Site Assessment and Evaluation of the Structural Damages After the Flood Disaster in the Western Black Sea Basin on August 11, 2021

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Abstract

On August 11, 2021, one of the most destructive flood disasters occurred in the Western Black Sea Basin of Turkey. The flood resulted in the death of 76 individuals, with an estimated 30,000 people being affected by the disaster. A maximum precipitation depth of 400 mm/day was recorded at one station, indicating that the flood occurred at least during a 500-year rainfall event. During a two-day site visit immediately following the flooding event, damages to infrastructures, water structures, bridges, revetment walls, highways, and residentials were observed in the Bozkurt and Ayancık regions. Based on the observations, the flood wave propagated through the original meandering river bed and floodplain, exceeding the restored river bed capacity. Due to the massive sediment transport and drifting trees, the basements of the structures in these regions were flooded and blocked. The enormous flood flow triggered extensive scouring on bridge piers, building foundations, and revetment walls, eventually causing the walls and bridges to collapse. The collapse of structures blocked the waterway and amplified the backwater effect when combined with the sediment transport. The total collapse of the revetment walls in some sections of the stream caused accelerated scouring beyond the foundations of the nearby buildings. Partial damages on the side roads along the river beds were also observed. This paper evaluated the driving mechanism of damages caused by flood flow from hydrological, structural, and geotechnical perspectives. Based on these observations and assessments, recommendations on engineering design guidelines for structures close to the floodplain, such as bridges, revetment walls, and side roads, were elaborated. Emphasis was placed on the flood-resistant design of these structures to develop a comprehensive approach for flood risk management.

1. Introduction

Flood events increase tremendously due to uncontrolled urbanization, global warming, and climate change. As a result, countries suffer not only from the loss of life but also from direct and indirect economic losses. To reduce the adverse effects caused by the flood, it is of great importance to learn from past events and understand the causes and consequences of the flood. Therefore, investigating and assessing extreme flood events and large-scale structural damages caused by flood flow play an important role in explaining the physical mechanism.

Flood events deeply affect many countries on a global scale and cause one-third of the total economic losses due to natural disasters (Chikwiramakomo et al., 2021; Loucks and Van Beek, E., 2017; Moel and Aerts, 2011; Uddin et al., 2013; Koç et al., 2021; Ozmen, 2019; Mogollon at al., 2016; Abdo et al., 2012). The most common cause of flooding is heavy rainfall or snowmelt (Paveluc et al., 2021). In addition to natural causes, human intervention in nature plays a vital role in the emergence of floods (Cai et al., 2016). With the increase in population and urbanization, uncontrolled construction interferes with the river beds (Jian et al., 2021). Therefore, the cross-sectional area of the stream decreases, and a flood occurs as a result of the construction on the floodplain (Dang et al., 2011).

Flood disaster poses a significant risk for the environment and human life (Siddiqui, 2011; Cook and Merwade, 2009). Millions of people lose their lives, and financial losses are experienced due to floods in various parts of the world. For example, Pakistan, India, and China were severely affected by floods in 2010 and Australia between 2010 and 2011 (Mueller et al., 2019; Kundzewicz, 2019; Atta-ur-Rahman., Khan, 2013). In 2008, the flood occurred due to the heavy rain and snowmelt severely affected the US State of Iowa; damaged many residences and workplaces, and 40,000 people had to leave their homes (Sönmez et al., 2013). The maximum damage caused by river flooding in a country in one year was seen in China in 2010 with 51 billion dollars (Kundzewicz, 2019). In 2010, almost 2000 people lost their lives due to monsoon floods in Pakistan (Kundzewicz et al. 2014). In May and June 2016, extreme storms in Europe caused heavy rains; the Sen River overflowed in France and flooded Germany. These disasters caused an economic loss of approximately US$ 4 billion (URL 1). In Serbia, the floods affected 1 million people and resulted in 51 casualties, of which 23 were due to drowning (Dottori et al., 2017). In Bosnia-Herzegovina, over a million people were affected by flooding, almost 90,000 were displaced, and 25 casualties were recorded (Dottori et al., 2017). In Romania, more than 11 million hectares of agricultural land was affected by floods; more than 2,000 bridges and more than 700 km of roads were destroyed; 85,000 houses were affected by floods from which 13,000 were destroyed, and 215 humans lost their lives in the flood event between May and July 1970 (Urzica and Grozavu, 2021; Chendeș et al., 2015).

Many flood events were also observed in Turkey. The Turkey Disaster Database (TABB), which was established in 2009 to collect all documents related to both natural and anthropogenic disasters, reported 1076 flood events that caused 795 deaths and economic losses of US$ 800 million from 1960 to 2014 (Koç et al., 2021; Koç and Thieken, 2018). The Black Sea, Mediterranean, and Western Anatolia regions are the most sensitive places to floods in Turkey (SYGM, 2019; Oğuz et al., 2016). The highest event frequency highest economic and human losses due to flood hazards are seen in the Black Sea region (Koç, 2021). During the flood events in Istanbul, Ankara, and Senirkent in 1995, 74 people lost their lives; 46 people were injured; 2000 people lost their homes, and 65 million dollars of economic loss occurred (Ertek, 2014; Korkanç and Korkanç, 2006). More than 2 million people were affected by the flood disasters that occurred in the Western Black Sea Region in 1998; more than 30 lives were lost, and 478 houses were completely inundated (Kömüşçü and Çelik, 2013; Ceylan et al., 2007, Ergunay, 2007; Zeybek, 1998). During the Ayamama flood, which took place in Istanbul between 8–12 September 2009, 32 people lost their lives, 3816 houses and 1490 workplaces were damaged (Kömüşçü et al. 2011). Fourteen people lost their lives in the flood in Rize on August 26, 2010 (AFAD, 2018). In addition, 77 and 30 flood incidents in Kastamonu and Sinop Provinces of Turkey from January 01, 1950, to June 01, 2018, are observed (AFAD, 2018). A review of national reports on natural disasters shows that floods are the most economically damaging natural disasters after earthquakes (Ozmen, 2019). Based on these events, it is crucial and necessary to carry out studies on floods to prevent and reduce the damages and losses in Turkey.

