3rd International Conference on Natural Hazards & Infrastructure

5-7 July 2022, Athens, Greece

Initial geo-structural performance observations of critical infrastructure components during the 2021 Western European Floods

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ABSTRACT

Record rainfall triggered devastating and deadly flooding in Western Europe between July 14-16th, 2021. The extreme weather event killed more than 230 people in Germany and Belgium and cost billions of dollars in damage. Reconnaissance studies within some of the most affected areas of all three countries, provided insight into geotechnical and geo-structural performance behavior of critical infrastructure elements, such as bridges and road networks. This paper presents selected reconnaissance observations of infrastructure elements in Germany to investigate the water-soil-structure interaction during flood events, as well as the resulting damage evolution and failure progression based on documented case studies. The reconnaissance team used terrestrial LIDAR technology, visual observations, and UAV imaging to discern critical damage patterns at the foundation level (e.g., loss of local and/or global stability due to support failure) and the abutment connection (disconnect of bridge and adjacent soils due to flushing and erosion), as well as to document soil relocation patterns. These mechanisms also appear to represent key failure initiators, alongside heavy impact loading from debris and tree logs.

Keywords: 2021 Western European Flood, reconnaissance, bridge damage, infrastructure damage

INTRODUCTION

Floods, often triggered by heavy rainfall or snowmelt, are the most common natural disasters worldwide. In the last 20 years, 36.5 percent of recorded disaster events were associated with flooding (Schafferus, 2021). The July 2021 Western European flood is considered the deadliest flood in recent European history. According to floodlist.com, July 2021 represented the worst flood month on record with over 920 casualties in floods, landslides, and other rain-related incidents worldwide (Davies, 2021). While areas in Germany

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(e.g., Valley of the river Ahr, “Ahrtal”) have historically experienced multiple significant flood events, the 2021 event surpasses any of the previously recorded death tolls in Europe (Figure 1).
Over a period of two days (July 14-15th, 2021) the low pressure system “Bernd” stalled over Western Europe, leading to record-setting rain over Belgium, Germany, Luxembourg, Switzerland, France and the Netherlands, with local precipitation volumes of up to 240 l/m^2. Along the severely flooded 40 km long stretch of the Ahr valley in Germany, water levels exceeded roughly 9 m, where the typical water height of the Ahr is between 0.7 m and 1.0 m. Considerable damage to the built environment included residential houses, motorways and railway lines, bridges and other essential facilities (e.g., industrial plants, wastewater treatment plants, power transmission structures and telecommunication facilities). Road destruction and closures left many areas inaccessible for days, cutting off villages from evacuation routes and emergency response units. Recent estimates by the German insurance and risk analysis company *Munich Re* estimate flood related damages in Germany to accumulate to 33 billion Euros (Tagesschau.de, 2022).

Figure 1. *Historic death toll in European countries over the last 20 years. (adapted and updated from https://ednh.news/why-have-the-floods-in-europe-been-so-deadly/)*

An international team of the Geotechnical Extreme Events Reconnaissance association (GEER; geerassociation.org) mobilized in August 2021 to collect perishable data associated with soil response, soil/rock erosion and deposition, and soil-structure interaction during the flood event. Within Germany, the reconnaissance efforts focused on the river Erft and the river Ahr. The reconnaissance team visited the most heavily affected flood areas from Aug 8, 2021 - Aug 18, 2021 and had the opportunity to meet with emergency response agencies, governmental representatives, and on-site response units (e.g., Technisches Hilfswerk, German Military, German Red Cross), local authorities, as well as flood survivors to learn about hazard warnings, flood progression, post-flood response, emergency care, and temporary infrastructure rehabilitation in the devastated areas. This conference article provides initial insights from observations and data collected during the reconnaissance mission and discusses preliminary considerations regarding the performance of geo-structures.

