Funded by European Union Civil Protection

Grant Agreement Number 874421

Vulnerability assessment of embankments and bridges exposed to flooding hazards

D6.4 Strategy for adaptation measures to flood events

Project Information

Grant Agreement No.	874421
Project Acronym	oVERFLOw
Project Full Title	Vulnerability assessment of embankments and bridges exposed to flooding hazards
Starting Date	1 December 2019
Duration	32 months
Call Identifier	UCPM-2019-PP-AG
Topic	UCPM-2019-PP-PREV-AG: Prevention in civil protection and marine pollution
Project Website	www.projectoverflow.eu
Project Coordinator	Prof. Meho Sasa Kovacevic
Organisation	Faculty of Civil Engineering, University of Zagreb
E-mail	msk@grad.hr
Telephone	+385 (1) 4639 250

Partner Information

Sveuciliste u Zagrebu Gradevinski Fakultet	Croatia	
Infra Plan Konzalting	Croatia	
GEKOM - geofizikalno i ekološko modeliranje d.o.o.	Croatia	
VEILIGHEIDSREGIO ZUID-HOLLAND ZUID	Netherlands	
INGEO BV	Netherlands	
ZAVOD ZA GRADBENISTVO SLOVENIJE	Slovenia	
Uprava Republike Slovenije za zaščito in reševanje	Slovenia	

Document Information

Work Package	6
Deliverable Title	Strategy for adaptation measures to flood events
Version	1.0
Date of Submission	29/07/2022
Main Editor(s)	Bau Valentina, Mirko Kosič, Andrej Anžlin, Mario Bačić
Contributor(s)	Meho Sasa Kovacevic
Reviewer(s)	Ken Gavin, Irina Stipanovic
Citation	V. Bau, M. Kosič, A. Anžlin, M.Bačić (2022). oVERFLOw Deliverable 6.4 Strategy for adaptation measures to flood events

Document Classification:									
Draft		Final	X	Confidential		Restricted		Public	X

History			
Version	**Issue Date**	**Status**	**Distribution**
1	07/06/2022	Draft	InGEO, IPK
2	28/07/2022	Final	All partners

Executive Summary

This deliverable is a report on the development of a strategy for adaptation measures to flood events for the embankments, riverbanks and bridges, which can afterwards be used for the case study areas considered in the Overflow project. The deliverable presents a comprehensive approach that enables the choice of the best adaptation measures to overcome the vulnerability of critical infrastructure to flooding events. The most suitable countermeasures can therefore be selected based on the outcomes of the vulnerability assessment and risk forecasting tool. Such a strategy will be essential for the relevant authorities and IMs. The strategy proposes optimal adaptation measures depending on areas specificities, incorporating socio-economic and environmental multi-objective optimization.

Keywords: adaptation measures, countermeasures, vulnerability, flooding, resilience, embankments, bridges

Table of Contents

1 Abbreviations and Acronyms

Abbreviation / Acronym	Description
ACB	Articulating concrete blocks
ADM	Adaptation decision matrix
CPAs	Civil protection agencies
CFD	Computational Fluid Dynamic
FA	Fly Ash
IM	Infrastructure Manager
PVC	Polyvinyl chloride
SFRC	Steel fibre reinforced concrete
SHM	Health monitoring measurements
WRS	Water retaining structure

2 Introduction

Climate change represents a major threat to the integrity and the operability of infrastructure facilities. The temperature and humidity rise and the increase of storms in frequency and intensity have led to more severe flooding events. Therefore, embankments, riverbanks and bridges have become among the most vulnerable assets to floods, posing a significant risk to human life. While embankments have become more prone to movements and collapse due to the changes in seasonal cyclic stresses, riverbanks have been increasingly exposed to flow erosion. Bridges, nevertheless, are yet more vulnerable as they have undergone an accelerated risk of deterioration due to the increased hydrodynamic pressures and erosive events. Therefore, water, civil and earth infrastructures have been adversely affected by climate change, and greater investments should be made in the research of appropriate adaptation measures and risk management strategies to increase their resilience. To choose the most appropriate adaptation measures, a solid selection process that considers socioeconomic, environmental, and economic factors should be used. With such a strategy, infrastructure owners, managers, and authorities can select the best and most resilient countermeasure.

This report will explore in detail the vulnerability to floods of embankments, riverbanks (Chapter 3) and bridges (Chapter 4). Based on this, a discussion on several adaptation strategies that can be adopted within a strategy frame and all the aspects that have to be considered in the decision-making process are highlighted.

3 Adaptation strategies for the case-study riverbanks and embankments

Floods, the main focus of the oVERFLOw project, are inevitably linked to climate change events. Climate change leads to extreme weather events in most parts of the world (EEA, 2016; World Economic Forum, 2019), such as droughts, heat waves and extreme precipitation, which, in turn, raise the water levels of rivers. Flood protection embankments and riverbanks are particularly sensitive to climate events. This is due to a combination of the increase in their loading conditions and a decrease in their performance as the soil strength reduces with increased water content. For this reason, we need to develop adaptation strategies to address these issues adequately.

3.1 Generalities on the adaptation strategies for flood protection systems

There are several relevant documents dealing with the challenges of adapting civil infrastructures to climate change. One of the most recent documents is the report *'Technical guidance on the climate proofing of infrastructure in the period 2021-2027'* (CN, 2021), highlighting several key questions for addressing climate adaptation issues. One of them is the question *'Are embankments stable enough to withstand flooding?'*, which is related to the flood regimes and extreme rainfall events. As a response, the document offers an example of an adaptation measure to climate change, and that is to *'consider changes in construction design that allow rising water levels and ground water levels.'* However, the issue of adaptation of embankments and riverbanks to climate change is much more complex and will be discussed in this deliverable.

Prior to the analysis of the adequate adaption measures, the degree of vulnerability of an asset must be identified, which then serves as an input for the identification of critical risks related to the asset. Within the oVERFLOw project, the vulnerability of flood protection assets in two case study areas has been thoroughly analysed. The vulnerability assessment results are shown in the Deliverable 4.1 *'Report on Vulnerability Assessment Methodology - Fragility curves for embankments subjected to flooding'* (Gavin & Reale, 2022). The overall idea of this deliverable is not to go step-by-step in 'vulnerability – risk – adaptation' protocols but rather to show the possibilities of the assets' adaptation from the engineering point of view, with the overall aim to increase their resilience to omnipresent climate change.

Resilience, as defined by the Intergovernmental Panel on Climate Change (IPCC, 2014), is *'the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions'*. Igigabel et al. (2020) give a thorough elaboration of the IPCC definition, with the overall conclusion that the 'preservation' and 'restoration' contribute to a common objective of stability which is achieved by the structural strength (the objective is achieved if the structures resist deterioration) or when structures have been damaged, by their ability to be repaired, by natural or human actions. However, the search for stability is only meaningful when the evolution of the system occurs slowly, which may be no longer sufficient and may even be inappropriate with changes in hazards. Therefore, as discussed by Igigabel et al. (2020), the term 'improvement' differs from the previous ones since it corresponds to the capacity of adaptation and where during and after each event, the system can be transformed to protect against dangerous effects with new characteristics. This is particularly valuable in a changing environment such as that caused by climate change. However, this ability to adapt appears less often in the field of engineering. The concept of resilience is usually used for the development of flood risk prevention policies, with particular emphasis on protective measures. In the Netherlands, the Four Capacities approach (de Graaf et al., 2009) is based on:

- the threshold capacity (ability to resist floods);
- the coping capacity (ability to reduce damage from floods that exceed the damage threshold);
- the recovery capacity (ability to recover from losses after an event);
- and the adaptive capacity (ability to apply a wide range of adaptive measures).

AECOM (2015) describes several adaptation strategies and responses which would result in more climate resilient infrastructure, and these approaches include:

1) accommodate and maintain;
2) harden and protect;
3) relocate; and
4) accept or abandon.

Where the selection of proper strategy depends on a number of factors, including location, temporal scale, and the specific impacts faced, these adaptation strategies can help categorize various adaptation responses for new and existing infrastructure, as shown in Table 1, and understand the various advantages and disadvantages of selected responses, as shown in Table 2.

Table 1: Approach to the adaptation strategies, from AECOM (2015)

Strategic approach		**Adaptation strategy**	
		Existing infrastructure	**New infrastructure**
1	**Accommodate & Maintain**	- Extend, strengthen, repair or rehabilitate over time - Adjust operation and maintenance	- Design and build to allow for future upgrades, extensions or regular repairs
2	**Harden & Protect**	- Rehabilitate and reinforce - Add supportive or protective features - Incorporate redundancy	- Use more resilient materials, construction methods or design standards - Design for greater capacity or service
3	**Relocate**	- Relocate sensitive facilities or resources from the direct risk	- Site in area of no, or lower, the risk from climate change
4	**Accept or Abandon**	- Keep as is, accepting the diminished level of service or performance	- Construct based on the current climate, accepting the possibly diminished level of service or performance

Table 2: Advantages and disadvantages of adaptation approaches, from AECOM (2015)

Strategic approach		Advantages	Disadvantages
1	**Accommodate & Maintain**	- Less costly - More pragmatic and flexible allows adjustment over time as more climate change data becomes available	- Requires monitoring, possibly frequent repairs, adjustments or more rigorous operations - Necessitates design for more flexible or upgradeable structures
2	**Harden & Protect**	- Proactive - Straightforward to implement and justify	- More costly - Assumes reasonably accurate climate forecasts
3	**Relocate**	- Proactive	- More costly - Sub-optimal location may decrease the period of performance or service
4	**Accept or Abandon**	- No extra up-front costs	- Proper communications are needed to inform decision-makers and beneficiaries to expect lower performance or service

Among the range of adaptation measures, the oVERFLOw project focuses on the harden and protect strategic approach for embankments and riverbanks. This choice is based on the fact that the assets considered are pre-existing. This approach usually consists of the implementation of structural adaptation measures. Based on the EU Commission guidances (CN, 2021), **structural (i.e. engineered) measures** include modifying the design or specification of physical assets and infrastructure or adopting alternative or improved solutions. On the other hand, **non-structural measures** tend to be more inherently adaptable to changes in flood frequency. These include land-use planning, improved monitoring or emergency response programmes, staff training and skills transfer activities, development of strategic or corporate climate risk assessment frameworks, financial solutions such as insurance against supply chain failure or alternative services. Generally, structural measures try to keep floodwaters away from people, while non - structural measures keep people away from floodwaters (ADB, 2007).

Therefore, this document will focus on asset-level engineering solutions as a response to climate change. Relevant infrastructure managers of embankments and riverbanks would be primary beneficiaries of the proposed adaptation solutions. However, the Civil Protection Agencies would also profit due to the fact that increasing the resilience of flood protection assets in case study areas also means increasing the resilience of the critical evacuation routes during and after the flooding event.

3.2 Vulnerability of riverbanks and embankments to floods

In the broadest sense, a flood protection system can be defined as a set of structures or protective elements presenting an overall coherence from a hydraulic point of view to ensure effective protection against floods (Igigabel, 2020). They can include a range of structures such as riverbanks, levees, breakwaters, seawalls, groynes etc. and inland measures such as drainage, storage and evacuation systems. Among these, embankments and riverbanks are most commonly constructed and usually represent the first line of flood defence. If these fail during the high-water event, flooding of a protected area is usually imminent. This was the case with the flood protection embankment in north Croatia, which was overtopped (Figure 1 - left) and breached (Figure 1 - right).

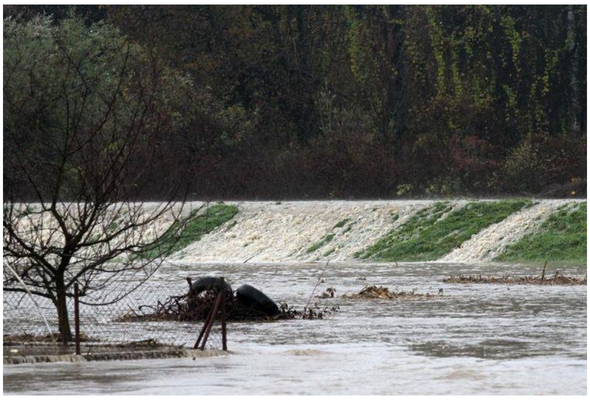

Figure 1: Overtopping (left) and breaching (right) of a flood protection embankment Virje – Otok Brezje in north Croatia in 2012., from Bačić et al. (2017)

Embankments and riverbanks have a long history of use in many countries and are a quite popular flood protection solution measures. Wenger (2015) attributes that to the fact that having a visible barrier to keep water out provides the impression of security and tangible evidence of "protection". In addition to this community benefit, embankments are popular with policymakers as they are regarded as being the most cost-effective mitigation measure for existing development or the only real option available. Having all this in mind, Wenger (2015) concludes that increasing exposure to floods, rising damages, and political pressure are likely to lead to increased levee construction and reinforcement. This will probably not be hindered by the mounted noticeable criticism of the structural approach for the adaptation, usually posed by the environmentalists concerned about impacts on ecosystems.

3.2.1 Overview of the failure mechanisms

Before evaluating various structural adaptation measures, appropriate failure mechanisms need to be considered when discussing the vulnerability of riverbanks and embankments to flooding events. A comprehensive overview of the failure mechanisms can be found in the International Levee Handbook (CIRIA, 2013), and this chapter will present only the most important ones which the climate stressors could trigger.

When the embankment (or riverbank) is made of coherent, fine-grained material, its initial shear strength will depend on the strength characteristics, moisture content and degree of compaction. However, over time material will erode on the surface and eventually progress towards the interior of the embankment body. This will be exacerbated by seasonal variations - the embankment will dry out and possibly crack during the increased temperature period of the year, and these cracks will create a prerequisite for easier infiltration of rainwater in the period characterised by increased precipitation. A combination of material softening, along with the infiltration of surface water or the presence of high water, leads to a combination of lower strength (resistance) of the embankment material at the time of highest external loading and consequent sliding (Figure 2, left).

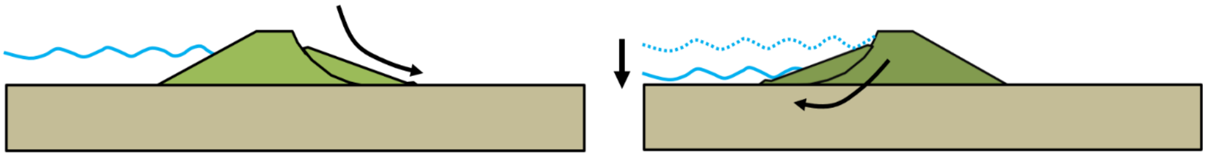

Figure 2: Sliding of the downstream embankment slope during the high waters (left) and of the upstream embankment slope after the high waters – rapid drawdown (right)

Rapid drawdown failure occurs when the water level on the river side of the slope experiences a rapid reduction in level after a flood event. The material in the body of the embankment remains saturated. Therefore, it has a large destabilising weight and low strength and is prone to form a slip failure towards the river (Figure 2, right). This is a commonly occurring failure mechanism in river embankments and riverbanks, as external water levels can drop rapidly whilst the soil on the slope remains fully saturated.

Further, external erosion includes the wearing away of the embankment slopes due to the action of external water (floods, waves), but also wind, rainwater (surface runoff) or some other process (action of humans, animals, vegetation, etc.). It can result in scouring of the slopes, local or global slope instability, the appearance of cracks in the embankment, etc (Figure 3).

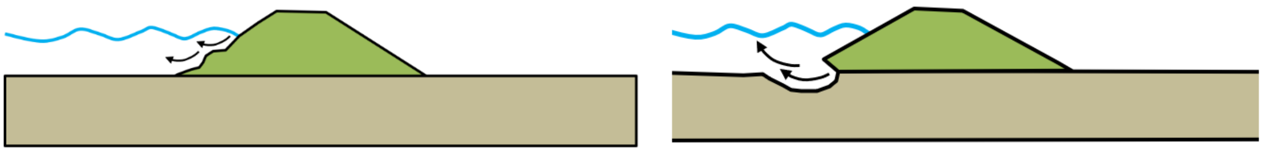

Figure 3: External erosion of the upstream slope of the embankment (left), which can lead to the scouring at the upstream toe level (right)

Overtopping / overflowing failure occurs when water flows over the top of the embankment (Figure 4). For this to occur, the flood level has to be larger than the height of the embankment. This makes it a very unlikely failure mechanism in most well-designed flood defences. Nevertheless, it remains a possibility during extreme events. If overtopping were to occur, the water velocity will increase down the landside slope of the embankment until such time as the water momentum and slope frictional resistance equilibrate, and the flow reaches a steady state.

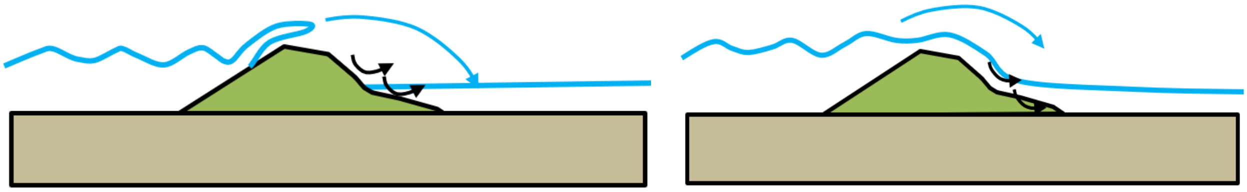

Figure 4: Overtopping (left) and overflowing (right) of the embankments

While external erosion is linked with the seepage above the embankment, either by overtopping or overflowing, hydraulic instability is linked with the through–seepage (flow of water within the embankment body) or with the under-seepage (seepage within the foundation soil). An increase in the pore pressure of a permeable layer that lies below a thin, low-permeability layer can uplift the covering layer (buoyancy) due to excessive water pressures at the contact of the poorly permeable and permeable layer. The increase in pressure occurs due to water seeping through the underlying soil, Figure 5 (left). Similar surface failure manifestation can occur due to hydraulic failure, Figure 5 (right), which occurs if forces from water percolation, directed upwards, acting against the weight of the soil, reduce the effective vertical stress to zero. When the vertical percolation of water raises soil particles and breakdown, so-called ‘boiling’ occurs.

