from breached levees

At the time of the above-mentioned survey, fill materials were retrieved for the laboratory tests from the land-side slope surfaces of each undamaged levee section adjacent to the damaged area at a depth shallower than about 0.1 m. At some sites, the fill materials were retrieved from the inside of levees and the river-side slope surfaces.

Fig. 36 shows the grain size distribution of the retrieved materials. The values for the maximum and mean particle diameters (D_{max} and D_{50}), fines content (F_c), uniformity coefficient (U_c), and plasticity index (I_p) of those materials are summarised in Table 3. These test results revealed that

Fig. 25. Damage to levee at breach point. The embankment contains many boulders along with the soil. The embankment was presumably constructed from the surrounding sediment (Photos taken by Unno on December 2, 2019).

most of the retrieved materials were non-/low-plastic sandy or gravelly soils with fines contents less than 20%. According to Briaud et al. (2001) and Fujisawa et al. (2011), the erosion velocity of levees decreases with the increasing clay contents of the employed fill materials. Therefore, the slope surfaces of the breached levees presented in Sections 4 and 5 may have been relatively susceptible to overtopping-induced erosion.

6. Erosion and inland flooding along Tamagawa River

6.1. Overview of damage

The Tamagawa River is a river that flows through the Metropolis of Tokyo and Kanagawa Prefectures into Tokyo Bay. The origin of the Tamagawa River is at Mt. Kasatori in Yamanashi Prefecture. The total length is 138 km and the basin area is 1240 km^2. The levee damage and inland floods caused by the typhoon along the Tamagawa River system are reported here. According to a report by the MLIT, although overflow occurred at six locations, the typhoon did not cause any levee breaches in the Tamagawa River system.

However, the typhoon led to the recognition that flood control systems in urban areas are vulnerable. Redeveloped urban areas, such as Futako-tamagawa (Setagaya Ward, Tokyo) and Musashi-kosugi (Kawasaki City, Kanagawa Prefecture), suffered from flooding damage in residential areas because of the existence of temporary levees and an insufficient storm drainage system. Inland flooding, caused by a combination of the topological conditions and problems with the storm drainage system, also occurred in the Noge and Tamazutsumi areas of Setagaya Ward, Tokyo.

6.2. Levee damage at L23.4 k on Tamagawa River

The erosion of the flood channel, i.e., enlarged stream channel occupied during periods of high water, occurred in the Motoizumi area of Komae City, Tokyo (around 35.627736N, 139.568626E). The length of the eroded section was about 340 m (Ministry of Land, Infrastructure, Transport and Tourism, 2020a). Fig. 37 provides a bird's eye view of the levee at 23.4 k on the Tamagawa River before the typhoon. In this section, there is the low-water revetment that consists of concrete blocks and gabions. Fig. 38 shows the state of the flood channel after the typhoon. A 1-m section of the surface of the flood channel, i.e., backfill soil of the low-water revetment, was eroded due to the flooding.

6.3. Overflow in no-levee section (at L17.8 k on Tamagawa River)

The Tamagawa River was partially flooded at Futako-tamagawa in Setagaya Ward, Tokyo. Overflow in the no-levee section (35.611955N, 139.625151E) occurred at the upstream of the Futako Bridge near Futako-tamagawa Station. The river water level exceeded the highest water level recorded in the past and the elevation at the no-levee section during the typhoon. Fig. 39 shows the time history of the water level observed at the Tamagawa Water Level Observation Station (Ministry of Land, Infrastructure, Transport and Tourism, 2020b). Tempo-

