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The Polish system for riverbed scour monitoring in the proximity of bridge supports

Abstract: Given the increasing frequency of extreme hydrological phenomena, bottom scouring around bridge supports poses a significant threat to transport infrastructure safety. The article presents the results of a research and development project carried out by MOPMO (Monitoring system for bridge pillars and their surroundings). The project aimed to develop a national system for continuously monitoring bottom scouring at bridge supports in Poland's major rivers. An analysis of historical data from the last 1,000 years has demonstrated the cyclical nature of floods and an increase in their intensity since the end of the Little Ice Age, with particular intensification in the last three decades. These phenomena correlate with an increased number of bridge disasters, primarily caused by the erosion of bottom soil layers. Bottom scouring is the primary mechanism by which bridge supports are destroyed. Erosion caused by water flow results in the local weakening of foundations' load-bearing capacity, leading to displacement, loss of stability, and potential collapse of the structure. The intensity of scouring is influenced by various factors, including the geometry and orientation of the support, the ratio of flow depth to pier width, hydrotechnical changes in the catchment area, river valley development, and geotechnical subsoil conditions. In response to these threats, an innovative bottom scour monitoring system has been developed. This consists of above-water and underwater modules equipped with 3D sonar, temperature and pressure sensors, and a remote data transmission system, among other things. This system enables continuous monitoring, even during floods, allowing critical erosion conditions to be detected in real time. The article also describes the technical challenges encountered during implementation and the design solutions applied. The collected data provides the basis for further research into risk modelling, the impact of climate change, and improving the operational safety of engineering structures.

Keywords: bridge, climate change, flood, inspection, monitoring, scour, SHM.

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1. INTRODUCTION

The article is the result of research conducted as part of the research project "Monitoring system for bridge supports and their surroundings" (MOPMO), financed by the National Centre for Research and Development under grant no. INNOTECH-K2/IN2/63/182967/NCBR/13, which initiates a series of articles on this topic. The project was initiated in response to a pressing need expressed by bridge infrastructure managers in Poland for real-time data on changes in the elevation of the bottom scour at bridge supports, particularly during periods of flood activity. The project entailed the formulation of a comprehensive solution for the monitoring of scouring at bridge supports and the internal condition of said supports located along the principal rivers in Poland. In order to achieve this objective, a selection of bridge structures in Poland were examined. As was subsequently revealed, the project had been undertaken without the necessary information being available. This included details on the depth of the bridge supports, the soil and water conditions, and the quality of the internal filling of the bridge supports themselves. The data pertaining to all the structures examined were anonymized. Between 2015 and 2024, a permanent monitoring system was installed and was fully operational on four bridges in Poland using six manufactured systems.

The primary motivation for conducting the research was the paucity of information regarding the type and depth of foundation of the majority of bridge supports in Poland. The documentation of antiquated structures is practically non-existent, especially with regard to the method of foundation and the soil and water conditions in the vicinity of bridge supports.

Secondly, the age of bridge structures, which frequently exceeds 100 years in the case of railway structures [1], was a significant motivating factor. In the case of railway structures in Poland, the age of a bridge is defined as the age of the oldest element of the bridge or viaduct. As demonstrated in the table, which was compiled on the basis of questionnaires sent by Railway Infrastructure Managers in Europe [1], the issue of ageing infrastructure is not exclusive to Poland, but is a concern in all European countries. It is estimated that in excess of 66% of all railway structures in Europe are over 50 years old, with 31% being over 100 years old. As demonstrated in [2], a substantial body of evidence has been found to suggest that approximately 1,000 railway engineering structures in Poland are over 140 years old.

The national railway infrastructure manager in Poland, PKP PLK S.A., acknowledges that "In Poland, the oldest structural elements of railway bridges date back to 1840. These are not entire crossings, but fragments, e.g. supports on which new, currently rebuilt spans rest" states Magdalena Janus from the PKP PLK press office [3].

The third rationale for conducting the research is the numerous bridge disasters caused by the phenomenon of bottom scouring and increasingly frequent flash floods. The scale and frequency of these floods cause significant damage to transport infrastructure. The following article will provide a comprehensive overview of the relevant details. The fourth rationale for the project was the absence of a cost-effective national production system for real-time monitoring of bottom scouring in the vicinity of bridge supports during flood waves.

The fifth, and by no means least significant, reason pertained to the tangible demand from national railway infrastructure managers in Europe. As part of the "Sustainable Bridges" project [4], bed erosion and decay of wooden piles were identified as primary maintenance concerns.

2. FLOOD TRENDS IN POLAND AND WORLDWIDE OVER THE LAST 1,000 YEARS

Flood is understood as a hydrological event characterized by peak discharge with a defined probability (return period, e.g., Q100), but also by destructive hydraulic forces and debris loads. In Poland, a comprehensive record of historical flood occurrences has been established, as documented in the in-depth study available at [5]. The temporal trends of these flood events are presented in Fig. 1. A thorough examination of data spanning the period from 1001 to 1800 reveals that, on average, over 40% of documented flood occurrences – encompassing those for which the causative factors remain undetermined – are associated with precipitation and its associated phenomena.

The study further reveals a marked increase in flood frequency beginning with the termination of the Little Ice Age (Fig. 1). However, it is important to note that this positive trend underwent a reversal during the 20th century, largely attributable to the elevated incidence of floods that occurred within the initial four decades of that century (Fig. 2). However, during the past three decades, an upward trend has re-emerged, indicating a renewed rise in flood occurrences. This recent pattern corresponds with similar hydrological developments observed across numerous regions worldwide (Figs. 3 and 4).

It is important to highlight that the most pronounced concentrations of extreme flood events occurred during two specific 40-year intervals: 1501-1540 and 1651-1690. Furthermore, elevated decadal frequencies of such events – ranging from 20 to 25 occurrences – were also observed in the periods 1561-1570 and 1731-1740 [5].

Projections indicate an increased probability of riverine flooding, accompanied by a reduction in return periods for specific flood magnitudes. Nevertheless, the spatial and temporal extent of such events remains subject to considerable uncertainty. This phenomenon was exemplified by the 2021 flood event in Western Europe, the severity and impacts of which were largely unanticipated [8].

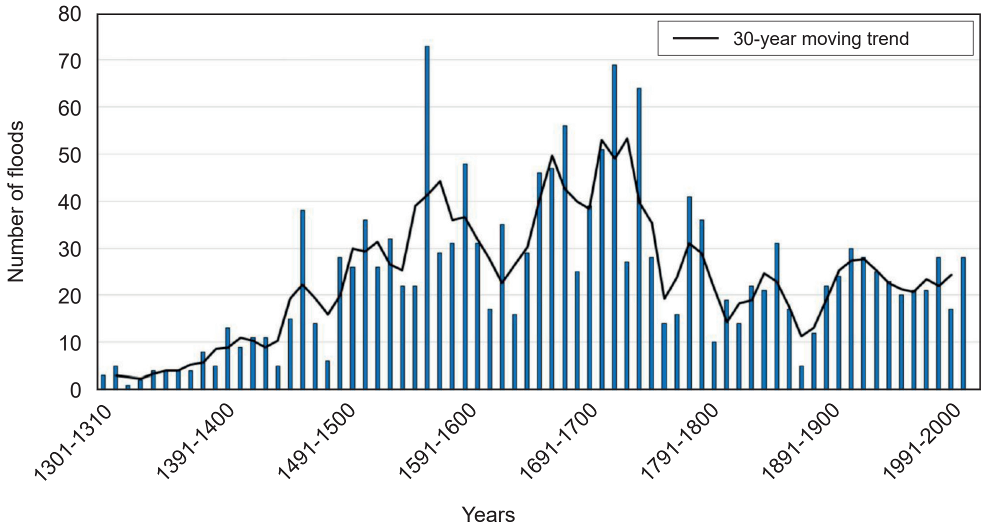

Fig. 1. Trends in the number of floods in Poland in the 14th-20th centuries based on 10-year flood totals [5]