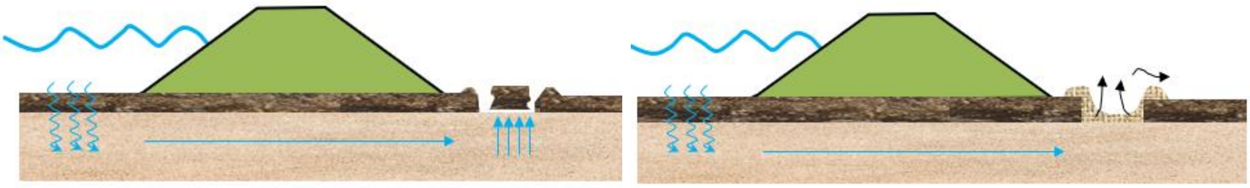

Figure 5: Failure by buoyancy (left) and soil-boiling (right) – both commonly appearing near the downstream toe

Piping occurs when particles within or below the levee are eroded due to seepage. If seepage forces become large enough, particles can get washed out of the soil, promoting increased flow which in turn can wash away larger particles and create a channel or a “pipe”. This channel works its way through the embankment, at which point the embankment is breached as there is a continuous erosion channel allowing water to flow from one side to the other freely. The speed at which this occurs is controlled by the pore pressure and the permeability of the material, as shown in Figure 6.

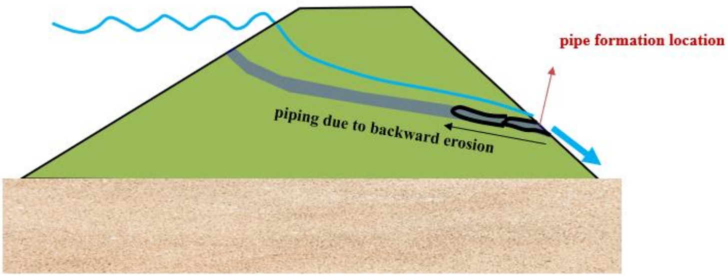

Figure 6: Failure by the formation of pipes within the embankment body or the foundation soil below the embankment

Even though it is linked with the serviceability limit state and not the ultimate limit state as the mechanisms described above, excessive settlement or differential settlement can lead to many problems (Figure 7). The embankment settles due to its own weight, additional load (static and/or dynamic), own weight and due the settlement of the foundation soil. The latter is especially important since most flood protection embankments are constructed on flood plains, often consisting of soft clay or peat layers of variable thickness. The characteristic of these materials is that they are subjected to relatively long-term consolidation and creep settlements, as is the case of the flood protection embankment in one of the oVERFLOw case study areas.

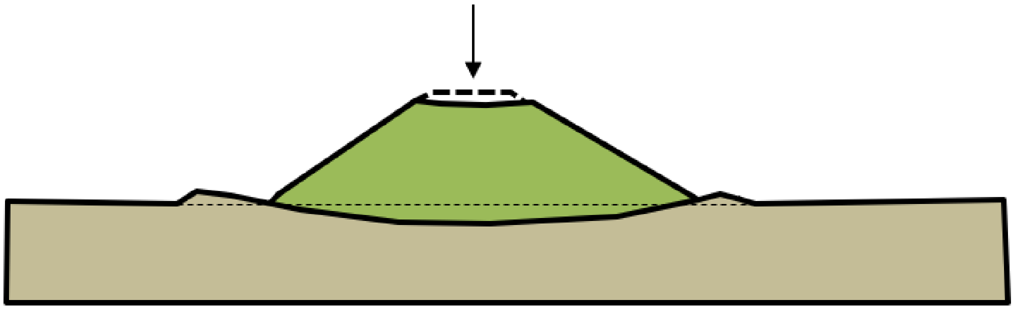

Figure 7: Excessive settlement of an embankment resting atop the soft soils

3.2.2 Influence of climate change on failure mechanisms

Earthen structures, embankments and riverbanks, are extremely vulnerable to climate impacts and therefore have gained much attention in recent years. In a series of papers, Vahedifard et al. (Vahedifard et al., 2016a; Vahedifard et al., 2016b; Vahedifard et al., 2017; Vahedifard et al., 2018; Vahedifard et al., 2020) discuss the influence of various climate stressors on failure modes of earthen structures. It can be concluded that historical observations and future projections indicate that we should prepare for more intense and frequent extreme events, which have multiple drivers that interact with earthen infrastructure and natural slopes.

The effects of climate-induced droughts on earthen structures are shown in Figure 8. Further, heavy rainfall may cause fluctuation of the groundwater table, erosion, and dynamic pore pressure changes resulting in the failure of earthen slopes, while the risk of erosion to slopes during high-intensity rainfall events will depend on the soil's composition and vegetative cover. Nevertheless, the authors concluded that the greater risk posed by climate change effects is due to the compounding of events in multi-hazard scenarios when compared to the risk posed by an extreme individual event.

Table 3 gives a summary of predicted climate change trends and their resultant effect on geotechnical infrastructure, along with the relevant failure mechanisms which may be triggered by the specific climate stressor.

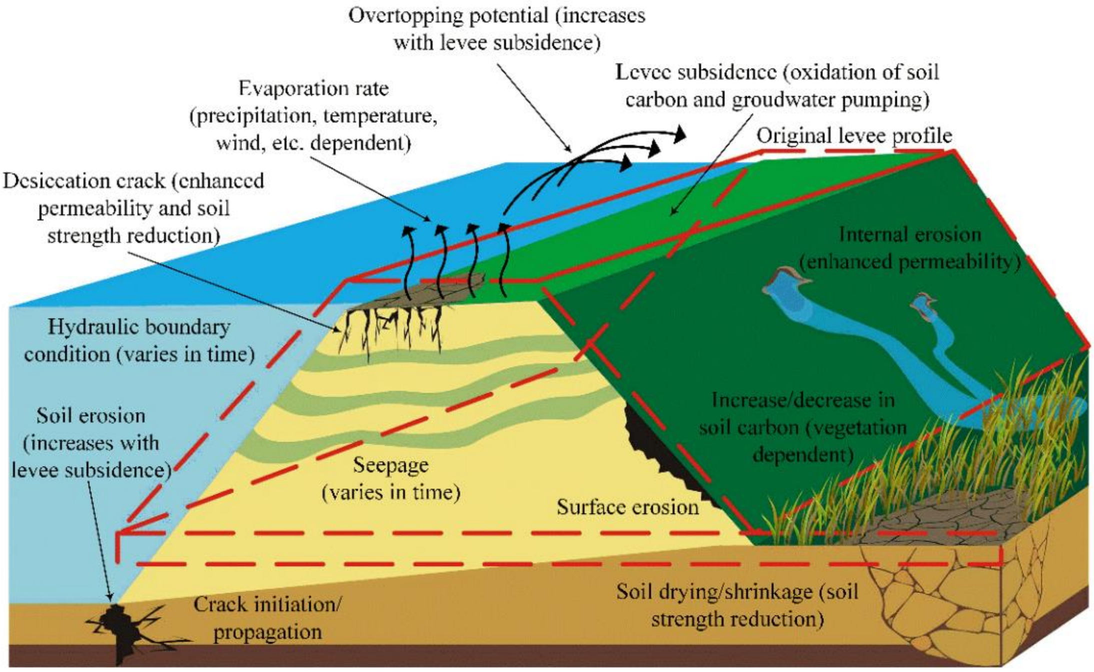

Figure 8: Weakening Processes Due to Drought, from Vahedifard et al. 2016a

Table 3: Potential Failure Modes Induced by Climate Change, from Vardon 2015

Climate change feature	Impact on earthen structures/slopes	Potential failure modes affected
Increased temperature	- Drying - Ice and snow melt at higher elevations	- Uplift - Slope instability
Decreased mean precipitation	- Possible desiccation cracking - Shrinkage	- Piping, internal erosion, slope instability - Piping - Piping, slope instability
Increased mean precipitation	- Soil wetting - Water table rise	- Erosion, slope instability, piping
Drought	- Elevated risk of impacts given for decrease in mean precipitation	- See *decreased mean precipitation*
Increased extreme precipitation	- Rapid soil wetting - Overland flow	- Piping, soil instability - Soil stability erosion
Flood / Sea level rise	- Large pore pressure increases - Soil wetting	- Piping, internal erosion, slope instability, external erosion, costal erosion

Climate downscaling models were developed for the case study areas given in Deliverable 2.2. (Burić & Grgurić, 2020), predict a decrease of precipitation in future periods for the city of Karlovac, while for the Dutch case study, increased precipitation is expected in all climate scenarios. The increasing precipitation foreseen for the Netherlands, in addition to causing a higher frequency of high water events and greater river flood magnitude, will result in the increased infiltration of water in the embankments during rainfall, reducing the soil strength and causing sudden failure. Foreseen decrease in precipitation in Croatia also implies a change in rainfall patterns, where although the events occur with reduced frequency, these will be more intense, causing rapid loading and increasing the failure potential. Additionally, these periods of intense precipitation will follow after long dry spells. This means that riverbanks are influenced by the impact of such events as drying and cracking of near-surface soils during dry periods, allowing rapid infiltration of surface run-off waters. The analysed climate scenarios are accounted for RCP 4.5 or RCP 8.5, where usually RCP 8.5 should be used for initial 'screening' analyses, while RCP 4.5 may be more relevant for projects where the increase in the level of climate resilience during its lifetime is a more practical option.

3.3 Structural adaptation measures for case study flood protection assets

When discussing adaptation measures for embankments and riverbanks, the integration of site-specific characteristics is of huge importance, especially in uncertain conditions created by climate change. This particularly refers to the identification of geographical, geological, geotechnical and hydraulic characteristics of the site, using a range of methods as described in Deliverable 3.1 (Bačić & Kovačević, 2021). Therefore, this section will provide information on structural adaptation measures separately for the Netherlands and for Croatian case study locations,

Igigabel et al. (2020) state that the adaptation measures should account for the characteristics of the environment, as well as the level of expertise and the material and financial resources available. Since structural adaptation usually means some physical intervention, this can impact negatively on the environment, and these impacts should be avoided, eliminated, reduced or mitigated in so far as possible. An important aspect of the implementation of adaptation measures is providing a piece of information to the infrastructure managers on when the specific structural improvement, as a response to the changing climate, should be integrated since their decision-making usually relies on large and heterogeneous data.

The mentioned International Levee Handbook (CIRIA, 2013) is a good compendium of state of the art in the field of structural measures for embankments. However, there is much literature that includes papers, reports etc., providing general or particular insights into the actions to be carried out throughout the structure life cycles of embankments and/or riverbanks. Generally, embankments and riverbanks will have to be raised, enlarged or extended, while the erosion of their slopes needs to be prevented or minimised. Also, if situated on deposits containing high organic matter, structural interventions must be implemented to ensure that the settlements are controlled in a proper manner. In addition to the structural adaptation, embankments and riverbanks will have to be regularly inspected and reassessed to continue performing properly.

3.3.1 Adaptation measures for embankments – Oosmolendijk

3.3.1.1 Overview of the climate-related issues

Flood protection embankments have been used in the Netherlands since the thirteenth century, and due to soil dried and peat decomposed, they have been continuously raised higher to retain increasing volumes of water (Wenger, 2015). The Delta Works program, following catastrophic floods in 1953, included an immersive structural works program that raised embankments and built flood surge barriers and closure dams across the mouths of coastal inlets. Wenger (2015) further notes that the embankments are ultimately maladaptive since they reduce the vulnerability of the populations they protect, but only for more frequent, low-level flooding - vulnerability to infrequent, major floods increases. Nevertheless, despite the fact that these are also marked inflexible, adversely affect other communities and natural-resource-based sectors, are high cost, and introduce path dependency. The reinforcement of key flood protection embankments remains an important strategy to adapt to future threats. Other measures, such as embankment setbacks (relocation landward) and removal of embankment areas, can widen the active floodplain, lower flood height, and reduce the risk of levee failure.

Within the oVERFLOw project, an Oud – Ijsselmonde - Oostendam flood protection section in the Netherlands is chosen as a case study asset located between Rotterdam and Dordrecht. This embankment section, 9.4 km long and consisting entirely of engineered soil slopes, protect the eastern part of IJsselmonde against the influence of the North River. Particularly, a section named Oostmolendijk was selected for the calculation of vulnerability and implementation of adaptation measures. Two types of climate-induced issues are analysed for the Oosmolendijk:

a) Ultimate limit state –with the vulnerability results shown in Deliverable 4.1 (Gavin & Reale, 2022), for which several relevant failure mechanisms have been analysed for the increasing water levels,

b) Serviceability limit state –with the results shown by Kovačević et al. (2022), where predictions of future behaviour of the Oostmolendijk are analysed. These creep settlements can be in future be affected by accelerated organic soil decomposition due to higher temperatures.

For the ultimate limit state, the mentioned report presented a methodology for developing fragility curves to assess the likelihood of embankment failure. The methodology considered embankment and riverbank failure through global stability, piping, overtopping and rapid drawdown. It is concluded that global instability was by far the biggest threat to the embankment system under normal operating conditions. However, as flood waters increased in magnitude, the likelihood of piping and rapid drawdown failures progressively increased. The system curve shows that for a 1 in the 1000-year flood event, there is approximately a 1% chance of failure. Calculated values of probability of failure for different scenarios provided the basis for the classification of Oostmolendijk sections based on their vulnerability and the development of an inventory of critical flood protection infrastructure (Figure 9).

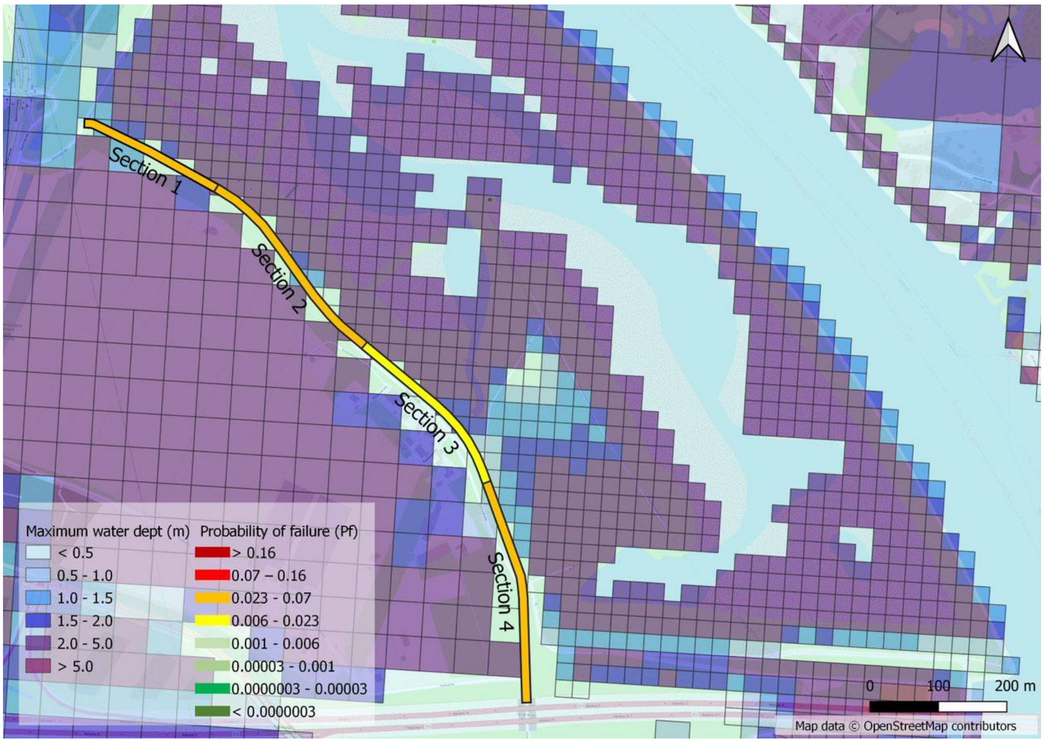

Figure 9: Vulnerability of Oostmolendijk divided in Sections 1 to 4 for the flood return period of 100.000 years, from Bačić et al. (2022)

Oostmolendijk is experiencing large settlements due to the underlying soft layers, which may cause progressive spreading of the embankment. This is the most likely driver for ongoing maintenance works. Archive data shows that prior remedial work at Oostmolendijk, between 1962 and 1968, proved to be very difficult with regular crack development and pore pressure variation resulting in large settlements. This, in turn, caused numerous delays in remediation. In 2013, a section of the embankment at Oostmolendijk was under repair when a global shear failure occurred within one section. This was likely due to the underlying soft peat and clay layers being unable to support the additional weight added by the construction of a reinforced inner berm. Second elevation works were conducted in 1991 when the embankment was elevated by 30 cm. However, after the 2013 reconstruction works, which included the installation of the additional material on the crest and downstream slope, the excessive settlement continued, leading to the present state with many cracks along the road resting on the crest, as well on the slopes (Figure 10).

Figure 10: Cracks on the Oostmolendijk crest road and on the embankment slopes, from Kovačević et al. (2022)

The time-dependent settlement of Dutch embankments is a well-known problem, where Speijker et al. (2000) note that these embankments slowly sink "away into the sea" due to a combination of factors such as soil settlement and relative sea-level rise. While the sea-level rise can be directly associated with climate changes, the settlement is primarily the result of soft soil deposits which contain a high percentage of organic components. In addition to the prevailing creep of these sediments, as reported by Kovačević et al. (2022), land subsidence due to soil drying and decomposition of organic materials during prolonged drought can lower the height of embankments, increasing the risk of overtopping. To assess the future settlements, Kovačević et al. (2022) used geophysical, geotechnical, and unmanned aerial vehicle data, along with InSAR and GPS monitoring data, to provide reliable estimates of the long-term behaviour of Oostmolendijk (Figure 11). A fully defined numerical model, supported by the neural networks and particle swarm optimization algorithms, with the best estimate of input creep parameters, also provides insight into the long-term soil stress state, which cannot be obtained by simple extrapolation of the regression functions used merely on monitoring data.