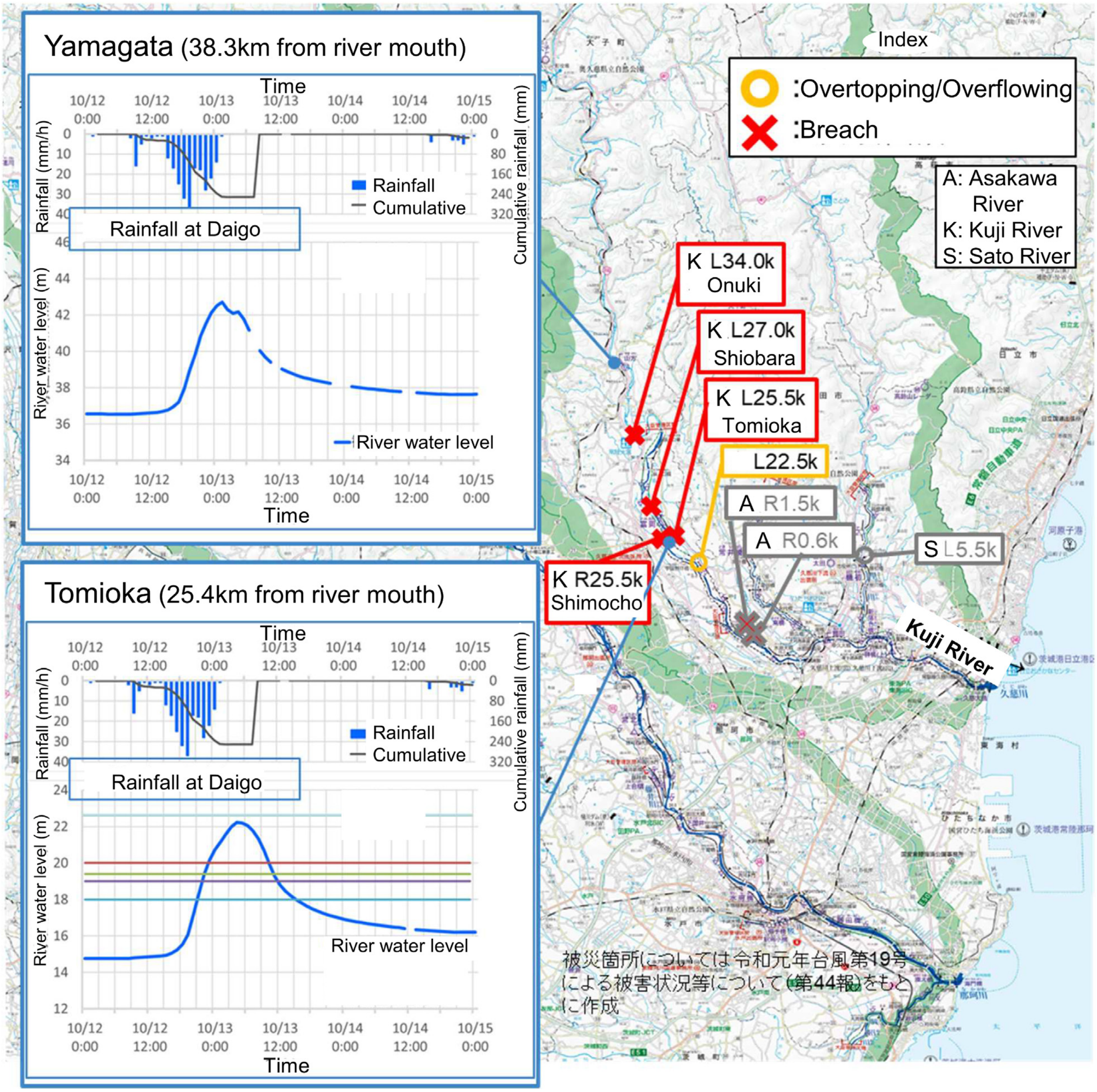


Fig. 26. Locations of representative breaches in Kuji River system and hydrographs (Investigation Committee for the Levee Breach by the 2019 Typhoon Hagibis in the Kanto Region (2020) with English translation).

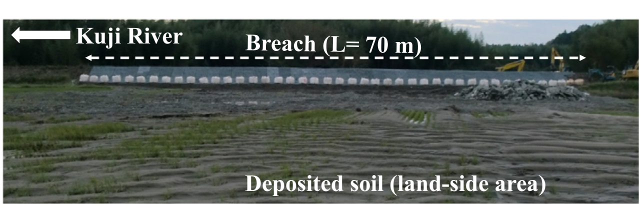


Fig. 27. Temporary restoration works of left levee at 34.0 k of Kuji River and deposited soils in land-side area.

Fig. 28. Crest pavements and revetment blocks for river-side and land-side slopes constructed before failure at 34.0 k of the Kuji River.

rary water barriers, namely, large sandbags, were placed upstream and downstream of the overflow section. Due to the section that was left open, however, flooding of approximately 0.7 ha occurred where 40 houses are located.