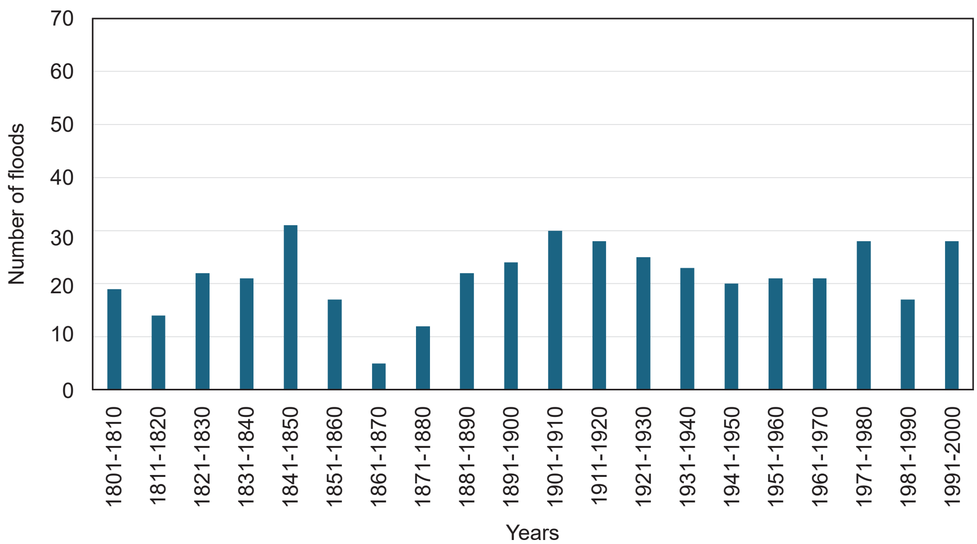

Fig. 2. Change in the decadal number of floods in Poland in the period 1801-2000 [5]

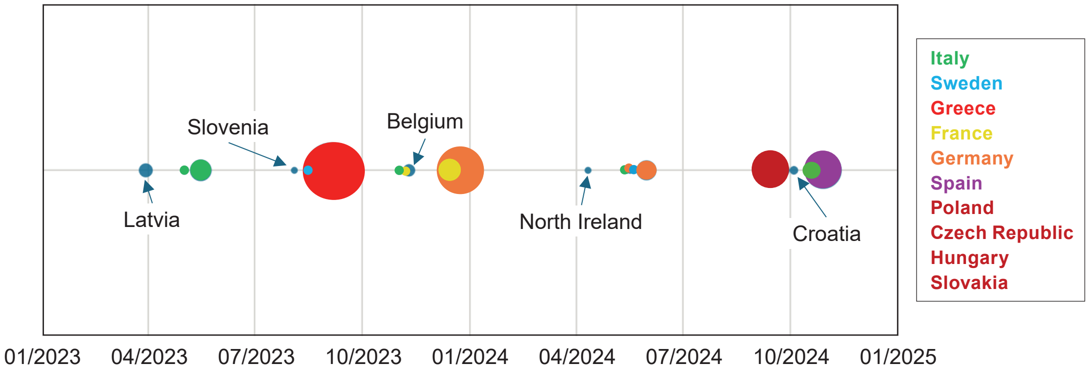

Fig. 3. Floods in Europe in 2023 and 2024 – circle diameter shows the extent of the flood at the given area – modified after [6]

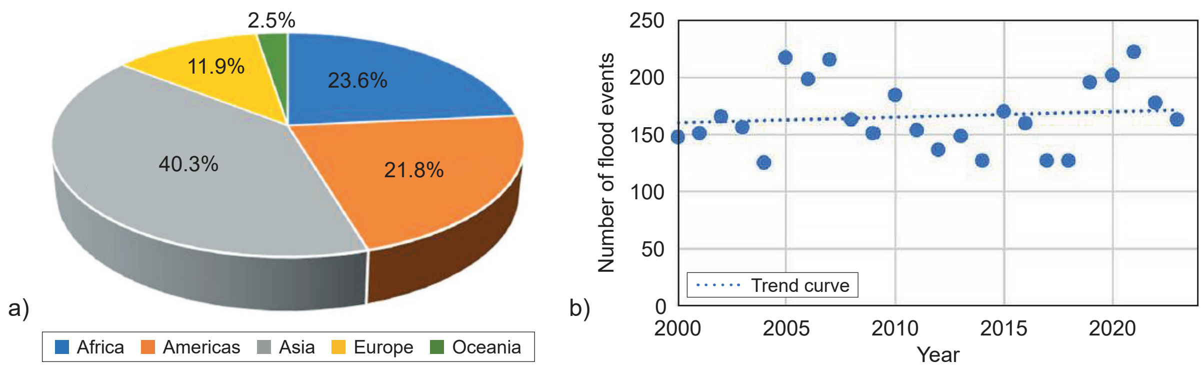

Fig. 4. Worldwide flood events from 2000 to 2023, categorized by: a) geographic regions, b) annual distribution [7]

3. SELECTED DATA ON DAMAGE TO BRIDGE INFRASTRUCTURE AS A RESULT OF FLOODING

The financial implications of repairing crossings damaged by scour are substantial; however, the societal costs associated with such damage are estimated to be five times higher than the costs of repairing and replacing bridges [9]. The phenomenon of riverbed scouring around bridge supports has always occurred and will continue to do so, as bridge piers located within a watercourse constrict the river channel and disrupt its natural flow [10]. A noteworthy analysis of 143 bridge failures was conducted in 1976 by D. W. Smith [11], who classified the events based on their timing and underlying causes. Of the bridges examined, 113 (79%) failed after more than two years of service, with 67 of these failures directly attributed to the scouring of supports during flood events. During the 1997 flood in Poland, water caused varying degrees of damage to 4,000 bridges [12]. During the flood event that occurred in Poland in September 2024, approximately 110 road bridges were either destroyed or severely damaged. The most significant concentration of damage was reported in the Lower Silesian Voivodeship, particularly in the city of Jelenia Góra, where losses related to bridge infrastructure were estimated at 750 million PLN. While the precise quantity of damaged railway bridges remains undisclosed, the national railway operator PKP PLK has allocated a budget of 100 million PLN for the reconstruction of railway infrastructure, encompassing bridges. A significant proportion of the damage affected railway lines in mountainous regions, such as the Wrocław – Kłodzko – Kudowa-Zdrój route [13-15].

The 2021 flood event in Western Europe resulted in extensive damage to bridge infrastructure, particularly within the German federal states of North Rhine-Westphalia and Rhineland-Palatinate. A total of 25 bridges along the Inde and Vicht rivers were damaged, while 80 bridges along the Ahr River were also affected. It is noteworthy that bridges situated in densely populated residential areas sustained more severe damage in comparison to those located in rural regions. The accumulation of debris was identified as a significant contributing factor to structural failures. The direct economic impact of the 2021 flood in the affected German regions has been estimated at approximately €33.4 billion. Water levels exhibited a marked increase that exceeded the thresholds typically associated with a 100-year flood event. A significant proportion of the hydrological gauging infrastructure was destroyed in the process. Consequently, analyses of the 2021 flood have had to rely primarily on discharge estimations rather than direct measurements [8].