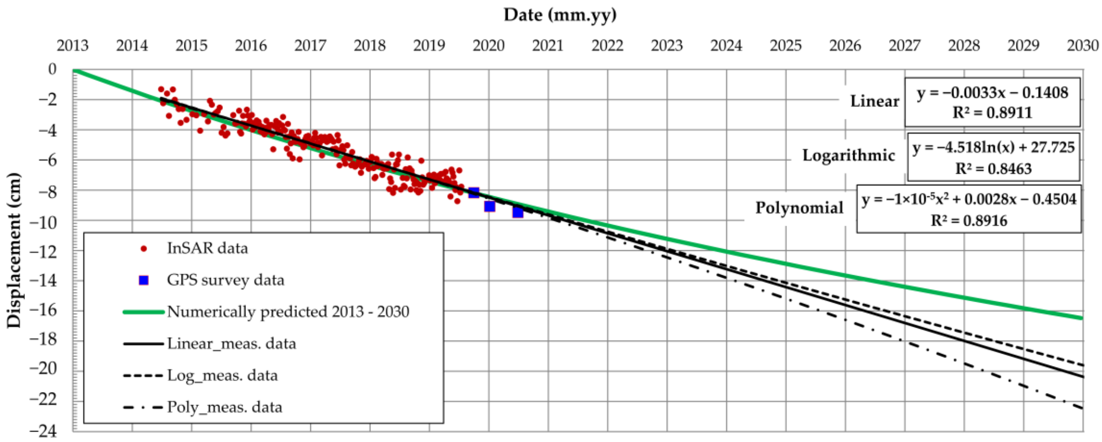

Figure 11: Numerically predicted displacements of Oostmolendijk by the year 2030, from Kovačević et al. (2022)

3.3.1.2 Proposed adaptation measures

Considering the ongoing problems at Oostmolendijk are due to a combination of future sea level rise and the foundation soil settlement, this two phenomena will be analysed separately.

If only **sea-level rise** is considered, it should be noted that the corresponding flood for the 100.000-year return period is associated with the level of +3.826 m NAP (Amsterdam Datum Level), whereas the embankment crest level is at +4.7 m NAP. This means that there is a sufficient difference between the 100.000-year flood level and embankment crest to prevent the overflowing (and overtopping) of the Oostmolendijk. Gavin and Reale (2022) note that overtopping is extremely unlikely to occur at Oostmolendijk and that the presented calculation is merely for illustrative purposes. When the system probability failure curve for Oostmolendijk is analysed (Gavin and Reale, 2022), it is shown that the curve is dominated by the global stability fragility curve until the flood level surpasses 3 m, at which point the piping mechanism becomes the dominant failure mechanism. A 1 in 100-year flood event has a probability of failure of 1%, which means the embankment condition is significantly below average, verging on poor using the USACE rating system. The analysis does not take flood return periods into account, and as a result, the true probability will be lower. However, even without a flood event, Oostmolendijk has below-average reliability, driven by the low undrained shear strength in **its bearing layers.**

The **settlement of the foundation soil,** due to creep effects probably accelerated by the high-temperature induced decomposition of the organic matter within organic layers, is a driver for the ongoing maintenance works. Speijeker et al. (2000) have tried to define optimal maintenance decisions for embankments, where the focal point of the methodology is on the proper estimation of the future settlements, stressing that the embankments should therefore be heightened regularly (at present, every 50 years). However, the heightening works do provide satisfactory crest height for a certain period of time, but an additional load of the added material poses an additional load on the soft bearing layers causing them to continue with their settlement, both in the consolidation phase but also in creep phase. The fact that the embankment body is in still motion and is not stable raises doubts about the appropriateness of remediation works to increase the crest level as it was done in the past. Kovačević et al. (2022) highlighted these heightening efforts as ineffective or even counterproductive, while Gavin and Reale (2022) note that any remedial works that aim to increase the stability of the Oostmolendijk should be undertaken using light-weight fill materials or another alternative that do not over-stress these very soft soil deposits.

It is evident that the combined probability failure curve clearly demonstrates that the analysed failure modes have a relatively low likelihood of occurrence. One method to address the resilience of the embankment to piping and rapid drawdown failures would be to introduce a lower-permeability layer (not necessarily) structural to the river-side of the structure. In order to change the height or width of the structure, lightweight fill materials should be considered. For Oostmolendijk, these are linked to limiting settlements within the subsoil to limit embankment settlement and lateral spreading. In this way, the necessity for the periodical heightening of the Oostmolendijk crest will be reduced to a minimum. However, some of the proposed solutions for settlement limitations may reduce the probability of failure of the analysed mechanisms of stability and piping.

The proposed adaptation measures for embankments resting on soft soils include one of the following, or even their combination:

I. The use of **lightweight or recycled materials** to replace some of the existing embankment structures and increase the height of existing levees with smaller increases in width while limiting the loads posed on the soft soils, thus reducing their long-term settlements.
II. Installation of **an embedded retaining wall**, e.g. sheet pile wall at either downstream only or both downstream and upstream side would lead to the limitation of lateral deformation of the embankment and consequently to limitation of settlements. This adaptation would also contribute to the cutting of a deep-seated slip surface, increasing the stability of sliding surfaces crossing the deep, low strength, layers. Also, by intercepting the sandy layers of the foundation soil, the piping resistance of the embankment would increase.
III. Soil improvement of the subsoil bearing layers by implementing some of the well-known and proven methods of deep-soil stabilization, such as grouting or vibro-based methods. In addition to increasing the average stiffness characteristics of soft soils, thus reducing the settlements, these methods significantly contribute to the average increase of strength parameters and reduction of subsoil permeability, having a positive effect on both stability and piping mechanisms. Consideration could also be given to soil-mixing techniques where material like fly ash or slag could be added to increase the geotechnical properties of the in-situ soil layers.

These measures will be elaborated on below. Even though all of the shown methods can be used as a measure to limit settlements, the Oostmolendijk may benefit mostly from soil improvement methods since these imply the least invasive works on the current embankment body if the positions and depths of soft layers are properly identified. The use of lightweight materials to heighten the embankment and to increase its stability, and especially the use of embedded retaining walls, require significant construction work having the mind current layout and state of Oostmolendijk. Further, the use of crest structures such as a gravity wall or temporary or demountable crest structures is not envisaged, both due to limited space (road on the top of Oostmolendijk) and due to the fact that these will not contribute to the limitation of additional loads in the subsoil.

Lightweight fill can be used for the construction of embankments on poor soil, where the materials range from pulverized ash, expanded slate, clinker, sawdust, wood chips, tire chips and light expanded polystyrene blocks. Manufactured lightweight materials such as expanded polystyrene blocks are relatively expensive, while waste or industrial waste materials may be obtained almost free at the source but will probably have a cost due to transportation and placement on site. However, lightweight embankments provide greater stability and generate less settlement than conventional embankments. The benefit of using this material is in situations where the embankment can not support any heavy material, or the crest width is too narrow to facilitate the use of fill, sandbags or floodwalls.

Reducing the load may be the simplest and cheapest way to increase stability and reduce settlement (CIRIA, 2002) of compressible soils. The unit weight of these materials can vary from 0.3-10 kN/m^3. Early implementation of these fills was limited to the less important roads, where long-term deformations of light embankments are acceptable, and since then have expanded to be used both on major roads embankments and in flood protection embankments. In the late 1970s expanded polystyrene blocks, weighting approx. 30 kg/m^3, have started to be implemented in practice. Figure 12 shows the possible scheme of installation of the light blocks. The blocks, routinely treated to be flame retardant and to deter insect infestation, have to be placed on a level surface and must be protected against buoyancy (for example by anchoring) and petroleum spills (by leveling the foundation surface, followed by placing a membrane and soil cover over the blocks once they are installed).

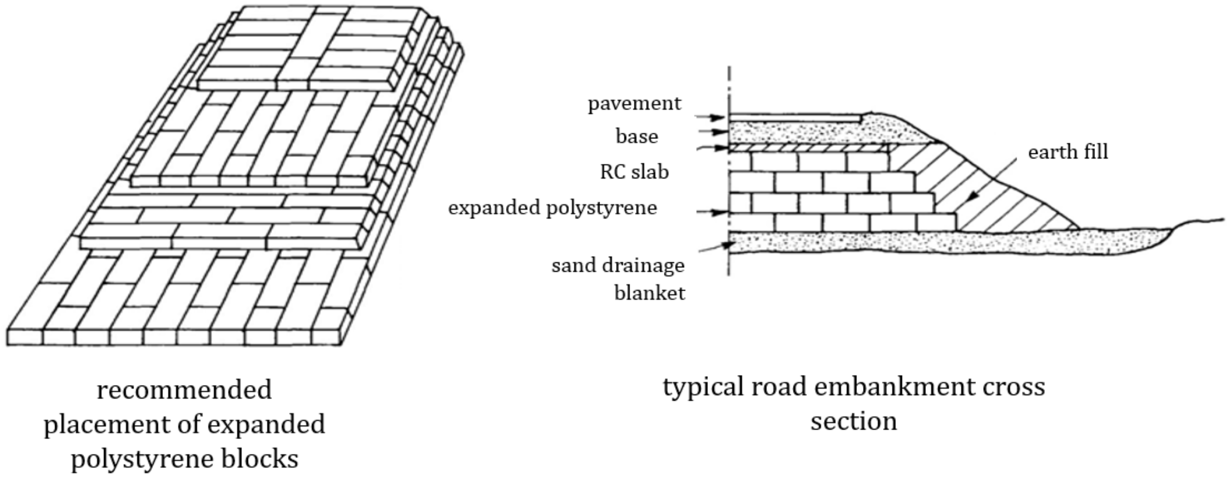

Figure 12: Scheme of installation of lightweight blocks, from CIRIA (2002)

Perry (1998) states that expanded polystyrene blocks offer the greatest advantage in weight saving, noting that they are inert, nonnutritive, and highly stable and, therefore, will not decompose, decay, or produce undesirable gases or leachates. The influence of groundwater and seepage water on the blocks can have dual effects on the blocks. The submerged blocks will have a relatively small gradual increase in the unit weight of the expanded polystyrene blocks. They therefore will cause a small increase in the amount of consolidation settlement of a soft foundation, while due to their small weight, buoyancy could be an issue.

Further, fly ash can also be used to create embankments. The primary function of fly ash in this application is to act as a substitute for standard fill materials, i.e. forming the body of the embankment. However, due to its poculan properties, it can partially affect the stability of the embankment itself. It is desirable that the fly ash has as few self-cementing properties as possible for easier installation. When using fly ash as a material for the embankment body, the compressibility and shear strength parameters must be met. The significantly lower compressibility of fly ash causes slight subsequent subsidence within the embankment itself. It should be noted that the content of fines is similar to the silty materials, with the permeability varying around 10^{-7} m/s. The engineering efforts of using fly ash to construct or strengthen the flood protection embankments are, however often questioned by environmental activists due to their chemical characteristics.

Using **a sheet-pile embedded wall** to reduce the settlements of a flood protection embankment has been analysed in several reports and implemented on several sites. Not all possible forms of installation will be shown here since the idea is to present the solution as a measure to resist the displacements. One example of such a solution is a so-called implant levee developed in Japan (GIKEN, 2015), where steel sheet piles are installed into the embankment to a depth determined for proper stability and/or cut-off of flow. The press-in machine utilises reaction force from previously installed piles and performs piling work on top of the piles, Figure 13.

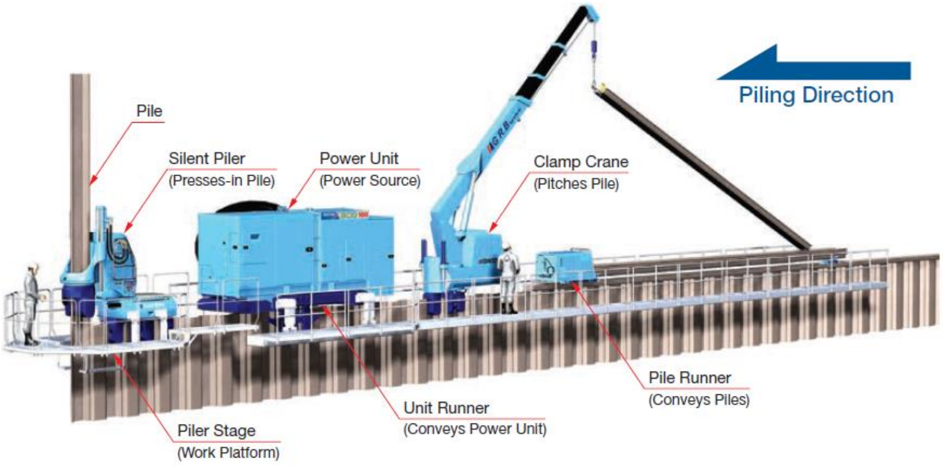

Figure 13: The installation of the so-called implant levee, from GIKEN (2015)

When discussing the settlement of the flood protection embankments, Fujiwara et al. (2017) stress that the implant levee has negligible to low risk for the settlement of the subsoil, Figure 14. However, if deemed necessary, the dual sheet-pile system should be enhanced by the partition walls, which are usually installed in the same manner as the sheet pile system, Figure 15.

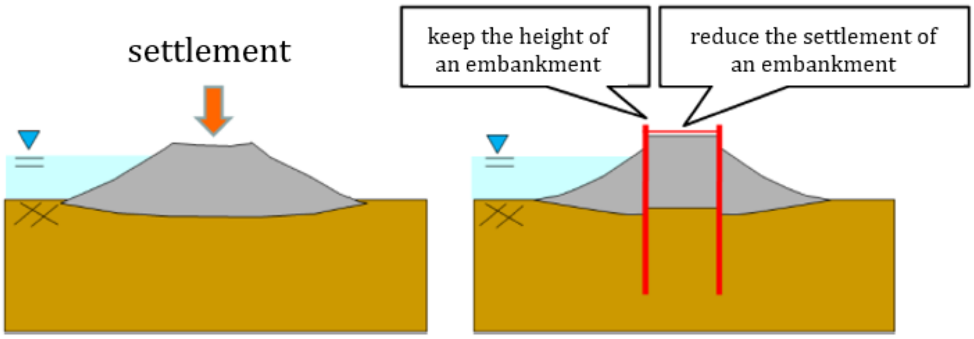

Figure 14: The effectiveness of the double sheet-piles countermeasure, from Fujiwara et al. (2017)

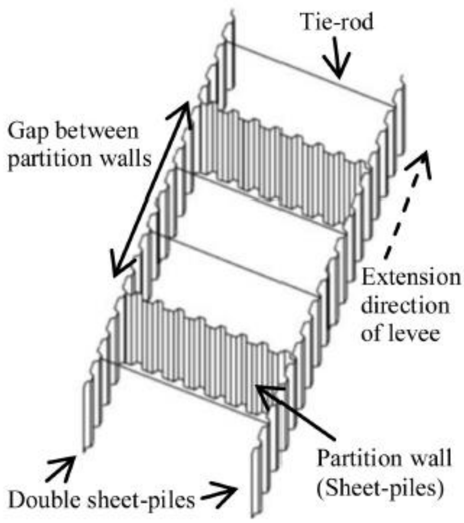

Figure 15: Double sheet piles with partition walls, from Fujiwara et al. (2017)

As an alternative to a sheet pile wall, a variation of a contiguous tubular pile wall (GIKEN, 2015) can be used, which includes steel tubular pile wall as a vertical barrier to a depth determined for proper stability to withstand large dynamic and hydraulic loading.

Traditionally, three common approaches in **dealing with poor characteristics of subsoil** can be implemented when constructing on a peat layers:

1. Removal of peat and replacement with inorganic aggregate fill, so-called method of mass replacement;

2. Improving the peat layers, whereas the peat stays in place;

3. Transfer of a load through the peat layer via piles to lower, load-bearing soil layers.

For Oostmolendijk, the most suitable approach would be improving the characteristics of peat layers. The mass replacement with aggregate fill is of questionable benefit for Oostmolendijk and would require complex and extensive construction works, considering that the peat layers are identified on lower depths, cca 5 m below the terrain surface and up to 10 m below the embankment crest. Further, transfer of embankment loads using the piles is not discussed further mainly because od the high costs of such measure when compared with soil improvement.

Many studies, followed by the practical implementations have been dealing with **improvement of peats**, with the overall aim of altering their strength and stiffness characteristics, since the problems of construction on peats are usually linked with the high compressibility and rather low undrained shear strength of peat. Forsman et al. (2018) suggest a mass stabilization method as a solution to improve the properties of a peaty subgrade, where hardened soil mass is created by adding binder into soil and by controlled in-situ mixing. Mass stabilization is just one of the deep stabilization methodologies used to stabilize peat masses in-situ. The success of stabilization process is impacted by many factors, including the peat properties, binder type and quantity, curing time, temperature, preloading level, etc. Figure 16 shows possible mass stabilization solutions, as presented by Forsman et al. (2018), including the full penetration depth through the whole thickness of soft soil layers (Figure 16a); partial penetration to a given depth (i.e. a “floating” structure, Figure 16b) and optimized as a combination structure—mass stabilization on top of column stabilization (Figure 16c). Since the embankment at Oostmolendikj is poreexisting a system of treatment to one or both sides of the existing structure to prevent lateral spreading could be considered. Depending on the depth of mass stabilization, a reduction of settlements vary, so appropriate variant should be analysed. For Oostmolendijk, considering the position and thickness of identified peat layers, a solution of column stabilization is envigased. Column stabilization carried out under mass stabilization reduces the settlements of the soft soil layers underneath mass stabilization and in same time it improves the stability of the embankment by impeding the formation of a slip surface.