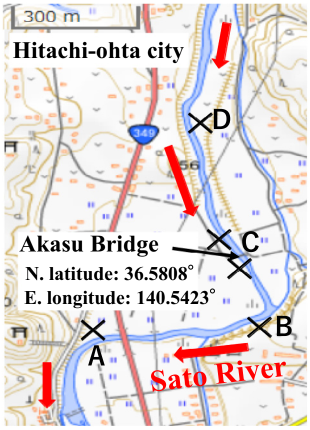


Fig. 29. Locations of levee breaches at Sato River. The standard map was obtained from the base map information of the Geospatial Information Authority of Japan. (https://cyberjapandata.gsi.go.jp/xyz/std/15/29176/12801.png, https://cyberjapandata.gsi.go.jp/xyz/std/15/29176/12802.png).

Fig. 30. Temporary restoration works of right levee of Sato River at Point C in Fig. 29 (near Akasu Bridge).

Fig. 31. Akasu Bridge constructed across Sato River.

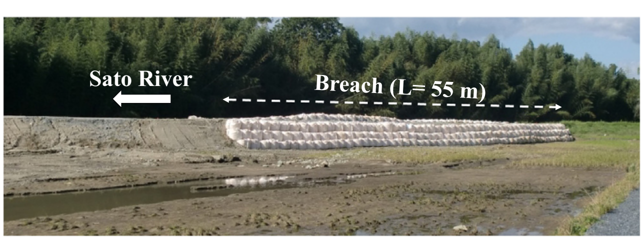


Fig. 32. Temporary restoration works of left levee of Sato River at Point D in Fig. 29.

6.4. Inland flooding

Since there were no levee breaches along the Tamagawa River, the inundation from the Tamagawa River did not bring any devastating damage over a large area. However, there was some inland flooding in the downstream areas of the Tamagawa River. In the Noge area of Setagaya Ward, Tokyo, 151 buildings, including a hospital, were damaged by inland flooding (Setagaya Ward, 2020). Noge is located between the Tamagawa River and the Maruko River, as shown in Fig. 40. In this area, the Shimonoge main storm sewer system was developed for topographical reasons. The dashed line in Fig. 40 indicates the area covered by this storm sewer system. At ordinary times, rainwater is drained via the Shimonoge sluice gate to the Tamagawa River through the storm sewer system. The Noge area also has two additional rainwater drainage facilities, Shintamagawa sluice pipe connected to the Tamagawa River and Myojin-ike spillway connected to the Maruko River.

Fig. 33. Temporary restoration works of left levee of Sato River at Point B in Fig. 29.

Fig. 34. Temporary restoration works of right levee of Sato River at Point A in Fig. 29.

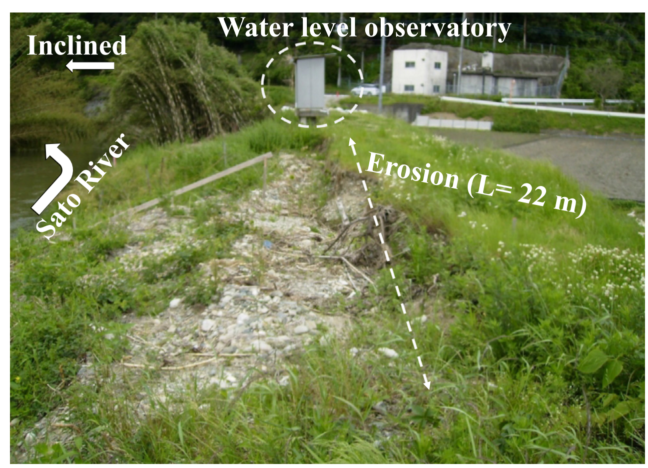


Fig. 35. Traces of erosion of river-side shoulder observed at downstream side from Point A in Fig. 29.

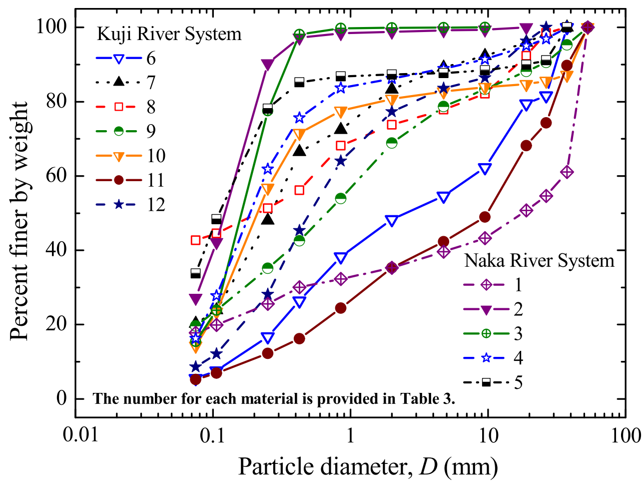


Fig. 36. Grading curves of fill materials retrieved from breached levees reported in Sections 4 and 5.