The hydrodynamic forces resulting from flooding cause damage to structures such as bridges, culverts, roads, revetment walls, and buildings. The direct flood damage to the structures is typically observed in two ways, i.e., wall failure or scour under foundations (Chung and Adeyeye, 2018). Flood actions that result in scour are a leading cause of bridge and structural failure (Prendergast et al., 2018). For example, washing away the soil from around bridge foundations by hydraulic action causes bridge collapse since it reduces the stiffness and capacity of foundations of bridges located in waterways (Prendergast et al., 2018; Prendergast & Gavin, 2014; Arneson et al., 2012). Therefore, there are many examples of scouring failure at bridges and culverts due to flooding (Dyke et al., 2021; Sung and Wang, 2013). Moreover, roads and highways are commonly damaged by flooding, resulting in their dysfunctionality or reducing their serviceability (Fathy et al., 2020; Ismail et al., 2019; Lertworawanich, 2012; Keller and Ketcheson, 2011). The damage on the road and highway due to flood is particularly critical since the road and highway are used to assess the area affected by the flood. Therefore, precautions should be taken to prevent damages caused by flooding, especially on roads.

Observations and site assessments of Bozkurt and Ayancık regions in the Western Black Sea Basin were reported after the flood disaster on August 11, 2021, to contribute and shed light on the existing studies on flooding. For this purpose, first, the flooded region and the flood event were explained and assessed, along with the photographs taken during the two-day site visit. Then, the causes and effects of flood and damages of flood on infrastructures, bridges, culverts, revetment walls, and highways were discussed. Finally, recommendations were made on the design guidelines of the structures located in or nearby the floodplain, which were subject to potential frequent flooding.

2. Study Area: Bozkurt & Ayancık Regions

Bozkurt and Ayancık regions are within the boundaries of the Black Sea Basin located on the northwest side of Turkey, shown in the red line in Fig. 1a. The Black Sea Basin, which is among the 25 basins in Turkey, is affected by flooding due to high rainfall intensity. The annual average precipitation was reported as 774.05 mm in Western Black Sea Basin (SYGM, 2019).

Bozkurt, the district of Kastamonu city, is located between $42^{o}\ 0^{'}\ 00^{''}$ – $41^{o}\ 40^{'}\ 0^{''}$ north latitudes and $33^{o}\ 45^{'}\ 0^{''}$ – $34^{o}\ 10^{'}\ 0^{''}$ east longitudes (Fig. 1b). The altitude of the region from sea level varies between 27 and 400 meters. The population of the region was reported about 10,000 by the Turkish Statistical Institute (URL 2). Ezine Stream flows through the Bozkurt region, with a watershed area of 375 km^2, and reaches the Black Sea downstream. The stream flows in a south-north direction, and there are high-density residential and commercial areas located on the east and west shores of the Ezine Stream.

Ayancık, the district of Sinop city, is located between $42^{o}\ 0^{'}\ 00^{''}$-$41^{o}\ 45^{'}\ 0^{''}$ north latitudes and $34^{o}\ 20^{'}\ 0^{''}$-$34^{o}\ 45^{'}\ 0^{''}$ east longitudes (Fig. 1c). The population of the region was reported about 24,000 by the Turkish Statistical Institute (URL 2). Ayancık Stream Watershed has an area of 675 km^2, and Ayancık Stream reaches the Black Sea downstream. Ayancık Stream flows through the center of the Ayancık region, and there is a residential area on the east and west sides of the Ayancık Stream at the downstream part of the watershed. While 28% of the region consists of agricultural areas, the rest of the area consists of forest since the clayey and calcareous character of the soil type provides a suitable environment for the cultivation of forest products (URL 1).

3. Assessment Of The Flood Event

3.1. Field Observations

There are several factors influencing the magnitude, frequency, and mechanisms of the flood generation, i.e., topographical, physical, or man-made. Thus, the flood development and its impact differ from one region to another (Wohl, 2000). Nevertheless, Bozkurt and Ayancık regions have their particular cases, detailed below, based on the field evidence.

3.1.1. Bozkurt Region

Although the extreme measured rainfall in Bozkurt was on the 10th of August, the destructive flood affected the region almost twenty-four hours later. The storm event started with a typical rainfall intensity followed by a peak rainfall intensity of 60 mm/h measured at the upper basin of Bozkurt on the 11th of August. Particularly, Kuz and Mamatlar areas, located 20 km away from the city center at elevations between 700–1,200 m, are significantly affected. Heavy rainfall and the steep topography of the region increased the energy of the flood flow. Due to the forestry characteristics of the region, lots of trees were washed away with the flood, which resulted in a tremendous increase in the loss of life and property. Based on the reconnaissance survey findings and individual eyewitness records, the effect of flood in the Bozkurt city center is detailed below and in Fig. 2a.

- The first indication of the flood was observed close to Grids B1 and C1, located at the intersection point of two sub-branches of the Ezine Stream. The flood carried lots of trees and logs from the forest in the early hours of the event.
- A pedestrian bridge named Bridge B5 at Grid B3 was destroyed, and the impact of the flood washed away its deck. While being dragged, the deck of Bridge B5 remained intact until it was stopped by a reinforced concrete Bridge B4 located at Grid B4. The dragged deck of Bridge B5 blocked the flow and reduced the waterway of Bridge B4, and soon backwater effect was observed as given in Fig. 7b. As the flood debris, i.e., timber logs and trees, accumulated in a short period, the depth of the flood behind Bridge B4 increased, and water flowed over the bridge in a few seconds. Based on the eyewitness videos, the flood wave amplitude was at least 2 meters higher than the bridge deck. After the backwater effect was observed, the water flowed over Bridge B4, and the city center located on the floodplain of both sides of the river was completely inundated. Since Bridge B4 was located at the city center, very close to the densely populated area (Grids C4-C5-C6 and D4-D5-D6), the flooding led to many casualties in the residential areas.
- The flood damage was more pronounced at Grids C2 to C6 and D2 to D8 located on the eastern side of the river since the ground level was approximately 2 to 4 meters lower than the western side. Therefore, the flood extent was almost 200 meters on the eastern side, whereas it was about 40 meters on the western side. Consequently, the flood effect on the residential buildings on the western side was almost negligible (Grids B2 to B4), except for the four residential buildings in Grid B5.