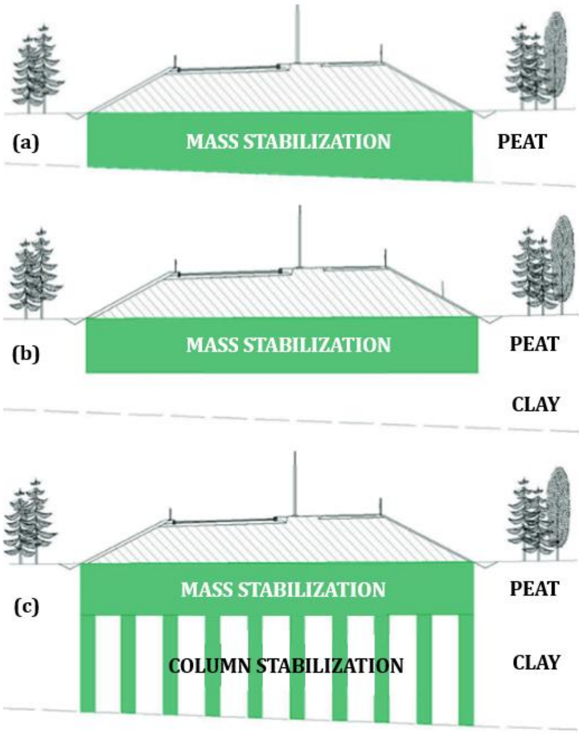

Figure 16. Possible mass stabilization solutions, re-drawn from Forsman et al. (2018)

For the execution of the mass stabilization, the mixing tool is attached to an excavator and it allows the execution of stabilization to depth of 7 to 8 m under favorable conditions, while the optimal stabilization depth ranges from 3 to 5 m. Prior to injection of the binder, a soft soil layer is homogenized by mixing. After the pre-homogenization, a pressure feeder injects the binding agent through the hose of the mixing tool. The mixing rotating drums then mix the binder with the soil. Depending on the geometry of the site, the work is usually divided into block of equal size. The columns are constructed usign the deep-mixing technology which includes rotation of mixing equipment down to the planned depth of the column, Figure 17. As reported by Bačić et al. (2014) on its way down, the equipment breaks the soil structure and, after reaching the final depth, the equipment is taken out to the surface by rotating in opposite direction than the one when going down. In its return, mixture containing binder is implemented in the soil, under pressure, thus forming the final cylindrical pillar of improved soil.

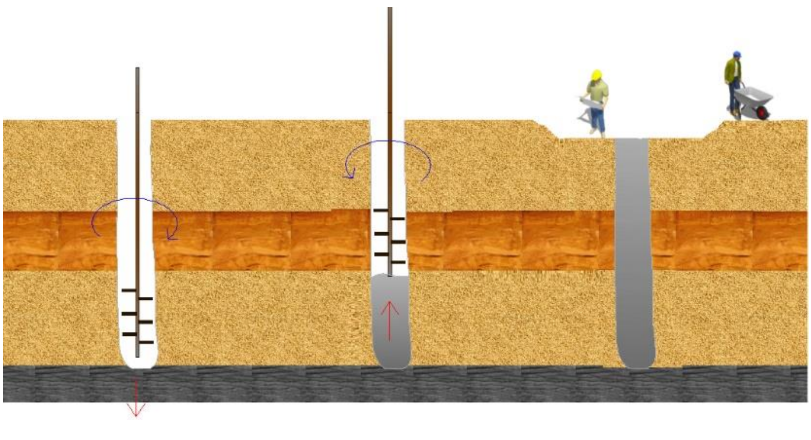

Figure 17. Formation of deep soil mixin columns, from Bačić et al. (2014)

An additional benefit of stabilizing the peats with bidners is presented by Duggan et al. (2015), who conclude that the stabilized peat not only holds its carbon but also the binder used uptakes CO_2 both from the atmosphere and the peat. This is significant considering the mentioned increase of temeperature due to climate changes. The CO_2 reduction is, according to this study, greater than the CO_2 emissions associated with the production of binder materials. Production of standard binders, cement and lime, consume large amounts of natural raw materials and fossil fuels. As a result of chemistry, this leads to the release of significant amounts of CO_2 into the atmosphere. Based on the several studies, Bačić et al. (2014) suggest that the fly ash, as an industrial by-product, can be used as a partial supplement to standard binders in the deep soil mixing technologies. Hansson (2008) obtained satisfactory results when mixing fly ash, cement and lime, where fly ash involved with as much as 70%, indicating the potential use of larger amounts fly ash in the process of deep soil mixing.

Another method which may be considered for the improvement of peat layers below the Oostmolendijk is a method of vibro-stone columns. It consists of formation of columns in the ground by using heavy vibrator which displaces in-situ ground and compacts the imported material, Figure 18. To make the method more environmentally friendly, Bačić et al. (2014) discussed possibilties of using a slag, as a waste product generated by the purification of metals, to substitute the commonly used gravel (or crushed stone) aggregate for formation of columns. This was also suggested earlier by 'BRE Report 391 - Specifying vibro-stone columns' (2000), where a steelmaking slag is mentioned as one of aggregate potentially to be used in vibro-stone columns. Even though there were some practical implementation of slag as an aggregate in stone columns, extent of application practice is not implemented worldwide, because possibility of application largely depends on type of slag and ground conditions. A range of testing procedures must be conducted prior to implementation.

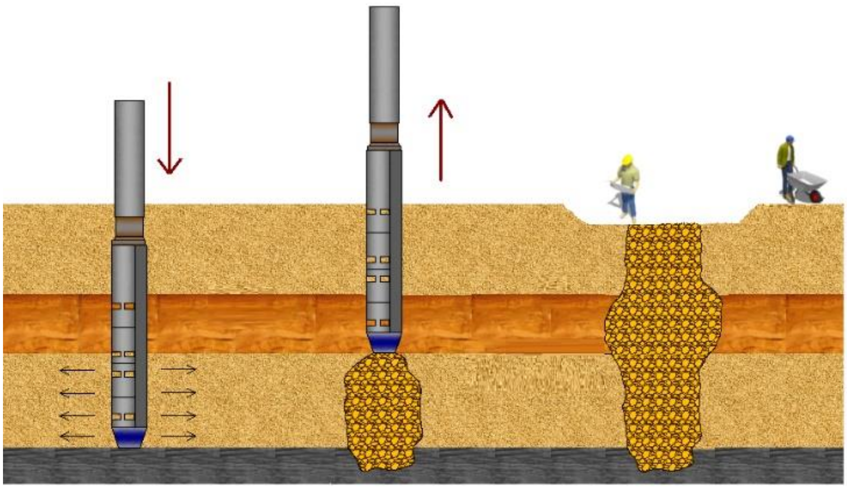

Figure 18: Vibro-stone columns (vibro–replacement) technique, from Bačić et al. (2014)

3.3.2 Adaptation measures for riverbanks – city of Karlovac

3.3.2.1 Overview of the climate-related issues

Currently, there is more than 11 km of flood protection systems in the city of Karlovac, which are considered structures of national importance. Within the oVERFLOw project, investigated assets include 1.5 km of riverbanks on each side of river Kupa, in the city centre. The riverbanks are mostly up to 10 m high, however, with very variable geometry and slope angle. In some parts, a stone wall is located on the top of the riverbanks, serving as additional protection during high water events. However, this wall is generally in poor condition with many washed-out joints, Figure 19 (left). The embankments in the city of Karlovac are also experiencing several geotechnical issues; such are the cracks along the promenade on one of the embankments due to its excessive settlements, Figure 19 (right).

(a) (b)

Figure 19: Stone wall on the top of riverbanks in the city of Karlovac (a); cracks along the promenade on one of the embankments (b)

Burić & Grgurić (2020) noted that, for the Karlovac region, an increase of temperature of 2°C by 2070 for a moderate scenario and 2.7°C by 2070 for an extreme scenario is expected compared to the period from 1971-2000. The authors also conclude that simulations of water flow and water level show that climate change will likely impact future flows and water levels of the Kupa River. Even though the changes in annual average flows and water levels are expected to be small and not significant, models predict a significant increase in flow and water level in winter months and a decrease in summer months for both moderate and extreme scenarios. Having this in mind, the climate-induced issues which should be analysed for Karlovac riverbanks include:

a) Ultimate limit state – analysed, and the results are shown in Deliverable 4.1 (Gavin & Reale, 2022), which include stability issues, mostly after the high-water events (rapid draw down mechanism). Also, the stability could be negatively affected by the high-intensity precipitation events foreseen for the area in the climate scenarios. Additionally, the seismic stability was shown as critical for the riverbanks; however, this will not be analysed in detail, but will be addressed through the adaptation measures, which generally increase the riverbank resilience to sliding failure.

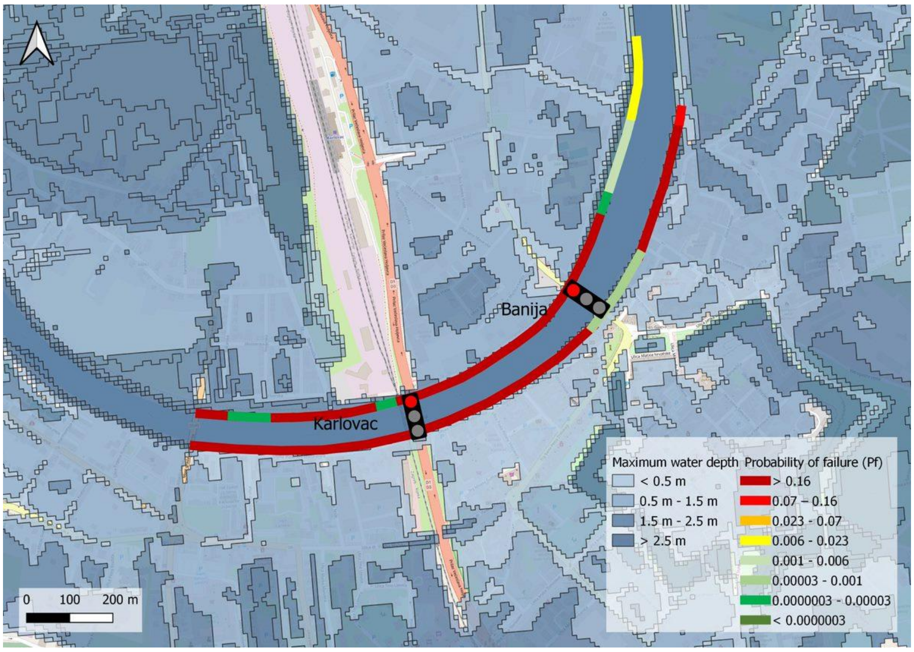

Figure 20: Results of the vulnerability analysis for embankments and bridges for low probability of flood occurrence (return period 1000 years), from Bačić et al. (2022)

b) Serviceability limit state – including the (i) cracking and dissection of the surface layers of riverbanks due to increased temperatures, accelerating erosion of the riverbank; (ii) washout joint of stone wall, laying on the top of the embankment. Even though this is not directly linked to climate change, this will be addressed through adaptation measures, since this wall is measure which prevents the overtopping of the system and consequent flooding of the area during the high-water events.

3.3.2.2 Proposed adaptation measures

The proposed adaptation measures follow the above-mentioned possible climate-change-induced failures of the riverbanks. To increase the resilience of the analysed riverbanks following measures should be implemented:

1. **Structural reinforcement of a deteriorated stone wall** by using the FRC to make it more resilient to high waters;
2. **Installation of horizontal drains** to accelerate the drainage of residual water in clayey deposits during the rapid drawdown;
3. Increase erosion resilience by installing **surface protection measures**, whereas the erosion results from increased Kupa flows and velocities and is accelerated by the surface desiccation due to higher temperatures.

A **flood wall resting on the top of the Karlovac riverbanks must be reinforced** to resist the high waters and associated hydrostatic, but also hydrodynamic, loadings. In addition, water within the flooding event usually carries some sort of debris, varying in weight, size and shapes. The current condition of the wall is unsatisfactory with many deteoriated and washed-out joints between the stone blocks. Therefore, the structural failure of this wall is more likely than the geotechnical failure.

One of the potential solutions could be in application of the steel fibre reinforced concrete (SFRC), which is becoming more popular and more used. Because of its improved material properties over plain concrete, where it reduces the need of steel rebar, the application of SFRC makes projects less time consuming and more cost effective (Dahabreh, 2014). Alternatively, polypropylene fibers can used for this purpose instead of steel fibres.

Figure 21: An example of using the fibre reinforced concrete for construction of a flood wall (left), from ADFIL (2015), and its application by the sprayed concrete technology(right), from Contech UK, (2022).

Ryan et al. (2021) notes thatFRC can be particularly advantageous for the water-retaining structures (WRS), for two main reasons:

(a) FRC mixes are well known to effectively reduce cracking, which is key to the serviceability requirements that determine the design of WRSs which are dominantely horizontally loaded;

(b) climate change means increased risk of flooding in many areas leading to an increased requirement for WRSs.

Further, in the same study on the applicability of FRC in WRS, a methodology was developed and applied to a range of mixes representing varying concrete strengths, fibre types, and other parameters to produce thousands of alternative solutions to the scenarios considered. Overall, the economic and environmental merits of utilising FRC for the design of WRSs were demonstrated. Considering that the stone wall is present at the site, the adaptation measure could include installation of the FRC on the expposed surface of the stone wall, by using the sprayed concrete technology, as shown in Figure 21 right.

The vulnerability analysis, with the results shown in Deliverable 4.1 of this project (Gavin & Reale, 2022), demonstrated that the rapid drawdown design situation is critical for the riverbanks. During the rapid drawdown, water level external to the riverbank slope experiences a rapid reduction, while residual water levels in the riverbank remains on higher levels. This residual water, and associated pore water pressures, reduce the effective stresses in the soil, thus reducing the overall shear strength. This, in addition to imposed seepage forces, leads to potential instability of the riverbank slopes. Therefore, additional structural adaptation measures includes installation of **horizontal drains** in the upper clayey deposits of Karlovac riverbanks, enhancing the permeability of these low-pemeability layers. As Nicholson (2015) note, horizontal drains are generally the best alternative when the depth to desired dewatering is great and where the costs of excavation and/or placement of a trench or blanket drain are deemed to be uneconomical or unrealistic.

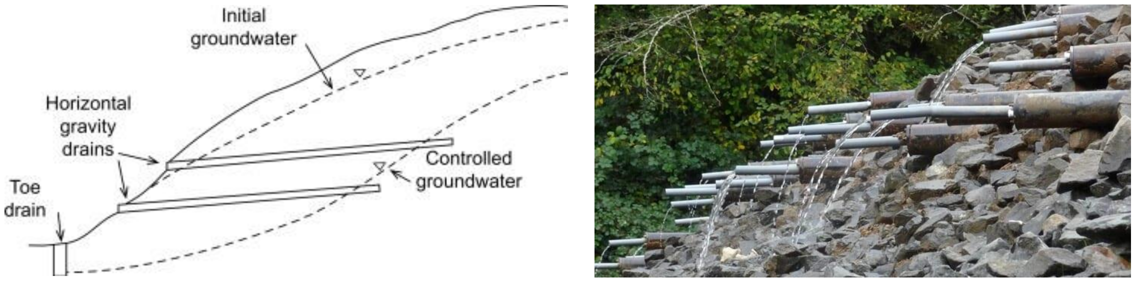

Figure 22: Example of subsurface drainage with horizontal and toe drains (left), from Nicholson (2015) and installed and functioning drains (right) from GSI (2022)

Horizontal drains are usually installed as a 5 – 6 cm diameter perforated pipes, which are positioned in filters in slightly larger diameter drilled holes. To prevent the clogging of the pipes with fine particles, during the seepage, pipes are usually wrapped with geotextile. Even though they are called horizontal, these pipes are installed at small inclines of 2-5° so they can drain by gravity. Their lenght and separation depends primarly on the permeability of the soil in which it is installed and the volume (quantity) of the anticipated flow. For soils with lower permeability, spacing between horizontal drains is usually closer. When it comes to the lenght, horizontal drains are dimensioned in a way to should ensure that water is drawn down and away from any potential slide mass. The first 1 – 2 m of the pipe, closest to riverbank surface, is usually not perforated to to avoid intrusion of roots or looser material.

The **erosion of a riverbanks** is a natural process in stable rivers. Still, it can become accelerated and exacerbated by many factors, including the direct and indirect human impacts and climate change stressors. For the later, the high temperature can cause desiccation of the surface layers during the drought period, whereas river and surface run-off water can penetrate more easily during the wet period. In addition, high-intensity precipitation events could lead to increased water flows and velocity, thus accelerating the riverbank surface erosion. In general, the most erosive banks are sandy and/or silty, and the least erosive are gravelly and/or clayey. The investigation works on the riverbank in Karlovac, as shown in Deliverable 3.1 (Bačić & Kovačević, 2021), have shown generally uniform layering along the riverbanks, consisting of fine grained clayey cover (up to 6 m from terrain surface) overlying the clayey sand material to larger depths.

Most usually, the hard approaches to increase erosion resilience include riprap, a from of permanent ground cover structure made up of large loose angular stones. The riprap, in combination with the the earthworks of mass redistribution, present successful countermeasures to increase both riverbank stability and erosion resilience, Figure 23.