OVERVIEW OF DATA COLLECTION METHODS

Perishable field data was collected using portable and small-scale devices due to access limitations and to facilitate mobility. Soil samples were obtained at sites of particular interest. To expand the coverage, density, and diversity of data collected, a variety of remote sensing technologies including unmanned aerial vehicle (UAV) and mobile phone photography, terrestrial LiDAR, multispectral photography, and optical satellite imagery were utilized. Mobile device photography was used for the purpose of rapid documentation. UAV photography provided different vantage points of features of interest, and allowed for larger spatial coverage and maneuverability. UAVs are particularly useful in post-disaster reconnaissance to observe and document damage in areas that are inaccessible or unsafe to access on foot. Additionally, UAV imagery was used to generate Structure-from-Motion (SfM) models, which provide three-dimensional point clouds and meshes, digital elevation and surface models, orthomosaics, and optical panoramics of features of interest. Terrestrial LiDAR scans, similar to UAV SfM models, provide a three-dimensional point cloud to document damage with high precision and resolution and, unlike UAVs, can effectively collect measurements in the presence of vegetation. Terrestrial LiDAR collection generally offers higher resolution and accuracy than SfM models and individual scans are quickly and easily registered to create the resulting point cloud; however, the instrument can only collect data by line-of-sight which often results in large areas where there is no coverage. As such, terrestrial LiDAR is ideal for generating detailed models of specific portions or features of structures where access is available, while UAV data collection provides broad and rapid documentation of damage in three dimensions. The three-dimensional models, whether generated using LiDAR or UAV data, document the spatial extent of damage in high-resolution which enables measurement of feature geometries, inputs and validation of numerical modelling and simulations, and more in-depth investigation into how elements performed.

The collection of post-event satellite imagery served as a tool for the GEER team to assess the condition of large areas as well as confirm reports of damage. Copernicus Emergency Management Service (EMS) provided open-source post-event imagery with damage classifications at the asset level, including estimates of damage to individual buildings and roads as well as flooding extent. Pre-event satellite images from Google Earth were equally useful in determining the local conditions before the flooding. This provided insights into general performance behavior and damage extent across a wide area of flooded terrain.

RECONNAISSANCE OBSERVATIONS

Road/Embankment damage

Road damage and/or complete road destruction was amongst the most critical infrastructure loss immediately following the flood event. Approximately 130 km of road damage with repair costs of more than 100 million Euros was recorded for Germany’s freeway system “Autobahn” (Wehman, 2022). Even well after water levels dropped to normal levels several major freeway intersections (e.g., A1/A62 near Erftstadt Blessem) have remained closed with repair work to be completed no earlier than summer 2022 (Wehmann, 2022). The German state of North Rhine-Westphalia (NRW) reported road closures of 220 roads immediately following the flood and more than 350 damage incidents of which 89 have been repaired by mid-August 2021. Approximately 70 state and federal roads were still completely or partially closed at the time of the reconnaissance team's visit (RP Online, 2021). Within the Ahr valley (Rheinland Palatine, RP), over 74 kilometers of roads, paths, and bridges along and across the Ahr river were (critically) damaged. Many parts of the Ahr valley (e.g., near Altenahr, Mayschoss, Dernau) remained inaccessible for up to three days following the flood, due to road infrastructure being washed away. In addition, thousands of cars, caravans, and other debris, carried by the flood, blocked streets, bridges, and other critical access gateways.
Approximately 50,000 cases of vehicle damage have been reported in RP and NRW, accumulating to a financial loss of more than 450 million Euros (ADAC, 2021). This puts damage to vehicle caused by storm "Bernd" in second place among the worst natural catastrophes in Germany to date with hail "Andreas" in July 2013 leading the ranking (ADAC, 2021). Many urban communities experienced similarly heavy infrastructure damage. Roads to and within city centers were destroyed in large parts of Bad Münstereifel, Euskirchen, and Erfstadt-Blessem (Fig.2). Road damage extended beyond surface elevations into deeper subsurface regions, often exposing critical utility infrastructure, commonly buried at a minimum depth of 80 cm below ground.

