Repair and upgrading of movable hydraulic steel structures after failures

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An obvious objective of hydraulic projects is to ensure that water retaining structures remain in service during their life cycle, i.e. that they do not fail. While this should certainly continue to be the engineers' main concern, it ought not to discourage them from considering scenarios in which failures actually happen. This applies to all structures, but particularly to hydraulic gates in river weirs, dam spillways, navigation locks and the like, as the consequences of their failures are relatively large.

This article will focus on the repair of movable hydraulic structures after their failures. It is good to realize, however, that repair is not the only and certainly not the first issue that must be taken care of in case of such a failure. Other urgent issues include, globally:

– Preventing failures and damages of related other structures;
– Rescuing endangered individuals and property;
– Informing stakeholders and parties involved (e.g. navigation);
– Restoring (as far as possible) control of water flows;
– Documenting the event, collecting all relevant evidence;
– Investigations, choice of repair method, planning etc.;
– Temporary measures and regulations prior to actual repair.

These issues are discussed in more detail in chapter 16 of the book "Lock Gates and Other Closures in Hydraulic Projects" [1] by the authors of this article. That discussion also presents several examples of handling the failures of hydraulic gates, mostly from the USA and the Netherlands. Readers are encouraged to take note of these examples. After all, the work on resolving large structural failures often takes place under very different conditions than those of routine engineering.

SOME TERMINOLOGY AGREEMENTS

There exists an extensive discussion on the definition of a structural failure. Generally, *failure* is associated with not meeting the intended objectives. Yet, the perception of these objectives by parties involved is often different. This leads to controversies. An example is the behavior of the New Orleans' levees when attacked by the waves of Hurricane Katrina in August 2005 [2], see Fig. 1. The popular opinion is that these levees failed. Yet, the prevailing engineering opinion is that their collapse was exactly what they were supposed to do under the loads that clearly exceeded their original design specification. In fact, these levees would have failed if they did not collapse, as that

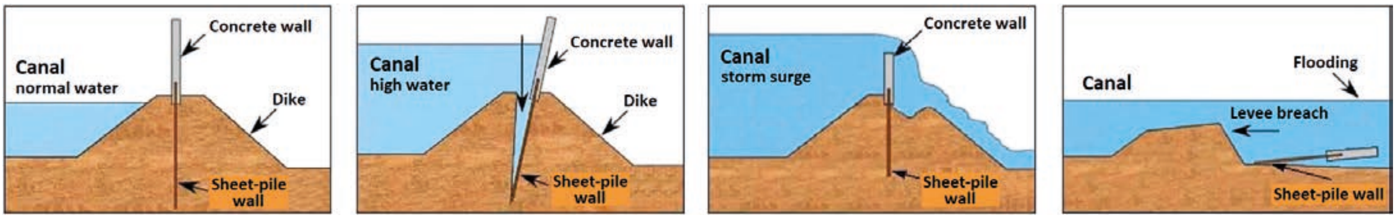

Fig. 1. Typical levee breaches in New Orleans during Hurricane Katrina

would indicate their unintended high strength. It is, obviously, another matter whether their intended strength was correctly specified.

Without going into statistics, we shall accept the engineering concept of failure, if only for the reason that the "popular" concept is not verifiable. Verifiability of failures is required for economic reasons, but also to prevent failures of entire systems. Examples are fuses and breakers in electrical circuits, sacrificial anodes in cathodic protection systems, deliberate levee breaches in rural areas to spare cities etc.

Two other terms that may need clarification are *accident* and *calamity*. Both terms refer to undesirable, so-called "upset events", but not every accident involving hydraulic structure is a calamity. Merriam Webster defines a calamity as a disastrous event marked by great loss and lasting distress and suffering. In that respect, any accident or failure that results in life safety consequences should be categorized as a calamity. However, the definition of a calamity is also one of perspective. A failure of a lock gate or a gate drive that only takes a lock out of service for 1 or 2 hours should not be considered a calamity. On the other hand, accidents such as a barge or ship running into a lock gate, which in turn takes a heavily used lock out of service for weeks or months, could be considered a calamity. See the authors' recent book [1] for a more detailed discussion of this matter.

One may question why it matters to differentiate between accidents and calamities. After all, if any of these events occurs, the goal will be to get the hydraulic gate fixed and get it back in service. However, the identification of an upset event as "routine" accident or calamity is crucial for waterway administrations and will trigger different procedures, investigations, contracting rules and financing of the repair. In the Netherlands, for example, accidents are supposed to be handled and fully resolved within the regular maintenance budgets of regional waterway administrations, the Rijkswaterstaat Regions. Calamities, on the contrary, entitle these administrations to claim repair funds from the country's national budget. In the United States, the rules are similar with, additionally, the differentiation for the financing from state budgets or the federal budget. Another, practical difference between America and Europe is that the U.S. Army Corps of Engineers (USACE), steward of the American waterborne infrastructure, still has technological expertise, crews and equipment to restore the damages inflicted to hydraulic gates. Some European waterway administrations, like the Netherlands' Rijkswaterstaat, do not possess such assets any longer. They have disposed of them as result of short-sighted privatization policies in the first decade of twenty first century.

An example of the difference between the damage categorized as a calamity and the damage categorized as "routine" accident is presented in Fig. 2. To eliminate the correction for perspective (see discussion above), both examples are from comparable lock and dam sites in the USA. Below is a short description of the events that caused these damages.

Photo (a) shows the wrecked barges that broke free and jammed against the Maxwell Dam on the Monongahela River Nov. 5th, 1985 during a flood event. The accident halted the shipping for six weeks in order to remove the barges and repair the dam [3]. Businesses were losing $500,000 each day, because no coal could be shipped on a river dotted with coke plants, steel

a) b)

Fig. 2. Damage as result of calamity and 'routine' accident
a) Monongahela River Maxwell Dam barge accident in 1985, b) miter gate damage at Lock 5a on the Mississippi River in 2013

mills and coal-burning power plants. 5 coal mines were shut and 1,500 miners laid off. This upset event could undoubtedly be classified as a calamity. In was also handled as such by the US Government and USACE; making even part of the hearing by a Congress Committee of Public Works and Transportation [4].

Photo (b) in the same figure shows the damages induced to a miter gate leaf of Lock 5a on the Mississippi River, about 100 km south-east of Minneapolis. On May 16th, 2013, a push-tow barge impacted the upstream miter gate while in recess. This happened in a busy navigation season under extremely high flows. The collision caused damage to the gate but the pool was not lost. There is no second lock chamber at this site, so an extended shutdown would have halted the navigation on the entire Upper Mississippi River. Fortunately, a spare gate was available, and was installed shortly after. The waterway reopened to normal traffic within a week. No formal investigation board was utilized. The removal of the damaged gate and the installation of the spare gate were carried out by USACE in-house forces.