- The impact of the flood was dramatic both on the river bed and revetment walls along the river. Four residential buildings in Grid B5 (Buildings B2-B3-B4-B5) and almost entire industrial buildings in Grids D7 and D8 suffered from significant or total damage since the revetment structures protecting these shores lost their stability. These failures are discussed in detail in the following sections of the paper.

3.1.2. Ayancık Region

Ayancık region, located 50 km east of Bozkurt, was also significantly affected by the heavy rainfall on the 10th and 11th of August. The loss of life and property caused by the flooding in Ayancık was relatively less than the one in Bozkurt. The damages observed in the Ayancık region are presented in Fig. 2b. Locations of scoured areas, collapsed buildings and bridges can be seen in this figure. Unlike Bozkurt, the damage was observed along the river, and the flood wave did not reach the city center. The main reason for less damage was the river bed's extensive width, which is at least 100 m or greater than this value for most sections. The sediment transport over the revetment walls due to the flood was noticeable only at a couple of locations along the river-side. However, the most dramatic and extensive damages were observed in the bridges in this region. In this context, emphasis is given to the failure of the bridges in Ayancık in this paper.

3.2. Hydrologic and Hydraulic Evaluations

The causes and effects of flooding were presented based on the recorded data and observations done after post-disaster as follows:

The total precipitation recorded during the storm event at 4 rain gauge stations, i.e., Abana, Mamatlar, Kuzköy, and Devrakani, was used to find the average rainfall for the Bozkurt disaster area with Thiessen Polygon Method. The precipitation data were obtained from the Turkish State Meteorological Service (TSMS) Republic of Turkey Ministry of Environment, Urbanization and Climate Change. The weighted rainfall depth was calculated as 296.8 mm/day (Table 1). This value was by far greater than the maximum total precipitation recorded between the years 1930–2021, which was 104.7 mm/day measured in 1953 in Kastamonu (URL 3).

The total precipitation recorded during the storm event at 3 rain gauge stations, i.e., Akören, Ayancık, and Çangal, was used to find the average rainfall for the Ayancık disaster area with Thiessen Polygon Method. The weighted rainfall depth was calculated as 223.5 mm/day (Table 1). This value was greater than the maximum total precipitation recorded between 1930–2021, which was 203.2 mm/day measured in 1948 in Sinop (URL 4).

Table 1
Ezine and Ayancık Stream Watershed Weighted Rainfall Depth.

Rain Gauge Name	Effective Area (km^2)	Rainfall Depth (mm/day)	Weighted Rainfall Depth for 24 hr (mm/day)
Abana	84	228.6	**296.8**
Mamatlar	23	399.9	
Kuzköy	236	333.3	
Devrekani	32	132.8	
Akören	72	163.3	**223.5**
Ayancık	222	279.7	
Çangal	381	202.1	

In the flood management plan done by the General Directorate of Water Management (SYGM) of the Republic of Turkey Ministry of Agriculture and Forestry in 2015, the 500-year, 100-year, and 50-year flood flow rates for the Ezine Stream were calculated as 384 m^3/s, 289 m^3/s, and 245 m^3/s, respectively (SYGM, 2019) by using flow gauge station located at the downstream of the Ezine Stream Watershed shown in Fig. 1b. The flood flow and velocity estimated using the videos taken during the flood event at Bridge B5 in Fig. 2a (Grid B3) were 560 m^3/s and 7 m/s, respectively. Thus, the flood flow observed on August 11, 2021, was by far greater than the 500-year flow reported by the SYGM.

In the flood management plan done by the SYGM in 2015, the 500-year, 100-year, and 50-year flood flow rates for the Ayancık Stream were calculated as 1085 m^3/s, 815 m^3/s, and 686 m^3/s, respectively (SYGM, 2019) by using flow gauge station located at the downstream of the Ayancık Stream Watershed shown in Fig. 1c. The flood flow and velocity estimated using the videos taken during the flood event at Bridge A2 in Fig. 2b (Grid C6) were 1350 m^3/s and 5 m/s, respectively. Thus, the flood flow observed on August 11, 2021, was by far greater than the 500-year flow reported by SYGM.

To support and further strengthen the above argument, the hydrological models of both Ezine (Fig. 3a) and Ayancık (Fig. 3b) Stream Watersheds were developed by using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). Soil Conservation Service (SCS) Curve Number (CN) model was selected in the hydrological model. The CN was chosen as 65 and the percent of the impervious area was chosen as 5%. Models were simulated under the August 9–12, 2021 rainfall events (Fig. 3c-d), and hydrographs at the outlets of the watersheds for the Ezine Stream in Fig. 3e and the Ayancık Stream in Fig. 3f are obtained. Based on the HEC-HMS models outputs, the maximum flow rates in the watershed were calculated as 1026 m^3/s for the Ezine Stream and 1603 m^3/s for the Ayancık Stream (Table 2). The calculated peak flow rate for the storm event using HEC-HMS model, the observed peak flow rate using videos, and the 500-year peak flow rate (Q_{500}) calculated by SYGM (2019) for the Ezine and Ayancık Stream watersheds are given in Table 2.

Table 2
Bozkurt and Ayancık Stream flow rate.

Flow rate	Ezine Stream	Ayancık Stream
Q_{500} calculated by SYGM (2019)	383 m^3/s	1085 m^3/s
Flow rate estimated by using videos	560 m^3/s	1350 m^3/s
Flow rate for the storm event calculated by using HEC-HMS	1026 m^3/s	1603 m^3/s

- Based on the rainfall records and flow observations for the flood event, one can argue that the flood event that occurred on August 11, 2021, falls into the category of at least a 500-year storm or even a storm with a greater return period than a 500-year. The flood flow exceeded the capacities of Ezine Stream with an average width of 32 m and depth of 2.5 m and Ayancık Stream with an average width of 100 m and depth of 3 m since both Ezine Stream and Ayancık Stream were restored by taking into account the 100-year storm event.
- The flood disaster in the Bozkurt and Ayancık regions occurred due to the overflow of the Ezine Stream and Ayancık Stream. The fact that both regions are located downstream of the watershed, where the maximum flow was observed, intensifies the effect of the flood for Bozkurt (Fig. 2a) and Ayancık regions (Fig. 2b).
- The base elevations of some of the structures built on the riversides were at or even below the 100-year flood water level in the stream bed (Fig. 4).