Figure 2*. Road damage in urban areas at the Werther Tor (gate), Bad Münstereifel (left) and in the city center of Euskirchen (right)*

Key connection roads between towns were also destroyed or damaged to the level that required immediate repair to reintroduce or maintain safe access to towns and areas. Figure 3 shows ongoing repairs of localized embankment failure along highway L73 near the town of Schuld (in the Ahr valley). The local embankment failure was unique in that it included soil nailing, which is rare in the region. Failure likely occurred as a result of increased active earth pressure due to backfill saturation and insufficiently long soil nails (which were roughly 2m in depth). Repair work was underway at the time of the team's visit and involved 10 m long soil nails and the top row of pins will be driven into bedrock (personal communication with onsite contractors).

Figure 3. Ongoing repairs of localized embankment failure along highway L73

Bridge damage

Of the 112 bridges located in the flooded 40 km of the Ahr Valley (Rheinland Pfalz), 62 bridges were destroyed, 17 were severely damaged, and only 35 were in operation a month after the flood event (Rheinland-Pfalz ADD 2021; Staib, 2021). Most historic bridges were either destroyed and carried away by the flood or suffered irreparable damage at almost all bridge components (abutments, piers, deck). Figures 4 shows a historical bridge in Wershofen. This bridge suffered significant erosion and scour around the bridge abutment —a phenomenon that was observed at many of the bridge failures—which likely triggered the collapse of the bridge deck. The abutment structure was missing at the time of the team's visit and construction work was in place to fill the missing bridge segment with soil to enable vehicular cross passage.