LIFE SAFETY RISK AND LOSS OF LIFE

This article focuses on technology and the means that it offers to resolve structural failures. It is, however, impossible to assess and select such means without a thorough risk analysis. After all, any significant upset event related to the operation of a hydraulic gate provides new data and should be followed by an evaluation and implementation of lessons learned. Risk analysis is a leading tool in this process.

Life safety risk should normally be given the most prominent place in this analysis. This is also the case in the practices of waterway administrations in most countries, including the Rijkswaterstaat and USACE. Yet, the analysis of life safety risks is often limited to those gated closures, of which the failures directly expose the population of downstream areas to such risks. These are mainly the closures of high head dams, flood barriers and storm surge barriers. In the USACE risk analysis on dams, any life safety risk is plotted, analyzed and evaluated on a risk matrix. In the Netherlands, risk analysis – life risk in particular – was a base for dividing the country into regions, so-called "embankment circles", with specified legal limits to the probabilities of exceedance for inundation [5]. The Dutch methodology to

Fig. 3. Elizabeth M towboat after going through Montgomery Dam, U.S. Coast Guard photo by Jesse Garrant

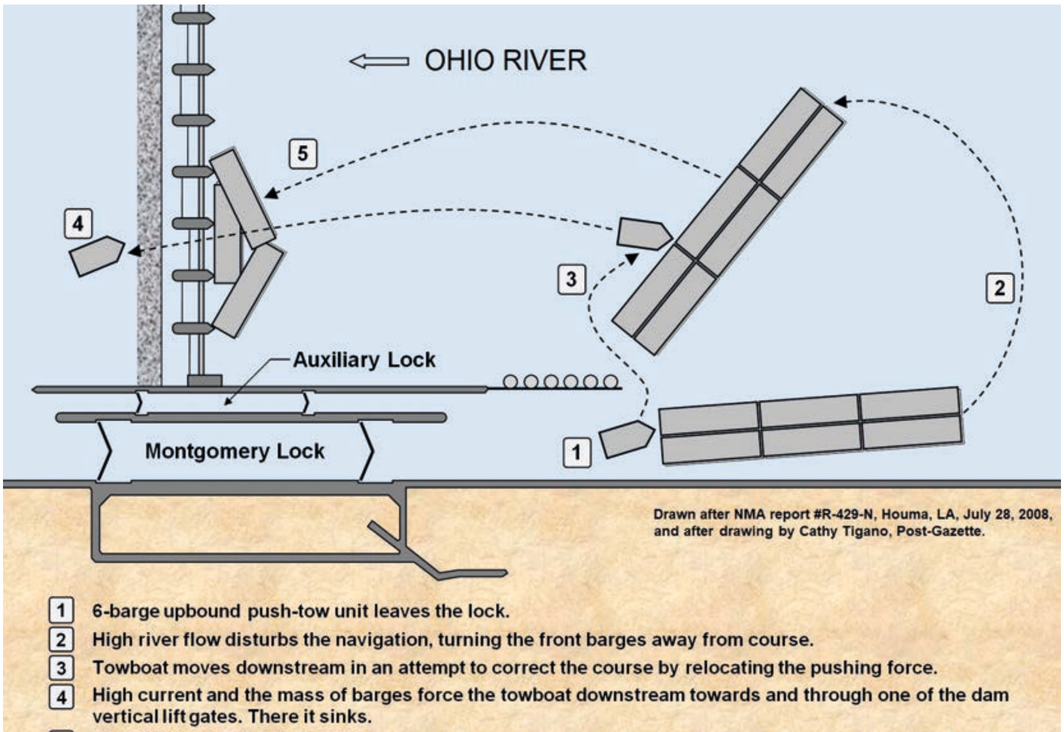

Fig. 4. Course of the accident with Elizabeth M towboat

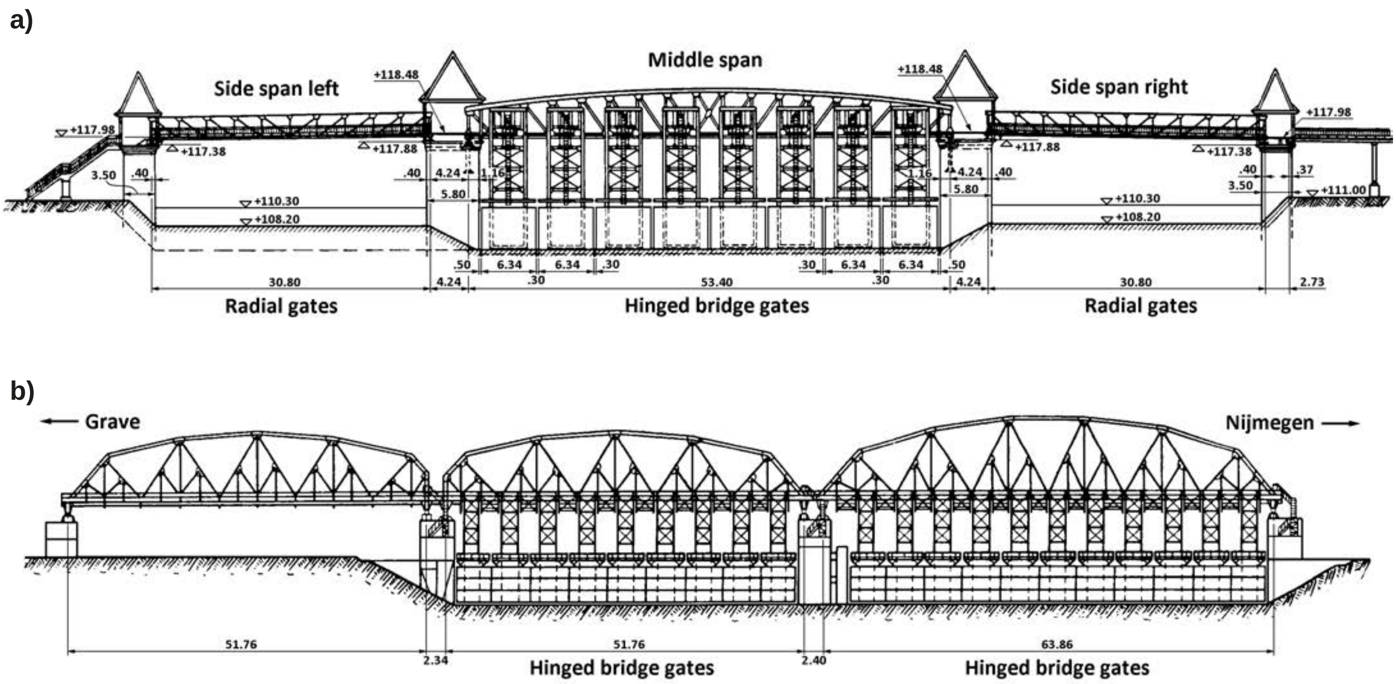

Fig. 5. European “bridge-weirs”, drawn after [8]
a) Oder Weir in Rędzin near Wrocław, Poland, b) Meuse Weir in Grave near Nijmegen, the Netherlands)

estimate the loss of life in flood risk management has, e.g., been outlined in [6].

