BIG – Branschsamverkan i grunden

Forskningsprogram för effektiv och säker grundläggning av vägar och järnvägar

Projekt A2020:08

Towards contemporary erosion solutions

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CHALMERS
TRAFIKVERKET
STATENS GEOTEKNISKA INSTITUT
LULEÅ TEKNISKA UNIVERSITET

BIG – Branschsamverkan i grunden
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Rapport BIG projekt A2020:08

Towards contemporary erosion solutions

Final report for project

Eleni Gerolymatou, Jelke Dijkstra, Gunnel Göransson

CHALMERS

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Geology & Geotechnics
Författare Eleni Gerolymatou, Jelke Dijkstra, Gunnel Göransson

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CHALMERS



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Eleni Gerolymatou
Geology & Geotechnics, Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Göteborg

Jelke Dijkstra
Geology & Geotechnics, Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Göteborg

Gunnel Göransson
Department of Geotechnical Risk and Climate Adaptation
Swedish Geotechnical Institute
Hugo Grauers gata 5 B
SE-412 96 Göteborg

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Preface

With the increasing need for climate resilient infrastructure, an understanding of the erosion processes and designing adequate but environmentally friendly protection measures becomes increasingly more important. In Sweden, there are no clear national guidelines or methods to address this. Current guidelines include the design of traditional bed and shore protection in waterways which are often ecologically unsustainable, especially for smaller streams. The research reported herein is the final deliverable of BIG project A2020-08 “Erosion mot tid” funded by Trafikverket. This project aimed at mapping the current approaches in use at Trafikverket (The Swedish Transport Administration) for addressing erosion related issues near infrastructure. The behavior of the water filled soil (strength and drainage properties), the flow above and at the soil-water interface (hydraulic roughness, bed stress) are interdependent and evolve non-linearly. Meanwhile, the requirements of infrastructure have also changed. Mitigating solutions should be environmentally non-intrusive, cost-effective, and ideally prevented altogether.

The state of the art for the prediction of the need for protection measures, the modelling of the extent of erosion in their absence and the different solutions available was investigated. It was found that advanced erosion modelling, while it could provide optimization of the mitigating solutions and their impact on the system, is impractical for the majority of Trafikverket’s projects, that have a modest budget. The costs of obtaining suitable input data experimentally for the advanced numerical analyses prevents the use of these advanced methods for small projects.

At the same time, traditional solutions for such streams create ecological issues, for example obstructing the movement of fauna at low water levels. It is, therefore, concluded that alternative, nature friendlier solutions need to be found for a variety of Trafikverket’s assets, but especially for smaller applications, which are very common due to the Swedish topography. In this context, nature-based solutions are a prime candidate, though at the current stage there are no clear guidelines in place for their application.

Summary

This report for project A2020-08 is concerned with safety measures for riverbank erosion and protection against scour. The first part of the report summarizes the fundamentals of erosion in general, in order to provide the context for the main focus of the report, as well as the physical background for the simulation of erosion and for the design of countermeasures.

Local scour near structures and riverbank erosion are treated separately. For each of the two the governing mechanisms are discussed, the common approaches for modeling and prediction are briefly touched upon and the common countermeasures are presented.

In reviewing the literature, nature-based solutions were found to be of particular interest for the future. While some such solutions are available for protection against scour near structures, most and the ones most widely used concern riverbank erosion. The most widely used nature-based solutions currently in use are collected from the literature in this report. For each support measure the area of application and the most common installation or implementation process are briefly presented.

Following this, the results of a series of discussions with experts within Trafikverket are summarized. The suitability of the guidelines currently in use is discussed for different applications. The experiences made in the last years with installation and maintenance for different projects, including the use of nature-based solutions and the problems involved in the use of numerical techniques, are also outlined.

The report closes with conclusions drawn and recommendations for future action.

1. Introduction

1.1. Motivation

With the increasing need for climate resilient infrastructure, designing suitable protection against erosion becomes more urgent. It is also very important to design such protection in an environmentally friendly manner, both for the protection of the local ecosystem and for aesthetic reasons. There are no clear guidelines or methods to address this, as the focus of existing guidelines is on the design of traditional bed and shore protection in waterways. The objective of this study is to summarize the erosion problems for Trafikverket's (The Swedish Transport Administration's) assets and elaborate the state-of-the-art on the physical processes underpinning those as a prior for future projects within BIG.

There are no updated Swedish guidelines for predicting river erosion. The focus of existing guidelines (e.g. [65]) is on the design of traditional bed and shoreline protection in watercourses and waterways, not including nature-based solutions. Meanwhile, the requirements of infrastructure have also changed. With respect to an increasing need for climate resilient infrastructure, better prediction of the extent of bed and shore protection measures for current and future conditions is required. The impact of climate change, both in terms of precipitation, water levels and flow velocities, further necessitates more accurate means of predicting erosion and assessing mitigation measures for existing and new infrastructure. Such mitigating solutions should be environmentally non-intrusive, cost-effective, and ideally prevented altogether.

The following objectives are formulated:

1) Conduct a state-of-the-art and a literature review.
2) Review available nature-based solutions.
3) Summarize the erosion related problems for Trafikverket's assets.

1.2. Scope

The present report aims to summarize briefly

- the fundamentals of erosion in riverbeds, both concerning watercourses and scour at bridge piers,
- commonly used remediation measures,
- nature-based solutions,
- common practices within Trafikverket and
- open questions linked to Trafikverket's assets

1.3. Limitations

Coastal erosion is not considered, furthermore scour near foundations of offshore installations, such as wind turbines, are also excluded.

2. Fundamentals

2.1. Initiation of motion

Soil (sediments) on a riverbed or on a streambank is subjected to drag forces, from the flow of the water. Assuming that soil in its simplest form consists of spherical particles, the forces acting on a particle can be schematically illustrated as shown in Figure 1. after [50].