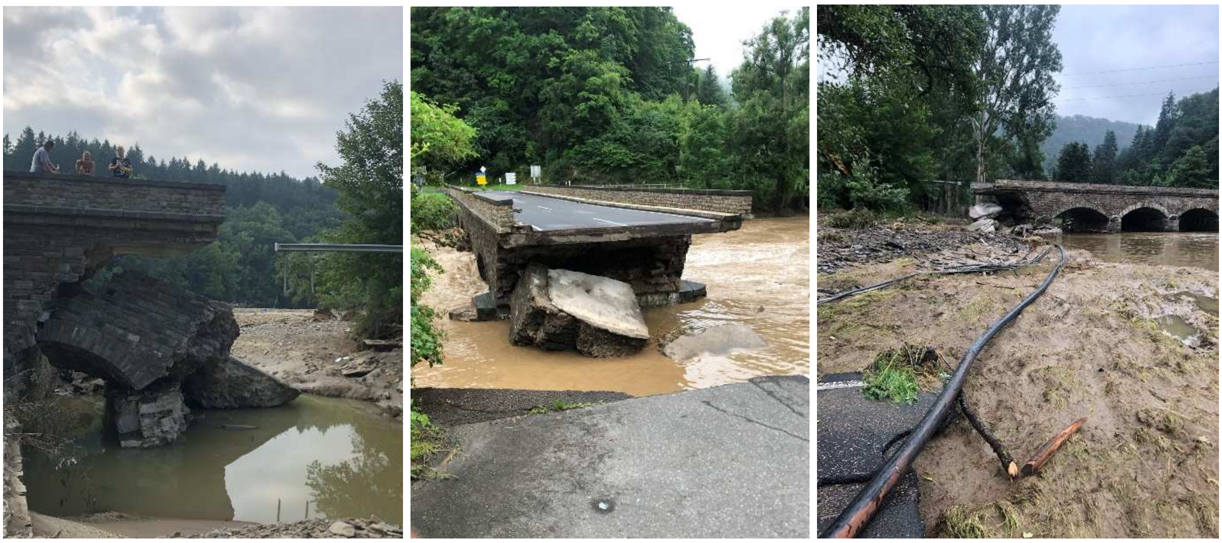

Figure 4. Bridge damage to historical bridge near Wershofen

Temporary bridges were erected by the German Emergency Response Unit (Technisches Hilfswerk) and the German Military. Some of these bridges are likely to remain in place for several years until the construction of replacement bridges begins. Six months after the flood event, eight emergency bridges with spans ranging from 24 m to 52 m have been built or are currently in construction (Dernau, Bad Neuenahr-Ahrweiler, Ahrbrueck, Insul, Laach, Liars, Rech), (Zeit.de, 2021).
Newer bridges also suffered substantial damage, as shown in Figure 5: a road bridge in Bad Neuenahr-Ahrweiler before and after the flood event (Fig. 5 top row, (note the large amount of entangled debris)), an unrepairable road bridge in Dernau, and a destroyed bicycle bridge in Reimerzhoven. Both cable span bridges followed an identical damage pattern, where one abutment is still standing while the bridge deck has been lifted up at its opposite support and subsequently rotated (and failed) in downstream direction. The bridge deck of the two-span reinforced concrete bridge in Dernau (Figure 5 bottom, left) collapsed due to failure of the middle pier foundation, which was destroyed/removed by the flood.

Figure 5: *Otlerbruecker, Bad Neuenahr Ahrweiler: before the flood (top left) Source: (https://www.aw-wiki.de/w/index.php?curid=49168), and at the time of the visit (top right); Road bridge failure in Dernau (bottom, left), and bicycle bridge damage in Reizenhoven, near Altenahr (bottom, right).*

Road damage and bridge damage at the tunnel exit in Altenahr

The tunnel exit in Altenahr has been one of the most highlighted damages in the news coverage of the Ahr valley in Germany. Figure 6 (a) shows a Google Street View of the tunnel exit in May 2021, followed by a photograph of the tunnel exit during the 100-year flood in 2016 (Fig. 6 (b)). Figure 6c shows the tunnel exit and surrounding area on August 13, 2021, approximately 4 weeks after the flood. The tunnel street (Tunnelstrasse) was completely destroyed by the water efflux rushing out of the tunnel exit and exposed underlying bedrock to depth of about 2-3 m. Near the tunnel exit a double bridge connected railway tracks and a road across the Ahr river. Figure 7 shows the severe damage to both bridges, but also the extent of sediment relocation and streambed destruction at this location. In the back of the image, a water treatment plant is visible which was also affected by the flood event. The image also highlights a key geological and topographic characteristic of the Ahr valley: its steep slopes and limited width of the river valley. This topography has been highlighted as a key issue that led to the severity of the flood in the Ahr valley. This location is especially of interest for documenting how soil relocations near the tunnel and interjecting with the Ahr river relate to local hydraulics, geology, and abundant infrastructure. The location serves as an example of multiple key infrastructure items intersecting with a restrictive, steep geology, and the river, and where the presence of infrastructure, such as the tunnel, led to a significant change in local hydraulics.

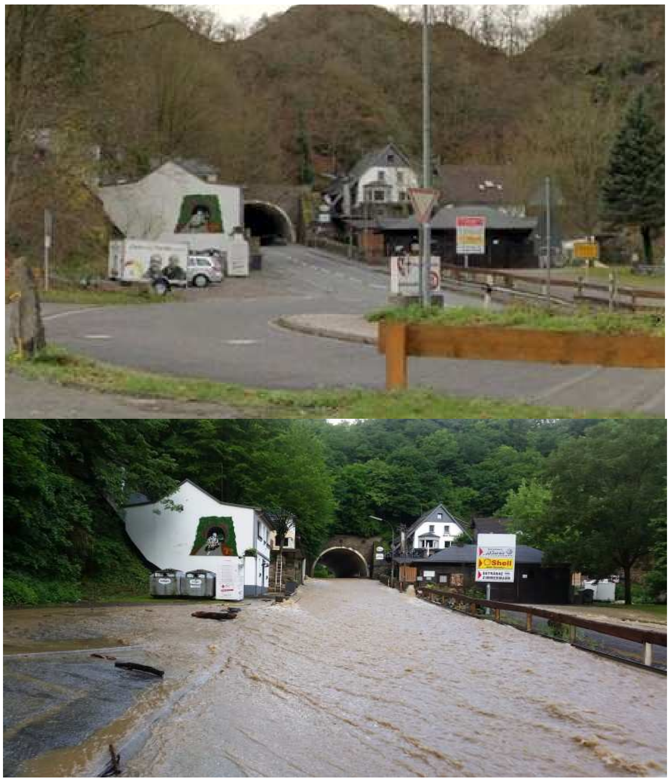

Figure 6. *Top: Google Earth/Maps Street View of the Altenahr tunnel from May 2021; center: photo during the June 2016 flood event; bottom: photo by the reconnaissance team after the 2021 flood, August 2021.*