- The residential areas exposed to flooding in the Bozkurt region are located in the original stream bed (Fig. 5a) and floodplain, where the restored river (Fig. 5b) bed capacity was exceeded. The original streambed in Fig. 5a had a meandering shape when the topography of the area was examined. In areas where revetment walls lost their stability, the stream bed tends to return its original position with severe signs of scour. This finding is supported by the scouring locations compatible with the original stream bed as given in the 1968 map in Fig. 5b with solid red zones.

- The heaviest damages on structures were observed where the original or restored stream bed has meanders. The reason was attributed to the existence of big momentum fluxes on meanders which causes big reaction forces exerted on the fluid by the structural components or soils lying under the structure. The reaction force effects on meander are shown in schematic view (Fig. 6a) and photograph (Fig. 6b).

- The water passages through water structures such as bridges and culverts on the stream bed were blocked with the deposit of trees and sediment, resulting in capacity losses in the cross-sections (Fig. 7a). Clogging of the bridges causes the backwater effect, and the water accumulated behind the bridges overflows from the stream bed towards the residential areas located on the floodplain of the stream. The backwater effect occurred in the Ezine Stream at Bridge B4 (Fig. 7b). The location of Bridge B4 (Grid B4) is shown in Fig. 2a.

- The big magnitude of flood flow along with high flood velocity and high flood depth has caused extreme scouring on bridge piers, the foundation of buildings, and revetment walls on the sides of the restored river beds. In addition, the deposit of large pieces of wood and logs carried from the forest by the flood amplified the damage to the piers and the decks. As a result, total collapse of the walls and bridges was observed (Fig. 8a-b).
- A combination of the said effects of flood, i.e., big momentum fluxes on meanders, extreme scouring, and deposition, also result in partial damages on the side roads and highways next to the river beds (Fig. 8c-d).

4. Observed Damage To Structures

The reconnaissance study carried out by our group a few days after the flood disaster covered an extensive area between Bozkurt and Ayancık regions where the regional centers and connection roads were included. Based on the findings of this survey, the damaged structures due to floods can be categorized as follows;

- Revetment walls (RW)
- Residential and commercial buildings,
- Transportation network: roads, bridges, and culverts.

The level of damage observed in the buildings can be classified as ranging from low to very high, mainly based on their proximity to the river and the land’s topography. The following sections of this paper present the observed damage and the possible causing mechanisms.

4.1. Observed damage to revetment structures

One of the most devastating effects of the flood event was on the revetment walls. Total or partial failures and collapses occurred in the revetment walls, which eventually caused amplification in the damage levels for the nearby roads and structures. It can be argued that if the revetment walls could have survived the flood, the losses would have decreased considerably.

Visual observations revealed that the walls along the riverside were either reinforced concrete T type or trapezoidal masonry walls in the flood region. Severe damage was observed in the regional center and along the connection roads and mountainous roadsides for both wall types. Along the flooded river, the failure modes of reinforced concrete revetment walls can be listed as moving out of the alignment, toppling, and separation at the joint planes. Structural failures were also observed. Masonry walls also had similar types of failures in addition to the collapse of the masonry body. It has been observed that the partial damage or total collapse on the revetment walls;

- sometimes occurred with a similar mechanism along the entire riverside section
- but in many cases, the damage was concentrated at a particular section of the wall and
- even different damage conditions could be observed on the walls on either side of the stream.

Typical damages observed in revetment walls due to the flood effect are discussed using the findings of a river section located at Grid C7 as given in Fig. 9. The authors defined three locations as L1, L2, and L3 and further evaluations are made through photographs taken during the field survey at these locations.

RW-A and RW-B were gravity-type revetment walls, RW-C was a T-type reinforced concrete wall. One of the most important findings was that the damage levels observed at RW-B and RW-C were more significant than revetment RW-A. This finding may be attributed to the bend scour mechanism in the meander regions where high shear stress zones occurred. This phenomenon was also expressed in Section 3.2. of this paper as presence of large reaction forces at these points due to big momentum fluxes. Observations made at L1 and L2 locations give evidence through Figs. 10 and 11 for why and how these revetment walls may have collapsed. Walls that toppled out of the alignment, weak joint connections, structural damage in the walls and scour below the foundations are visible in Fig. 10. Although the foundation depths of the walls were not known for certain, the walls had shallow (almost surficial) foundations, and the reinforced concrete revetment walls did not have any shear keys, which could have increased lateral stability.

- The photograph taken from the L2 location is given in Fig. 11 and shows that there is no leftover of RW-B since the entire wall totally collapsed and was washed away with the flood sediment. Therefore, only the concrete basement of the gravity-type revetment wall could be observed. As seen in Fig. 11, the bedding concrete of the RW-B gravity walls was still visible without any sign of scouring.
- The photograph taken at the L3 location is Fig. 12, which shows a collapsed revetment wall section where it is probable that the driving forces behind the revetment wall increased significantly due to the strong water flow. The water came from the back of the revetment wall and increased the driving forces, which caused the revetment wall to collapse. This effect was accompanied by the erosion of most of the backfill material.

Although heavy damage was observed on the reinforced concrete and masonry walls, there was almost no structural damage on the mass concrete walls with artificial concrete blocks to protect the wall footings (Fig. 13). These walls were located through Grids B2 to B4 in Fig. 2a. Revetment sections of these walls were supported with a concrete block along the toe for scour protection, which was probably one of the reasons to help these walls stay stable. These revetment walls were located along the west side of the river before Bridge B4 and remained stable while those walls after Bridge B4 were significantly damaged. This was an important finding as it was consistent with the progress of the flood given in Section 3.1.1.