The United States witnessed two catastrophic floods in 1993 and 1996, resulting in a total of 171 bridge failures. This figure highlights the disproportionately high contribution of flooding to bridge failure in comparison to other causes. A comparable event occurred in China's Guangdong Province in 2013, where severe flooding led to the disruption of 316 roads, the collapse of 83 bridges, and economic losses exceeding one hundred million USD [16].

A total of 246 collapses were documented in Italy between the years 2000 and 2023. It is estimated that approximately 80.5% of all bridge failures (198 cases) in Italy are attributable to the effects of water-related forces acting on bridge supports [17]. In the United Kingdom, the 2009 floods resulted in the collapse or severe damage of 29 bridges in Cumbria alone [18].

In [19], the authors conducted a comprehensive study, examining 138 incidents of failure of rail bridges or culverts associated with flooding in the UK during the period spanning from 1846 to 2013. The annual probability of observing a flood event in which one or more structures fail is estimated to be approximately 41%, or 1 in 2.44 years.

In 2018, the Misasa Railroad Bridge in Japan suffered a structural failure, along with 22 out of 94 nearby bridges. This event was attributed to the combined effects of hydrodynamic forces and scouring. The flood-induced loads were found to be almost double those considered in the seismic design of the structures. As outlined in [7], the failures can be categorised as follows: in 11 cases, the bridges collapsed entirely; in six cases, there was localised scouring; in four cases, the bridges sustained damage due to abutment erosion; and in one case, other forms of structural impairment were experienced.

In the aftermath of the flood that occurred in Montenegro in 2010, a significant number of bridges were either destroyed or damaged. The estimated cost of the damage was reported to be in the region of several million euros [20].

According to the report, the floods that occurred in the Czech Republic in May and June 2010 resulted in damages estimated at 2.6 billion CZK. The total number of bridges damaged was 199, and the total length of roads affected was approximately 550 kilometres. In Slovakia, 733 bridges were destroyed, along with more than 100 kilometres of intercity roads and over 500 kilometres of local roads. The total financial impact of flood-related damages in Slovakia in 2010 was estimated at approximately €337 million. In Romania, the most severe flood impacts were recorded between June and August, with total losses estimated at around 3.7 billion Lei (approximately €870 million). The floods affected approximately 707 large bridges, 2,729 small bridges, and over 5,200 kilometres of national and regional road infrastructure [21].

In September 2020, a substantial flood event impacted the Greek province of Karditsa, resulting in direct infrastructure losses surpassing €30 million. A significant number of bridges were severely damaged, with several experiencing complete structural failure. In a similar fashion, in September 2022, the regions of Marche and Umbria in Italy were subjected to an extreme flood event, during which more than 30 bridges sustained significant damage [22].

The study [23] analysed a flash flood event that occurred along the Avenida Venezuela channel in Arequipa, Peru. On 8 February 2013, a total of 124.5 millimetres of rainfall were recorded within a three-hour period, which is significantly higher than the monthly average of 29.3 millimetres. This intense precipitation triggered a flash flood that affected 23 out of 53 bridges in the area, including pedestrian, vehicular, and railway structures. The event also caused partial collapses of key road sections, resulting in the paralysis of central parts of the city for over a week. The El Niño phenomenon, which occurred between 2016 and 2017, resulted in the destruction of 449 bridges in Peru [24].

The 2018 Western Heavy Rainfall event resulted in substantial flooding across a considerable area of western

Japan between 5-8 July 2018. In the Misasa River, a constituent of the Oota River in Hiroshima Prefecture, Japan, 22 out of 94 bridges were damaged by the flooding [25].

4. THE SCOUR PHENOMENON OF RIVERBEDS – BASICS

Bridge supports are often compromised by the erosive forces of flowing water, which act by dislodging and transporting soil from the riverbed and banks [26]. Scour is defined as the erosion or removal of a streambed or bank material from bridge foundations due to flowing water. This is usually considered to be a long-term bed degradation, contraction, and local scour (Fig. 5). The removal of material from beneath (or surrounding) the foundation during scouring will result in increased stress and, consequently, reduced stiffness in the remaining soil (Fig. 6), thus increasing the lateral deflection of the foundation head (Fig. 7). Furthermore, when the critical scour depth is reached, the foundation may undergo bending buckling as a consequence of the combined effect of a dead load of bridge superstructures and traffic load (Fig. 7) [27].

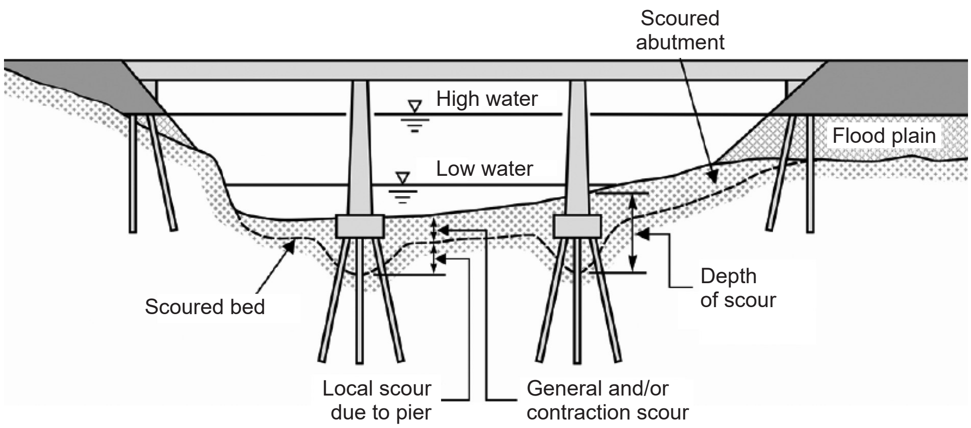

Fig. 5. Scour types at bridge opening [28]

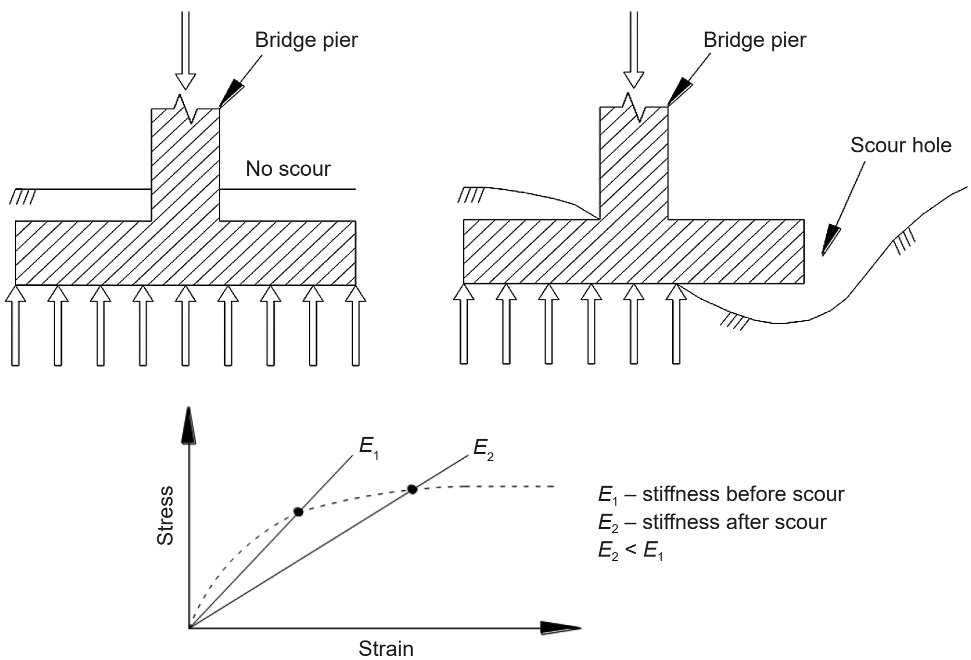

Fig. 6. Reduction in stiffness caused by scour [27]