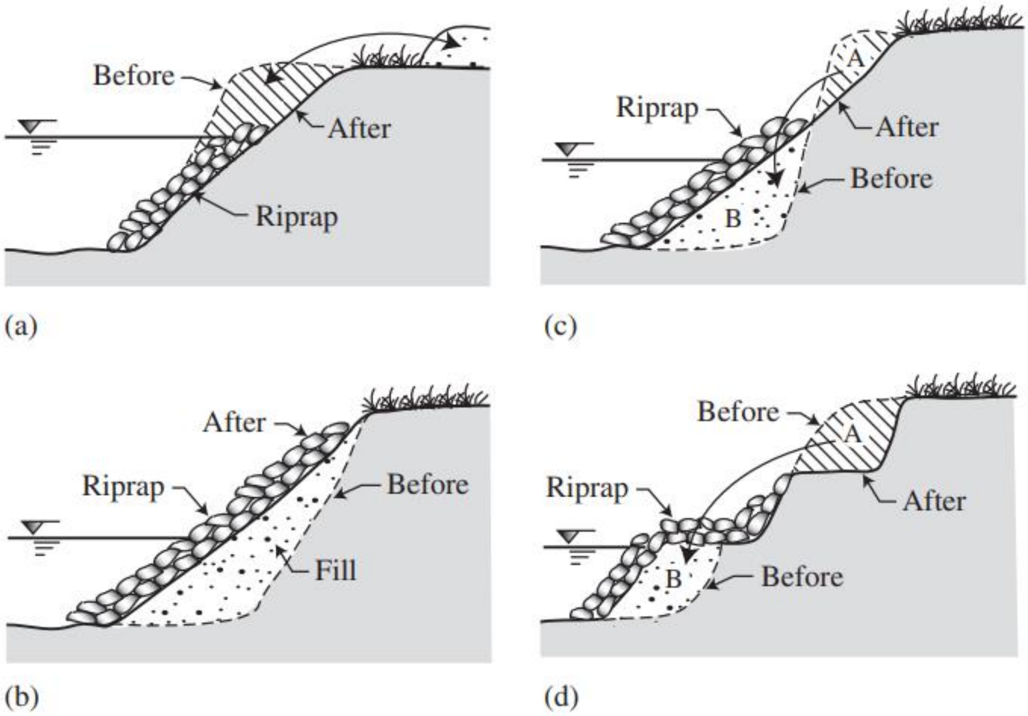

Figure 23: Slope reduction methods to increase riverbank stability: (a) cut, (b) fill, (c) cut and fill, and (d) benching, from Julien (2018)

Rock riprap is commonly used for surface protection, since the construction is relatively simple and does not require special construction equipment. The fact that widely used material of rocky blocks is main material, is an addition for considering the riprap as economically most suitable solution. The durable riprap blanket is usually not weakened by settlement and differential settlements, owing mostly to its flexible nature. Additional benefit of the riprap, as reported by Julien (2018), is that it is permeable and allows the free flow of water to and from the riverbanks.

Another erosion control measure for riverbanks are **sacks and blocks.** Sacks are usually precast and manufactured using sandy material from the site, commonly present near the river inundations, along with the cement and agregates. They are usually more aesthetically acceptable when comapred to riprap, but are also more highly labor-intensitve. Blocks are usually made of concrete and as such are durable under the effects of freeze/thaw cycles. Between the riverbank slope face and the blocks, a permeable geotextile or a gravel blanket can be used as a filter. For both sacks and blocks, drain holes must be installed to allow free drainage of groundwater, thus minimising the pressure build-up just below the surface protection structure. Figure 24 shows different possibilites of installing the sacks and blocks, depending on the steepness of the slope. Since the Karlovac riverbanks have steepness in range of 1:1 to 1:2, the bags should be overlapped.

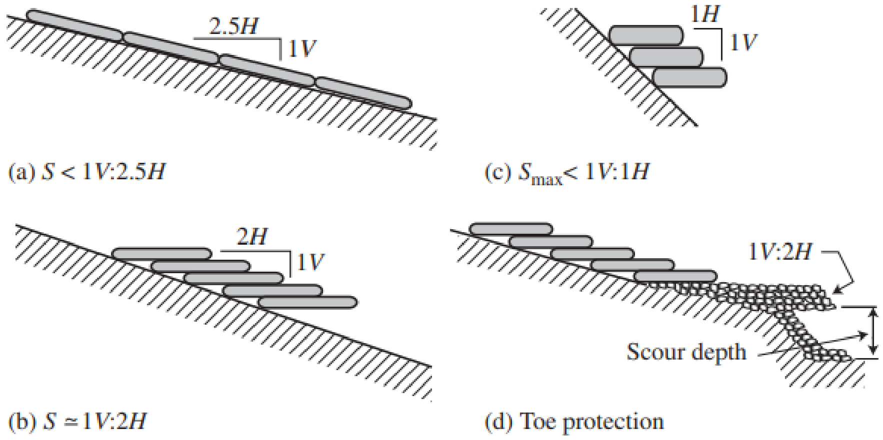

Figure 24: Sacks and blocks, from Julien (2018)

For erosion control, gabions and gabion matresses can be also considered, when the maximum flow velocity is in range of 2 to 5 m/s, as reported by the Julien (2018). They consists of twisted steel wire which is usually both galvanized and has PVC coating to prevent the corrosion. The steel framework is brought on the site and filled with crushed rocky material with te size larger than the basket opening, making the solution relatively flexible and insensitive even to larger displacements. When they are in form of a box, these can be stacked on steep slopes. For mattresses, the technical solution is similar, however the formed framework usually consists of shallow, broad baskets and as such require smoothly graded slope face for installation.

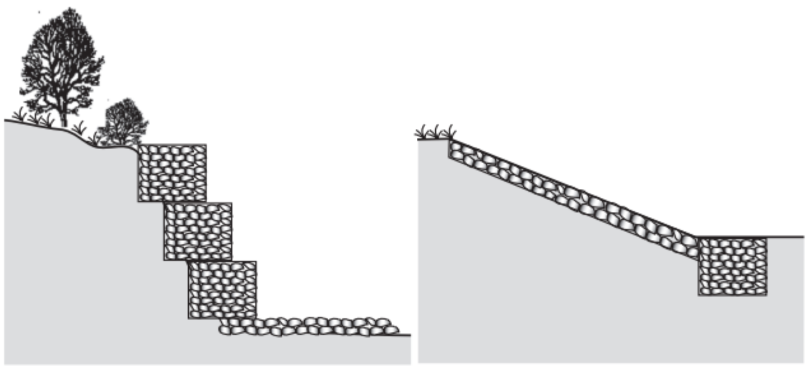

Figure 25: Gabion and gabion mattresses, from Julien (2018)

In addition to the above mention structural measures against the surface erosion, several others measures exist, including the Articulated Concrete Mattresses (ACM), a soil–cement blanket or vegetation. Some of them are hardly applicable on Karlovac riverbanks due to relatively steep geometry of these and due to fact that the local construction practice does not have much experience working with such measures (for example with ACM or soil-cement blankets). Vegetation, on the other hand uses, most natural material which improves environmental conditions for wildlife. Considering that the riverbanks are protecting from the influence of river Kupa which is part of Natura 2000 as a network of nature protection areas, it could be considered as appropriate measure for erosion prevention and stability increase. The question may arise on its negative impact on the for the views for which the city of Karlovac is well-known.

4 Adaptation strategies for the case-study bridges

4.1 Vulnerability of bridges to floods

Meeting the safety requirements for bridge design requires accurate modelling and a careful analysis of the hazards that could undermine the performance of the structure during its lifetime. Designing major infrastructures like bridges holds high responsibility for engineers and stakeholders, who need to strive for constant compromises in strategic decision-making and a balanced cost-benefit ratio. Engineering and economic decisions are further challenged by the requirements for new and existing infrastructures to be able to perform properly when taking into account climate change scenarios. It has been consolidated that global warming is exacerbating the increase of atmospheric temperature, a rise in the sea level, and the occurrence of more frequent extreme events, such as storms, rainfalls, and flooding (Kopp et al. 2014; Semmler and Jacob 2004). Alas, some of the infrastructure built in the past years had been designed with deterministic approaches and for recurrence time events that make them now very susceptible to the effects of climate change (Mondoro, Frangopol, and Liu 2018). Hence, at the current state, many bridges are deemed to be unsafe and maintenance procedures and adaptation measures are required to counteract climate change impact. Selecting the appropriate adaptation and risk management strategies represents a new challenge for the design and monitoring of new and existing bridge infrastructures. A thorough analysis of climate change evolution and projection and proper identification and analysis of the hazards that can potentially harm the structure can enhance the infrastructure's resilience to climate change impacts.

One of the biggest threats posed to bridges by climate change is the occurrence of floods (Argyroudis and Mitoulis 2021). The increase in precipitation frequency and intensity, the expansion of urbanized areas at the expense of green ones, the intensive deforestation activity, and river regularization are only some of the driver variables that have led to the augmented flooding events (Clark 1987; Feng, Zhang, and Bourke 2021). In this last decade, scientists and practitioners have therefore put considerable effort into focusing on the vulnerability of riverine bridges and flood defence structures (e.g. embankments) to flood hazards. Evidence of such a pivotal danger is the scientific literature that has reported several failures of bridges triggered by flooding events in the USA, the United Kingdom, and Europe (Benn 2013; Kumalasari and C. 2003; Zampieri et al. 2017). Flooding events are crucial for bridge infrastructure performance. This is not only for the flow-induced load transferred to the structure but also for the fact that the hydrodynamic load may be amplified by the accumulation of debris. This is a combined load impact on the piers and abutments of bridges and a damming and build-up of water (known as afflux) (Tubaldi et al. 2021). The uplift forces exerted on the submerged components of the bridge also provide a relevant contribution to the hydraulic action of floods. Additionally, the narrowing of the streamflow induced by the presence of the supporting structures of the bridge (e.g. piers and abutments) lead to a rise of the water surface that, in turn, may cause the submersion of the superstructure of the bridge or, under certain hydrodynamic conditions, to a back-up of the flow (Hunt, Brunner, and Larock 1999). Stream-induced deviations due to bridge piers also cause a local increase in the flow speed and the possible development of local scour (Melville & Sutherland, 1988). Local scour found to be one of the leading causes of bridge failure during floods, thus leading to casualties and severe economic losses (Lin et al. 2005). The Sava Bridge in Zagreb (Croatia), the Malahide Viaduct in Dublin (Ireland), and the collapse of the Hintze Ribeiro Bridge in Entre-os-Ríos (Portugal) are just a few examples of bridge failures in Europe due to scour. In the United States, local scour has contributed to causing more than 50% of bridge failures between 1987 and 2011(Cook 2014). Hence, nowadays, such statistics are possibly magnified when considering the impact that climate change has led in this last decade.

The basic mechanism of local scour at bridge piers and abutments is related to the formation of horseshoe vortices (Shen, Schneider, and Karaki 1969) (see Figure 26). The occurrence of horseshoe vortices is caused by the combined action of downflow and boundary layer separation that both arise when water flow is obstructed by an obstacle. An additional contribution to the scour is also given by the wake vortex, which develops at the downstream section of the obstacle. The intensity of the wake vortices decreases rapidly as the distance from the pile decreases, leading to the deposition of the sediment material that has been removed upstream by the horseshoe vortices (Heidarpour, Afzalimehr, and Izadinia 2010). Local scour can arise in what has been defined as clear-water and live-bed conditions, which describe the conditions of absence and presence of sediment transport in the undisturbed flow upstream of the piers/abutments, respectively (Brandimarte et al. 2006). Local scour in live-bed conditions involves a succession of partial filling and deepening of the excavation. This makes the process more difficult to predict, and the scour equilibrium hard to achieve. Local scour in live-bed conditions can be especially encountered in cases where bridges cross morphologically active rivers for which the riverbed instability leads to erosion and deposition processes of the river sediment.

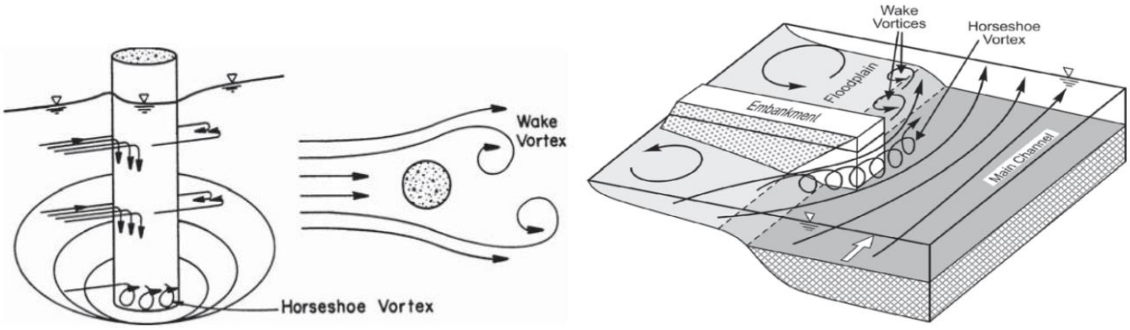

Figure 26: Schematic representation of scour at a cylindrical pier and on the abutment, respectively (modified from Lagasse, (2007) *and* Barkdoll et al., (2007)*, respectively)*

Local scour prediction has been widely investigated in small-scale experiments, and the scientific community has been able to provide an appropriate variety of empirical formulations that allow computing the entity of the excavation at the equilibrium configuration (Melville & Chiew, 1999; Melville & Coleman, 2000; Richardson & Davis, 2001; Sheppard et al., 2014; Sheppard & Miller Jr, 2006). The most used formula is the HEC-18 pier scour equation which refers to Richardson and Davis's method (Richardson and Davis 2001). However, the implementation of these deterministic approaches neglects the history and time-dependent nature of scouring, thus leading to bias and overestimated scour depth excavations. In this respect, a big step forward was made by some scientists that used quite elaborated stochastic frameworks (e.g. Markovian modelling approach) to simulate the temporal evolution of local scour (Tubaldi et al. 2017). The formulas available for the calculation of local scour at the abutments are less numerous than those elaborated with reference to the piers. This is probably due to the fact that the complexity of the local scour at abutments is emphasized by the simultaneous occurrence of bank erosion processes as often rivers are flanked by floodplain areas (Chiew 2008). A brief summary of the most used formulas is reported in Barbhuiya and Dey (2004).

Local scour estimation becomes yet more challenging when considering the potential presence of debris jam accumulations on the piers (Pagliara and Carnacina 2011). Debris jam does not only contribute to exacerbating local scouring but also increases the loading impact on the bridge and the rise of the upstream flood levels (afflux). It was found that the debris accumulation at bridge piers leads to more than one-third of the bridge failures in the United States (Diehl 1997). The underlying mechanism that causes the accumulation of debris on the piers of the bridge is complex and still partly unknown. The presence of woody debris in rivers depends on the availability of vegetation in the vicinity of the river banks and on recruitment, transportation, and deposition processes (Gasser et al. 2019). Recruitment is a combination of selection and delivery mechanisms of trees and branches from river banks into streams and is triggered by stochastic geophysical events such as hillslope failure, bank erosion, snow avalanches, and wildfires (Bebi, Kulakowski, and Rixen 2009; Comiti, Lucía, and Rickenmann 2016; Downs and Simon 2001). Transportation of wood material is influenced by hydrodynamics, river morphology, and wood properties (e.g., orientation, size, and density) (Kundzewicz et al. 2016), whereas deposition is the process by which wood material settles on fluvial bedforms or accumulates on flow obstacle structures (e.g. piers of bridges). Although the physical processes of debris movement and aggregation at bridge piers have still been largely unexplored, it was found that flow characteristics and debris geometry (e.g. the length of the wood logs) play an important part (Panici and de Almeida 2018). Nonetheless, the estimation of the shape and size of wood jams at bridges is difficult to assess, and, in the current state, there are no clear guidelines in this respect (Francisco Nicolas Cantero-Chinchilla and grant DEBRIEF 2018). Analytical extrapolations obtained from experimental results have recently shed light on the important parameters that influence the size of the debris jams (Panici and Almeida, 2018). However, upscaling rules and the replicability of such processes in real case scenarios represent relevant impediments to an accurate estimation of the debris accumulation. As a result, among practitioners, the estimation of the local scour induced by debris jams relies on empirical formulas.

The most popular methodology to assess the local scour with debris accumulation is the one suggested by Melville & Dongol (1992). They assessed the scour by introducing the so-called effective diameter, which is the equivalent single-pier width that would induce the same local scour that would develop in the presence of debris. Lagasse (2010) found that Melville and Dongol's approach overestimated the scour. Hence the formulation was modified by taking into account additional parameters with which the formula showed a better agreement with experimental data. However, Lagasse's formula was still found to overestimate the local scour when applied to a wide range of experimental datasets. A new concept was recently introduced by Ebrahimi et al. (2020), who established a new parameter called "debris factor" that directly evaluates the local scour in the presence of debris. In spite of this, the estimation of debris jams' sizes and their impact on local scour is still affected by substantial uncertainties.

Even though bridges' vulnerability to flooding has been widely investigated, flood damage model availability is yet very limited (Pregnolato et al. 2020). The hydrodynamic load acting on the structural system increases the shear and the flexural structure's demand, which becomes more relevant when considering the relocation on the pier of the hydraulic load acting on the superstructure of the bridge (Mondoro, Frangopol, and Liu 2018). When transverse and uplift hydraulic forces become extreme, they can lead to the misalignment and dislodging of the bridge deck (Lebbe et al. 2014).). On the other hand, the local scour changes the boundary conditions and the dynamic characteristics of the bridge (e.g. it affects the period and the higher mode shapes of the structure) (Wang, Dueñas-Osorio, and Padgett 2014) and directly impacts the foundations by reducing their lateral stiffness and the load-bearing capacity that, in turn, negatively influences the critical sections of the bridge (Prendergast and Gavin 2014). Local scour, when combined with seismic action, can also lead to damage to the superstructure through cracking, differential settlement, and pier impairments (Argyroudis and Mitoulis 2021). Piers' impairments in particular, are not only caused by local scouring but are also related to the corrosion of the steel reinforcements caused by exposure to chlorides (Guettala and Abibsi 2006). The water infiltration on the concrete can significantly undermine the stiffness of the bridge as the effective area of the concrete decreases enhancing the complexity of the failure mode of the bridge (Tubaldi et al. 2019).