Yet, the existing legislation and risk analysis methods usually do not capture the life safety risks of accidents such as, for example, a push-tow getting stuck under a dam gate, a pleasure vessel going through or over a gate, gate maintenance crews losing control of their equipment and the like. In all these cases, life safety risks concern the users or crews of hydraulic sites rather than the population of surrounding areas. The challenge for engineers is to identify such risks and to take measures that minimize them.

A dramatic example is here the sinking of the towboat Elizabeth M that went through the Montgomery Dam on the Ohio River on January 10, 2005 (Fig. 3). Four crewmembers lost their lives in this accident. The course of it is depicted in Fig. 4 and shows how difficult and stressful choices crews can be exposed to. The 2,200 horsepower towboat was pushing a six-barge unit, fully-loaded with coal, when it got caught by the outdraft current while exiting the lock. The current was very heavy due to high water on the Ohio River. To correct the course and save the barges and their cargo, the towboat moved further from the bank and relocated its pushing force. This did not help. The unit was taken downstream by the river, three barges smashed against the piers and blocked the dam bays; and the other three barges including the towboat went through the dam vertical lift gates and sunk on their downstream side. According to the Pittsburgh Post-Gazette, “Screams for help echoed from the towboat Elizabeth M as it sank into the swirling, frigid Ohio River” [7]. Only three crewmen were rescued from drowning by other towboats.

Very different were the consequences of the motor barge collision with the gates of the Dutch Grave Weir on the Meuse River in December 2016. This weir is of so-called “bridge-weir” type, of which only two exist in the world. The second (chronologically first) is the Poland’s Rędzin Weir on the Oder River near Wrocław. Schematic side views of both structures are presented in Fig. 5 [8]. Hydraulic loads are carried here by liftable water retaining panels, supported to vertical beams that, in turn, are hinged to the girders of a bridge spanning above the weir bay. During floods, the weirs can be “folded” by hoisting the beam free ends out of water to the horizontal position under the bridge deck.

On December 29, 2016, a German downbound tanker *Maria Valentine* carrying 2000 tons of benzene, went through one of the weir spans at full speed. This happened in the morning in a very dense fog. The ship damaged several vertical beams that hang from the bridge to support the water retaining panels. The ship dove down about 3 m passing the weir under the free ends of those beams. This, however, did not cause any injuries or fatalities on board, which was generally considered a miracle. Despite the damage on deck, the crew managed to anchor the vessel downstream of the weir and no benzene leaked into the river. Nevertheless, the damage to the water retaining structure (Fig. 6) in combination with too late closures of weirs in lateral canals caused the loss of navigation and substantial other damage in wide area.

This accident resulted in the total navigation shutdown of about two weeks, immobilizing the vessels already present in the area; with another two weeks of various navigation restrictions. The total cost of repairs and financial claims by various parties are not settled yet at the time of writing this article, but they will likely run into many millions of euros. Yet, no loss of lives is symptomatic as well. Although more is required to support this, a tentative conclusion can be that life safety risk by ship collision is relatively low for this type or weir. One can take it into account when considering the future of the Oder Rędzin Weir.

Fig. 6. Damage to the Meuse bridge-weir in Grave, photo Rijkswaterstaat

IDENTIFYING AND REDUCING THE RISKS OF ACCIDENTS

Accidents, including life safety issues, happen not only at large lock and dam sites but also at small river weirs and other structures with hydraulic gates. What increases the risk then is that there is normally no operation personnel at such structures. Therefore, it is important that all possible measures are taken to discourage swimming, boating, fishing and other activities that may generate risks, without changing the structure into a fortress. Hydraulic structures attract public attention and they should continue doing so. After all, openness to the public pays back in local understanding, acceptance and care. The simplest way to discourage risk generating activities is to place signs that clearly prohibit them. Fig. 7 shows two examples of this from small river weirs (one with a fish ladder) in the Netherlands.

Other ways include providing appropriate rescue conditions and rescue equipment on site, like safety nets, grapples, lifebuoys and rescue poles. Engineers should not play down such precautions. Life safety of hydraulic closures is an issue of growing importance for many reasons. The most evident of these reasons include:

- growing social and legal pressure in favor of safe and healthy structures;
- remote control policies reducing the presence of personnel in field.

Various guidance for ensuring the safety and health conditions of hydraulic sites can be found in the documents of appropriate waterway administrations, like the USACE manuals [9] and [10], and Rijkswaterstaat report [11]. The latter also includes examples and guidance on providing sufficient security of lock and dam complexes, particularly in view of their remote

a) b)

Fig. 7. Prohibition signs for swimmers (a) and boaters (b) at small river weirs

control. It is true, however, that all these guidance documents are primarily focused on the safety and security of own personnel and equipment. The safety risk of users, passersby and visitors, whether or not behaving as desired, is too often underestimated.

There are diverse life safety issues that hydraulic gate engineers should be aware of, although many of these issues are a prior concern of other disciplines, like spatial planning, hydrology and hydraulics. Some of these issues are listed below after [1]. This list is not exhaustive, and is intended to direct the attention to the subject rather than to fully discuss it.

- The risk of a vessel going through a dam rather than through lock is inherent to every lock and dam complex. After all, the dam is where the flow goes through; and that flow induces forces on vessels. It is the task of site planners and managers to provide sufficient safety conditions in order to reduce this risk to an acceptable level. This also applies to the conditions of high (e.g. flood) water levels, intensive navigation, extreme weather conditions etc. Yet, gate engineers should be aware that there is always a probability of such events happening.
- Most dam gates let water through either as overtopping or as undertow flow. Both cases involve the risk mentioned above, although the forces induced and the consequences of potential accidents may differ depending on the type and size of vessel, local situation and other factors. Also this is a consideration for hydraulic gate engineers.
- The basic three scenarios to consider in overtopping and undertow flow are that a vessel:
    - hits the dam gate causing some damage and remains in place;
    - goes over or under the dam gate with little damage to it;
    - goes over or under the dam gate causing major damage.
- Both overtopping and undertow flows introduce specific life risks to swimmers and crews of small vessels. The basic difference is as follows:
    - Overtopping flows generate horizontal currents on the upstream side and vertical currents on the downstream side. They also aerate the downstream water (see Fig. 7a) decreasing its specific gravity and increasing the risk of drowning.
    - Undertow flows generate both horizontal and vertical currents on the upstream side, normally without aeration. The main drowning risk comes from the scenario of being sucked to the bottom and clamped between the gate and its sill or dam crest.
- Various gate types may introduce very specific life risks. It goes too far to discuss all those risks in a single article. An example is the so-called "hydraulic roller" that can occur at some types of gates. A swimmer, animal, boat or another object trapped in a "hydraulic roller" may remain there for weeks before being flushed down the river. Gate engineers should be aware of such phenomena.