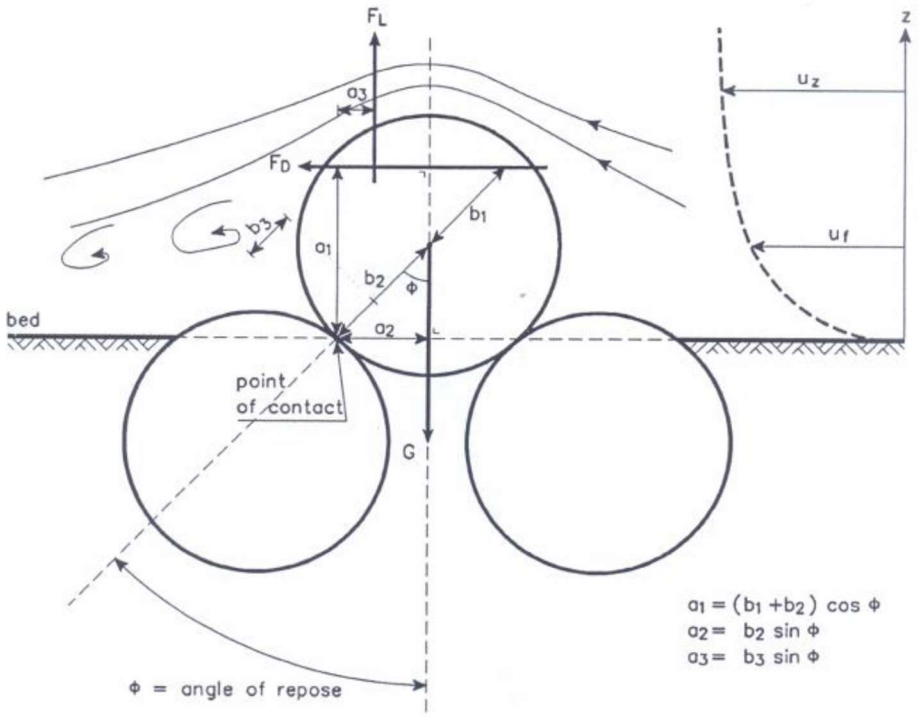


Figure 1. Forces acting on a sediment particle after [50].

The particle will move around the pivot point of contact, if the moments due to the driving forces are larger than the moment due to the resisting force of gravity. So, the flow of the water results in a drag force and an uplift force, which increase as the flow velocity increases. The result is a shear stress acting on the sediment, which increases as the flow velocity increases. When this shear stress, referred to as bed-shear stress, becomes sufficiently high, the soil particles start moving. In addition to gravity, additional shear resistance from, e.g. cohesion or biofilms, can be mobilized in the sediment, however, they typically appear as an empirical correction of the following equations.

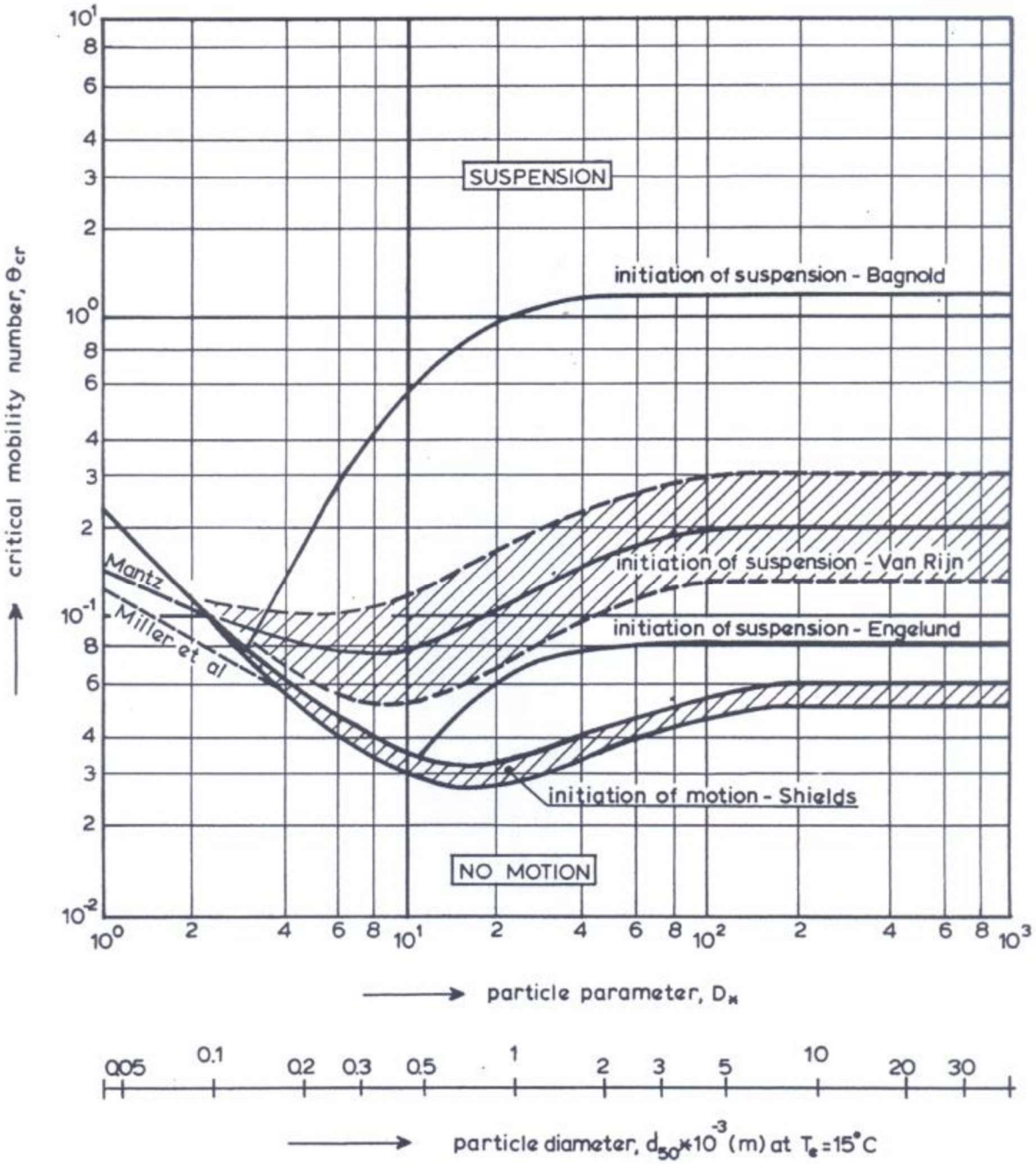


Figure 2. Shields' curve as function of dimensionless particle size D* after [47].

The transport of sediment due to high flow velocities is generally subdivided into two main modes: bed-load transport and suspended load transport [51]. The bed-load transport is defined to consist of gliding, rolling and saltating particles [47] in close contact with the bed and is dominated by flow-induced drag forces and by gravity forces acting on the particles. The suspended load transport is the irregular motion of the particles through the water column induced by turbulence-induced drag forces on the particles. The distinction between the two is not clear cut.

Shields [57] developed an approach for the prediction of the flow velocity at which the initiation of motion takes place. With this he introduced the Shields parameter, also

called the Shields criterion or Shields number, which is a nondimensional number used for the calculation of the behavior of a sediment in a fluid flow. It is a non-dimensional form of the bed-shear stress and is typically denoted as θ.

$$\theta = \frac{\tau}{(\rho_s - \rho_f)gD}$$

where τ is the bed shear stress, ρ_s and ρ_f are the densities of the solids and fluids respectively, D is the grain diameter and g is the acceleration of gravity. This makes it possible to construct diagrams such as the one in Figure 2., which allow the determination of the behavior of the sediment, based on the grain diameter, physical properties and flow velocity.