Based on the above observations, the possible mechanisms for the failure of the revetment walls can be listed as follows;

- Due to the high flow rate and velocity of the flood, the alluvial soils, on which the revetment wall foundations were located, experienced extensive scour. This caused two critical problems for the revetment wall stability; loss of passive pressure at the foundation level and loss of bearing capacity at the foundation base.
- Due to high flood velocities (up to 7 m/s in some locations), large hydrodynamic forces combined with impact forces due to the carried tree logs caused significant lateral forces on the revetment walls.
- The increased depth of the water increased the uplift pressures; thus, revetment structures lost their vertical stability and probably lost their contact with the foundation soil which resulted in a complete loss of stability.
- The observations revealed significant soil erosion at the subsoil under building foundations and the backfills behind the revetment walls. Since the flood water washed away fine particles from the voids between the large grains, the soil skeleton became looser, resulting in lower strength and stiffness values.
- Logs and rocks carried by strong river flow directly hit the revetment walls resulting in structural damage.
- Due to increase in water levels, effective stresses changed behind the walls and below the foundations. For soils, effective stress is the main concept in geotechnical engineering which governs the compressibility and shear strength of soils. However, for the cases observed in this paper, the effect of this concept on the stability of the structures seems to be negligible compared to the effects mentioned above.

It should be noted that although all these mechanisms have separate significant effects on the revetment walls, the dominant ones on the observed damages or collapses cannot be identified because of the complexity of the flood event.

4.2. Damage to residential structures

A significant number of residential buildings were affected by the flood. Following the flood, governmental authorities carried out field surveys, and the damage distribution of buildings was listed in Table 3. Damage levels ranged from slightly damaged to collapsed, and the surveys were carried out for Kastamonu, Sinop, and Bartın cities. Therefore, based on the number of buildings affected by the flood, the flood in the Western Black Sea Region on August 11, 2021, caused one of the highest flood damage in Turkey. According to the damage assessment data published by the Ministry of Environment, Urbanization and Climate Change, 1,186 buildings were damaged at different levels due to the flood, and

154 buildings collapsed in Bozkurt and Ayancık regions (Table 3). Four of the collapsed buildings were multi-storey structures used as residences. The remaining buildings were single-storey and were used as warehouses or workplaces.

Some typical photographs of building damages are presented in Figs. 14 to 17. Building damages can be classified into two different groups;

1. Damage to infill walls due to large hydrodynamic and impact forces: Typical examples are shown in Fig. 14. McBean et al. (1988) expressed that a water velocity of 3 m/s acting over a 1 m depth can produce a force sufficient to exceed the design capacity of a typical residential wall. As given in the previous sections of this paper, the flood height increased to approximately 3–4 meters above the ground level and the flood velocity to around 7 m/s at Grid B3 in the Bozkurt region. Flood height and velocity of these magnitudes are expected to cause high lateral forces on the residential building walls. It is anticipated that the impact forces due to the materials carried by the flood amplified the lateral forces significantly.

2. Damage due to scour: Typical examples are shown in Figs. 15, 16 and 17. This type of damage ranged from,

a. local scour in the foundations, which caused none, to partial structural damage below the foundations (as exemplified in Fig. 15) to

b. total scour of the foundation materials, which led to partial or total collapse in the building (as seen in Fig. 16 and Fig. 17)

Table 3
Damage distribution of buildings (URL 5)

Location	Collapsed	Required urgent demolition	Heavily damaged	Moderate damaged	Slightly damaged
Kastamonu, Abana	6	8	2	-	65
Kastamonu, Azdavay	20	2	23	-	134
Kastamonu, Bozkurt	**27**	**71**	**43**	**3**	**541**
Kastamonu, Çatalzeytin	5	-	18	1	47
Kastamonu, Devrekani	8	-	4	-	20
Kastamonu, İnebolu	15	14	10	-	163
Kastamonu, Küre	11	3	14	-	35
Kastamonu, Pınarbaşı	-	-	-	-	2
Kastamonu, Şenpazar	-	-	3	-	100
Sinop, City Center	-	-	-	-	20
Sinop, Ayancık	**127**	**98**	**38**	**1**	**799**
Sinop, Boyabat	2	-	3	-	2
Sinop, Erfelek	1	-	-	1	1
Sinop, Türkeli	10	10	14	1	435
Bartın, Ulus	26	4	37	-	135
Total	**258**	**210**	**209**	**7**	**2499**

One of the most striking effects of the flood on the buildings occurred in Bozkurt region in Grid B5 of Fig. 2a. Three residential buildings entitled B3, B4, B5 in Fig. 17a suffered partial or total structural collapse causing several fatalities after a significant amount of scouring occurred below their foundations. All buildings in Fig. 17 were located on shallow foundations on loose alluvial deposits, which consisted of loose clays, silts, sands, and gravels. The series of events for buildings in Fig. 17 are explained below and are schematized in Fig. 18.

- In Fig. 17, the collapsed buildings were located at varying lateral distances to the revetment walls. The three collapsed buildings given in Fig. 17a were approximately 12 to 25 m far from the walls, but the building that collapsed in Fig. 17b was almost 35 m far from the revetment walls. In both cases, the buildings collapsed due to the loss of stability of the revetment walls. Once the revetment walls collapsed, the buildings founded on shallow foundations suffered partial or total collapse due to the scour of their foundation soils. Buildings as far as 35 m were affected due to the scour of the foundation subsoil.

- In Grid B5 of Fig. 2a, total collapse of the revetment walls occurred for a long portion of the riverside, which made the foundation subsoil of the buildings vulnerable to scour since the loose alluvial subsoil has a high potential for this effect. Some local people argued that a discontinuity was present in the revetment walls in this area due to some logistic and shipping purposes. This discontinuity probably accelerated the overflow of the flood and the loss of stability of the revetments. Eventually, the foundation subsoils experienced different scouring levels dominating the observed structural damage levels.

- Figure 18 presents the interrelation of stability of the revetment walls and the stability of the building on shallow foundations in Fig. 17.

- Figure 18a represents a typical building on a shallow foundation in locations where the revetment walls retained their stability. In these cases, the buildings did not suffer from any scour at the foundation soil and therefore the structural stability was provided.

- Figure 18b represents the buildings B1, B4, and B5 of Fig. 17. Although it was not possible to observe the exact foundation depth of these three buildings, the foundation depth can be accepted to be about 2 meters since it is a typical implementation in the area. These buildings experienced significant amount of scour in the foundation subsoil resulting in partial collapse of the building.