INVESTIGATIONS OF ACCIDENTS

Investigations and evaluations of accidents are something that every waterway administration should do. Some organizations, such as USACE, have the capability to conduct investigations in-house. Some other, like Rijkswaterstaat, have outsourced the technical expertise and will only be able to investigate the management aspects of accidents, leaving the technology aspects to external specialists. Still other, smaller organizations may need to contract out this entire work. It is imperative that any investigation contracted out is impartial. For the USACE investigation personnel, some key instructions to consider include [1, 9]:

- Investigation needs to be initiated in a timely manner, preferably within 1 or 2 days after accident. The longer this takes, the more likely it is that details will be forgotten and the evidence material removed.
- Investigation needs to be impartial.
- Ensure that only knowledgeable and experienced personnel conduct the investigation and are members of investigation team.
- Ensure that all reports are completed in a timely manner, preferably within 30 days after accident;
- Determine who caused the accident, what caused the accident, why did the accident happen, where did it happen and how it could have been prevented;
- Describe all circumstances in detail in regards to the accident or failure. Was there high water? What time of day was it? What time of year was it? What was the temperature? Was it raining, storming etc.?
- Provide details, lessons learned and steps to prevent similar accidents or failures from happening again.

USACE often establishes a Board of Investigation (BOI) for significant accidents or failures. The requirements for these investigations follow regulation [9] that defines accidents either by monetary value (here in 2010 dollars) or by loss of life. The issue with assigning monetary value to accidents and failures is that such a value typically only captures the repair cost or replacement cost of the asset such as a gate. It often doesn't truly capture the other costs such as delays to navigation industry. In particular, USACE accidents are classified as follows:

- Class A Accident: An accident in which the resulting total cost of USACE property damage is $2,000,000 or more; an injury that results in a fatality or permanent total disability to USACE civilian personnel or contractor personnel. Class A accidents are recordable and require a preliminary accident notification, a report of serious accident, an accident investigation report, and a Board of Investigation;
- Class B Accident: An accident in which the resulting total cost of USACE property damage is $500,000 or more, but less than $2,000,000; an injury that results in permanent partial disability to USACE civilian personnel or contractor personnel, or when three or more personnel are hospitalized as inpatients as the result of a single occurrence. Class B accidents are recordable and require a preliminary accident notification, a report of serious ac-

cident, an accident investigation report, and a Board of Investigation.

– Class C Accident: An accident in which the resulting total cost of property damage is $50,000 or more, but less than $500,000; a nonfatal injury that causes one or more days away from work or training beyond the day or shift on which it occurred. Class C accidents are recordable and require a preliminary accident notification and an accident investigation report;
– Class D Accident: An accident in which the resulting total amount of property damage is $2,000 or more, but less than $50,000; Class D accidents are recordable and require a preliminary accident notification and an accident investigation report.

USACE Boards of Investigation perform in-depth inquiries into and analyses of the events before, during, and immediately after an accident, determining its causes and contributing factors. This includes who, what, when, where, why, and how. Boards of Investigation are not supposed to assign blame or determine punitive actions for an accident. As follows from the classification above, BOIs are used for accidents with one or more of the following:

– fatal injury (loss of life);
– permanent total disability;
– permanent partial disability;
– hospitalization of three or more people;
– USACE property damage of $500,000 or more.

BOI reports have been done for several USACE accidents and failures described in the book “Lock Gates and Other Closures in Hydraulic Projects” [1] including the failures at Mel Price and John Day Locks. For the Markland Lock failure, the purpose of the BOI was to gather and evaluate information to determine the cause of the accident that resulted in the damage to the downstream miter gates in September, 2009. The BOI was to determine the cause(s) of the accident and to develop recommendations for the prevention of future occurrences of similar accidents. The BOI was required to prepare a report of their investigation, analysis and recommendations within 30 days of the incident.

In the Netherlands, investigations of serious accidents or failures of hydraulic structures are initiated and coordinated by regional crisis teams, following Regional Crisis Plans (RCPs). The members of crisis teams represent diverse organizations responsible for regional safety, with Rijkswaterstaat as one of the main players. Rijkswaterstaat also has an internal network of crisis teams. However, since the large-scale dismantlement of in-house expertise in the first decade of the 21st century, this network only provides management services. All in-depth investigations have corporate character and need to be carried out by third parties. This can partly be justified by the country’s strong culture of dialogue, but it also has its critics.

The Grave Weir accident discussed earlier in this article, was initially seen by Rijkswaterstaat crisis team an internal water management problem. Other issues, like the fact that the *Maria Valentine* tanker that had ran into the weir carried 2,000 tons of highly flammable benzene, were not immediately addressed. Also the consequences of the descending water level of the

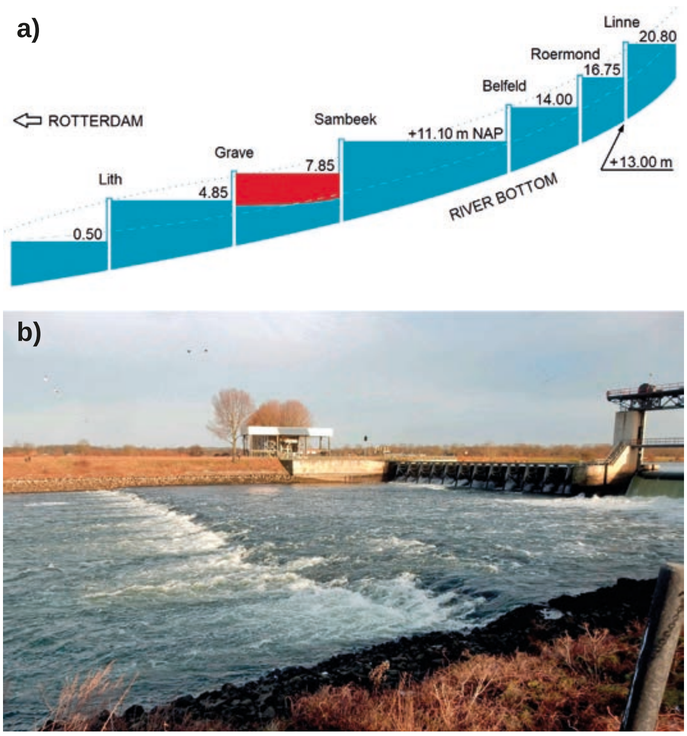

Fig. 8. Loss of upper pool as result of Grave Weir accident in 2017
a) navigation profile of the Meuse River in the Netherlands,
b) Meuse Weir in Sambeek with lost downstream pool, photo Rijkswaterstaat)

Meuse River and its lateral canals were not entirely and not soon enough clear for the crisis team. The most evident consequence, the loss of the upper pool, is depicted in Fig. 8. There is a lot that went wrong in both the assessment and the management of the accident. The details of it are described in the report by the national Investigation Council for Safety (Onderzoeksraad voor Veiligheid) [12] along with appropriate recommendations and lessons learned.