Figure 7. *Aerial image of the Altenahr tunnel exit and double bridge, August 13th, 2021*

Figure 8 depicts an excerpt of initially collected 3D point cloud data of the double bridge using the terrestrial LiDAR. Data processing from this location (as well as most others) is still ongoing. The generation of the point cloud model (Figures 8 and 9) from terrestrial LiDAR allows for geometric measurements of features of interest. As shown in Figure 9, estimates of the total bridge height, clearance height, and cross-sectional distance of the river were found to be 17.96m, 14.72m, and 45.50m respectively. Possible future geometric measurements include volume of soil lost due to scour and erosion, angle of pier tilt, deck deflection, and the dimensions of resulting cracks in decks or piers. Similar measurements will be possible in point clouds generated from UAV imagery, albeit with less accuracy.

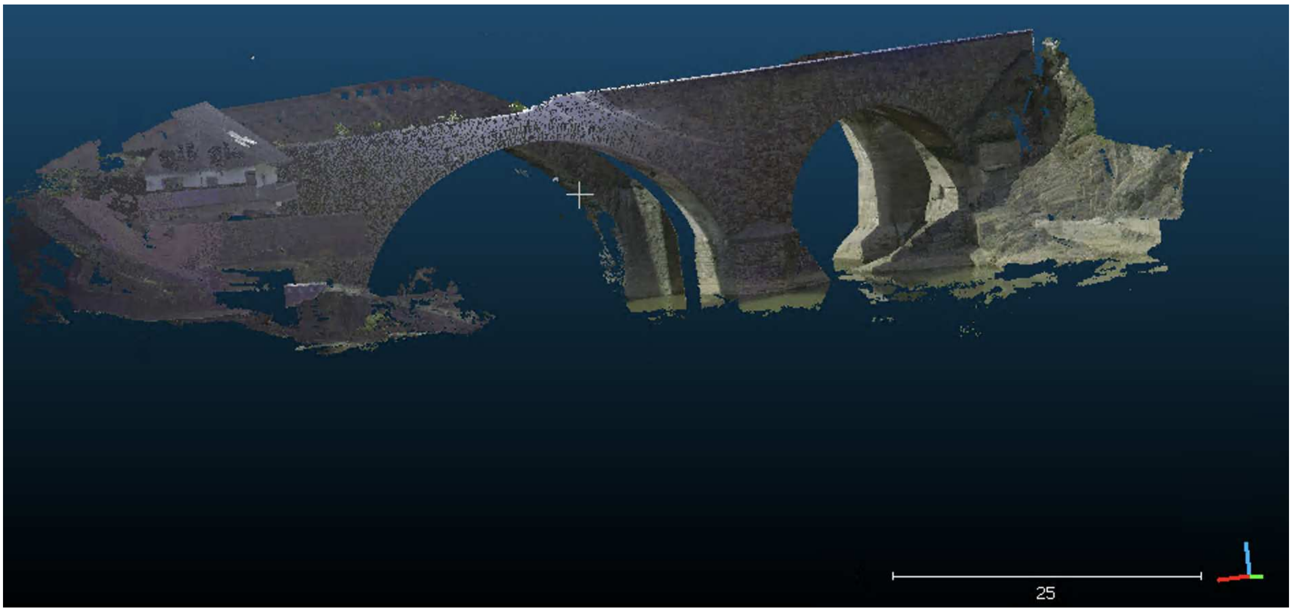

Figure 8. *3D point cloud excerpt derived from terrestrial LiDAR at the Altennahr double bridge.*