This approach is not accurate for small particles (D<0.1 mm, see [51]) even in the absence of cohesion. In this area the bed-shear required to initiate motion is overestimated by the approach discussed above. Van Rijn [52] suggested an increase of the critical bed-shear stress depending on the mud content for mixtures of sand and mud. The proposed equation reads

$$\tau_{b,cr,mix} = (1 + p_{mud})^b \, \tau_{b,cr,Shields}$$

where p_{mud} is the mud content and b is set to 3 on the basis of results measured in situ. Other modifications have been introduced by various authors [3] [24], while the effect of various physical properties of the cohesive soil[1] has been considered for example in [26]. The above is valid for mixtures where the sand content is relatively high, with p_{mud} in general not becoming greater than 0.4.

In reality for mixtures, the critical bed-shear stresses for erosion of the clay-silt fraction and the sand fraction can only be determined by testing either in situ or in the laboratory. The sediment size composition, the percentage (by weight) of clay, silt and fine sand and the bulk densities of the top layer (3 to 5 mm) should be known (measured) [50].

The same is true for muddy, silty or clayey beds, though in general cohesive soils, especially when compacted, have a higher resistance to erosion. A compilation of experimental results can be found in [51].

Various types of erosion of muddy beds can be distinguished [69] [70]:

- floc erosion, which concerns individual particles and small-scale flocs of the bed by the turbulent vortices of the fluid flow just above the bed, and which occurs at $0.5\tau_{cr}<\tau_b<1.5\tau_{cr}$ with τ_{cr} = erosion threshold stress and τ_b = applied time-averaged bed-shear stress;

[1] In this report the term cohesive soils has been used to denote fine-grained soils with average particle size < 63 μm.

- surface erosion for $1.5\tau_{cr}<\tau_b<3\tau_{cr}$, which involves the simultaneous mobilization of several layers of particles and flocs (failure of the bonds of particles-floc skeleton/network); surface erosion is a drained process as pore water can freely flow away; some swelling of the toplayers is involved; the erosion rate is restricted by the rate of water inflow into the bed;
- mass erosion for $\tau_b>3\tau_{cr}$, which is the erosion of lumps of bed material when the applied fluid stresses are larger than the undrained (remolded) soil strength of the bed; mass erosion is an undrained process as pore water cannot easily flow inward the bed (pore water underpressures); mass erosion is most often observed for more compacted beds with low permeability.

Though some efforts have been made in this direction, it is currently not possible to predict the erodibility of cohesive sediment based on its material properties. The attempts made show large scatter and significant uncertainty, see also the discussion in [6]. Therefore, to determine the flow velocity at which erosion initiates or the critical shear stress, laboratory or in situ measurements are performed. More details on this point can be found below.

2.2. Transport of sediment

When the bed stress is sufficiently high, the particles of the sediment are suspended and start moving with the flow. The type of this movement depends on the size of the particles and, in the case of cohesive sediment, on other properties, and on the flow conditions. As a rule three modes of particle motion are distinguished [47] [48]:

- Rolling and sliding motion or both;
- saltation motion; and
- suspended particle motion.

When the force of the bed-shear velocity is barely larger than the force corresponding to the critical bed stress, the particles will begin rolling and sliding or both, remaining practically in continuous contact with the bed. As the flow velocity increases, the particles will start moving along the bed by more or less regular jumps, which are called saltations. Finally, when the bed shear flow velocity exceeds the fall velocity of the particles, the sediment particles will be suspended in the flow. The flow velocities at which this occurs have been described in the form of diagrams, with an example given in Figure 2. Since the transport of sediment in the suspended form depends on the concentration of the sediment, which is highest close to the bottom, and the velocity of the flow, which is highest closer to the surface, the rate of sediment transport is maximum at intermediate depths, see Figure 3.

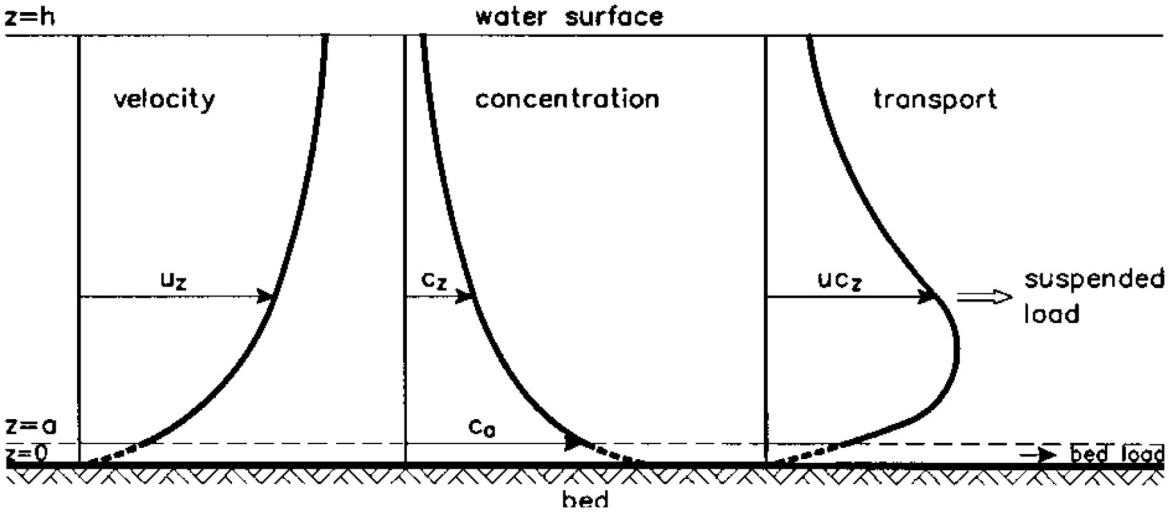


Figure 3. Sketch of suspended sediment transport after [52].

In reality there is no clear division between the bed-load transport, which includes sliding, rolling and saltating particles, and the suspended load transport. However, the definition of a layer corresponding to bed-load transport is often used in mathematical representation and has proven a valuable tool for the description of the erosion process.

Bed load-transport is generally modelled considering the momentum equilibrium of particles and the distribution of the velocity of the flow with the distance from the bed [47]. For suspension transport, the suspended density of the sediment is considered in conjunction with the flow characteristics both in space and time, see [49] and [14] as examples. This required three dimensional simulations, which are often simplified using assumptions to two dimensions, see [1] and [19]. Simplified forms evaluating the sediment transport exist and some are discussed in [6]. In this case empirical values that are not always available and that depend on the properties of the sediment are required for cohesive materials.

If the flow velocity diminished locally, then sediment particles that are in transport, either in the form of bed load transport or in the form of suspension, may become deposited. The initiation of motion at one location and its interruption at another over time changes the morphology of the river bed. In addition, as particles with different dimensions have different values of critical bed shear stress, this behavior also changes the spatial granulometric distribution of the sediment.

The deposition process is controlled by the settling velocity of the sediment, which depends on different factors, among which most notable are the grain size of the sediment and the depth. For silty and clayey material to arrive at densities that mobilize an initial critical bed shear strength, consolidation needs to take place [52], a process that generally requires a significant time duration. As for the critical bed shear stress,

the settling velocities in the case of clayey or silty sediments depend on a number of properties [20], meaning that predictive formulae for the settling velocities are not available for such sediments.