HANDLING THE DAMAGE AND PLANNING THE REPAIR

The discussed examples of accident handling allow to distinguish some stages in handling accidents and calamities. Specialists in process management often make use of graphical models, like circles, pyramids, stairs, spirals etc. for visualizing complex processes. In this article and in book [1], we have chosen a model that resembles fish. After all, this discussion concerns hydraulic gates, i.e. structures that, by definition, operate in water. Fig. 9 schematically shows some typical stages in handling accidents and calamities involving hydraulic gates. It also globally indicates the relative urgency of these stages and the demand for personnel, material and other resources.

Some general rules and relations indicated in this figure can be summed up as follows:

– The urgency to act is typically the highest directly after (if possible even during!) the accident or calamity. The emerging situation is then out of control. The absolute priority is to regain that control, preventing or at least limiting any further damage.

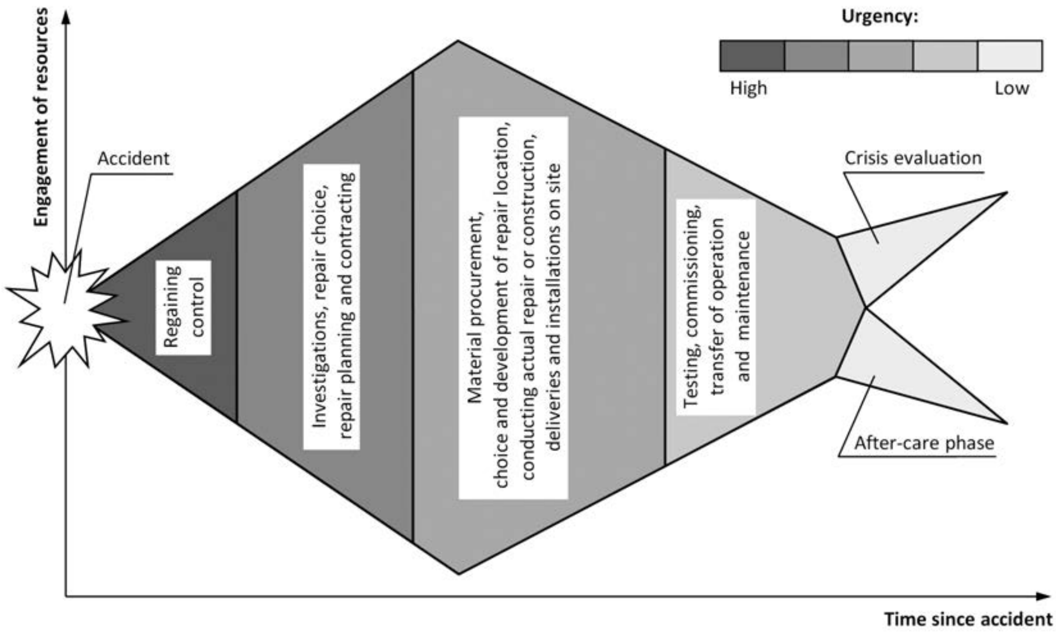

Fig. 9. Urgency and engagement of resources in handling accidents and calamities

- Although the urgency is the highest, the available resources to meet the emerging needs are in the first instance the lowest directly after the accident. This applies to all resources: human, material, equipment, etc. Organizations may and should train freeing these resources as soon as possible but it will always take time to fully mobilize them.
- Once the situation is under control, the next step is to inventory the damage, investigate its causes, and choose the necessary repairs. The urgency has decreased a little at this stage, but it is still high. The engaged resources are already substantial but the main bulk of work still has to be done. It is important to let it begin quickly and efficiently.
- This main bulk of work can be done either by the in-house forces or by contractors or by a joined effort of both. USACE will largely rely on the in-house forces. Rijkswaterstaat does not have such forces anymore and will need to contract all works. The result must in both cases be a permanently repaired or replaced hydraulic gate that can be operated for years to come.
- Once the repaired or replaced gate has been delivered and installed, and all other accompanying damage has properly been fixed, the system will undergo a series of routine tests. Then it will normally be commissioned and handed over for operation and maintenance by the owner's crews. At this point, the handling of an accident begins to resemble a regular project, although the urgencies are often higher.
- The last stage includes the so-called after-care phase when various "teething problems" may occur and should be solved in accordance with the guarantees issued or other agreements. At the same time, the evaluation of crisis handling can take place. The evaluating team should include all main players, but it should also keep some distance from the issues of the day. This is indicated by a split in the fish's tail in Fig. 9.

REPAIR OR REPLACEMENT?

A question that often arises after a serious accident is whether the damaged gate should be repaired or entirely replaced by a new structure. This question is basically economical and an answer to it follows from the known economical formulas for comparing the capitalized costs of more maintenance and delayed gate replacement to the costs of new construction and replacement. It is important, however, that this comparison is objective and takes all relevant factors into account. The practice shows that objective, well-balanced judgments are not easy in emotional situations after the accidents.

Disturbances to such judgments may be of various nature. First is that the personnel involved does not like to be blamed for the accident; and the easiest way to counter the blame is to put it on the technology. Therefore, investigators of an accident and designers will often hear that the gate, its drive machinery or control system did not function properly, was "impossible" to properly maintain or difficult to operate. The challenge is to objectively verify these views rather than to simply echo them in final recommendations and decisions.

Other disturbances of decision making may come from organizations or individuals who have particular interests in the nature of final decisions. These can be diverse stakeholders, lobbies, but also individuals within the waterway administration. After the damage of the Lith Weir gate, discussed further in this article, the investigators and project team were under strong pressure from some Rijkswaterstaat managers to trigger a large-scale new construction project instead of simply to repair the damage. Engineers are encouraged to read the Naomi Klein's book *The Shock Doctrine* [13] for a study on such pressures.