4.2 Adaptation measures for bridges to flood events

It is evident that to ensure the safe maintenance and operability of bridge infrastructures in future flood scenarios, and it is necessary to introduce appropriate adaptive measures. The identification of a simple flood adaptation plan allows easier communication among stakeholders and bridge managers that, in turn, can conceive more strategic investments and an easier allocation of financial resources. An effective strategy for adaptation measures requires a holistic approach, in which different levels of operational phases (e.g. monitoring, early warning systems) can be envisioned as a means to identify risks. The level of the risk that bridge managers are willing to accept controls the selection and the design of the adaptive measures and the benefit-cost ratio of the operations. A robust approach to developing adaptation strategies relies first on a solid outcome of the vulnerability assessment of the infrastructure, which aims at assessing the exposure and the sensitivity of the asset (AECOM 2017). The identification of the flooding hazards and the extent to which the asset is exposed are fundamental steps to tackle. Furthermore, the implementation of a likelihood and consequences analysis (i.e. risk assessment) contributes to and facilitates the identification of the needed countermeasures. Moreover, the selection of the proper adaptation strategies depends on other factors such as:

- the current status of the asset and its performance of the structure during past floods
- the extent of the hazards that undermine the asset (e.g. hydrodynamic load, local scouring)
- the location of the asset and its economic and social relevance
- the availability of resources
- the availability of material and equipment
- the hydraulic characteristics and local geotechnical conditions

A critical approach in decision-making enables us to evaluate each hypothetical countermeasure by analysing the feasibility of choice based on the benefits and drawbacks of the selected adaptive measures. The consequences that arise from embracing adaptation measures have also to be reviewed and examined with respect to their impact on other nearby assets and the environment. Hence, a good methodology consists in creating an "adaptation decision matrix" (ADM) in which each adaptation measure is qualitatively ranked (e.g. inadequate, acceptable, poor, and good) based on its benefits, drawbacks, and repercussions. Such an approach is schematic, efficient, straightforward, and easy to follow by CPAs and practitioners with little engineering experience.

The input-out diagram in Figure 27 can provide an overview of the process used for the adaptation measures assessment. Blue and red colours represent the different nature of the input elements of the process. The blue colour indicates the operation step that is needed to obtain the vulnerability and risk assessment of the asset, whereas the red colour refers to the input defined by external factors (e.g. available resources, hazard extent). Both inputs are essential to provide an appropriate evaluation of the adaptation measures relevant to the infrastructure. The green box represents the output that can be obtained from the analysis of the countermeasures considered.

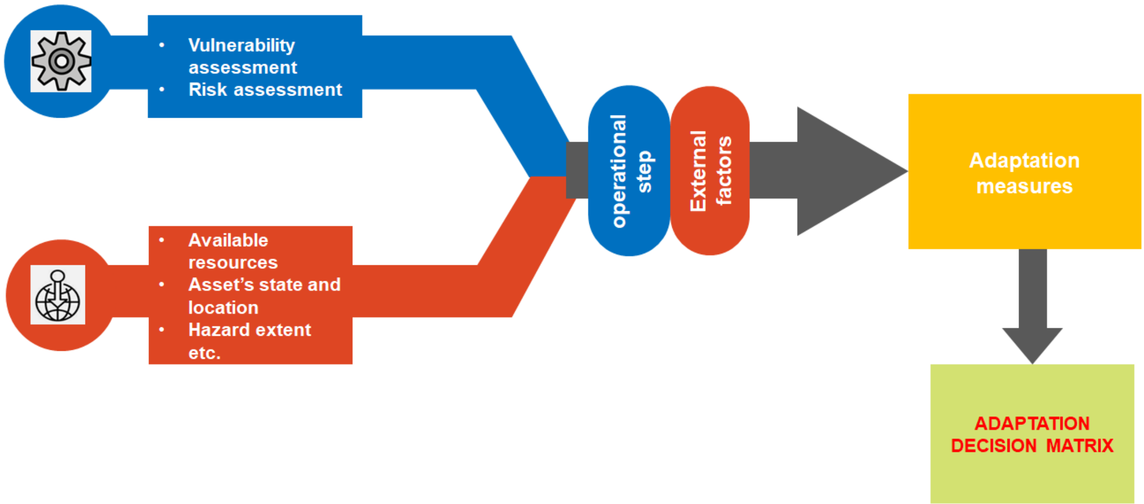

Figure 27: Flow diagrams (input-output diagram) illustrating the steps to obtain the adaptation decision matrix.

The adaptation decision matrix shown in Table 4 outlines the main strategic countermeasures that are envisaged when solving flooding issues in bridges. Note that the feasibility level of each countermeasure cannot be generally assigned *a priori* as it strictly depends on the factors mentioned above in the bulleted list. Hence, only after a thorough analysis of the case study it is possible to assess the feasibility level of each countermeasure and adopt the one that appears to be best overall.

Table 4: Adaptation decision matrix for bridges vulnerability to flooding.

ACTIONS	INTERVENTIONS		ADAPTATION MEASURES	BENEFITS	DRAWBACKS	REPERCUSSIONS	FEASIBILITY LEVEL
Local scour	indirect	River engineering counter measures	Bed armouring devices	Act locally and relatively economic	A sustained level of maintenance	low environmental repercussion (e.g. sediment continuity and issues in aquatic organism migration)	- Inadequate - Poor - Acceptable - good
			Flow-altering devices	Improve flow conditions	Not very effective when used alone as scour countermeasures	Low environmental repercussion (e.g. river encroachment)	- Inadequate - Poor - Acceptable - good
			River management strategies	Generally cost-effective and do not affect the asset's structure	Undesired river morphodynamics consequences	Low/mild environmental repercussions	- Inadequate - Poor - Acceptable - good
hydrodynamic forces	direct	Structural retrofitting	Structural intervention (e.g. rise of the deck or usage of air-trapping cells)	Alleviate the vulnerability of the deck to hydrodynamic impact	Moderate environmental repercussions if the structural retrofitting is carried	Moderate environmental repercussions if retrofitting is carried out with a sustainable approach	- Inadequate - Poor - Acceptable - good
		abandon	New infrastructure in a new location	The new structure is designed to respond to events that take into account climate change scenarios	Very high environmental repercussions (high carbon footprint, biodiversity loss)	Very high environmental repercussions (e.g. high carbon footprint, biodiversity loss)	- Inadequate - Poor - Acceptable - good

As illustrated in the Table **Error! Reference source not found.**, the levels of adaptation measures that can be implemented to improve the vulnerability of a bridge subjected to flooding issues depend on the action to which the bridge is subjected (i.e. local scour, significant hydrodynamic loading or both) and on the type of intervention ("indirect" and "direct"). The indirect interventions include engineering actions that aim at reducing the flood risk by not operating on the asset's infrastructure. On the other hand, direct interventions involve the structural assessment of the asset and its retrofitting. Indirect and direct interventions will be further explored hereinafter.

4.2.1 Indirect interventions

Indirect interventions tend to have a relatively low cost-benefit ratio as they are characterized by shorter realization times and do not require sophisticated engineering structural designing tools, as in the case of direct interventions. Indirect interventions, referred here to also as "river engineering countermeasures", intend to reduce the hydrodynamic loads and local scour by modifying the flow field and the river properties. River engineering countermeasures include river management strategies, riverbed armouring, and the implementation of flow-altering devices. River management strategies include a series of measures that aim at changing the state of the river, which include solutions such as river widening, bed roughness adjustments, embankment construction or adaptation, river diversion, implementation of flood lamination strategies, and detention basins.

The widening of the river section is a beneficial procedure that can create more space for the river by enabling its natural course and ensuring a higher conveyance flow capacity (Rohde et al. 2005). This can be achieved by moving the river embankments landward. However, the main drawback of this action is the reduction of the bed shear stress, which may lower the transportation of the sediment load in the downstream sections (Da Deppo 1997). Hence, in order to keep the river section morphologically active, sediment removal should be implemented periodically. If the recalibration of the embankments cannot be a valuable option (e.g. in case the river crosses a residential area), the roughness adjustment of the riverbed or of the riverbanks can be accomplished. Roughness adjustment (i.e. change of the Manning coefficient) can be achieved either by implementing a periodical cleaning and uprooting of the vegetation growing on the bed of the river or by lining the riverbanks (Da Deppo 1997).

The adaptation of river embankments consists of increasing the height and/or the thickness of the embankments in order to enhance the cross-section of the river. This is the most dated engineering measure used to safeguard residential areas from flooding events. However, the lack of space and material availability makes this retrofitting measure difficult to implement. Diverting a river to a drainage system with a higher drainage capacity can also be performed in order to reduce the water inflow rate in the sections located upstream of the bridge. Even though this solution appears to be easy and free from disadvantages, such a procedure is quite expensive, radical, and leads to a series of cascading negative effects on the riverine and aquatic ecosystems (e.g. habitat fragmentation, change in sediment transport) and issues of hydraulic nature (e.g. the establishment of return water profiles if certain hydraulic conditions are met) (White et al. 2019).

Flood lamination and detention basins are very effective strategies as they aim at mitigating the pick of the flood hydrograph. However, the implementation of these methods also requires high space availability in the vicinity of the river, high financial resources, a careful investigation of the flow dynamics, and high engineering design techniques.

According to the literature, using bed armouring countermeasures is the most traditional methodology for scouring remediation, given their flexibility, near-term and easy installation, and environmental acceptability (Fioklou 2019). Armouring adaptive measures act as a resistant layer to the hydraulic shear stress protecting the riverbed from erosive forces.

Riprap is the most widely used treatment for protecting bridge piers and abutments; it is available, economical, easy to install, and flexible (Agrawal et al. 2007). Riprap consists of layers of rocky materials that are laid down to the base of piers and abutments and are able to resist high flow velocity and turbulence (Figure 28). For riprap to serve its purpose, the size of the rocks must be determined before installation. Using a threshold size for the rock is a practical and efficient way to control the shear failure and the buoyant forces for the associated design flow. The most common formula used to size riprap at piers is the one proposed by Lagasse (2007), who provides the median size of the riprap by using the rearranged version of the Isbash equation. However, literature provides at least another twelve equations to size the riprap at bridge piers. The size of the ripraps is intimately linked to the critical velocity, which is the threshold velocity for which the load riprap transport is initiated. For abutments, the riprap formulas are equally numerous and are listed in Barkdoll et al. (2007). An efficient riprap fitting always requires the previous installation of a layer of granular or geotextile filter, which serves to retain the coarser particles of the subgrade and ensure, at the same time, water infiltration. Choosing the right filter material and selecting the right installation method contribute to the overall performance of riprap. A good riprap outcome also requires a certain level of maintenance in order to avoid failure. Therefore, riprap should be inspected (especially in the downstream section) after the occurrence of any flood that is bigger than the design flood (Peter Frederick Lagasse 2007). As a result, repairs should be carried out promptly and, for instance, remove the occurrence of woody debris that can compromise the stability of the layer. When the maintenance is not carried out regularly, riprap cannot be considered a permanent countermeasure. Nonetheless, riprap can remain operational, even if it loses some individual stones, and it is fairly easy to repair. Full guidelines on the placement level, coverage area, thickness, and failure causes of the riprap are extensively gathered in Lagasse (2007).

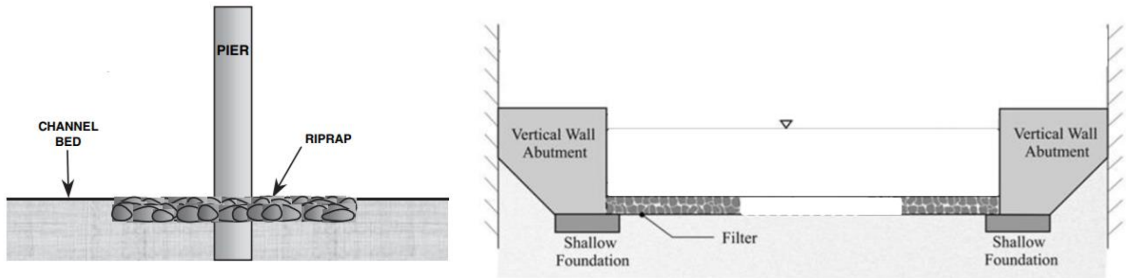

Figure 28: Example of a typical riprap configuration on a bridge pier (modified from Lagasse, (2007)) and riprap configuration at the abutment(modified from Suaznabar et al., (2017)).

When the required minimum stone of riprap is not available or expensive, partially grouted riprap can represent a different solution for riverbed armouring (Figure 29). Grouting enables the use of small rock sizes to create a conglomerate that can help to increase the stability of the layer. Total grouting converts the riprap layer into a rigid mass, increasing the overall stability without sacrificing flexibility and permeability. The construction methods for partially grouted riprap require a high level of monitoring to ensure appropriate voids and surface opening ratio (Lagasse et al., 2008). At the same time, maintenance requires a certain frequency, and, in case of damage, the riprap repair can occur relatively easily. The partially grouted riprap design methodology lacks a relationship that allows selecting the size of the rock. However, the literature provides some practical considerations about the proper proportion of void sizes and stone-to-stone contact areas (Lagasse, 2007).

Figure 29: Example of partially grouted riprap (modified from Heibaum (2000)*).*

Another efficient armouring measure is the use of gabion mattresses (Figure 30). Gabion mattresses are porous devices like riprap; they are wire mesh containers filled with loose stones or similar material. The wire mesh has certain flexibility that allows the gabion mattresses to be deformable. The choice of the wire, the size, and the type of filling material determine the successful performance of these devices. Guidelines for the design of gabion mattresses for bridge piers are provided in Parker et al. (1998), who set the minimum thickness and volume of the container, and in Heibaum (2000), who analytically defines the stone size. The drawback related to the implementation of gabion mattresses is the failure of the wire, which can lead to the loss of the stones and compromise the functionality of the entire system. Such a condition may occur when the river is characterized by a high bedload rate in turbulent flows or due to the lack of maintenance (e.g. corrosion and rupture of the wire). Hence, the material used to make the wire has to be strong and durable; for this reason, wires are made with galvanized steel covered with PVC (Barkdoll, Ettema, and Melville 2007). Gabion mattresses require regular maintenance, likewise ripraps. Abboud and Kaiser (2012) estimated that gabion mattresses should undergo maintenance every ten years and should be inspected for basket tearing caused by the stranding of woody debris.

Figure 30: Example of a gabion mattress installation (Gabionet Environment Solution 2014).

Using articulating concrete blocks (ACB) is another useful countermeasure to reduce local scouring (Figure 31). These devices consist of units that are bonded to a geotextile layer and are kept together by cables and rods to create a continuous mat. The use of concrete blocks for piers is limited as this solution is often implemented in cases where the covering of the riverbed reaches extended areas (Lagasse, 2007).

The articulating concrete blocks have a high ability to withstand strong currents, they are flexible, and their interlocking properties make them more stable compared to riprap. The failure mechanisms that have been identified for articulated concrete blocks are the rolling and uplift of the leading edge and the centre of the mat, respectively. Winnowing can also occur when the mat does not lie on a geotextile filter. Also, in this case, the construction observations and inspections are fundamental to ensure that the instalment of the blocks is implemented within the design tolerance.

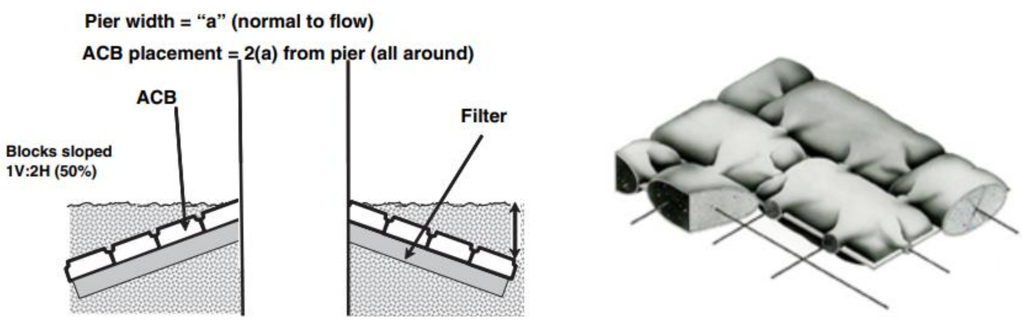

Figure 31: Example of baseline ACB design (modified from Lagasse, (2007)*) cable-tied block systems* (NILEX 2022).

Concrete armour units or "artificial riprap" are used when there is a lack of rock riprap (Figure 32). Concrete armour units are precast units (e.g. tetrapod, tetrahedron, toskane shapes) that have their greatest use in the erosion control of revetments more than for bridge substructures. The main benefit that this solution brings is the ability to create interlocking positions that not only favour their installation but also increase the stability of the structure. The most common concrete armour units used for pier and abutment scour applications are toskane and A-jacks modules. The failure mechanisms of concrete armour may be caused by riverbed instability, the development of a gap between the edge of concrete blocks and the structure, and the formation of scouring holes adjacent to the armour unit.

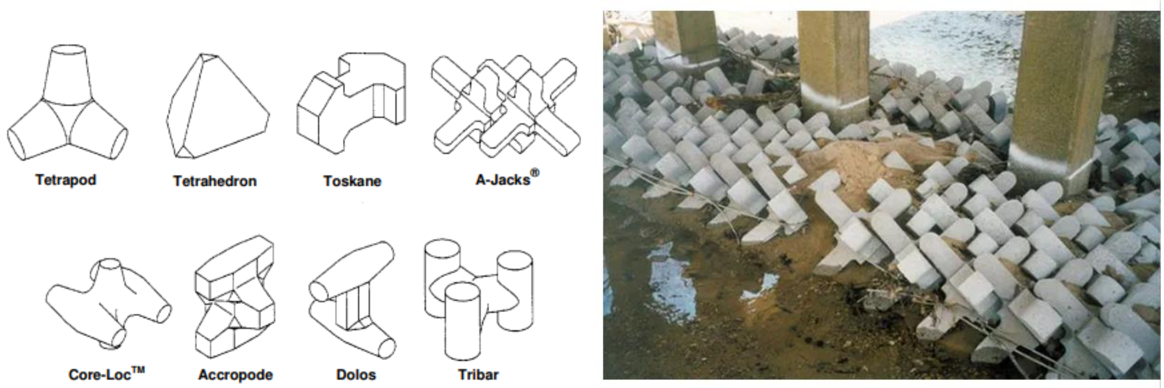

Figure 32: Example of Concrete armour units shapes (modified from The Federal Highway Administration (2009)*) and installation* (CONTECH ENGINEERED SOLUTIONS 2022).

Grout-filled bags are other armouring devices; they are permeable synthetic shells filled with concrete grout (e.g. wet sand, dry mixture of sand and cement) and connected internally by ducts to create mats (Figure 33). When compared to riprap or cable tied blocks, the grout-filled bags are more prone to failure due to the poor interlocking, smooth surfaces, and leeching of sand (Parker et al., 1998). Grout-filled bag's optimal design depends on their height which, if it is well designed, prevents the instability of the mats due to the upcoming flow. Even though grout-filled mattresses are considered to be not that advantageous in terms of cost and maintenance, grout-filled mattresses have high resilience to debris susceptibility and environmental disruption.