- Building B3 of Fig. 17a is schematized in Fig. 18c. For this building, the foundation depth was about 2 m, and since a great portion of the subsoil was lost, this resulted in total collapse of the building.

- Building B4 in Fig. 17a is schematized in Fig. 18d. B2 was located at a depth of 5 m. This depth saved the foundation subsoil from being scoured and this building remained undamaged.

4.3. Effects of Flood on Transportation Network

The disaster, which was defined by experts as the most devastating flood in the history of Turkey, affected three provinces and 12.000 km^2 in total in the Western Black Sea Region. The extraordinary rainfall in Kastamonu, Bartın, and Sinop provinces caused various damage to the transportation infrastructure. These damages resulted in both increased loss of life and property, difficulty in post-disaster first aid, and search and rescue efforts. Efforts were made to open the roads to traffic and to keep the main arteries open by establishing portable bridges to enable rapid transportation in the disaster area and also first aid.

Figure 19 shows the Western Black Sea Region of Turkey, and the road network of the flooded provinces of Kastamonu, Sinop, and Bartın located in this region, which were devastated by the flood (URL 6). The flood was observed to be devastating and caused various levels of damage in an area of 240 km in length, especially in areas close to the coast. Damages in the transportation infrastructure were reviewed by two separate classes; road and hydraulic structures.

4.3.1. Road Damages

The total area of the three provinces where precipitation occurred is 21,300 km², and the areas where floods were devastating in these provinces are approximately 12,000 km². In this area, there is an average of 96 m road per km². All of the roads are asphalt paved roads (URL 7). Kastamonu Province has a road network of 553 km, and a total of 59.5 km of damage was detected at different spots. 54 km of damage occurred in 564 km of road network in Sinop Province, and 41 km of road damage occurred in 111 km of road network in Bartin Province. In total, 154.5 km of roads were destroyed due to the flood and had to be rebuilt. Although there was no structural damage in some areas, roads and bridges were flooded due to rising water levels and disrupted the traffic. The roads could be made functional only after the floodwaters receded. As a result, 967 km of roads were damaged at various levels, partially or completely closed to traffic, and affected by flooding.

Damages on the roads can be reviewed under three headings;

1. Major collapses caused by floodwaters hitting the road platform

2. Partial collapse and asphalt damage due to settlements on the road platform

3. Flooding and collapses on the road platform due to insufficient capacity of the culvert.

It has been observed that the damages occurred mostly in the sections where the hydrodynamic forces act perpendicular to the road platform, depending on the flow direction. Since the damages were generally due to scour, they did not occur all along the way but occurred locally in the areas affected by the water. An example road section for this type of damage is given in Fig. 20a. In addition to these, the insufficient excess capacity of the hydraulic vents under the road platforms also caused road damage. Especially with the overflow of the culverts, the body of the road was carved from the bottom, and there were collapses on the roads. In Fig. 20b, the damaged road platform due to the culvert with insufficient capacity is shown.

In the second type of damage, a part of the road platform collapsed due to the effect of the flood, and there were ruptures in the asphalt layer in these places. Roads were partially closed to traffic in such places, or driving safety was reduced. Examples of the damage are given in Fig. 21.

4.3.2. Bridge Damages

There are many bridges with different lengths and widths due to the streams flowing through the neighborhoods and even different blocks. Bridges can be evaluated in two groups in order of importance.

1. Bridges located on the main transportation arteries, which connect the provinces, are under the responsibility of the to the Turkish Directorate of Highways for construction and maintenance.

2. Bridges connecting towns and neighborhoods, whose construction and maintenance are under the responsibility of local administrations.

Most of the bridges over the main arteries were built between 1955 and 1965. These bridges constructed between 1955 and 1965 were designed according to 100-year flood, taking into account the H20-S16 load class. Bridges on roads with less Annual Average Daily Traffic (AADT) were designed according to the H15-S12 load class. These bridges were built with simple support beams or Gerber beams. In general, they have shallow foundations without piles, with reasonable embedment depths. Between 1965 and 1975, bridges were constructed with reinforced concrete slabs. The foundations of some of these bridges were piled depending on the local soil conditions. Their load class was H20-S16.

Bridges connecting towns and neighborhoods were constructed with simple techniques, and load classes were generally H15-S12. Therefore, the damage levels were more severe in these bridges. These bridges were typically reinforced concrete slab bridges built between 1965 and 1973, consisting of 12.95 m spans. These bridges were 26 m, 39 m, 52 m, 65 m long depending on the number of spans. They often had shallow foundations.

Due to the increasing flood disasters caused by global warming and other reasons, consecutive changes have been made in the legislation. Formerly, the bridges over the main arteries were designed considering the 100-year flood depth according to the bridge design criteria set by the General Directorate of Highways. These criteria were revised five years ago due to the frequent flood events observed within the region and 500-year flood depth has been taken into consideration since then.

However, almost all of the bridges damaged in flood in the Western Black Sea Region were bridges designed and built about 40 years ago according to the previous legislation, i.e., based on 100- year flood. Therefore, the hydraulic sections of the bridges built according to the 100-year flood flow were insufficient and severe damages were observed after flooding on August 11, 2021.

Damages on bridges can be summarized under two main categories.

1. Completely damaged bridges which were washed away by flood

2. Partially damaged bridges which can be opened to traffic in a short period of time with emergency repairs

The main arteries, towns, and neighborhoods in this region are connected by 115 bridges. The total length of these bridges is approximately 4,600 m. There are 27 bridges on the main arteries that are under the responsibility of the State Highways Administration, and their total length is 1,100 m. Six of these bridges were completely damaged, and twelve were partially damaged. Of the destroyed bridges, three are in Bartın, two are in Kastamonu, and one is in Sinop (KGM, 2021a)

An example of a collapsed bridge, the Şevki Şentürk Bridge (Fig. 3.1b - Bridge A1), which failed due to the scouring of the shallow foundations, is seen in Fig. 22a. This bridge was built in 1965 to connect neighborhoods and is under the responsibility of local governments. As a result of the collapse of the piers, it lost its stability, and the middle spans crumbled. Another destroyed bridge was the 68 m long Çatalzeytin Bridge on the İnebolu-Abana-Çatalzeytin road (Fig. 22b). Çatalzeytin Bridge was a Gerber girder bridge built in 1963 with spans of 21.30 m + 24.75 m + 21.45 m (KGM, 2021b). The cross-section of the destroyed bridge is shown in Fig. 23a. Since the foundations of the bridge were superficial, the original soil, in which the bridge abutments were founded, has been carved because of the flood, and the bridge completely collapsed and was washed away. A new bridge with pile foundations was designed based on the 500-year flood flow and constructed to replace the damaged Çatalzeytin Bridge. Figure 23b shows the cross-section of new Çatalzeytin Bridge.