In this view, it is important that the exceptional regulations and powers that can be assigned to crisis teams to speed up solutions to accidents and calamities are not misused. Justifiable as they are, such regulations should in no case be extended beyond the stage of regaining control of the situation. The regulations of this kind comprise, for example [1]:

- shortened communication lines;
- expedited or bypassed bidding;
- shortened contracting procedures;
- bypassing other regulatory procedures;
- sizing or damaging other party's property;
- introducing restrictions of various nature.

Below are short descriptions of two hydraulic gate rehabilitation projects that allowed for a total restoration of gate functionality after an accident. The first of these accidents, the Melvin Price Lock gate failure, was resolved by repairing the gate. The second accident, the Lith Weir gate failure, was resolved by a partial replacement of the gate.

MELVIN PRICE LOCK MITER GATE FAILURE

The Melvin Price Lock is located on the Mississippi River just north of St. Louis, Missouri. It comprises two adjacent parallel lock chambers: the main and the auxiliary chamber. The main chamber is 33.5 m wide and 365.7 m long; the auxiliary chamber is 33.5 m wide and 182.8 m long. At normal upper and lower pools, the locks have a 7.3 m hydraulic lift. The auxiliary lock has miter gates in both crowns while the main lock has a vertical lift gate on the upper crown and a miter gate on the lower crown. The accident, described in detail [14] and [15], occurred on the auxiliary lock. The description below is quoted from [1].

On October 3rd, 2004, both leaves of the auxiliary lock downstream miter gate were forced past their mitered position (Fig. 10), resulting in extensive damage to the leaves and various other damages in the vicinity of the gate. The failure prompted an investigation board and emergency measures to get the lock

Fig. 10. Mel Price auxiliary lock downstream gates after failure, photo USACE

back in operation. The gate was repaired by combined effort of USACE in-house forces and contractors. Since the damage occurred to the smaller lock, the large push-tow barges could still use the main lock. However, the failure did create significant traffic delays. The gate was repaired and the lock back in service in July 2005.

The immediate cause of the failure was the premature opening of the Tainter valves and filling of the lock chamber without the gate leaves being in a mitered position. This created a significant unbalanced head in the lock chamber that subjected the gate leaves, their supports and anchorages to forces beyond their design capacity. The auxiliary lock at this location utilizes mechanical gate drive systems and struts.

Three contributing causes that allowed the chamber to begin filling without the leaves being correctly mitered can, according to [14], be summarized as follows:

- Incorrect indications of Programmed Logic Controller (PLC), identifying that the gate was mitered while it was not;
- No operator verification to check for a successful gate mitering;

a)

b)

Fig. 11. Mel Price Lock gate failure, details, photos USACE
a) damage to gudgeon anchors, b) damage to the pintle

– Improper adjustments of hydraulic system relief valve settings, higher than the original design values, resulting in undetected fracture of the gate strut bolts.

The failure resulted in an extensive damage done to the gate gudgeon anchorages, as shown in photo (a) of Fig. 11. The anchorages were essentially ripped off the gate leaves. Also the gate operation struts failed and were heavily damaged. The pintle socket sheared off as shown in photo (b) of Fig. 11. The bottom seals and their supporting structure on both gate leaves were also damaged.

Despite the significant damage, investigations performed by the USACE team supported by experts from various universities, heat straightening experts and other specialists, showed that both miter gate leaves could be repaired. The repair was also believed to be quicker than new construction, thanks to the engagement of USACE in-house forces for disassembly, transport and reassembly of the gate. The gate leaves needed, however, to be shipped to the service base, where they would undergo complex heat straightening, replacement of hinges, anchor bars, struts and other damaged components.

Photos in Fig. 12 present some subsequent stages of this repair. Note that such works require utilization of diverse auxiliary structures, like hoisting beams (so-called “spreaders”), tilting supports, temporary supports and the like. The tilting supports (also called “turning feet”) prevent local dents by spreading the contact pressures that would otherwise have to be carried on the gate edges. The USACE maintenance forces also have vessels that allow gate leaves to be shipped in a vertical position, in the so-called “toasters”. This is particularly desired when the installation of new or refurbished gates must be quick in order to hinder the navigation as little as possible. It also allows to perform some inspections and finishing works while during the shipment of the gate.

LITH WEIR FLAP GATE FAILURE

The details of this accident have been presented for the Polish colleagues in paper [16] at the Szczecin conference “Structural Failures” in 2011. Other readers can also find them in the author’s paper and presentation [17] from the PIANC MMX

a) b) c) d)

Fig. 12. Mel Price Lock gate, stages of repair, photos USACE
a) gate leaves freed for transport by cutting the anchors, b) gate leaf placed on barge using turning feet,
c) heat strengthening of gate girders, d) coated gate leaf in a “toaster” ready for shipment back to the site

Congress in Liverpool. Below is an abbreviated description quoted from [1]. The Lith Weir flap gate accident can be seen as an example of quick and effective handling after a failure of hydraulic gate.

At the end of January 2007, the southern gate of the Meuse weir in Lith, the Netherlands, suffered a serious damage. The top flap section – meant to control the river flow – broke off from its hoisting chains and fell down on the rear structure of the bottom section. The accident caused an uncontrolled flow (Fig. 13) threatening the navigation on the river, which is one of the Europe's most navigated inland waterways.

The failure of the southern gate occurred in a period of high water levels on the Meuse, when the flap position often had to be adjusted. During these operations, the control weir system signalized malfunctioning. From the interviews held afterwards by the author of this article, it was established that such malfunctioning signals had been frequent in the past. The operators routinely reported them but the maintenance works brought no improvement. In order to control the flow, the crew used to ignore these signals by pressing the "reset" button and applying more tension to the flap chains. This usually worked. On that day, however, there was a chain blockage at one lifting tower, causing asymmetrical lifting and torsion of the flap. One overloaded chain broke and the flap fell down to its lowest position, damaging the massive hinge components and other items, as shown in Fig. 14. Quick decisions and actions were required in order to regain control over the river and to restore the gate operation.

Fig. 13. Uncontrolled flow as result of Lith Weir gate damage

Immediately after the accident, Rijkswaterstaat called a crisis team, in this case supported by a so called "Out of the Box" team of experts that included the first author of this article, other experienced employees (some of them retired), and a few external specialists. The immediate concern was to get the situation back under control by halting the uncontrolled river flow.