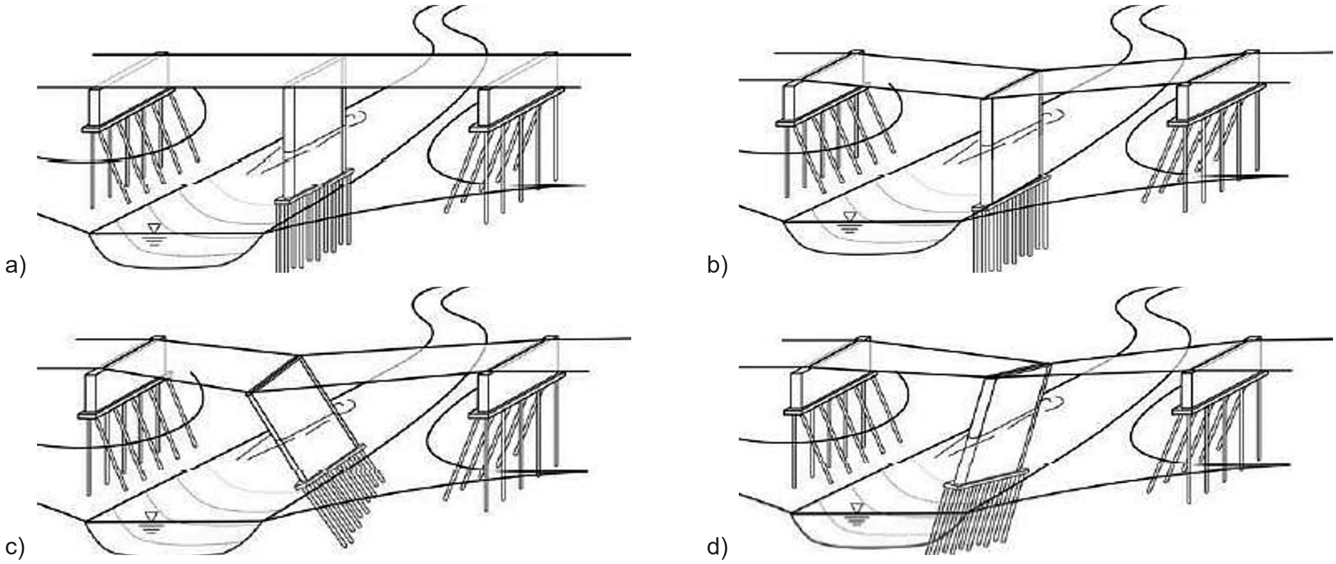

Fig. 7. Scour reduces pier support, causing: pier settlement (a > b), bottom rotation of pier (a > c), and top rotation of pier (a > d) [28]

Pier scour is a prevalent issue that can result in various forms of bridge pier failure, as illustrated in Fig. 7a-d. Initially stable bridge piers (Fig. 7a) can undergo vertical settlement (Fig. 7b) or complete collapse. Furthermore, scouring has been observed to potentially diminish the streamwise longitudinal support of a pier, thereby inducing a tilt in the pier or a loss of support in the streamwise direction of a bridge. The hydrodynamic loading against the pier, in conjunction with the lateral strength of the connection between the pier and the bridge deck, can result in the flow pressure exerting a force that is either retrogressive to the pier or the support piles (Fig. 7c-d).

Scour can be a consequence of [9]:

- narrowing of the watercourse (natural, e.g. by ice congestion or by man, including the construction of a bridge crossing),
- lateral movement or lowering of the watercourse,
- hydrotechnical works shortening the length of the meandering section of the river,
- changes occurring in the catchment area of the river and
- other changes in his hydrology.

The construction of a bridge crossing interferes with the natural floodwater flow conditions in its area and can change the normal water flow conditions. The crossing reduces the flow section, which increases the speed of the stream and the intensity of erosion of its trough. River aims to stabilize its trough – to restore the natural flow section. The bridge supports also turn the laminar flow of water into turbulent (turbulent). The whirlpools caused by the bridge supports wash out bumps with a depth that can significantly exceed the overall trough scour. Access embankments prevent the flow of floodwater in floodplains (terraces) and direct water from them into the bridge spans. This causes the crossing to change the current system in the stream and scour the bottom and edges of the stream [9].

The riverbed can change position and shape as a result of the flow of floodwater and the continuous washing away and/or depositing of sediment. The troughs migrate and oscillate between lowering (degradation) and rising (agradation) over relatively long distances until they reach a short-term balance. An increase in scour can also be caused by changes in land use in the area of the bridge, e.g. construction of dikes or even low road embankments that change the direction of flood water flow.

Changes in the catchment area above the bridge crossing may result in an increase or decrease in the scour of the riverbed, or an increase in the deposition of soil brought from the upper parts of the riverbed. The intensity of these phenomena depends on the geotechnical conditions.

The following factors can significantly increase the scour in the proximity of the bridge [9]:

- hydrotechnical works (deepening of the watercourse near the bridge crossing or regulation of the watercourse with hydrotechnical structures changing the location and deepening of its trough),

- reduction of surface rainwater runoff and deterioration of vegetation covering the catchment area.

Changes in hydrological conditions result in the construction of engineering structures in the catchment area which hinder the flow of large water, e.g. dikes, road and rail embankments and bridge crossings. The knowledge of hydrology and geomorphology of the river basin makes possible to forecast the extent and type of scour at the bridge crossing.

Local scours at the pillars are particularly dangerous. They depend on natural and constructional factors: hydrological conditions of the flow of the river and geotechnical conditions of its through at the place of the bridge crossing, the width, shape and position of the pillar in relation to the current of the river, as well as the height of the upper structure of the bridge over the river. If the upper structure is placed too low, it is an obstacle to the free flow of floodwater and causes more scour under the bridge.

The current pattern and intensity of local scour at the pillar depend on the geometry and dimensions of the pillar body and foundation and on the position of its longitudinal axis in relation to the main direction of the flow. The current pattern is influenced by the width and length of the pillar and, in the case of a cylindrical pillar, by its diameter and, when several pillars are located in one axis, also by their spacing. The pillar shape complicates the current pattern and increases local scour.

Significant differences in the morphology of pillar washing occur at different ratios of flow depth y to pillar width a. For the pillars:

- narrow ($y/a > 1.4$) – the deepest bottom scour is typically in front of the pillar head,
- of intermediate width ($0.2 < y/a < 1.4$),
- wide ($y/a < 0.2$) – the deepest scour occurs at the front and sides of the pillar.

Local scour at abutments occur when abutments and embankments of access roads to the bridge hinder the flow of floodwater. Damage to abutments can be caused by:

- flood water flowing in a wide floodplain, which is lead by the embankments of the access roads lead to the bridge,
- lateral displacement or process of widening of the riverbed, scour due to the the narrowing of the riverbed caused by the construction of the bridge crossing,
- overflow of flood water over the bridgehead and embankment or
- a combination of these factors.