Because the determination of critical bed shear or of the corresponding flow velocity is not currently possible using predictive equations, measurements are often performed in the laboratory or in the site, especially for fine grained sediments. Preliminary studies indicate that the results from the two approaches are consistent [56]. Additional information on these points may be found below. Regardless, the determination of the critical shear stress remains uncertain, especially as the critical shear stress may vary greatly with space and depth. Furthermore, empirical observations have shown to be reasonably accurate and consistent compared to measurements [15].

2.3. Experimental determination of critical shear stress

The critical bed shear can be determined in the laboratory in so-called flumes or other specifically designed setups. For tests performed in the laboratory it is obviously necessary to retrieve sediment or specimens from the site, while maintaining the stratigraphy and disturbing the material as little as possible. It is important to test the material as soon as possible and disturb it as little as possible by means of transportation. This is currently a challenging point, as no suitable laboratories currently exist in Sweden.

Different options are available for specimen retrieval, with characteristics that depend on the specifics needs, such as the required depth, the grain size of the sediment and whether the sediment is hard or soft. Generally, corers are used with a lining, to avoid specimen disturbance. For example in [58][58] a box corer by the Netherlands Institute for Sea Research (NIOZ) was used based on previous work by [66]. A review of different options and the criteria for their selection may be found in [36].

In the same way, a variety of experimental setups are available for the determination of both the critical bed shear stress and the rate of erosion, both in the laboratory and on the site. The most typical setup is the flume, such as used in [43] or [27] [30]. Notable among the straight flumes is the In Situ Erosion Flume developed in the Netherlands and used in [51]. An example after [56] is shown in Figure 4.

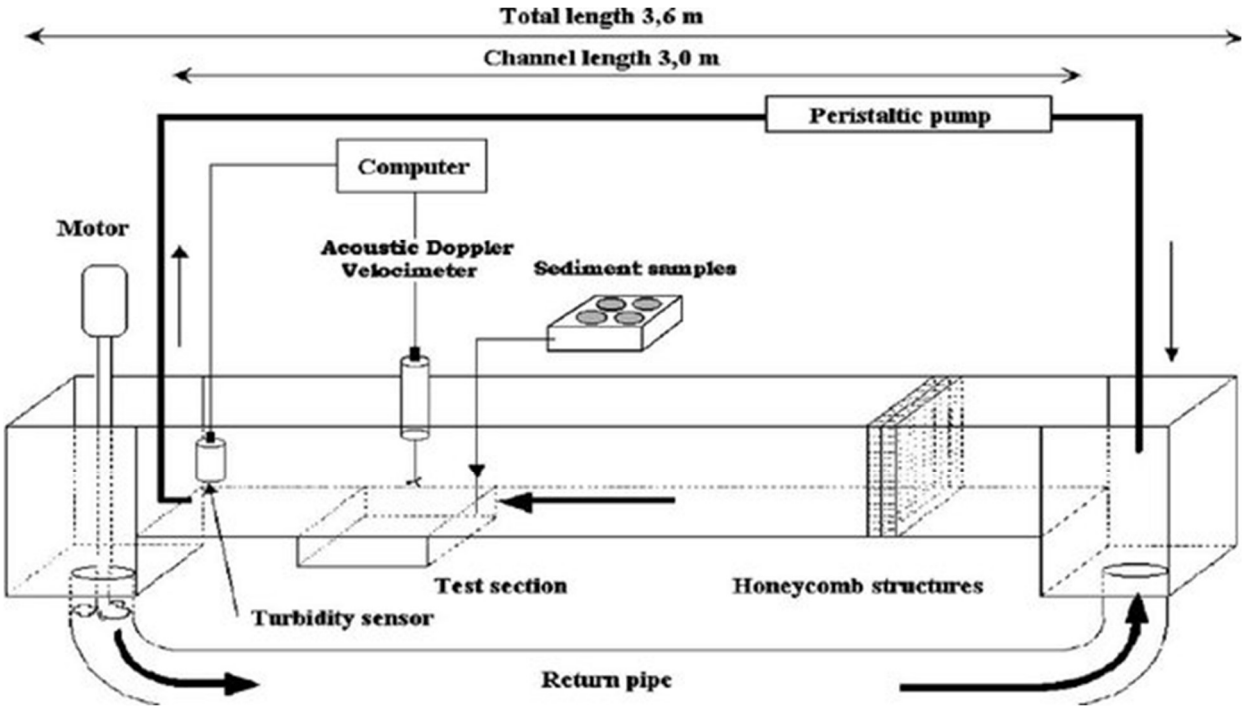


Figure 4. Straight flume apparatus after [54].

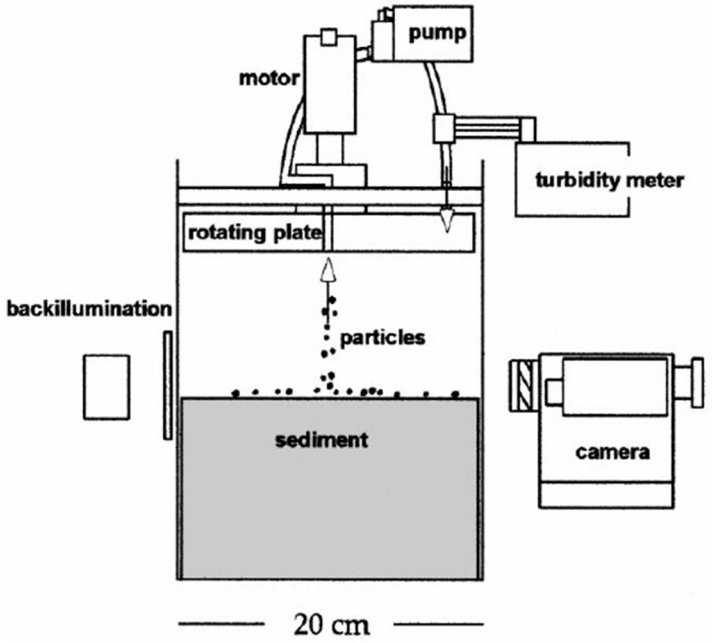


Figure 5. MICROCOSM apparatus after [61].

A number of alternatives to the straight flume design [2] exist, such as radial flumes [5] or the MICROCOSM device, developed in [61] and used in [58], shown in Figure 5. Among those is also the possibility of using jet test devices, see for example [16]. A recent study

comparing the results of different experimental setups found large deviations for results on the same test site, with deviations reaching up to two orders of magnitude [62].

3. Local scour near structures

Local scour is the local erosion in the vicinity of a structure due to the disturbance of the flow pattern by either the structure itself or other structures in the direct vicinity. Examples of such disturbance in the flow pattern are local accelerations and decelerations of the near bed flow and the creation of turbulence locally. An example for scour near a tubular pile foundation is shown in Figure 6.