The failed gate was clamped in a slightly inclined position above the sill. Setting it stable on the sill was the first goal and was accomplished the day after the accident. The next steps required the installation of an emergency closure on the upstream side, which, however could only be done at reduced flow over the gate. This was not easy since the calamity happened in the period of high flows. Yet, the upstream water level could temporarily be lowered by adjusting the upstream weir heights and allowing for more discharge through lateral canals. At the same time, the downstream water level could slightly be raised. This reduced the river flow in Lith, which, in turn, allowed to temporarily lift the other two weir gates out of water. The result was a still further local equalizing of water levels at both sides of the failed gate. Under these conditions, the emergency closure

a) **b)**

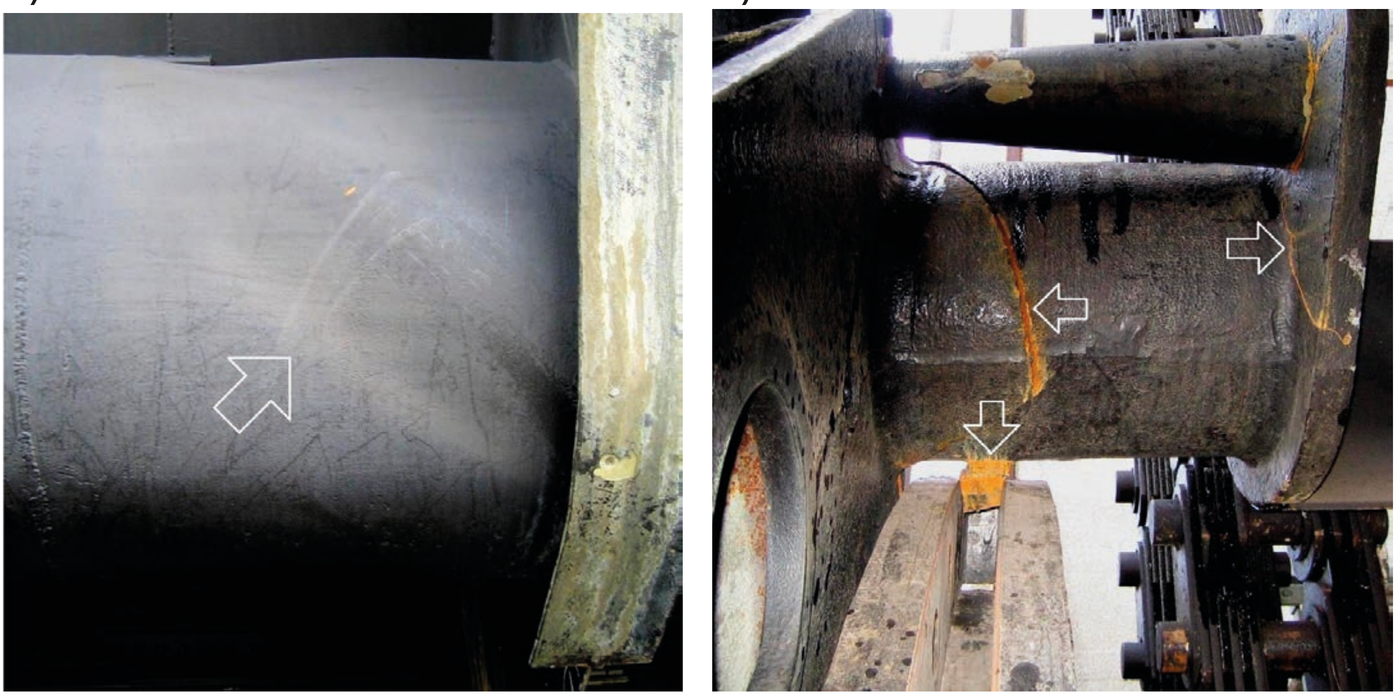

Fig. 14. Lith Weir gate damages, details, photos Rijkswaterstaat
a) deformed torque tube of the flap section, b) fractures of flap lever arm castings

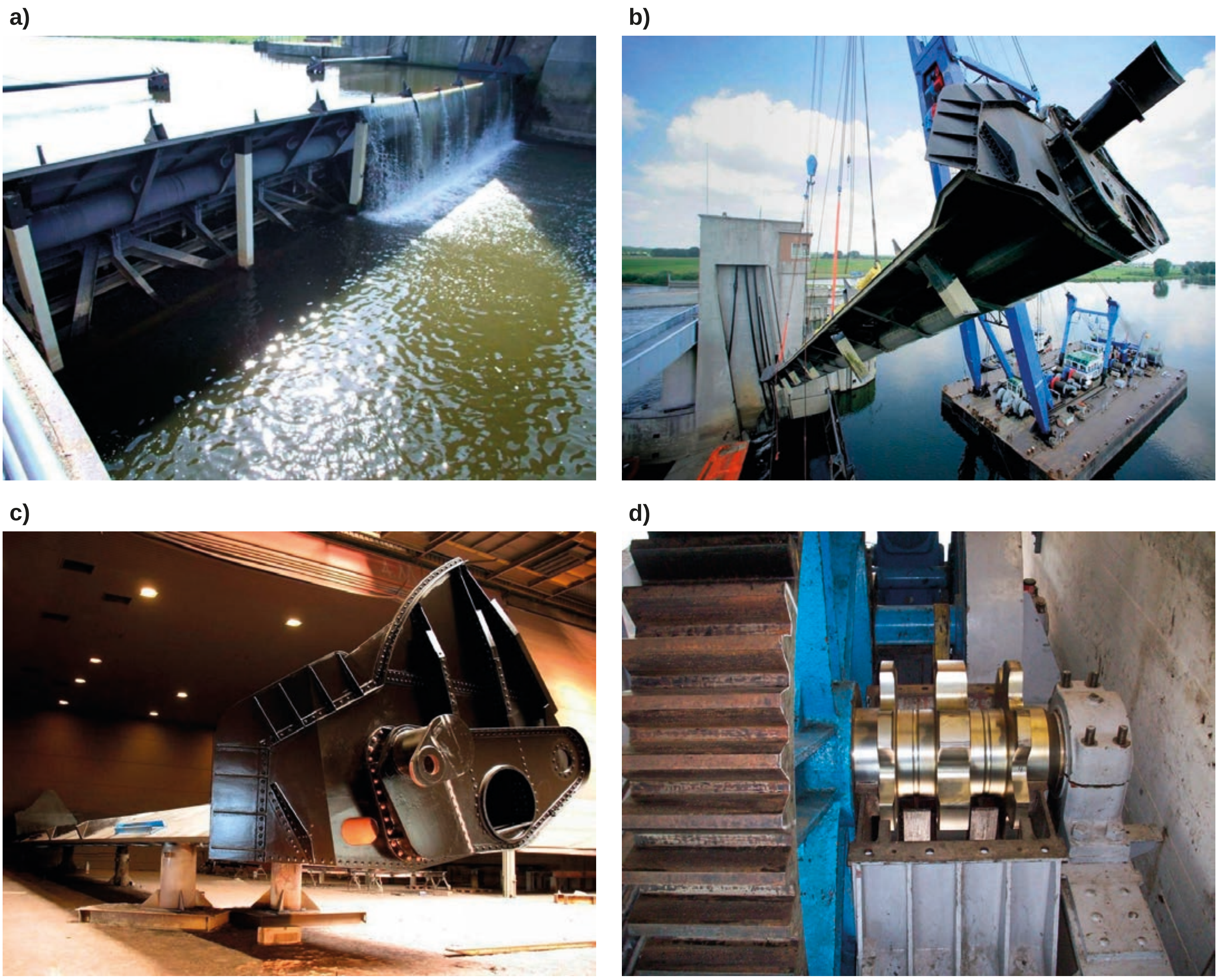

Fig. 15. Lith Weir gate, stages of repair, photos Rijkswaterstaat
a) flap section temporarily fixed in raised position, b) damaged flap being removed to make place for new one,
c) new flap section in construction shop by Hollandia B.V., d) new bull gear ready for chain installation