Scour at bridge supports with stone reinforcement may occur as a result of the stone reinforcement being destroyed by the flowing water. The destruction process is sometimes caused by:

- shearing – this type of destruction occurs when the stone reinforcement is too light to resist the hydrodynamic forces of flowing water; the weight of the stones must be appropriate to withstand the energy of flowing water,
- water intake of fine-grained soil, which is the result of sucking between the stones of fine material from the bottom by water flowing over the stone reinforcement; this causes destabilization of the stones – they are falling down with the bottom of the stream and are dispersed by water; the stone reinforcement should be placed on a layer of geotextile filtering fabric,
- washing the stone reinforcement flange – causes stones to gradually roll into bumps that are washed at the throw flange; this destruction mechanism occurs when the side range of the stone reinforcement protective layer is too small,
- general scour – the stone reinforcement settles with the bottom of the watercourse, which causes gradual dispersion of stones; this type of destruction dominates in the troughs of sandy-bottomed watercourses, where the migration of shoals occurs.

5. TYPES OF SCOUR MONITORING INSTRUMENTS AND APPARATUS

Bridge scour monitoring is vital for ensuring the safety and longevity of bridge foundations, especially during flood events. Monitoring systems are generally classified into portable and stationary devices, depending on site conditions and monitoring needs [29].

Portable devices include various probes and hydroacoustic instruments:

- rod probes (wood, metal, or plastic) are suitable for shallow waters (up to 3 m deep) and low velocities (≤ 2 m/s).
- weighted probes (with steel or lead weights on ropes) allow deeper measurements (up to ~5 m), though rope deflection can affect accuracy.

- portable hydroacoustic systems, such as single- or multibeam sonars, operate in deeper and faster flows and provide cross-sectional or point-based data.

Stationary systems are permanently installed near bridge supports to enable continuous or periodic monitoring. They are positioned in critical scour zones and may transmit data remotely. System selection depends on factors such as expected scour depth, hydrological conditions, mounting feasibility, and cost.

Hydroacoustic systems function in both portable and stationary setups. These use ultrasonic waves to create images of the riverbed and submerged structures. They consist of transducers, transmitters, processors, and display units. Advanced tools include 2D and 3D scanning sonars, multibeam echo sounders, and side-scan sonars, offering high-resolution imaging even in turbid water.

Conclusion: An effective scour monitoring strategy should combine portable tools for rapid assessment with stationary hydroacoustic systems for continuous, detailed observation – ensuring comprehensive protection of critical bridge infrastructure.

6. DEVELOPMENT AND IMPLEMENTATION OF A PERMANENT SCOUR MONITORING SYSTEM IN THE VICINITY OF BRIDGE SUPPORTS

6.1. SCOUR-RISK MANAGEMENT

It is imperative to acknowledge the sensitivity of the scour process to hydrological and hydraulic conditions when conducting a comprehensive assessment. This necessitates consideration of the entire discharge regime. Presently, scour-risk management is subject to considerable uncertainty, stemming from the limitations of existing predictive equations, the inability to fully characterize the complex dynamics of scour, and the challenges in assessing structural responses to these processes. Consequently, the implementation of continuous monitoring programmes for bridges vulnerable to scour is imperative. The collection of long-term scour time series will enable analyses with a stronger physical foundation, facilitate stochastic modelling, support the validation of time-dependent scour prediction models under real-world conditions, and ultimately help reduce uncertainty in scour assessment. Moreover, data obtained through such monitoring efforts will serve as a valuable resource for understanding the impacts of climate change on hydraulic infrastructure [26].

A particular challenge was to develop and implement a system that would show in real time the riverbed scour near the bridge piers under investigation during the passage of a flood wave. It is generally accepted that the profiling of river bottoms during periods of no flooding does not present significant issues. Hydroacoustic devices are commercially available and can be employed in an expeditious manner to study the river bottom profile. This phenomenon is particularly evident during periods of low water levels. In the context of fluvial disasters, the velocity of the current and the height of the water level can render the measurement of parameters from a boat an impractical undertaking.

Furthermore, it is imperative to note that only measurements obtained during the occurrence of a flood wave are capable of accurately determining the true maximum bottom scour. This is due to the fact that, in the aftermath of the flood wave, soil particles naturally settle back onto the river bottom. Additionally, the efficacy of inspecting the underwater components of bridge supports is significantly diminished in Polish rivers due to the limited water clarity.

6.2. STRUCTURE AND FUNCTIONING OF THE SYSTEM

The system is comprised of two primary components: the above-water component and the underwater component. The above-water component incorporates a control centre, which integrates a monitoring and control computer, a wireless communication module and external power sources, such as solar panels or wind turbines. The underwater component of the system consists of a 3D sonar equipped with a hydroacoustic transducer and temperature and pressure sensors. The fundamental function of the hydroacoustic transducer is to measure the distance to the seabed, thereby enabling the generation of a spatial image of the underwater terrain. The temperature sensor is instrumental in determining the speed of sound propagation in water, a process that is paramount for accurate depth estimation. The pressure sensor is responsible for monitoring the immersion of the sonar head, thereby providing information regarding the water level in the area of the bridge support.

The system has been engineered to ensure comprehensive coverage of the bottom sectors by utilising a dual rotary mechanism driven by stepper motors. This mechanism is rotated in two planes, thereby enabling the transducer to function effectively. The measurement cycle parameters, including frequency and sector range, are controlled remotely using a GSM network. The measurement data is then transmitted to the operator's headquarters, where it is meticulously archived and analysed.

6.3. VARIOUS STAGES INVOLVED IN THE IMPLEMENTATION AND DEVELOPMENT OF THE SYSTEM

The research and development process was divided into three main stages. The initial phase entailed the conceptualisation and development of a prototype system, accompanied by preliminary testing and remote transmission trials. The subsequent stage concentrated on enhancing the system and ensuring reliable, continuous data transmission. The objective of the third stage was to implement the system for long-term monitoring of the riverber near the bridge piers in the most vulnerable areas, with particular emphasis on periods of flooding. At the inception of the project, it was hypothesised that a single point sensor with rotation in only one plane would be utilised. However, during the course of the research, a more advanced version was developed, equipped with two rotating mechanisms, enabling a full scan of the bottom sector in two axes (vertical and horizontal). This modification resulted in a substantial enhancement in the quantity and quality of the data collected, whilst concomitantly reducing the number of point sensors required.

6.4. TECHNICAL ISSUES AND THEIR RESPECTIVE RESOLUTIONS

In the course of the design and implementation of the system, a plethora of engineering challenges were encountered. A significant challenge encountered pertained to the absence of a consistent power supply. This issue was addressed to a certain extent by the implementation of solar panels and batteries; however, during extended periods of darkness, the utilisation of power generators became imperative.

A further substantial issue was identified as mechanical damage to the measuring elements, which was attributed to impacts from floating tree branches, ice floes or vegetation. The primary design objective was to protect the measuring head with protective rods; however, this solution generated echoes in the echogram. Following a comprehensive evaluation of the available data, it was determined that the shield should be relinquished. This decision was informed by the positive impact on data quality and the enhanced safety measures inherent in the dome's design.

A further challenge was the frequent damage to the hydroacoustic transducer cables resulting from the rotational movement of the head. The issue was resolved through the implementation of a slip ring rotary connector, thereby obviating the requirement for conventional cables.

The system could be also equipped with two-axis tilt sensors (pan and tilt), which facilitate automatic data correction in the event of the sonar bracket tilting due to mechanical impact. Should riverbed scour be detected at a level below the designated threshold, the system could be programmed to automatically generate an alarm, thereby transmitting a signal to the designated services responsible for bridge infrastructure safety.

Thanks to its rotating mechanism with two stepper motors (Fig. 8c), the system functions as a dual-axis sonar. This allows acoustic measurements in both the vertical plane (from −90° to +90° relative to the central nadir position) and the horizontal plane (within a 180° range). The scanning resolution is adjustable between 0.5° and 1.0°. The system uses a round, single-beam 500 kHz transducer that generates a conical beam. It scans at a sampling rate of 2-2.5 Hz, with an effective range of up to 15 m. Power consumption is approximately 40 W. The sonar operates on a set schedule and remains on standby between scans. Capturing one profile takes 77 seconds, while completing a full 3D scan requires about 4 hours.