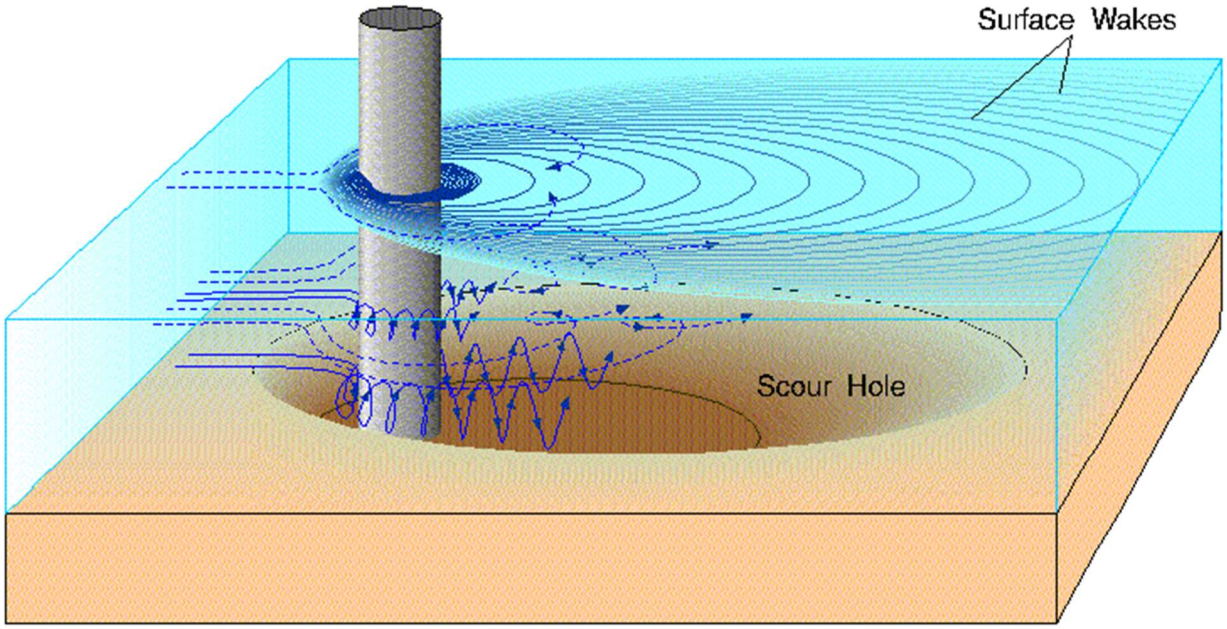


Figure 6. Flow disturbance and scour after *wikipedia.com*.

As shown in the figure, the flow pattern around a cylindrical pipe is characterized by the formation of a water surface roller in front of the pier, downflow in front of the pier, vortex-shedding in the separation zone, wake flow downstream of the pier and generation of horseshoe-vortices in the scour hole.

Such occurrences lead to an increase in the flow velocities near the structure, hence an increase in the local transport capacity. Local scour demonstrates itself in the form of a local lowering of the bed in the vicinity of the structure. Once such a scour hole is formed, flow patterns are modified further. This may intensify the scour leading to a positive feedback loop. Extreme scour next to the structure may lead to loss of stability (Ultimate Limit State - ULS) or serviceability (Serviceability Limit State - SLS) of the structure. Though scour may also arise due to the presence of waves, only scour induced by currents near the riverbed is considered here. The present discussion is also restricted to vertical structures, such as piles and piers, as being most relevant to the structures encountered in rivers.

3.1. Mechanisms

The scouring process around bridge piers, which may be viewed as vertical piles, is dominated by two consequences of the introduction of the piers. On the one hand the flow is locally disturbed and on the other hand the cross-section available for flow is reduced on the whole. The first type is referred to as local scour, while the second as contraction scour. Since the cross-section available for flow becomes smaller, the depth available needs to become larger, to accommodate the same volume of water:

$$h_1 \cdot b_1 = h_0 \cdot b_0,$$

where *h* is the depth and *b* the width available for flow and the subscripts *0* and *1* stand for upstream from the construction and the location of the construction, respectively.

3.2. Modeling

A large number of works are available in the international literature on the mathematical modeling of scour around piles or piers. A review may be found in [61]. A number of these approaches make use of computational fluid dynamics (CFD) codes coupled to morphodynamic codes. Though such approaches, which resolve the flow both in space and in time and include the turbulence, can provide interesting results, they are not directly suitable for application in the design of scour protection.

Time dependent solutions have also been proposed by some authors, notably Dey [18] and Miller and Sheppard [43]. However, for design purposes commonly only the maximum scour depth is evaluated. For scour around piers and pillars, it is commonly suggested that the other spatial characteristics of the scour hole depend solely on the pile diameter, with a length of the scour hole of 1D upstream, 5D downstream and 2D on either side of the pipe, where D is the pile diameter [51]. This of course cannot be the case for deep scour holes, it is however an acceptable assumption for the design of protection, where the aim is to prevent the formation of the scour holes in the first place.

The maximum scour depth depends on a number of factors, among which the geometry of the pile, the depth of the water and the velocity of the flow.

In [45], currently commonly used within Trafikverket, the formula of Laursen is used:

$$y_s = z_e \cdot k_a \cdot k_n$$

where y_s is the scour depth, z_e is the scour depth in dimensionless form for a pillar (pile) with rectangular cross-section normalized by the width *D*, k_a is a coefficient depending on the pillar's length and the angle between pillar and flow and k_n is a form coefficient for the pillar. The parameters z_e, k_a and k_n are provided in the form of diagrams or of tables. This equation differs from others in that it does not include the flow velocity [27].

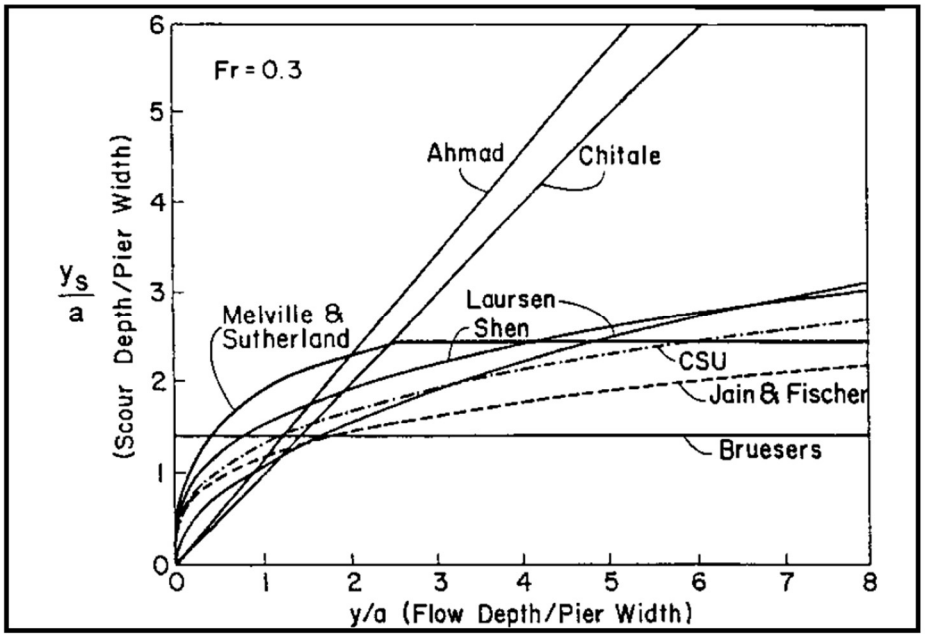


Figure 7. Comparison of scour equations for variable depth ratios (y/D) after [24].