Slight damages were observed commonly in bridges constructed on pile foundations. An example to this was the 113 m long Abana Bridge on the İnebolu-Abana-Çatalzeytin road. This bridge was a 7-span bridge with pile foundations. Only the pedestrian guardrails were damaged due to the flooded materials such as trees and logs. The bridge was submerged due to the overflow; however, the road was reopened to traffic after the flood water level receded.

For partially damaged bridges that could be reopened to traffic with rapid intervention, it was observed that most of the damage in these bridges were occurred due to scouring at the approach embankment. Figure 24a shows an example of this kind of bridge damage whose approach embankment was damaged due to flooding. Another important factor of the bridge damages was flood debris. The damage to the piers increased as large trees and logs, transported by the flood, hit the bridge piers laterally. In addition, these trees and logs blocked the waterway of the bridges, resulting in additional horizontal pressure on the bridges, as seen in Fig. 24b.

Striking damage to the bridge piers was observed on the 90 m long Ayancık Bridge (Fig. 2b - Bridge A2 at Grid C6), which consists of four middle piers. The superstructure of the bridge was Gerber beams. The oval geometry of the bridge piers was chosen to reduce the scour effect; and the foundations of the bridge were not on piles. During the field investigations, severe damages were observed on Pier 1 and Pier 2 (Figs. 4.25a and 25b). Pier 1 has indications of severe scouring, whereas Pier 2 has structural damage, most likely due to the interaction with the superstructure. The plan view in Fig. 25 shows that the stream bed has a curved geometry with an estimated radius of 350–380 m. The eyewitness records clearly showed that a massive amount of debris was carried by the flood very close to the shoreline as the river geometry curves towards the bridge location. As the dragged trees and logs hit the piers with the flooding, an additional impact and turbulence were induced on Piers 1 and 2. The observed damage on these piers may be attributed to the curved geometry of the river, which caused additional centrifugal impact forces on Piers 1 and 2. Piers 3 and 4, which were less affected by the impact of the transported materials on the other hand, remained stable after the flood. The damage observed in this bridge reveals that the curvature of the stream at the bridge location and the magnitude of the flood can make some of the bridge piers more vulnerable to flood damages than other neighboring piers.

5. Mitigation And Remediation

5.1. Hydrologic and Hydraulic Perspective

The following recommendations are made from the hydrological perspective to reduce the flood damages based on the lessons learned from the flood event:

a. The observations show that the classical approach of flood damage evaluation, which was done only with respect to flood depth and flood extent, was not sufficient for flood management. The structures may suffer from the forces due to the large momentum fluxes and high velocities, which will result in huge scouring and partial or total collapse of the structures within the area. Therefore, the engineering design guidelines of the structures, including bridges, culverts, revetment walls, and side roads and highways located close to the floodplain, should be elaborated by taking into account the flood conditions.

b. Settlements in the original stream bed and floodplain, downstream of the watershed, and in curvatures of meanders should be avoided.

c. The base elevations of the structures built on the riversides should be at least above the 100-year flood water level or possibly the 500-year flood water level.

d. The design of the water structures, especially the ones close to the residential areas, should be done by taking into account the 500-year flood flow. In addition, the hydraulic dimensions of all existing major bridges located in regions where frequent heavy rainfall is observed should be reviewed, and in case of necessity, cross-section enlargements should be recommended and implemented.

e. Flood management plans, which involve flood hazard and flood risk maps for 500-year floods for each basin of Turkey, were prepared by the General Directorate of Water Management and revised every six years. In light of these plans, it is of utmost importance to plan and implement the measures which should be taken before, during, and after floods, especially for regions with high flood risk.

f. “Best Management Practices” such as ponds and flood traps to reduce the effect of flood flow in the watershed and water structures to control the sediment transport due to the flood should be planned and implemented.

g. It is important to establish an early flood warning system in regions under extreme flood risk.

5.2. Structural and Geotechnical Perspective

a. The damage patterns observed in this disaster revealed that the most damage-prone areas in case of flood include high-velocity areas and meander bend zones, where higher shear stresses occur. Therefore, special precautions should be taken for these sections, such as revetments.

b. Revetment stability during floods becomes significantly essential for decreasing the losses due to flood damage. This requirement can be achieved by maintaining the lateral resistance during floods. Deeper shallow foundations combined with solid scour measures or deep foundations below the revetments should be considered, especially in urban areas. Revetments should be constructed continuously to ensure no weak zones or discontinuities. If such discontinuities exist, especially in bending zones, these zones may govern the flood damage.

c. The foundation depth is of utmost importance for buildings close to the river bed. In case the revetments fail during the flood event, a significant amount of foundation subsoil may be lost due to accelerated scour, resulting in structural collapses. Since these areas are generally loose alluvial soils, the vulnerability to scour is already very high.

d. The countermeasures for the foundations of the revetment walls against scour were not adequate for this flood. Foundation protection against scouring for these structures should be designed conservatively for both the depth and the width of the scour protection elements. Present revetment walls probably lacked appropriate scour protection countermeasures for the flood. In any case, scour measures in urban areas should use materials resistant to erosion in case ordinary soil measures do not work.