The following examples illustrate the type and range of data that can be obtained from the proposed system. The system is capable of measuring both the distance and the angle (bearing) to the bottom. The angular step size can be as small as 1 degree. During a single cycle, data for a complete raw profile is collected, as shown in Fig. 9a. These profiles can then be combined into a full 3D point cloud consisting of 180 individual profiles, resulting in a three-dimensional hemispherical image (Fig. 9b). After processing, the data can be displayed in different formats: as a chart of a single profile (Fig. 9c), a comparison of two profiles (Fig. 9d), or as a set of profiles recorded over a given time period (Fig. 9e).

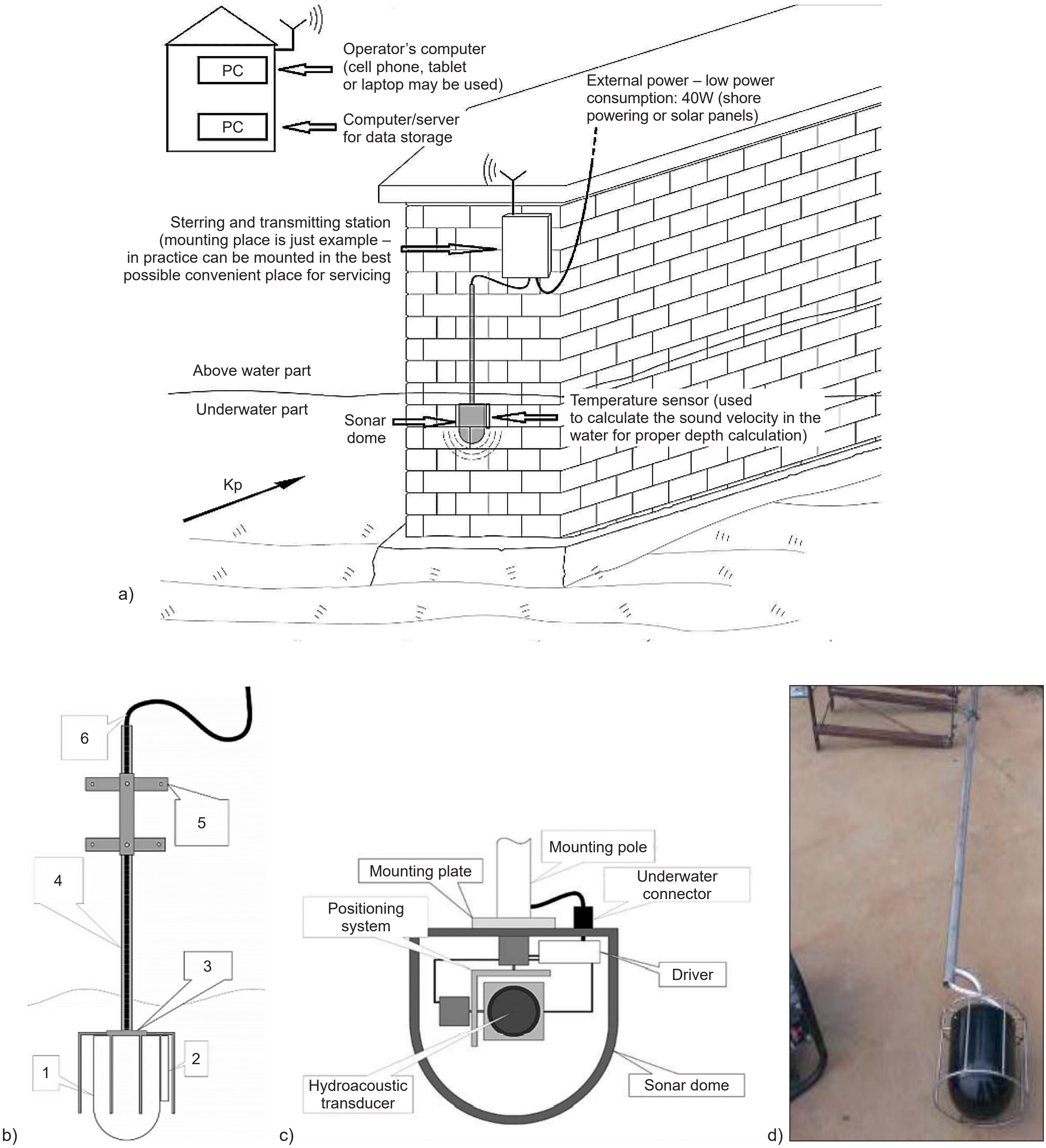

Fig. 8. General idea of the system operation (a); diagram of the sonar holder (b): 1 – sonar, 2 – temperature and pressure sensor, 3 – sonar cover, 4 – holder, 5 – holder mounting, 6 – power and data cable; rotating mechanism (c); sonar with holder (d); →

Fig. 8. three systems on a bridge pillar during low water (e)