Based on analysis of field and flume data, Breusers et al. [9] found for a single pile in uniform bed material:

$$\frac{y_s}{D} = a_1 \cdot a_2 \cdot a_3 \cdot a_4 \cdot a_5 \cdot a_6 \cdot a_7$$

with:

a_1 = coefficient related to the fraction of the depth averaged velocity U to the critical depth averaged velocity U_{cr},

a_2 = coefficient related to the flow depth to pillar width ratio h/D,

a_3 = coefficient related to shape of pipe,

a_4 = coefficient related to angle of attacking flow,

a_5 = turbulence effect,

a_6 = effect of short surface waves,

a_7 = group effect for more than one pillar.

Correspondingly, Melville and Sutherland [40] suggested:

$$\frac{y_s}{D} = a_1 \cdot a_2 \cdot a_3 \cdot a_4 \cdot a_5 \cdot a_6$$

with:

a_1 = coefficient linked to the flow intensity and of the form $(U-(U_a-U_{cr}))/ U_{cr}$, where U_a depends on the sediment characteristics

a_2 = coefficient related to the flow depth to pillar width ratio h/D,

a_3 = coefficient related to the sediment size,

a_4 = coefficient related to the sediment gradation,

a_5 = coefficient linked to shape,

a_6 = effect of alignment.

A large number of other formulations exist. A comparison for different ratios of flow depth to pillar width is shown in Figure 7. A Froude number of 0.3 was assumed for formulations taking into account the flow velocity [38].

All of the above approaches are not applicable to scour when it comes to abutments. For that other formulations are available, some of which are summarized in [51]. It is however uncommon for abutments to stand in water, so that this becomes relevant only during extreme events.

3.3. Mitigation measures

For scour around piles and piers, currently the guidelines after [70] are mainly used by Trafikverket. These guidelines cover the use of crushed stone, concrete mattresses and gabions, with emphasis on crushed stone and the filter rules required to establish a stable granular system with gradually increasing grain size. They are based on Laursen's method, see also above. Nature-based solutions, which are also not commonly considered in the international literature for scour, are not covered.

4. Erosion in watercourses

4.1. Introduction

Erosion and sedimentation are natural processes and part of the geological cycle. Sediment transport is necessary for the formation of deltas and to avoid coastal erosion. Sediments also bring important nutrients to the water system.

However, erosion may become a problem when buildings and infrastructure are located overly close to or within waterways modifying the watercourse and disturbing the sediment mass balance. It should be noted that local effects can have profound impact on the erosion and sedimentation regime at large distances down or upstream a waterway [46].

Erosion may undermine the stability of riverbanks and foundations. To mitigate detrimental effects of erosion, different types of erosion protection are installed. When improperly designed, erosion protection induces unexpected erosion in other places, i.e. they move the problem. It is therefore important to understand the processes that underpin erosion/sedimentation and how erosion evolves in space and time due to anthropogenic and natural processes.

4.2. What shapes a river

The river morphology is governed by catchment area, available water energy, soil types around the watercourse, vegetation and river valley confinement (e.g. [18]). The size of the catchment area at a given point and the precipitation over that area determines the runoff to the river and hence the discharge and mean flow velocity. Runoff erodes and transports particles to the river. Available water flow energy determines if deposition or erosion will govern at a certain place in the river. The soil types create the boundary conditions and affect the shape of the riverbed. Sediments that contain stones and boulders often give a wider and more rectangular river channel while channels in fine grained sediments often have a deeper parabolic shape. The valley confinement also plays a part where a narrow and steep valley tends to create a v-shaped river while a broad and flat valley causes the river to meander; to a lesser extent in clayey soils and to a larger extent in sandy and silty soils. The meander bends slowly move downstream as sediment is eroded upstream of the bend and deposited at the downstream of the bend. Vegetation and its root system have a stabilizing effect on the riverbank and adjacent land. In general, the river width increases downstream of the catchment area to compensate for the accumulated runoff, although that is not always the case (e.g.

[18]). The floodplain is the land adjacent to the river that recurrent becomes inundated. Due to the isostatic land uplift in the Nordic countries old floodplains can be found higher up in the terrain. Floodplains are also areas where people settled and the majority of our buildings and infrastructure are located.

The bankfull discharge is the river flow that corresponds to the water level just before it floods out from the main channel to the floodplain. At a river scale, it is assumed that it is the bankfull discharge that is the most effective to move sediments and shape a watercourse (e.g [32]. This is because the mean and low flows are too weak and the high flows do not occur often enough and when they do, the resulting flooding may reduce the flow velocity due to increased cross sectional area, which is also called the hydraulic radius of the open channel.