On the day of the typhoon, after the automatic closure of the Shintamagawa sluice pipe (35.609726N, 139.627997E), due to the river water level in the Tamagawa River, Shimonoge sluice gate (35.603063N, 139.638206E) was closed at 19:06 JST on 12th October 2019 to prevent backward flow from the Tamagawa River. The Myojin-ike spillway (35.604933N, 139.638334E) was closed at 19:30 JST on 12th October 2019. However, before closing the Myojin-ike spillway, river water from the Maruko River had already overflowed via this spillway to the Noge area. According to a report by the Setagaya Ward Investigation Committee (Setagaya Ward, 2020), the causes of the inundation in Noge are as follows: (1) Decreased drainage function of the storm sewer system due to the rise of the water level in the Tamagawa River, (2) Inland water that stayed in this area after the closure of the sluice gate, (3) Inflow of the river water from the Maruko River, and (4) Overflow of the river water in the no-levee section of the Tamagawa River at the upstream.

Similar inland flooding occurred nearby in the Tamazutsumi area of Setagaya Ward. Tamazutumi was also affected by the backward water flow through the storm sewer from the Tamagawa River. In Kanagawa Prefecture, the Musashi-kosugi area (Musashi-kosugi Station is located at 35.575025N, 139.663276E), that has been redeveloped in recent years, also suffered from inland flooding. In this area, water flowed backwards through the sewer from the Tamagawa River to the city because of the increased water level of the Tamagawa River.

7. Damage to river bridges due to local scour

7.1. Overview of damage

In recent years, there has been an increasing number of cases in which conventional types of river bridges are being damaged by the flooding of rivers. Most of the damage in

Table 3
Soil properties of fill materials retrieved from breached levees reported in Sections 4 and 5.

System	Naka River System					Kuji River System						
River City	Naka River Hitachi-Ohmiya					Kuji River Hitachi-Ohmiya	Sato River[1] Hitachi-Ohta					
Location	Noguchi			Shimoisehata		Onuki	Jyofukuji-cho					Chinone-cho
Position	LS	RS	IL	LS	RS	LS	LS (at A)	RS (at A)	IL (at A)	LS (at C[2])	LS (at C[3])	LS (at D)
Number in Fig. 36	1	2	3	4	5	6	7	8	9	10	11	12
D_{max} (mm)	53	19	9.5	37.5	37.5	37.5	37.5	37.5	53	53	53	26.5
D_{50} (mm)	17.74	0.12	0.16	0.19	0.11	2.51	0.26	0.21	0.67	0.21	9.86	0.51
F_c (%)	17.8	27.2	15.4	16.2	33.8	5.5	20.3	42.7	19.7	14.3	5.2	8.6
U_c	–	–	–	–	–	58.1	–	–	–	–	81.1	8.5
I_p	NP	NP	NP	NP	NP	3.3	NP	5.7	NP	NP	NP	5.5

LS: Land-side slope surface, RS: River-side slope surface, and IL: Inside of levee.
(1) All sampling locations are shown in Fig. 29.
(2) At end of upstream side of breached section with length of 80 m.
(3) At end of downstream side of breached section with length of 120 m.

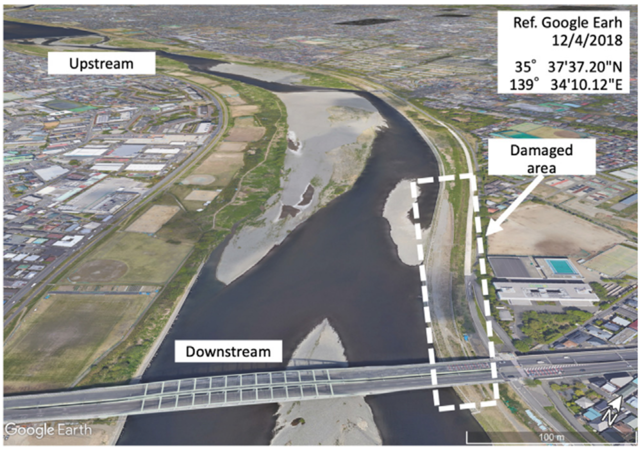


Fig. 37. Bird's eye view of levee at 23.4 k on Tamagawa River before typhoon.