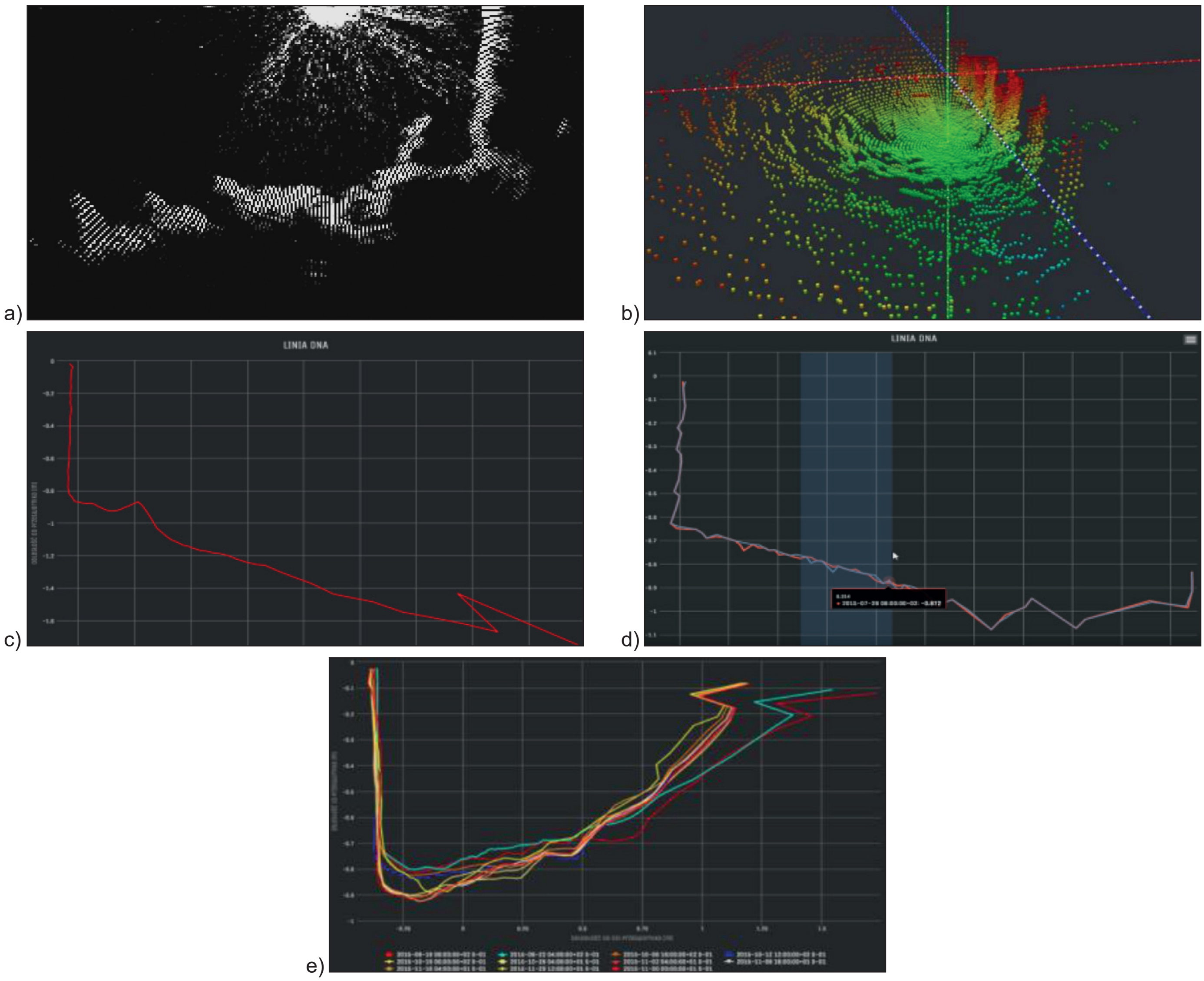

Fig. 9. One raw sonar image – echogram (a); 3D point cloud (b); profile – chart – single profile (c); profile – chart – two profiles (d); profile – chart – set of profiles (e)

7. CONCLUSIONS

Based on the conducted considerations, the following conclusions have been formulated:

1. Analysis of historical data suggests that flooding in Poland occurs in cycles over the long term. The most severe floods were recorded in the periods 1501-1540 and 1651-1690. The observed increase in flood frequency over the past three decades highlights the importance of considering hydrological risk in long-term infrastructure planning.
2. Contemporary floods, such as those in 1997 and 2024, demonstrate that, despite technical progress, transport infrastructure remains susceptible to extreme hydrometeorological events. The damage and destruction of hundreds of bridges results in high economic costs and multidimensional social effects.
3. Given the lack of comprehensive technical documentation for many bridges in Poland, particularly railway bridges, and their advanced age, it is crucial to implement modern solutions to support their maintenance and operational safety.
4. The basic mechanism of destruction of bridge supports is the phenomenon of scouring. Erosion caused by water flow can result in the local weakening of the load-bearing capacity of foundations, leading to their displacement and loss of stability, which could potentially cause the structure to collapse.
5. The intensity of scouring is influenced by various factors, including the geometry and orientation of the support, the ratio of flow depth to pier width, hydrotechnical changes in the catchment area, river valley development, and the geotechnical conditions of the subsoil. Local scouring at bridge piers and abutments is particularly dangerous.
6. The bottom scour monitoring system developed as part of the MOPMO project is an innovative, domestic solution for the continuous monitoring of bottom scour at bridge supports. The system enables remote measurements to be taken, particularly during flood waves, which has previously been technically difficult to achieve.
7. The system architecture consists of above-water and underwater modules (using 3D sonar, as well as pressure and temperature sensors) which allow for the accurate imaging of the riverbed and the real-time detection of changes. Remote data transmission and an alarm system enhance the effectiveness of the technical services' response.
8. The data collected by the system is valuable for calibrating predictive models, analysing long-term scour dynamics, and assessing the impact of climate change on hydrotechnical infrastructure. This system could be pivotal in the operational risk management of bridge structures in Poland and beyond.

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REFERENCES

[1] *Bell B.*: European railway bridge demography. Sustainable Bridges SB-D1.2, 2004, https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-7499 (available: 23.07.2025)

[2] *Bien J.*: Railway bridges – damages, failures, collapses. XXIV International Scientific-Technical Conference Szczecin-Międzyzdroje, Poland, 26-29 May 2009, https://awarie.zut.edu.pl/files/ab2009/referaty/00_referaty_problemowe/03_Bien_J_Mosty_kolejowe-uszkodzenia,_awarie,_katastrofy.pdf (available in Polish: 23.07.2025)

[3] *Madej Ł.*: Ile jest mostów kolejowych w Polsce? Inzynieria.com, 2018, https://inzynieria.com/mosty/wiadomosci/51912,ile-jest-mostow-kolejowych-w-polsce (available in Polish: 23.07.2025)

[4] *Bell B.*: European railway bridge problems: Sustainable bridges SB-D1.3. Luleå University of Technology, Publications, 2004, https://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-74995 (available: 23.07.2025)

[5] *Ghazi B.*, *Przybylak R.*, *Oliński P.*, *Pospieszyńska A.*: Flood occurrences and characteristics in Poland (Central Europe) in the last millennium. Global and Planetary Change, **246**, 2025, Article ID: 104706, DOI: 10.1016/j.gloplacha.2025.104706

[6] *Szabo K.*, *Maltepioti K.*, *Zafeiropoulos K.*: Troubled waters. The multiple devastating impact of floods across Europe. Mediterranean Institute for Investigative Reporting, 2025, https://miir.gr/longreads/flood-in-europe-en.html (available: 23.07.2025)

[7] *Buka-Vaivade K.*, *Nicoletti V.*, *Gara F.*: Advancing bridge resilience: a review of monitoring technologies for flood-prone infrastructure. Open Research Europe, **5**, 26, 2025, 1-28, DOI: 10.12688/openreseurope.19232.2

[8] *Burghardt L.*, *Klopries E.M.*, *Schüttrumpf H.*: Structural damage, clogging, collapsing: Analysis of the bridge damage at the rivers Ahr, Inde and Vicht caused by the flood of 2021. Journal of Flood Risk Management, **18**, 1, Article ID: e13001, DOI: 10.1111/jfr3.13001

[9] *Topczewski Ł.*, *Jarominiak A.*, *Cieśla J.*, *Markowski Z.*, *Mikołajewski P.*, *Rafalski L.*, *Rymsza J.*, *Zajbert A.*: Wytyczne monitoringu rozmycia dna w otoczeniu podpór mostowych. Instytut Badawczy Dróg i Mostów & Escort Sp. z o.o., 2015, https://escort-technology.com/wp-content/uploads/WYTYCZNE_Lukasz.pdf (available in Polish: 23.07.2025)

[10] *Jarominiak A.*, *Rosset A.*: Katastrofy i awarie mostów. WKŁ, 1986 (in Polish)

[11] *Smith D.W.*: Bridge failures. Proceedings of the Institution of Civil Engineers, **60**, 3, 1976, 367-382, DOI: 10.1680/iicep.1976.3389

[12] *Bratkowski J.*, *Dubel A.*, *Hajto M.*, *Marcinkowski M.*, *Romańczak A.*, *Sadowski M.*, *Siwiec E.*, *Skotak K.*: Atlas skutków zjawisk ekstremalnych w Polsce. Instytut Ochrony Środowiska – Państwowy Instytut Badawczy, 2022, https://klimatycznabazawiedzy.org/wp-content/uploads/2023/01/Atlas-skutkow-zjawisk-ekstremalnych-w-Polsce.pdf (available in Polish: 25.07.2025)

[13] Trwa odbudowa mostów i szkół po powodzi. Gov.pl, https://www.gov.pl/web/premier/trwa-odbudowa-mostow-i-szkol-po-powodzi (available in Polish: 23.07.2025)

[14] 100 milionów złotych na odbudowę infrastruktury kolejowej. Będzie remont zapory w Pilchowicach. Gov.pl, https://www.gov.pl/web/premier/100-milionow-zlotych-na-odbudowe-infrastruktury-kolejowej-bedzie-remont-zapory-w-pilchowicach (available in Polish: 23.07.2025)