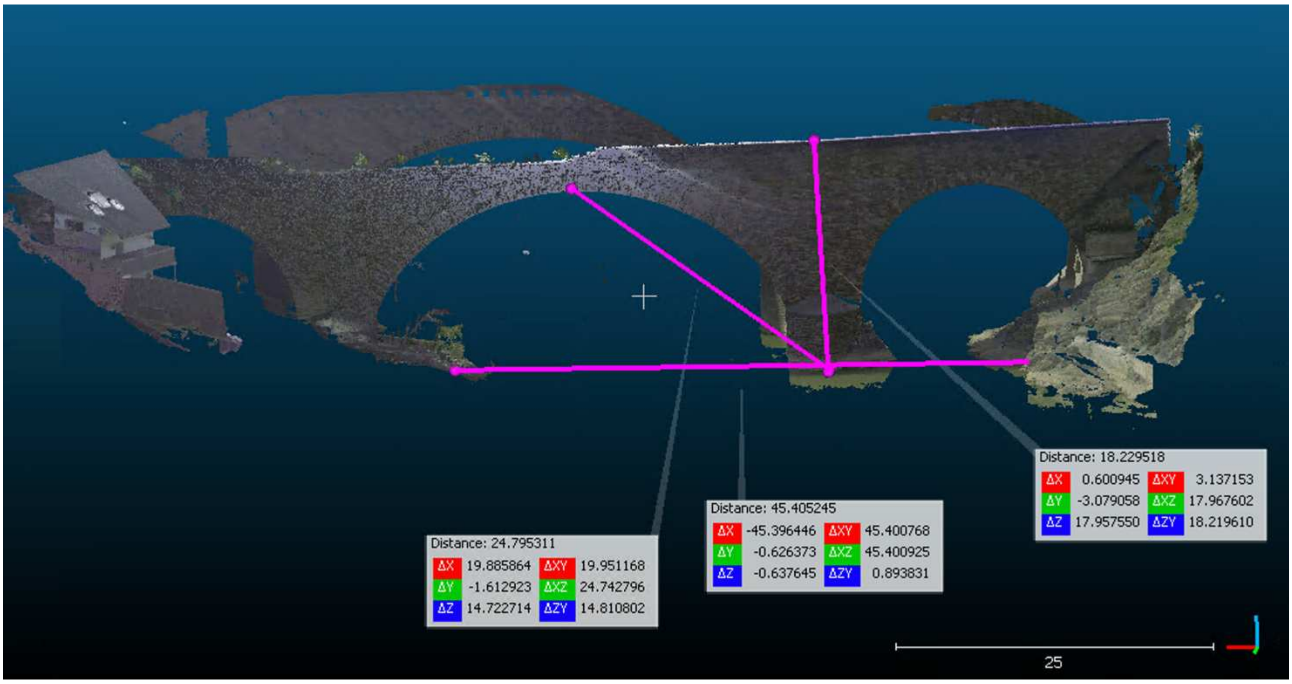

Figure 9. *From left to right, measurements of the bridge clearance height (delta Z = 14.72m), river cross sectional distance (delta X = 45.50m), and total bridge height (delta Z = 17.96m) were measured using the LiDAR derived point cloud.*

CONCLUDING REMARKS

The collection of perishable data immediately after extreme events is always a challenge. Immediate repair and response needs, particularly in urban areas and areas with immediate utility and infrastructure needs, must have priority, and thus, reconnaissance missions with small, portable gear and focused on the collection of most perishable often represents the only opportunity to collect the data needed to investigate the detailed performance and failure mechanisms. The excerpt and initial data presented here provides a glimpse into the information that was collected during the GEER reconnaissance mission after the flood events in July 2021 in Germany. The reconnaissance mission provides documentation and immediate data collection, and currently represents the base for more detailed investigations and follow-on research. More observations are available in the respective report published at geer.org (LINK), and the data, available at (DOI TBD).

ACKNOWLEDGEMENTS

The authors thank the geotechnical extreme event reconnaissance association (GEER; geerassociation.org) funded by the U.S. National Science Foundation (NSF) for financial support. The authors would also like to express their deepest gratitude to federal, state, and local authorities, local stakeholders, and residents who supported the data collection campaign in many ways including providing data and information, safe access, and guidance.

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