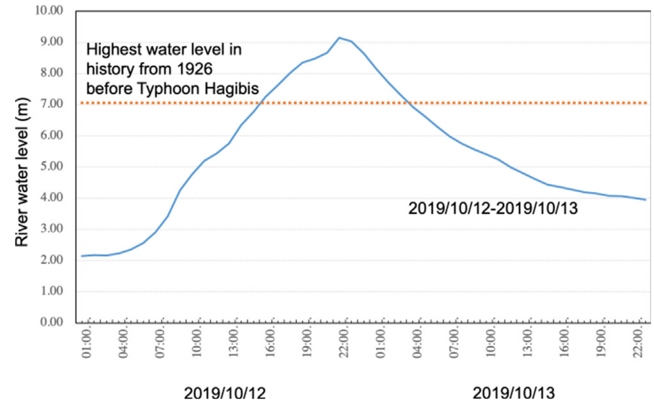


Fig. 39. Time history of river water level observed at Tamagawa Observation Station during typhoon. Data was obtained from the database maintained by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (http://www1.river.go.jp/).

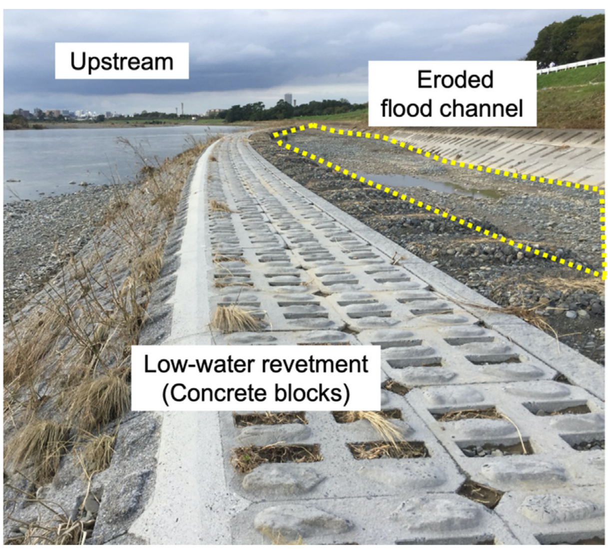


Fig. 38. Levee damage on left levee at 23.4 k on Tamagawa River.

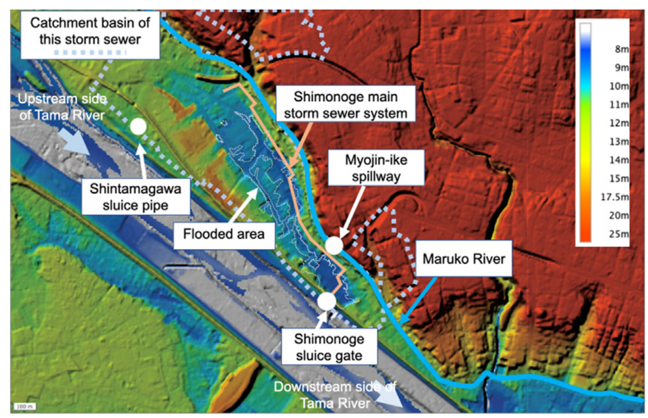


Fig. 40. Elevation map of Noge area and area flooded by typhoon with information by Setagaya Ward (2020). The colour elevation map was obtained from the base map information of the Geospatial Information Authority of Japan (https://cyberjapandata.gsi.go.jp/xyz/relief/13/7273/3227.png, https://cyberjapandata.gsi.go.jp/xyz/relief/13/7273/3228.png).

these cases has been caused by the scour around the river bridge pier foundation, and the piers have often become settled or inclined. Typical examples of scouring damage to roads, caused by the typhoon, are the Hino Bridge on Route 256 (Hachioji National Line) in Tokyo and the Hounji Bridge on National Route 20 in Yamanashi Prefecture, both of which are very important roads in Japan. Similar examples of damage caused by scouring have also been observed along railway lines, such as the Kannagawa Bridge of the JR Line.