[15] Koszty powodzi. Poznaliśmy pierwsze oficjalne podsumowanie strat. Business Insider, https://businessinsider.com.pl/gospodarka/ile-kosztowala-powodz-pierwszy-oficjalny-raport/20nkc9z (available in Polish: 23.07.2025)

[16] *Zhang G.*, *Liu Y.*, *Liu J.*, *Lan S.*, *Yang J.*: Causes and statistical characteristics of bridge failures: A review. Journal of Traffic and Transportation Engineering (English Edition), **9**, 3, 2022, 388-406, DOI: 10.1016/j.jtte.2021.12.003

[17] *D'Angelo M.*, *Civera M.*, *Giordano P.F.*, *Borlenghi P.*, *Ballio F.*, *Limongelli M.P.*, *Chiaia B.*: Bridge collapses in Italy across the 21st century: survey and statistical analysis. Structure and Infrastructure Engineering, epub ahead of print (online), 2025, 1-23, DOI: 10.1080/15732479.2025.2483500

[18] *Pregnolato M.*, *Elizabeth L.*: UK: Climate-driven extreme weather is threatening old bridges with collapse. UN Office for Disaster Risk Reduction (UNDRR), PreventionWeb, 2019, https://www.preventionweb.net/news/uk-climate-driven-extreme-weather-threatening-old-bridges-collapse (available: 23.07.2025)

[19] *Van Leeuwen Z.*, *Lamb R.*: Flood and scour related failure incidents at railway assets between 1846 and 2013. JBA Trust Limited, Railway safety & standards board, Project W13-4224, Skipton, United Kingdom, 2014, https://www.jbatrust.org/wp-content/uploads/2016/01/JBA-Trust-Flood-and-scour-failure-at-railway-assets-1846-to-2013-W13-4224-FINAL.pdf (available: 23.07.2025)

[20] *Pejovic J.*, *Serdar N.*, *Pejovic R.*: Damage assessment of road bridges caused by extreme streamflow in Montenegro: Reconstruction and Structural Upgrading. Buildings, **12**, 6, 2022, Article ID: 810, DOI: 10.3390/buildings12060810

[21] *Liska I.*, *Höbart A.*, *Teodor D.*: 2010 Floods in the Danube River basin: Brief overview of key events and lessons learned. International Commission for the Protection of the Danube River (ICPDR), Vienna, Austria, 2012, https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_flood_report_2010.pdf (available: 23.07.2025)

[22] *Perugini E.*, *Argyroudis S.*, *Tubaldi E.*, *Mitoulis S.A.*: Regional flood assessment of bridges using open data. EGU General Assembly, Abstract EGU25-17571, Vienna, Austria, 2025, DOI: 10.5194/egusphere-egu25-17571

[23] *Ettinger S.*, *Mounaud L.*, *Magill C.*, *Yao-Lafourcade A.F.*, *Thouret J.C.*, *Manville V.*, *Negulescu C.*, *Zuccaro G.*, *De Gregorio D.*, *Nardone S.*, *Uchuchoque J.A.L.*, *Arguedas A.*, Macedo L., Manrique Llerena N.: Building vulnerability to hydro-geomorphic hazards: Estimating damage probability from qualitative vulnerability assessment using logistic regression. Journal of Hydrology, **541**, Part A, 2016, 563-581, DOI: 10.1016/j.jhydrol.2015.04.017

[24] *Ccanccapa Puma J.*, *Hidalgo Valdivia A.V.*, *Espinoza Vigil A.J.*, *Booker J.*: Preserving Heritage Riverine Bridges: A hydrological approach to the case study of the Grau Bridge in Peru. Heritage, **7**, 7, 2024, 3350-3371, DOI: 10.3390/heritage7070158

[25] *Inoue T.*, *Yamamura Y.*, *Nihei Y.*: A suitable risk index for evaluating bridge damage in the Misasa River caused by the 2018 Western Japan floods. 22nd Congress of the International Association for Hydro-Environment Engineering and Research-Asia Pacific Division: Creating Resilience to Water-Related Challenges, IAHR-APD, 2020, https://tus.elsevierpure.com/ja/publications/a-suitable-risk-index-for-evaluating-bridge-damage-in-the-misasa-/ (available: 27.07.2025)

[26] *Pizarro A.*, *Manfreda S.*, *Tubaldi E.*: The science behind scour at bridge foundations: A Review. Water, **12**, 2, 2020, Article ID: 374, DOI: 10.3390/w12020374

[27] *Prendergast L.J.*, *Gavin K.*: A review of bridge scour monitoring techniques. Journal of Rock Mechanics and Geotechnical Engineering, **6**, 2, 2014, 138-149, DOI: 10.1016/j.jrmge.2014.01.007

[28] An illustrated guide for monitoring and protecting bridge waterways against scour. Iowa Highway Research Board Project TR-515 Final Report, https://publications.iowa.gov/3752/ (available: 23.07.2025)

[29] *Topczewski Ł.*, *Cieśla J.*, *Mikołajewski P.*, *Adamski P.*, *Markowski Z.*: Monitoring of scour around bridge piers and abutments. Transportation Research Procedia, **14**, 2016, 3963-3971, DOI: 10.1016/j.trpro.2016.05.493

Polski system monitoringu rozmycia dna wokół podpór mostowych

Streszczenie: Biorąc pod uwagę rosnącą częstotliwość występowania ekstremalnych zjawisk hydrologicznych, rozmycie dna wokół podpór mostowych stanowi poważne zagrożenie dla bezpieczeństwa infrastruktury transportowej. Artykuł przedstawia wyniki projektu badawczo-rozwojowego MOPMO. Celem projektu było opracowanie krajowego systemu ciągłego monitorowania rozmycia dna wokół podpór mostowych na głównych rzekach Polski. Analiza danych historycznych z ostatnich 1000 lat wykazała cykliczność powodzi i wzrost ich intensywności od końca małej epoki lodowcowej do szczególnego nasilenia w ostatnich trzech dekadach. Zjawiska te korelują ze wzrostem liczby katastrof mostowych, spowodowanych przede wszystkim rozmyciem dna. Rozmycie dna jest głównym mechanizmem niszczenia podpór mostowych. Erozja spowodowana przepływem wody powoduje lokalne osłabienie nośności fundamentów, co prowadzi do przemieszczenia, utraty stabilności i potencjalnego zawalenia się konstrukcji. Na intensywność rozmycia wpływają różne czynniki, w tym geometria i orientacja podpory, stosunek głębokości przepływu do szerokości filara, zmiany hydrotechniczne w zlewni, zagospodarowanie doliny rzeki oraz warunki geotechniczne podłoża. W odpowiedzi na te zagrożenia opracowano innowacyjny system monitorowania rozmycia dna. Składa się on z modułów nadwodnych i podwodnych wyposażonych między innymi w sonar 3D, czujniki temperatury i ciśnienia oraz system zdalnej transmisji danych. System ten umożliwia ciągłe monitorowanie, nawet podczas powodzi, pozwalając na wykrywanie krytycznych rzędnych rozmycia w czasie rzeczywistym. Artykuł opisuje również wyzwania techniczne napotkane podczas wdrażania systemu oraz zastosowane rozwiązania projektowe. Zebrane dane stanowią podstawę do dalszych badań nad modelowaniem ryzyka, wpływem zmian klimatycznych oraz poprawą bezpieczeństwa eksploatacyjnego obiektów inżynieryjnych.

Słowa kluczowe: inspekcja, monitorowanie, most, powódź, rozmycie dna, SHM, zmiany klimatu.