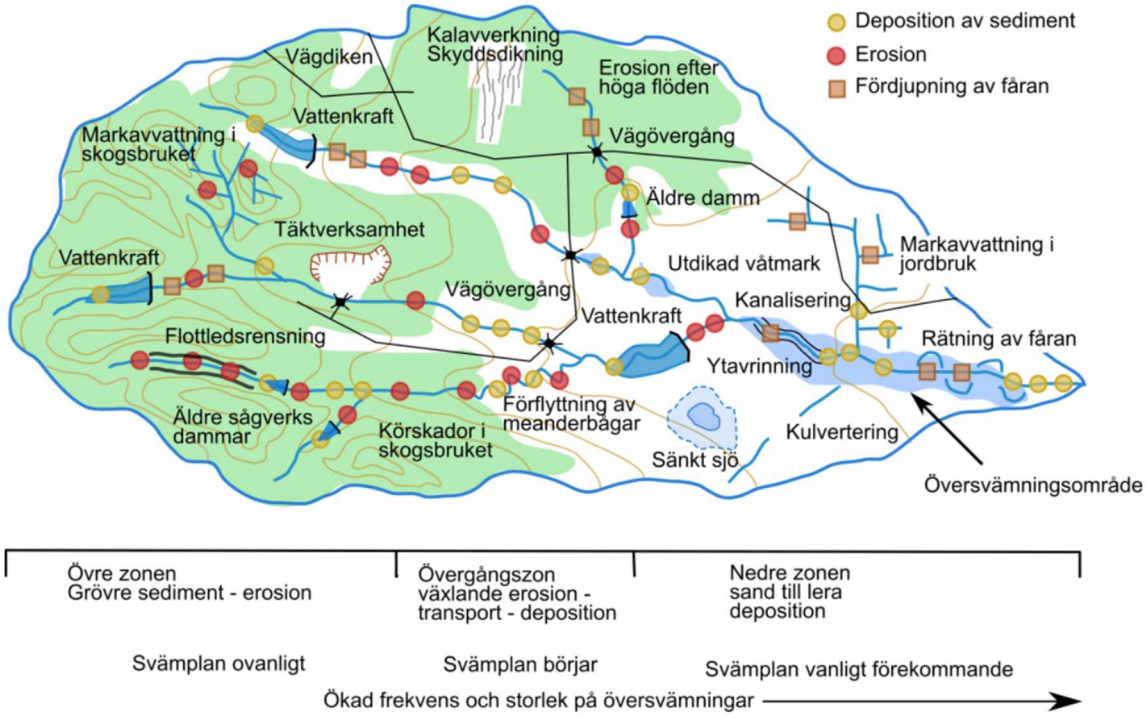


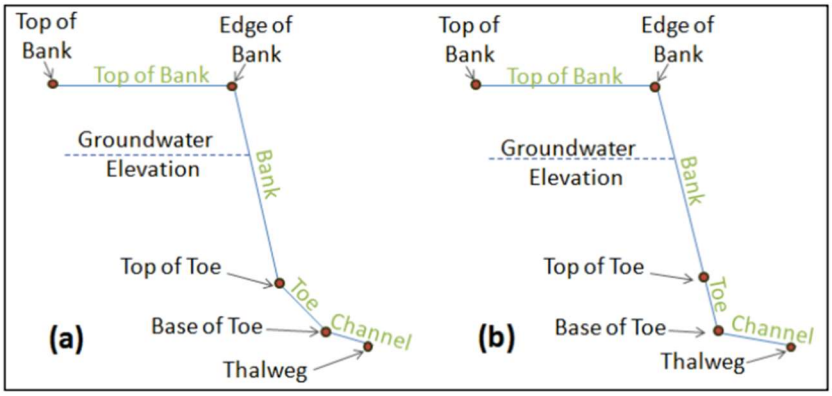
Figure 8. Schematic illustration (in swedish) of the various parts of a catchment area with human activities that affect the development of the watercourse. (Illustration: J. Kling, Swedish Agency for Marine and Water Management. In: [18].

Land use, buildings and infrastructures affect river morphology and the sediment budget as illustrated in Figure 8. For example, large hydropower stations with strong flow regulations and canalization of river sections strongly hinder the river to evolve

naturally. In addition, the effects of climate change may increase the run-off to the watercourse and thus the river flow with subsequent flooding.

4.3. River erosion and bank stability

When the bed shear stress of the flowing water current is sufficiently large, particles will start to mobilize as described in section 2. The particles that are suspended from the riverbed sediment will be transported with the flowing water. During the travel path, there will be an exchange of particles on the riverbed – some sediment and others are mobilized. Erosion occurs in areas that over time lose more material than is sedimented. Accumulation occurs in areas that over time gain more material than is lost. In some parts, there is a net transport of material over time. There are thus areas that are governed by erosion, accumulation or transportation which is, simply put, controlled by the prevailing energy (hydraulic) regime and sediment characteristics. Bed slope, flow depth, flow velocities, particle size, sedimentation rate of particles etc. are examples of factors that are important for the sediment transport (e.g. [15]).



River erosion has been studied by many in order to gain knowledge about the processes of bed and bank erosion and scour around foundations (e.g. [2][4][5][8][16][12]). However, to model how erosion over time affects river bed and banks, and e.g. bridge foundations, hydraulic properties that govern a watercourse need to be combined with geotechnical and structural properties of civil engineering structures in and near watercourses. That is, the combination of hydrodynamics and (geo-) mechanics.

Figure 9. Definition of station points for BSTEM half cross section. From [14].

According to [43], many experiments have been performed in order to link critical bed shear stress to soil properties, such as liquid limit, undrained shear strength and clay content. [43] summarizes various research results as follows:

- Critical shear stress is 2-3 times less than the soil's undrained shear strength.
- Erosion decreases with increased clay content. Erosion decreases with increasing density (decreasing void ratio). Critical shear stress can, however, vary greatly even for soils with the same liquid limit, undrained shear strength and clay content and its parameters cannot be used solely to determine critical bed shear stress. The latter finding is well known in the geotechnical engineering community, i.e. index properties of soils cannot be directly linked to its (hydro-)mechanical properties.
- Fractures along a sliding surface cannot be compared to the process of detaching particles. Here, from a geotechnical point of view, the term fracture is perhaps a misnomer for the localized failure along a shear plane in soils.
- The orientation of the clay particles has a pronounced effect on the erodibility - the erosion rate decreases with increasing degree of orientation, and vice versa.

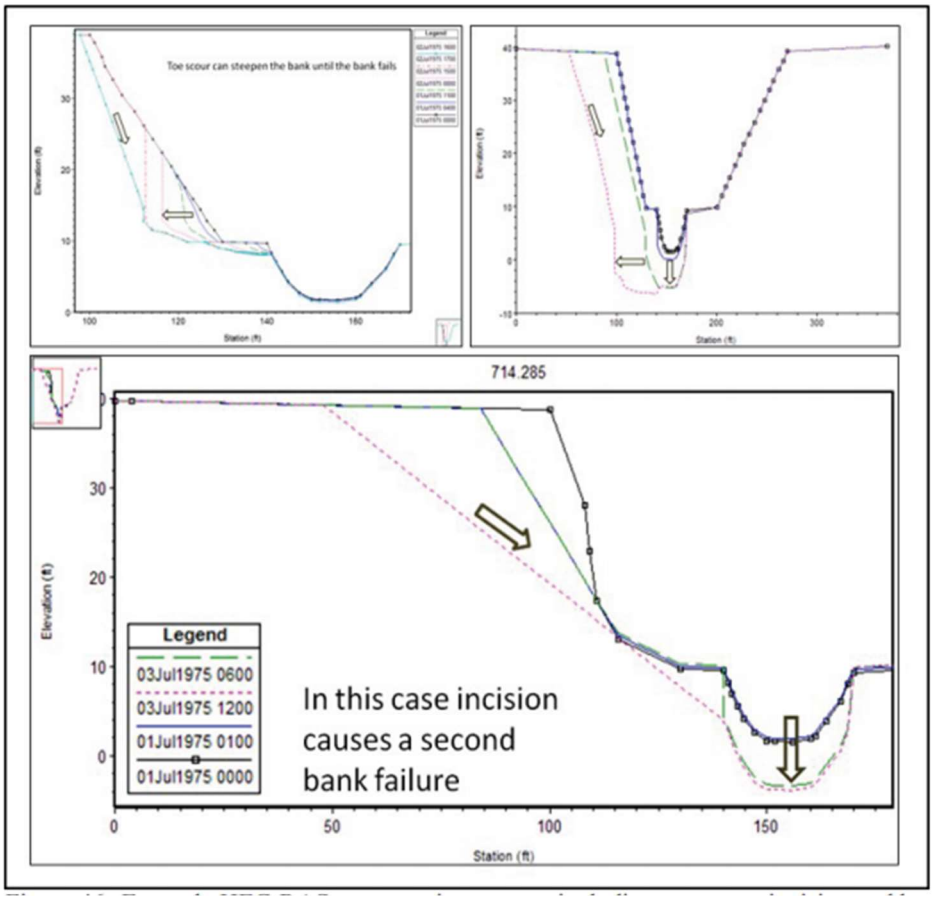


Figure 10. Example HEC-RAS cross section outputs including toe scour, incision and bank failure at various stages in the simulations. From [14].