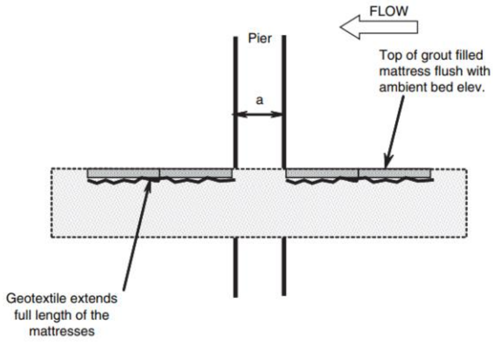

Figure 33: Example of grout filled bags installations (modified from Lagasse, (2007) and *SYNTHETEX,* respectively)

Another effective scour countermeasure consists of geocontainers which are large bags made of fabrics filled with sand and gravel filter material (Pilarczyk 2000) (Figure 34). Geocontainers are particularly suitable in strong currents due to their high resistance and well-performing filterability. The flexibility and deformability of the fabric enable the geocontainers to conform to the riverbed irregularities (Heibaum 2000). The size of the geocontainer must be chosen wisely to forbid its instability due to hydraulic load. The guidelines for the design of geocontainers are documented in Lagasse (2010). The geocontainers can also serve to fill a pre-existing scour hole around a pier before applying riprap or gabion mattresses.

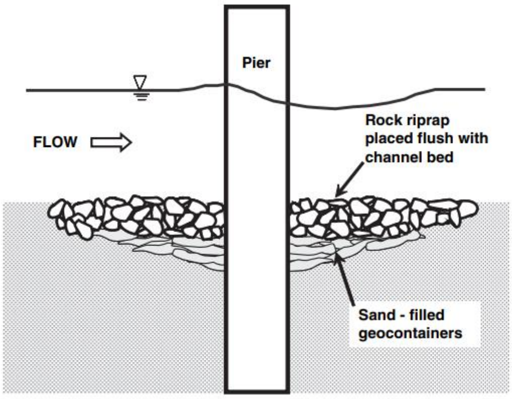

Figure 34: Schematic of pier scour repair using geocontainers as filter and fill with riprap as a cover layer (modified from Lagasse, (2007))

Among all the armouring devices abovementioned, riprap is, and probably will remain, the most common countermeasure used to prevent local scouring. However, for sustained flow velocities and high intensities of bed-load sediment fluxes, the efficiency of riprap fails. Hence, other countermeasures have to be considered. Overall, the most common option is to place additional material around the piers and abutments of the bridge, being mindful to check its influence on the dynamics of the river.

When debris accumulation on bridge piers and abutments becomes significant, Table 1 should include further adaptive measures. The extent of debris accumulation on piers depends on the location, type, and skew of the bridge pier. For instance, when the piers are located in the middle of the channel (e.g. in the thalweg), they are more likely to trap debris (Diehl 1997). Furthermore, piers have a higher chance of triggering debris accumulation if they are skewed and square-nosed. Adaptive measures for debris accumulation can also be distinguished into structural and non-structural. Structural countermeasures mainly include debris fin, in-channel debris basins, crib structures, flood relief sections, debris deflectors, hydrofoils, and debris sweepers. Structural measures are required to be sturdy enough to tolerate the static forces and the scour exerted by stranded debris. The prevalent debris control structures used are debris deflectors, which are placed at the cross-sections of the river located upstream of the bridge and are used to deflect the debris into wide bridge openings (Lagasse, 2007). Non-structural countermeasures consist instead of emergency and annual maintenance operations, which involve activities such as debris removal, repair of existing structural measures, and reduction of debris input in rivers through hillslope and streambanks stabilization.

Figure 35: Debris deflectors (cylindrical vertical structures) without and with debris, respectively (modified from (Dennis A. Lyn, Thomas Cooper, Yong-Kon Yi, and Sinha 2003)

Flow altering devices are instead grouped according to their shape and function into four categories: openings through piers, pier attachments, and bed attachments (Tafarojnoruz, Gaudio, and Dey 2010).

The openings through the piers devices (e.g. slot or internal connecting tubes) enable the attenuation of the downflow and the horseshoe vortex intensity of the flow. However, these techniques are deemed to be effective only when their geometrical configuration meets certain criteria (El-Razek, El-Motaleb, and Bayoumy 2003; Nandana, C., and Morteza 1994).

Pier attachments aim at weakening the magnitude of downflow and horseshoe vortex by attaching to the piers devices such as collars or plates. Collars are made of thin horizontal plates attached around the piers and can have different shapes. Collar effectiveness varies with collar size and placement (Heidarpour et al., 2010; Zarrati et al., 2006). For instance, it was found that in order to maximize vertical flow resistance, collars should be set up horizontally aligned and with a high and uniform gap between them. However, divergent opinions were reported on collars' performance as authors found consistent differences in efficiency rate when replicating the same geometric properties of collars in different experimental conditions (Mashahir, Zarrati, and Rezayi 1991; Moncada-M et al. 2009).

Bed attachments countermeasures imply the usage of measures such as sacrificial piles, vanes, surface guide panels, and sleeves. Bed attachments countermeasures are used to address scour prevention by diverting the flow and modifying the boundary layer. Sacrificial piles are single piles or a group of piles that are located upstream of a bridge pier, and they are recommended only in situations where the flow is likely to remain aligned with the pile and flow intensity is relatively small (Melville and Hadfield, 1999). In safety design, the effectiveness of sacrificial piles depends on their size, location, number of piles, their configurations, and the degree of submergence (Tafarojnoruz, Gaudio, and Dey 2010). Hence, these are very important factors that greatly impact the performance of such devices, especially when there is a high percentage of occurrence of debris accumulation during flood events. Besides the contribution provided to reduce the local scour, sacrificial piles can also enhance the overall performance of the load-bearing pier group of a bridge. Vanes are vertical plates installed in the stream bed just upstream of the pier and are angled outwards. They reduce the scour by generating secondary flow circulation altering the magnitude and direction of bed shear stress and modifying velocity distribution, flow depth, and sediment transport rate (Jacob and Yalin 1991). Surface guide panels are characterized by two vertical panels that are installed to create a diverging section of the flow upstream of the pier. The aim of the surface guide panels is to reduce the bed shear stress and to enhance the sediment deposition into the scour hole at the pier. Experiments carried out by Huang et al. (2005) showed how such countermeasures can lead to a maximum reduction of the scour depth of 90 %. Lastly, sleeves consist of cylinders encircling the piers and aim at restraining the scour vortex in the interspace between the sleeve and the pier. Further countermeasures are listed in Prendergast and Gavin (2014).

Even though flow-altering devices provided promising results, they are not very effective when used alone as scour countermeasures (Parkeret al., 1998). Hence, their implementation cannot be carried out without considering first an appropriate armouring countermeasure.

The most appropriate flood countermeasure shall not only be chosen on the basis of the current state of the asset but should also rely on the outcome of a suitable period of monitoring activity and environmental and health monitoring measurements (SHM) (Agrawal et al., 2005; Tubaldi et al., 2021). Monitoring can provide a continuous survey of the progression of the scouring so as to increase the awareness of the behaviour of the critical assets and lead to a better calibration of the hydraulic and structural modelling. Bridge inspections can also be considered as a further possible countermeasure as it allows scheduling repair options on the basis of the damages that would eventually build up and become fatal for the structure. Obtaining information regarding the evolution of the scouring and the integrity of the asset in real-time enables also to elaborate a data-rich risk assessment strategy and to plan the appropriate countermeasure to adopt. Nevertheless, difficulties related to costs and the lack of reliable data analysis techniques often discourages practitioners from implementing monitoring activities. Monitoring of local scour can be carried out by visual inspections or through depth-measuring instrumentation. Visual inspections are undoubtedly effective but also time-consuming and cannot be carried out during flooding events, during which the depth of the local scour reaches its highest values. Whereas, the instrumentations can be categorized as follows: single-use devices, pulse or radar devices, buried or driven rod systems, sound-wave devices, fiber-Bragg grating devices, and electrical conductivity devices. The functioning, advantages, and drawbacks of such instrumentations are reported in detail in Prendergast and Gavin (2014).

4.2.2 Direct interventions

Direct interventions are adopted mainly when the hydrodynamic forces acting on the bridge are such that they require the retrofitting of the structure or the design of a new structure with the resulting abandonment of the existing one. Retrofitting is the preferable route as it does not involve high money investment, a new design approach, and a long realization timescale.

The most suitable retrofitting intervention depends on the case study and is strongly interrelated to factors such as the entity of the hydrodynamic load, the geometry of the sections and the tensional stress-strain field of the structure. Retrofitting measures can vary widely; they can consist of actions such as the instalment of additional features to the bridge or the modification of important components of the structure (e.g. deck). Retrofitting strategies can be encountered in AASHTO and European specifications in which options such as open or sacrificial parapets, venting air-trapping cells, bridge fairings, and deck wings are suggested. The first option concerns the implementation of open or sacrificial parapets, which fulfil their function by reducing the amount of area exposed to the hydrodynamic load. Air vents consist of cavities located either in the bridge deck or diaphragm that dissipate part of the wave energy through air compression (Cuomo, Shimosako, and Takahashi 2009). Air vents are inexpensive and were found to be able to effectively reduce the buoyant forces acting on the bridge superstructure (Bozorgnia 2012). Bridge fairings are triangular structures that are attached to the superstructure of the bridge and are used to divert the wave impact from the deck, thus reducing the forces applied to the bearing supports of the bridge. The effectiveness of this countermeasure was tested by Zhang, Hoshikuma, and Usui (2012) utilising physical models and by Oudenbroek (2018) by using CFD modelling. The stability of the bridge towards hydrodynamic forces can also be increased by adding wings to the sides of the deck. Wings, when designed with an appropriate shape (e.g. with a sharp corner at the middle height of the deck), were found to decrease the drag force of the water (Naderi 2018). In fact, inappropriate shapes of the wings could lead to higher upward forces and endanger the vertical stability of the bridge. Strategies of foundation strengthening and soil improvements and pier geometry modifications can also be included in this category of interventions. Foundation strengthening involves techniques of reinforcement or/and extension of the foundations of the bridge that can prevent the bridge failure after the elevation of the riverbed is lowered by the scour (Brandi 2020; Kattell 1998). Direct intervention strategies also include the raise of the vertical clearance over the design wave crest line. This solution is more radical than the ones mentioned above and its feasibility challenges may prohibit its implementation. In practice, raising the deck involves accurate planning and engineering design that imply high realization time and costs. Nevertheless, this is the most effective mitigation measure as it enables a higher passing of flood flows and the improvement of roadway operability in vulnerable areas. Beyond hydrodynamic loading, the rise in flooding frequency increase also the volume of stormwater runoff which can lead to the instability and deterioration of the different components of the bridge structure. Therefore, bridges could also benefit from some improvements or upgrading of their storm drainage system.

The abovementioned countermeasures are only the most common options that are used to enhance bridges' resilience to floods; many more can be encountered in the literature. Conditions such as bridge geometry and design techniques, and the variability of spatial and temporal scales (e.g. rain frequency, river morphology) are crucial aspects in the decision-making process of the adaptation decision matrix. Nonetheless, the options illustrated in Table 1 can be considered to be a good starting point for analysing and seeking the best adaptive measures for the following case studies.

5 Conclusions

This report provides a methodology for selecting the most appropriate countermeasure to increase the resilience of flood-prone embankments, riverbanks, and bridges. After a detailed explanation of the most common failure mechanisms of embankments, the issues encountered in Oostmolendijk embankments and Karlovac riverbanks are discussed in detail, followed by a series of adaptation measures for both cases. For the case study in the Netherlands, different methods of soil improvements are discussed, and solutions such as the installation of retaining walls and subsoil bearing layers have been suggested. On the other hand, the installation of horizontal drains on the riverbanks of the Kupa River in Karlovac was deemed most appropriate as a countermeasure.

An extensive analysis of adaptation measures to counteract the local scour in bridge piers and abatements is also undertaken. Particular attention has been devoted to bed armouring devices that are, in most cases, the most common countermeasures adopted for the variety of solutions that they can provide in terms of materials, shapes, and installation methods. Countermeasures such as flow-altering devices and river management strategies are also mentioned. However, their success rate is highly dependent on different factors (e.g. the hydrodynamics and the sediment processes in the rivers), and, as such, they require a particularly scrupulous preliminary investigation. A more extreme countermeasure consists in modifying the structure of the asset. However, as the cost-benefit ratio plays an important role, this solution shall be accepted only in extreme cases.

The report also moves attention to the strategy elaboration process that shall be used to choose the most suitable countermeasures. Assessing different countermeasures is, in fact, a fundamental step for the successful outcome of the asset's recovery and improvement. It is clear that an optimal adaptation measure is derived generally through a careful preliminary analysis (e.g. vulnerability and risk assessments) and identification of external factors (e.g. hazard extent, resource availability) that can influence the asset. The selection of the most favourable adaptation measure should not exclude the recommendation of less invasive and less expensive countermeasures. The solutions examined, in fact, should all be sufficiently resilient and appropriate for the asset, regardless of the type and cost of the adaptation measures chosen.

Although this report cannot cover every possible adaptation measure for embankments, riverbanks, and bridges, it is intended that the information enclosed herein can still be readapted and used elsewhere as a guide or starting point for assessing flood vulnerability countermeasures.

References

Abboud, B., and Kaiser, S. 2012. *Selection and Design of Scour Countermeasures for Pennsylvania Bridges*. Harrisburg, PA.

ADB (Asia Development Bank), 2007: Flood Insurance as a Flood Management Tool: An Economic Perspective, ERD Working Paper SERIES No. 99. Available at: http://www.adb.org/publications/flood.insurance.flood.management.tool.economic.perspective

ADFIL (2015). The Benefits of Synthetic Fibres in Concrete for Flood and Coastal Civil Engineering, www.adfil.com

AECOM.(2015). Global climate change, adaptation, and infrastructure issues knowledge management support.

AECOM. 2017. *Overarching Guide for Incorporating Climate Change Adaptation in Infrastructure Planning and Design*.

Agrawal, A.K., Khan, M.A. and Yi, Z. 2005. *Handbook of Scour Countermeasures Designs*. New York, NY, USA.

Agrawal, Anil Kumar, Mohiuddin Ali Khan, Zhihua Yi, and Nazhat Aboobaker. 2007. *Handbook of Scour Countermeasures Designs*. New Jersey Department of Transportation.

Argyroudis, Sotirios A., and Stergios Aristoteles Mitoulis. 2021. "Vulnerability of Bridges to Individual and Multiple Hazards- Floods and Earthquakes." *Reliability Engineering & System Safety* 210: 107564.

Bačić, M., Marčić, D., Peršun, T. (2014). Application of industrial waste materials in sustainable ground improvement, Road and Rail Infrastructure III, Proceedings of Conference CETRA 2014, Zagreb: Department of Transportation, Faculty of Civil Engineering, University of Zagreb, pp. 609-615

Bačić, M., Librić, L., Kovačević, M. S.. (2017). Application of geosynthetics as hydraulic barriers in flood protection embankments, Proceedings of the 1st International Conference CoMS_2017, Zagreb, pp. 677-683

Bačić, M., Kovačević, M.S. (2021). oVERFLOw Deliverable 3.1: Report on investigation works and monitoring of embankments

Bacic, M., Ganic, E., Stipanovic, I. (2022). oVERFLOw Deliverable 6.1 Integration of Inventory of critical infrastructure assets as an operational layer in the existing GIS platforms

Barbhuiya, Abdul Karim, and Subhasish Dey. 2004. “Local Scour at Abutments: A Review.” *Sadhana* 29(5): 449–76. https://doi.org/10.1007/BF02703255.

Barkdoll, Brian D, Robert Ettema, and Bruce W Melville. 2007. 587 *Countermeasures to Protect Bridge Abutments from Scour*. Transportation Research Board.

Bebi, Peter, Dominik Kulakowski, and Christian Rixen. 2009. "Snow Avalanche Disturbances in Forest

Ecosystems—State of Research and Implications for Management." *Forest ecology and Management* 257(9): 1883–92.

Benn, Jeremy. 2013. "Railway Bridge Failure during Flooding in the UK and Ireland." *Proceedings of the Institution of Civil Engineers-Forensic Engineering* 166(4): 163–70.

Bozorgnia, Mehrdad. 2012. *Computational Fluid Dynamic Analysis of Highway Bridge Superstructures Exposed to Hurricane Waves*. University of Southern California.

Brandi, H. 2020. "Foundation Strengthening and Soil Improvement for Scour-Dangered River Bridges." In *Geotechnical Hazards*, CRC Press, 3–28.

Brandimarte, L, A Montanari, J.-L. Briaud, and P D'Odorico. 2006. "Stochastic Flow Analysis for Predicting River Scour of Cohesive Soils." *Journal of Hydraulic Engineering* 132(5): 493–500. https://www.scopus.com/inward/record.uri?eid=2-s2.0-33645798664&doi=10.1061%2F%28ASCE%290733-9429%282006%29132%3A5%28493%29&partnerID=40&md5=51f075d22ff842d5265c07a6030e8350.

BRE. (2000). Building Research Establishment Report 391 - Specifying Vibro Stone Columns, 2000.

Burić, M. and Grgurić, S. (2020). oVERFLOw Deliverable 2.2 D2.2 Climate downscaling and flooding scenarios for selected area

C Huang, C Tang, T Kuo. 2005. "Use of Surface Guide Panels as Pier Scour Countermeasures." In *International Journal of Sediment Research, 2005 - IRTCES*,.

Chiew, Yee-Meng. 2008. "Scour and Scour Countermeasures at Bridge Sites." *Transactions of Tianjin University* 14(4): 289–95.

CIRIA (2002). A guide to ground treatman, CIRIA C573, London, UK

CIRIA (2013). The International Levee Handbook, CIRIA C731, London, UK

Clark, Colin. 1987. "Deforestation and Floods." *Environmental Conservation* 14(1): 67–69. http://www.jstor.org/stable/44521025.