Fig. 41 shows the damaged Hino Bridge (see Fig. 2 for the location). The Hino Bridge was constructed in 1926 as a bridge that crosses the Tamagawa River. The foundation type was an open caisson made of reinforced concrete with a width of about 3.3 m and a depth of about 5.4 m. This bridge used to be along an important road that was employed as National Route 20 until March 2007. As shown in Fig. 41, the pier settled and tilted in the upstream direction due to scour, and it took about seven months to repair it. To carry out the restoration work of the damaged pier, it was necessary to secure a construction approach road and construction yard around the damaged pier, so

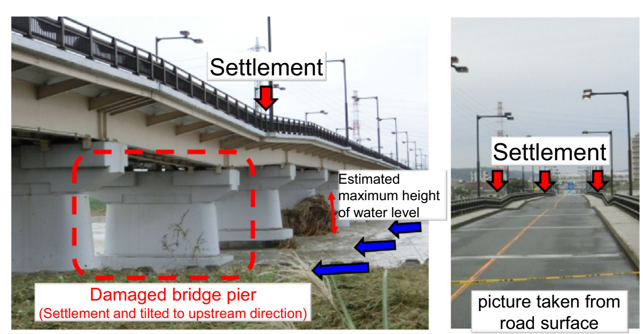


Fig. 41. Damaged river bridge pier caused by scour.

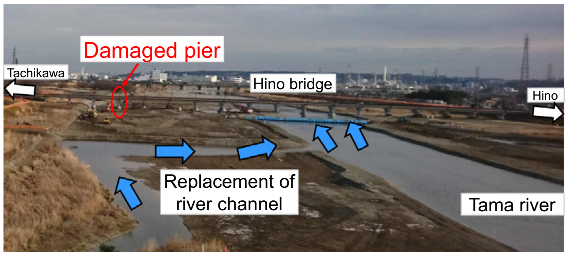


Fig. 42. River channel replacement for restoration work of Hino Bridge.

that a large-scale river channel replacement could be carried out (Fig. 42). It can be learned from this case that, once a scouring disaster occurs, the recovery work often takes a long time. Thus, it is important to take measures to prevent such disasters, as much as possible, by establishing a practical method for distinguishing the piers at high risk for scouring. As a characteristic of the recent scour damage to river bridges, bridge piers located in high water beds, which are supposed to have a low risk of scouring damage, are often damaged. The aforementioned Hino Bridge followed this exact disaster pattern, and details on it are provided in the next subsection.

7.2. Details of damage to Hino Bridge

In the 1990s, the river flow of the Tamagawa River was on the opposite side (right side) of the damaged pier (Fig. 43), and countermeasures, such as riverbed protection works, were mainly taken on the right side, which was considered to be at high risk for scouring. However, around 2010, water began to flow on the left side of the river where the damaged pier exists. This was probably due to the slow movement of a sandbar. Maintenance (general inspections) of river bridge structures is conducted in accordance with the standards or technical guidelines, and measures and reinforcement are carried out as necessary. However, it is difficult for field engineers to predict the increase in scour risk due to changes in the river flow conditions, as seen in the case of the Hino Bridge.

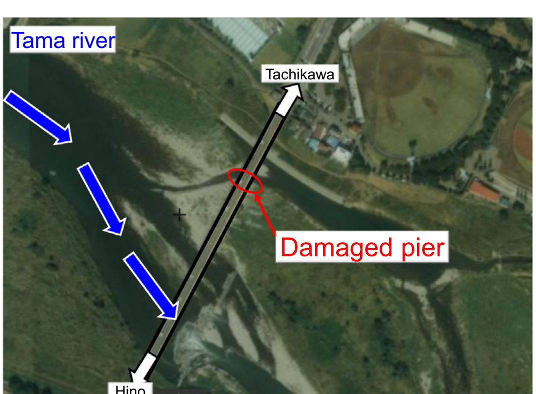


Fig. 43. River flow of Tamagawa River around 1990. The picture was obtained from the map information of the Geospatial Information Library, Geospatial Information Authority of Japan (http://geolib.gsi.go.jp//)

Fig. 44. Damaged pier during the restoration work (from downstream).