5.3. Roads and transportation structures perspective

a. The major collapse on the roads was observed with a direct impact of the flood to the road platform accompanied by the asphalt damage due to settlements on the road platform. At some sections, the insufficient capacity of the culverts also triggered the damages.

b. The bridges were destroyed due to the loss of foundation stability induced by scouring in the stream bed and the rotations and displacements of the piers. In addition, the bridge piers, which became unstable because of the scouring of the stream bed were either with piers or shallow foundations.

c. The performance of the bridges in Ayancık should be evaluated based on the fact that the bridges were about 40–50 years old and were designed according to the 100-year flood, and some strengthening options may be recommended.

d. Based on the field observations, it can be expressed that bridges with piled foundations were either undamaged or partially damaged and did not collapse. Another finding was that bridges with both pile foundations and continuous superstructures performed better against the destructive effect of flood. Considering that these bridges were built 40–50 years ago and were designed according to the 100-year flood, one can argue that bridges with pile foundations performed well.

e. From the design perspective, it can be concluded that even though the use of shallow foundations can be adequate from a geotechnical point of view, in regions prone to flood risk, the use of pile foundations should be recommended unless it is proven that shallow foundations can protect the bridge piers from flood induced loads and effects.

6. Conclusions

On August 11, 2021, one of Turkey's most destructive flood disasters occurred in the Bozkurt and Ayancık regions in the Western Black Sea Basin. The flood resulted in the loss of 76 individuals, with an estimated 30,000 people being affected by the disaster. To contribute and shed light on the existing studies on flooding, this paper presents the observations and site assessment of the Bozkurt and Ayancık regions after the flood disaster. For this purpose, first, the flooded region and the flood event were explained along with the photographs taken during the two-day site visit. The causes, effects of flood and damages of flood on infrastructures, bridges, revetment walls, and highways were discussed within an integrated framework involving hydraulics, geotechnics, structures, and transport perspectives. Finally, as a result of lessons learned, the following arguments and recommendations were made on the design guidelines of the structures located in or nearby the floodplain, which were subject to potential frequent flooding;

● The damage level of the flood was more pronounced in curvatures of meanders or in places where the original stream bed was located before stream restoration. Thus, urbanization and the construction of infrastructures should be avoided in these regions.

● The 500-year flood flow should be considered in the design guidelines of at least critical infrastructures such as bridges, highways, and revetment walls.

● The flood caused not only non-structural damage but also severe structural damages. These damages were mainly due to the high energy and momentum flux of the flood. Therefore, flood damage evaluation in flood management plans should emphasize the importance of the construction of flood-resistant structures and non-construction of structures in flood plain according to 500-year flood depth and flood extent.

● The revetment stability in urban areas should be provided at all cost. This stability can be achieved by maintaining the lateral resistance, i.e., increasing shallow foundation depths or using piled foundations and appropriate scour protection measures. In addition, weak zones and discontinuities in the revetments should be avoided.

● The foundation depths of the buildings close to the river bed should be chosen deep enough so that they are not affected by the flood-induced scour in case the revetments fail. For the existing buildings that do not have enough foundation depth, other protective measures should be taken within the context of the flood risk management projects in Turkey.

● The bridges were destroyed due to the loss of pier stability due to the scour in the stream bed and the rotations and movement of the pier foundations. In addition, the bridge piers, which became unstable because of the scouring of the stream bed, were generally with shallow foundations and no piles.

● Bridges with both pile foundations and continuous superstructures performed better against the destructive effect of the flood. Considering that these bridges were built 40–50 years ago and designed according to the 100-year flood flow, one can argue that bridges with pile foundations have performed well. Therefore, pile foundations in bridge piers should be considered for areas with high flood risk unless proven otherwise.

● Although the typical flood hazard microzonation studies consider the depth and the extent of the flood as the only damaging criteria, the damages observed in this flood showed that this should be accepted as the primary damage-making phenomenon. The floods inherently involve significant secondary damage-making phenomena, such as high energy and momentum flux on neighboring structures and meanders, and these secondary effects should be incorporated into flood hazard assessment studies so that a comprehensive approach can be developed.

Declarations

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Figures

Figure 1

Location and boundaries of (a) Turkey (b) Bozkurt (Ezine) and (c) Ayancık Stream Watershed

Figure 2

Key Plans: Bridges, collapsed buildings, and scoured areas (a) Bozkurt (Google Earth, 2021a) (b) Ayancık (Google Earth, 2021b)

Figure 3

Hydrological Models with HEC-HMS for (a) Ezine Stream Watershed and (b) Ayancık Stream Watershed; rainfall intensities for (c) Ezine Stream Watershed and (d) Ayancık Stream Watershed; and Flood Hydrographs for (e) Ezine and (f) Ayancık Stream.

Figure 4

Structure base elevation and flood level.

Figure 5

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(a) Schematic view and (b) photograph for the reaction force (momentum flux) on meanders.

Figure 7

The photograph taken (a) before and (b) after the backwater effect occurred at Bridge B4 (screen shot of a video record taken during the flood disaster).

Figure 8

Scouring effects on various structural systems and roads/highways.

Figure 9

Key plan for the damaged revetment walls at Grid C7

Figure 10

Most of the RW-C walls were damaged or collapsed, with indications of scour (at L1)

Figure 11

RW-B was washed away, and bedding concrete was seen at L2.

Figure 12

The backfill of the gravity type RW-B was heavily eroded at OP3.

Figure 13

Revetment walls which did not damage.

Figure 14

Infill walls collapsing due to hydrodynamic forces

Figure 15

The structures with local scour under the foundation with none to minor structural damage (Bozkurt region)

Figure 16

Single-storey workplace buildings partially collapsed due to the scour effect (Ayancık region)

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Multi-storey residential buildings partially-totally collapsed due to the scour effect (Bozkurt region)

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Scour effect on multi-storey buildings (a) Shallow foundation, no scouring, (b) Shallow foundation at about 2 m and partial collapse, (c) Shallow foundation at about 2 m and total collapse, (d) Shallow foundation at 5 m depth foundation, no damage

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Road network of the flood-affected area (URL 6)

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(a) Scouring in the road depending on the direction of the water flow in Ayancık region (b) Damaged road platform due to the culvert with insufficient capacity

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Partial collapse and asphalt damage due to settlements on the road platform

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Examples of (a) Damage of approach embankment (b) Blocked waterway of bridge.

Figure 25

Damaged Ayancık Bridge (Bridge A2) and schematic description of the damage mechanism (HGM Atlas, 2022).