Comiti, F, A Lucía, and D Rickenmann. 2016. "Large Wood Recruitment and Transport during Large Floods: A Review." *Geomorphology* 269: 23–39.

Commission Notice (2021). Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (OJ C, C/373, 16.09.2021, p. 1, CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03))

CONTECH ENGINEERED SOLUTIONS. 2022. https://www.archiexpo.com/prod/contech/product-126557-1525609.html.

CONTECH UK. (2022); URL: www.contechuk.com (accessed 31st May 2022)

Cook, Wesley. 2014. *Bridge Failure Rates, Consequences, and Predictive Trends*. Utah State University.

Cuomo, Giovanni, Ken-ichiro Shimosako, and Shigeo Takahashi. 2009. "Wave-in-Deck Loads on Coastal Bridges and the Role of Air." *Coastal Engineering* 56(8): 793–809. https://www.sciencedirect.com/science/article/pii/S0378383909000064.

Dahabreh, M. and Hssan, O. 2(014). The Strength of Fibre Reinforced Concrete in a Flood Wall Defence. EG-353 Research project, Swansea University

De de Graaf R., van de Giesen N., et al. (2009), Alternative water management options to reduce vulnerability for climate change in the Netherlands, Natural Hazards 51: 407–422

nnis A. Lyn, Thomas Cooper, Yong-Kon Yi, Rahul Sinha, and A. R. Rao. 2003. *Debris Accumulation at Bridge Crossings: Laboratory and Field Studies*. Indiana. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1519&context=jtrp.

Da Deppo, Datei. 1997. "Salandin-Sistemazione Dei Corsi d'acqua." *Ed. Libreria Cortina Padova*.

Diehl, Timothy H. 1997. *Potential Drift Accumulation at Bridges*. US Department of Transportation, Federal Highway Administration, Research ….

Downs, Peter W, and Andrew Simon. 2001. "Fluvial Geomorphological Analysis of the Recruitment of Large Woody Debris in the Yalobusha River Network, Central Mississippi, USA." *Geomorphology* 37(1–2): 65–91.

Duggan A, McCabe BA, Clifford E, Goggins J. (2015). Carbonation in stabilised peat: An accelerated pilot study. Proceedings of the 16th European Conference on Soil Mechanics & Geotechnical Engineering, Edinburgh. Vol. 5. Sep 13-17, 2015. pp. 2383-2388

Ebrahimi, Mohsen et al. 2020. "A Method for Evaluating Local Scour Depth at Bridge Piers Due to Debris Accumulation." In *Proceedings of the Institution of Civil Engineers-Bridge Engineering*, Thomas Telford Ltd, 86–99.

EEA. (2016). Flood risks and environmental vulnerability - Exploring the synergies between floodplain restoration, water policies and thematic policies. In EEA Report No 1/2016. (Issue 1).

El-Razek, Mohamed Abd, Mohamed Abd El-Motaleb, and Mosaad Bayoumy. 2003. "Scour Reduction around Bridge Piers Using Internal Openings through the Pier." *AEJ - Alexandria Engineering Journal* 42(2): 241–48.

Feng, Boyu, Ying Zhang, and Robin Bourke. 2021. "Urbanization Impacts on Flood Risks Based on Urban Growth Data and Coupled Flood Models." *Natural Hazards* 106(1): 613–27. https://doi.org/10.1007/s11069-020-04480-0.

Fioklou, Ameh. 2019. "Performance Assessment of Reinforced Concrete Bridges under the Multi-Hazard Conditions and Climate Change Effects."

Forsman, J., Korkiala-Tanttu, L. and Piispanen, P. (2018). Mass Stabilization as a Ground Improvement Method for Soft Peaty. In Peat, Bülent Topcuoğlu and Metin Turan (Eds), doi: 10.5772/intechopen.74144

Francisco Nicolas Cantero-Chinchilla, Gustavo A M, and NERC-ERIIP grant DEBRIEF. 2018. "Assessing the Effects of Debris Accumulations at River Bridges."

Fujiwara, K. et al. 2017. Study on Coastal Levee Reinforcement Using Double Sheet-Piles with Partition Walls, International Journal of Offshore and Polar Engineering (IJOPE), vol. 27, no. 3, 310-317, doi:10.17736/ijope.2017.cl05

"Gabionet Environment Solution." 2014. https://gabionet.com/gabion-mattresses/.

Gasser, Eric et al. 2019. "A Review of Modeling the Effects of Vegetation on Large Wood Recruitment Processes in Mountain Catchments." *Earth-Science Reviews* 194: 350–73.

Gavin K., Reale C. (2022), oVERFLOw Deliverable 4.1 Report on Vulnerability Assessment Methodology - Fragility curves for embankments subjected to flooding

GIKEN (2015). IMPLANT LEVEE - Highly Resilient Disaster Prevention Levee, Tokyo, Japan

GSI (2022); URL: www.geostabilization.com/technology/launched-horizontal-drains/ (accessed 3rd June 2022)

Guettala, A, and A Abibsi. 2006. "Corrosion Degradation and Repair of a Concrete Bridge." *Materials and structures* 39(4): 471–78.

Hansson, N. (2008). Deep soil stabilization with fly ash, MSc thesis, Department of Earth Sciences, Uppsala University, Sweden

Heibaum, Michael H. 2000. "Scour Countermeasures Using Geosynthetics and Partially Grouted Riprap." *Transportation Research Record* 1696(1): 244–50. https://doi.org/10.3141/1696-70.

Heidarpour, Manouchehr, Hossein Afzalimehr, and Elham Izadinia. 2010. "Reduction of Local Scour around Bridge Pier Groups Using Collars." *International Journal of Sediment Research* 25(4): 411–22. https://www.sciencedirect.com/science/article/pii/S1001627911600085.

Hunt, John, Gary W Brunner, and Bruce E Larock. 1999. "Flow Transitions in Bridge Backwater Analysis." *Journal of Hydraulic Engineering* 125(9): 981–83.

Igigabel, M., Diab, Y., Yates, M. (2020): Enhancing the resilience of levee systems through methodological developments, FLOODrisk 2020 - 4th European Conference on Flood Risk Management, DOI: 10.3311/FloodRisk2020.19.2

IPCC (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland

Jacob, Odgaard A, and Wang Yalin. 1991. "Sediment Management with Submerged Vanes. I: Theory." *Journal of Hydraulic Engineering* 117(3): 267. https://doi.org/10.1061/(ASCE)0733-9429(1991)117:3(267).

Julien, Y.P. (2018). Riverbank Protection, Published online by Cambridge University Press: 21 March 2018, www. cambridge.org (accessed 28 May 2022)

Kattell, John. 1998. 9877 *Bridge Scour Evaluation: Screening, Analysis, & Countermeasures*. USDA Forest Service, San Dimas Technology and Development Center.

Kilgore, Roger. 2017. "Hydraulic Performance of Shallow Foundations for the Support of Vertical-Wall Bridge Abutments" ed. L L C Genex Systems. http://www.ntis.gov.

Kopp, Robert E. et al. 2014. "Probabilistic 21st and 22nd Century Sea-level Projections at a Global Network of Tide-gauge Sites." *Earth's Future* 2(8): 383–406.

Kovačević, M.S., Bačić, M., Librić, L. and Gavin, G. (2022). "Evaluation of Creep Behavior of Soft Soils by Utilizing Multisensor Data Combined with Machine Learning" Sensors 22, no. 8: 2888. https://doi.org/10.3390/s22082888

Kumalasari, Wardhana, and Hadipriono Fabian C. 2003. “Analysis of Recent Bridge Failures in the United States.” *Journal of Performance of Constructed Facilities* 17(3): 144–50. https://doi.org/10.1061/(ASCE)0887-3828(2003)17:3(144).

Kundzewicz, Zbigniew W, Markus Stoffel, Tadeusz Niedźwiedź, and Bartłomiej Wyżga. 2016. *Flood Risk in the Upper Vistula Basin*. Springer.

Lagasse, P F, P E Clopper, and L A Arneson. 2008. “Partially Grouted Riprap as a Pier Scour Countermeasure.” In *World Environmental and Water Resources Congress 2008: Ahupua’A*, , 1–10.

Lagasse, Peter Frederick. 2007. 593 *Countermeasures to Protect Bridge Piers from Scour*. Transportation Research Board.

Lebbe, Mohamed Farook Kalendher, Weena Lokuge, Sujeeva Setunge, and Kevin Zhang. 2014. “Failure Mechanisms of Bridge Infrastructure in an Extreme Flood Event.” In *Proceedings of the 1st International Conference on Infrastructure Failures and Consequences (ICFC 2014)*, RMIT Publishing, 124–32.

Lin, Yung-Bin et al. 2005. “Real-Time Monitoring of Local Scour by Using Fiber Bragg Grating Sensors.” *Smart materials and structures* 14(4): 664.

Mashahir, M B, A R Zarrati, and M J Rezayi. 1991. “Time Development of Scouring Around a Bridge Pier.” *Time* (Figure 1): 1–8.

Melville, B W, and A J Sutherland. 1988. “Design Method for Local Scour at Bridge Piers.” *Journal of Hydraulic Engineering* 114(10): 1210–26.

Melville, Bruce W, and Yee-Meng Chiew. 1999. “Time Scale for Local Scour at Bridge Piers.” *Journal of Hydraulic Engineering* 125(1): 59–65.

Melville, Bruce W, and Stephen E Coleman. 2000. *Bridge Scour*. Water Resources Publication.

Melville, Bruce W, and D M Dongol. 1992. “Bridge Pier Scour with Debris Accumulation.” *Journal of Hydraulic Engineering* 118(9): 1306–10.

Moncada-M, A T, J Aguirre-Pe, J C Bolívar, and E J Flores. 2009. “Scour Protection of Circular Bridge Piers with Collars and Slots.” *Journal of Hydraulic Research* 47(1): 119–26. https://doi.org/10.3826/jhr.2009.3244.

Mondoro, Alysson, Dan M. Frangopol, and Liang Liu. 2018. “Bridge Adaptation and Management under Climate Change Uncertainties: A Review.” *Natural Hazards Review* 19(1): 04017023.

Naderi, Nader. 2018. “Numerical Simulation of Hydrodynamic Forces on Bridge Decks.”

Nandana, Vittal, Kothyari U C., and Haghighat Morteza. 1994. “Clear-Water Scour around Bridge Pier Group.” *Journal of Hydraulic Engineering* 120(11): 1309–18. https://doi.org/10.1061/(ASCE)0733-9429(1994)120:11(1309).

NCHRP. 2010. 653 *Effects of Debris on Bridge Pier Scour*. Transportation Research Board.

Nicholson, P.G. (2015). Horizontal Drain - an overview. In Soil Improvement and Ground Modification Methods, Butterworth-Heinemann, doi: https://doi.org/10.1016/C2012-0-02804-9

"NILEX." 2022. https://nilex.com/synthetex-articulating-block-concrete-linings/.

Oudenbroek, Kevin. 2018. "Experimental Research on Hydrodynamic Failure of River Bridges on Spread Footings."

Pagliara, Stefano, and Iacopo Carnacina. 2011. "Influence of Wood Debris Accumulation on Bridge Pier Scour." *Journal of Hydraulic Engineering* 137(2): 254–61.

Panici, Diego, and Gustavo A M de Almeida. 2018. "Formation, Growth, and Failure of Debris Jams at Bridge Piers." *Water Resources Research* 54(9): 6226–41.

Parker, G., Toro-Escobar, C., and Voight, R.L., Jr. 1998. *Countermeasures to Protect Bridge Piers from Scour*.

Perry, E.B. (1998). Innovative Methods for Levee Rehabilitation, Army engineer waterways experiment station VIcksburg MS

Pilarczyk, Krystian. 2000. *Geosynthetics and Geosystems in Hydraulic and Coastal Engineering*. Balkema, Rotterdam: A.A. Balkema.

Pregnolato, Maria et al. 2020. "Assessing Flooding Impact to Riverine Bridges: An Integrated Analysis." *Natural Hazards and Earth System Sciences Discussions*: 1–18.

Prendergast, Luke J, and Kenneth Gavin. 2014. "A Review of Bridge Scour Monitoring Techniques." *Journal of Rock Mechanics and Geotechnical Engineering* 6(2): 138–49.

R., Zarrati A, Nazariha M., and Mashahir M B. 2006. "Reduction of Local Scour in the Vicinity of Bridge Pier Groups Using Collars and Riprap." *Journal of Hydraulic Engineering* 132(2): 154–62. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:2(154).

Richardson, Everett V, and Stanley R Davis. 2001. *Evaluating Scour at Bridges*. United States. Federal Highway Administration. Office of Bridge Technology.

Rohde, Sigrun, Martin Schütz, Felix Kienast, and Peter Englmaier. 2005. "River Widening: An Approach to Restoring Riparian Habitats and Plant Species." *River Research and Applications* 21(10): 1075–94.

Ryan, C., Garcia-Taengua E. (2021). Fibre-Reinforced Concrete Is Sustainable and Cost-Effective for Water-Retaining Structures. Sustainability; 13(20):11479. https://doi.org/10.3390/su132011479

Semmler, Tido, and Daniela Jacob. 2004. "Modeling Extreme Precipitation Events—a Climate Change Simulation for Europe." *Global and Planetary Change* 44(1–4): 119–27.

Shen, Hsieh W, Verne R Schneider, and Susumu Karaki. 1969. "Local Scour around Bridge Piers." *Journal of the Hydraulics Division* 95(6): 1919–40.

Sheppard, D M, B Melville, and H Demir. 2014. "Evaluation of Existing Equations for Local Scour at Bridge Piers." *Journal of Hydraulic Engineering* 140(1): 14–23.

Sheppard, D Max, and William Miller Jr. 2006. "Live-Bed Local Pier Scour Experiments." *Journal of Hydraulic Engineering* 132(7): 635–42.

Speijker, L.J.P.,van Noortwijk, J.M.; Kok, M., Cooke, R.M. (2000). Optimal Maintenance Decisions for Dikes. Probab. Eng. Informational Sci. 2000, 14, 101–121. https://doi.org/10.1017/s0269964800141087.

"SYNTHETEX." https://synthetex.com/.

Tafarojnoruz, Ali, Roberto Gaudio, and Subhasish Dey. 2010. "Flow-Altering Countermeasures against Scour at Bridge Piers: A Review." *https://doi.org/10.1080/00221686.2010.491645* 48(4): 441–52. https://www.tandfonline.com/doi/abs/10.1080/00221686.2010.491645 (March 10, 2022).

The Federal Highway Administration, FHWA. 2009. "HEC 23 - Bridge Scour and Stream Instability Countermeasures: Volume 1." 1(23).

Tubaldi, E. et al. 2017. "A Framework for Probabilistic Assessment of Clear-Water Scour around Bridge Piers." *Structural safety* 69: 11–22.

Tubaldi, E. et al.. 2019. "Field Tests on a Soil-Foundation-Structure System Subjected to Scour." *Field tests on a soil-foundation-structure system subjected to scour*: 41–46.

Tubaldi, E. et al. 2021. "Invited Perspectives : Challenges and Future Directions in Improving Bridge Flood Resilience." *Natural Hazards and Earth System Science* (October): 1–21.

Vahedifard, F., Robinson, J. D., & AghaKouchak, A. (2016a). Can protracted drought undermine the structural integrity of California's earthen levees?. J. Geotech. Geoenviron. Eng., 142(6), 02516001.

Vahedifard, F., AghaKouchak, A., & Jafari, N. H. (2016b). Compound hazards yield Louisiana flood. Science, 353(6306), 1374-1374.

Vahedifard, F., Tehrani, F. S., Galavi, V., Ragno, E., & AghaKouchak, A. (2017a). Resilience of MSE Walls with Marginal Backfill under a Changing Climate: Quantitative Assessment for Extreme Precipitation Events. J. Geotech. Geoenviron. Eng., 143(9), 04017056.

Vahedifard, F., J. M. Williams, and A. AghaKouchak. (2018). Geotechnical engineering in the face of climate change: Role of multi-physics processes in partially saturated soils. In IFCEE 2018: Advances in Geomaterial Modeling and Site Characterization, Geotechnical Special Publication 295, edited by A. W. Stuedlein, A. Lemnitzer, and M. T. Suleiman, 353–364. Reston, VA: ASCE

Vahedifard, F., Jasim, F. H., Tracy, F. T., Abdollahi, M., Alborzi, A., & AghaKouchak, A. (2020). Levee Fragility Behavior under Projected Future Flooding in a Warming Climate. Journal of Geotechnical and Geoenvironmental Engineering, 146(12), 04020139. doi:10.1061/(asce)gt.1943-5606.00

Vardon, P. J. (2015). "Climatic influence on geotechnical infrastructure: a review." Environmental Geotechnics, 2(3), 166-174.

W., Melville Bruce, and Hadfield Anna C. 1999. "Use of Sacrificial Piles as Pier Scour

Countermeasures." *Journal of Hydraulic Engineering* 125(11): 1221–24. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:11(1221).

Wang, Zhenghua, Leonardo Dueñas-Osorio, and Jamie E Padgett. 2014. "Influence of Scour Effects on the Seismic Response of Reinforced Concrete Bridges." *Engineering structures* 76: 202–14.

Wenger, C. (2015). Better use and management of levees: reducing flood risk in a changing climate. Environmental Reviews, 23(2), 240–255. doi:10.1139/er-2014-0060

White, John R et al. 2019. "Consequences of Mississippi River Diversions on Nutrient Dynamics of Coastal Wetland Soils and Estuarine Sediments: A Review." *Estuarine, Coastal and Shelf Science* 224: 209–16.

World Economic Forum. (2019). Global Risks Report 2019, 14th Edition. World Economic Forum.

Zampieri, Paolo et al. 2017. "Failure Analysis of Masonry Arch Bridges Subject to Local Pier Scour." *Engineering Failure Analysis* 79: 371–84.

Zhang, Guangfeng, Jun-ichi Hoshikuma, and Toshihiro Usui. 2012. "An Experimental Study on Countermeasure for Mitigating Tsunami Effect on Highway Bridge."