As mentioned above, the foundation of the damaged pier was an open caisson with a width of about 3.3 m and a depth of about 5.4 m, but it will be verified here whether local scour of 5 m or more can occur with a single flood. Jones (1984) summarised several empirical equations that describe the relationship between the local scour depth normalised by the pier width and the average water depth normalised by the pier width. According to the empirical equations, the local scour depth can reach up to about 1.5 times the pier width when the water depth exceeds the pier width. In the case of the Hino Bridge, the embedded depth of the foundation (5.4 m) was about 1.6 times the width of the pier (3.3 m), so local scour could reach the bottom surface of the pier foundation according to past cases.

Fig. 44 is a photograph taken from the downstream side of the damaged pier during the restoration work. It can be seen that the width of the pier has been widened at the foundation of the damaged pier, probably due to recent seismic reinforcement works. However, such seismic reinforcement cannot be seen on the adjacent undamaged pier on the near side. It is thought that the foundation was recently widened on-site for seismic reinforcement, but it is highly possible that the local scour depth increased due to such an increase in pier width. A similar phenomenon can occur due to floodwood in the river. It seems that the influence of floodwood was small for the Hino Bridge, but a large amount of floodwood in a river can dam up by the river pier. In such a case, the floodwood may increase the "apparent pier width", which may increase the local scour depth. This phenomenon has been confirmed in model hydraulic experiments simulating scouring around bridge piers (Schalko et al., 2019).

7.3. Remaining issues on scour disaster

Scour around a bridge pier foundation is a very complicated phenomenon. It varies in a complex manner depending on the water depth, flow velocity, formation of reefs, types of riverbed material, and so on. Therefore, engineers still rely on empirical approaches for flooding risk assessments of old river bridges. To conduct a quantitative scouring risk evaluation, it is necessary to track the whole process of scouring starting from river flooding, the occurrence of scouring, the progress of scouring, and bridge pier instability through an interdisciplinary approach among river engineering, geotechnical engineering, and foundation engineering.

8. Summary

Flood-induced levee damage and bridge scour due to Typhoon Hagibis in the Kanto region in 2019 have been reported. The levee breaches brought about by the typhoon mainly occurred in the northern part of the region and were concentrated on the Kuji and Naka Rivers and tributaries of the Tone and Arakawa Rivers. In most of the breached locations, the cause of the damage was the landward overtopping of the river water. Apart from the flooding induced by an inundation of river water, inland flooding and damage to river bridges due to local scour around the pier were also found. The features of the flood-induced levee damage and bridge scour caused by the typhoon are summarised below:

- The breached points in the Arakawa River system are located in a flood plain, and the soil composition of the levee and the foundation is silty or clayey soil. In such a case, the risk of breaching due to river water overtopping can be reduced by protecting the toe of the slope on the protected side with concrete blocks.
- The main cause of the levee breaches in the Naka and the Kuji River systems in Ibaraki Prefecture may have been the erosion of slopes caused by overtopping. Most of the materials retrieved from the slope surface of these breached levees were non-/low-plastic sandy or gravelly soils with fines contents of less than 20%, which indicates that the materials used to construct the levees were vulnerable to erosion.
- In the tributaries of the Tone and Naka Rivers in Tochigi Prefecture, the old levees there were mostly built with sandy soil taken from around the levee, since such levees have often been repaired with such readily available materials. However, these sandy soils around the levee are not suitable for the construction of levees because they contain many cobbles and are erodible. Therefore, the materials used for the construction and repair of levees in post-disaster recovery works should be carefully selected.
- In the Tamagawa River system, the typhoon did not cause any levee breaches. However, the typhoon revealed the vulnerability of flood control systems in metropolitan areas. Due to the insufficient storm drainage system in redeveloped urban areas, the inland flooding occurred. Apart from this, the overflow in the no-levee section and the backward water flow through the storm sewer system from the Tamagawa River also flooded the surrounding residential areas.
- Damage to a river bridge due to local scour uncovered the importance of considering the movement of sandbars in river channels, i.e., changes in river flow conditions, in scouring risk assessments. Engineers still rely on empirical approaches for flooding risk assessments of old river bridges, To conduct quantitative scouring risk evaluations, it is necessary to track the whole process of scouring starting from river flooding, the occurrence of scouring, progress of scouring, and bridge pier instability through an interdisciplinary approach among river engineering, geotechnical engineering, and foundation engineering.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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