could be installed and the damaged gate became accessible and could temporarily be stabilized in raised position by a number of columns that supported the flap section (Fig. 15a). Within about a week, the river flow was under control and the emergency condition (including emergency regulations) could be called off.

The performed inspections made clear that the damaged flap section of the gate could not be repaired. The vertical lift section that supported the flap suffered, however, only a minor damage and could still be operated. The next stages comprised a number of projects to restore the full operation of the weir; and to upgrade the maintainability of its diverse components. The most essential was the fabrication and replacement of the gate flap section, shown in photos (b) and (c) of Fig. 15. Engineers succeeded to preserve the original, riveted technology in this historical structure. Other projects included upgrading measures such as the delivery and installation of new bull gears, shown in photo (d), improved hoist chains, structures for chain lubrication and the like.

CONCLUDING REMARKS

Repair and upgrading of steel structures after accidents or calamities are atypical projects of a specific character. It is utmost important that such projects are initiated and executed in a professional, well-controlled and timely manner. Unfortunately, there are many examples of accidents and calamities ending up in mutual blames and long legal struggles between parties involved, rather than in repair projects. The costs of such struggles, including the costs of delayed repair are often very high and affect many stakeholders.

Quick repair, desired as it is, should not prevent accidents and calamities from being properly documented. The documentation of such events should include all relevant details mentioned earlier in this article, but particularly the details that can no longer be verified once the repair has been initiated. It is important that such details are documented and the findings are correctly communicated so any lessons learned can be applied to future projects.

In this article, the authors tried to give a global overview of procedures, including repairs and upgrading projects, as result of accidents to hydraulic gates. This is a broad subject and it is impossible to comprehensively discuss all its aspects in a single article, as the nature of such accidents can be very different. Not discussed are, for example, accidents involving fire, damages due to vandalism, intended damages of terroristic or other nature. Readers seeking more guidance in this field are encouraged to consult the recent book [1] by the both authors of this article.

A possible critique can be that the presented discussion is focused on practical, engineering aspects, rather than on scientific analyses supported by statistic data. Without playing this argument down, the authors feel that accidents and calamities are events of an irregular and infrequent nature, which is difficult to sufficiently capture in databases. Therefore, it is also difficult to approach using statistical methods. The deterministic engineering imagination can in such situations be more useful than the statistics. This should not, however, discourage scientists from collecting appropriate data and developing the tools of its analysis in this field.

REFERENCES

1. Daniel R. A., Paulus T. M.: Lock Gates and Other Closures in Hydraulic Projects, Elsevier Butterworth-Heinemann, Oxford, November, 2018.

2. Daniel R. A.: Zapory morskie w Nowym Orleanie (USA) a 10 lat po huraganie Katrina, Inżynieria Morska i Geotechnika, no. 5/2015.

3. Sullivan T. M: Historical Perspective – Navigation Project Incidents, presentation on Periodic Assessment Workshop, USACE Institute for Water Resources, Risk Management Center, Louisville, KY, May 2016.

4. U.S. Government: Flood Damages along the Monongahela and Cheat Rivers … … as Result of Severe Flooding in November 1985, Hearing before the Committee on Public Works and Transportation, Washington 1986.

5. Overheid: Wet op de Waterkering, De Minister van Verkeer en Waterstaat, Den Haag, 21 december 1995, http://wetten.overheid.nl/BWBR0007801/2008-07-01.

6. Jonkman S.N.: Loss of life estimation in flood risk assessment, Theory and application, dissertation, Delft University of Technology, Delft, 2007, http://library.wur.nl/ebooks/hydrotheek/1875249.pdf.

7. Hopey D.: Oversize and overloaded tow accident: The Elizabeth M case, Pittsburgh Post-Gazette, January 10, 2005, http://nationalmariners.us/images/R-340-A_Oversize_and_Overloaded_Tow_-_Elizabeth_M_Case.pdf.

8. Kulka H.: Der Eisenwasserbau, Band 1. Theorie und Konstruktion der beweglichen Wehre, Verlag von Wilhelm Ernst & Sohn, Berlin, 1928.

9. USACE: Engineering Regulation ER 385-1-99, USACE Accident Investigation and Reporting, U.S. Army Corps of Engineers, Washington D.C., 15 March 2010.

10. USACE: Engineering Regulation ER 385-1-1, Safety – Safety and Health Requirements, U.S. Army Corps of Engineers, Washington D.C., 30 November 2014.

11. Rijkswaterstaat: Ruimtelijke kwaliteit in relatie tot Sociale veiligheid en Security, Kort Tielens architecten in opdracht van Rijkswaterstaat, 14 December 2011.

12. Joustra T. H. J. et al.: Stuuwaanvaring door Benzeentanker bij Grave, Onderzoeksraad voor Veiligheid, The Hague, May 2018.

13. Klein N.: The Shock Doctrine – The Rise of Disaster Capitalism, Metropolitan Books, New York, 2007.

14. USACE: Melvin Price Locks & Dam, Auxiliary Lock Downstream Miter Gate Failure, Engineering Investigation Report, USACE St. Louis District, 3 October 2004.

15. USACE: Mel Price – Auxiliary Lock Downstream Miter Gate Repair, presentation, Inspection and Repairs Workshop, USACE St. Louis District, 18 – 20 April 2006, https://slideplayer.com/slide/4767644/.

16. Daniel R. A.: Awaria i odbudowa stalowych zamknięć jazu Lith na Mozie, proceedings of XXV Conference „Structural Failures", Szczecin – Międzyzdroje, 24-27 May 2011.

17. Daniel R. A., Tromp A., Groot de M.: Damage and repair of an old weir gate in the Meuse after a calamity, proceedings of PIANC MMX Congress, Liverpool, 2010.