Most analyses on the consequence of erosion/sedimentation are not integrated, i.e. a change in geometry and hydraulic regime calculated from the hydrodynamic analyses is manually applied in subsequent geotechnical stability analyses at discrete instances in time. A more convenient software tool that integrates vertical bed changes with lateral bank erosion is HEC-RAS (Hydrologic Engineering Center's (HEC) River Analysis System) and its module BSTEM (Bank Stability Toe Erosion Model), developed by the U.S. Army Corps of Engineers and the U.S. Department of Agriculture [14]. It is a semi 2D model to simulate the interaction between channel incision and bank failure in chosen cross sections, see Figure 9 and 10. The software is freeware but not open source. Furthermore, the stability analysis is rudimentary when compared to effective stress based advanced limit state analysis in geotechnics. Other approaches that are used to model flow induced erosion/sedimentation processes in conjunction to stability of (cut) slopes are based on combining the Navier-Stokes equations with pick-up functions for erosion and a simplified breaching model for the stability of the slope [4].

4.4. Lessons learned from long-term erosion forecasting of four Swedish rivers

As part of a governmental assignment, SGI has carried out erosion forecasting in four rivers with the aim to assess bed and bank erosion with respect to the effects of climate change until year 2100 as input to landslide risk analysis (see further at https://www.sgi.se/sv/samhallsplanering--sakerhet/skredriskutredningar/). Changes in river geometry affects slope stability and hence probability of failure. The task has been a challenge because of its complexity and the lack of long-term monitoring of bed changes and sediment transport in Swedish rivers.

In the literature, most flow-related erosion studies have been made for single flow events - single flow peaks. For SGI's part and for the present study, a longer 50-100 years perspective is to be considered. This means that one needs to develop future flow scenarios (flow duration curves) that covers the whole time period and update the riverbed morphology and sediment characteristics after each flow event. To do so, data on flow statistics, water level statistics, comprehensive bathymetric data (preferably from several time periods), sediment characteristics at different depths and data on sediment transport is needed, as well as data on flow regulation now and in future (most rivers have flow regulation due to hydro power) and changes in flow regime due to effects of climate change (i.e. precipitation and runoff). If all data exists, simulations can be done by setting up a hydrodynamic model integrated with a sediment transport model that enables updating the calculation grids after each flow event. These models become three dimensional, or semi 3D, and thus require large computer capacity if large areas are to be run at one and the same time.

Some of the main challenges gained so far are listed below:

- For flow regulated rivers, data on river discharges and water levels can often be retrieved from the energy company. The time resolution is often limited to hourly averages. Water level data is often limited to the area adjacent to the hydro power station. Supplementary sampling to correlate discharge, water level and flow velocity may thus be necessary. Manning's value is often used to calibrate the hydrodynamic model. However, one needs to be careful not to employ values of Manning's to fit the measured response but are physically improbable. Bathymetric data are limited to individual cross sections from surveys carried out in connection to infrastructure projects. Comprehensive bathymetric data may be available near major hydro power stations but cannot be taken for granted. Hydroacoustic surveys to map bathymetry and the sediment surface have thus been mandatory in the studied rivers. These surveys have had some challenges concerning shallow areas, for which relevant data on slope stability is gathered. Most survey vessels have difficulties to measure depths <2 m due vessel draft

and instrument depth (multibeam sonars). Other challenges have been difficulty in keeping the RTK (positioning) in narrow and wooded sections, and to get the correct position of the bed elevation when the water surface changes due to flow regulation during ongoing measurement. Thus, measuring bathymetry in watercourses is somewhat more problematic than measuring bathymetry in the open sea.

- Data on sediment characteristics and bed substrate are important to assess erodibility but are in general missing. Conducted hydroacoustic surveys have thus been complemented with sediment samples. Sediment samples and backscatter data from the hydroacoustic soundings have been used to map the near-surface bottom engineering properties in order to determine erodibility. Sediment samples have been taken to analyze i.e. grain size distribution. It is however important that the aggregate samples represent the correct depth and that different sediment layers are not mixed. In areas with fine sediments, the uppermost millimeter may contain small grains, for example clay, which is a result of erosion processes. If this thin layer is mixed with the underlain clay, then the grain size distribution will not be interpreted correctly. The number of samples and where they are placed is critical in order to be able to make the best possible assessment of the bottom properties as possible, however the cost is a constraint.
- A general problem is that we often estimate erodibility /critical shear stresses from different equations (often based on grain size distribution), without really knowing how well they represent the case. This works probably well for sand, gravel and silt, but for larger fractions and cohesive sediments there is not that much information from Swedish watercourses, or internationally. Especially, for fine-grained sediments that are often encountered at the toe of natural clay slopes this poses issues in the subsequent analyses. Erodibility depends on bed substrate which may vary quite a lot in space and evolves over time. Determining critical shear stress and erosion rate in cohesive sediments is difficult. If the clay has elements of silt and sand, the uncertainty further increases. Clayey sediments can erode through classical erosion where single sediment particles loosen, but more often erode through entire aggregates loosen into large flocs. In addition, depending on the drainage conditions a clayey (underwater) slope can stand quite steep until it eventually fails and then may trigger progressive failure.
- There are no laboratories in Sweden that have equipment to analyze critical shear stresses, though a flume for saltwater is available at the Christineberg Marine Research Station. Nor do any field instruments exist in Sweden to measure an erosion threshold in the field, suitable for watercourses. For the Göta älv river

investigation, sediment samples were taken and analyzed by Stuttgart university. Stuttgart university uses a flume in which a sediment core is placed from beneath in that the sample's surface is exposed to a flow current. The level of flow velocity is measured for when the sediment begins to mobilize. This data is then used to calculate the critical shear stress. However, the difficulty in transporting undisturbed sediment sample cores such long distance, and associated costs, led to further assessment of critical shear stress based on sediment characteristics (mainly grain size distribution) and empirically derived equations found in the literature.

- Data on sediment transport for model calibration are scarce. Long term data sets are essential to calibrate and validate the model. Such data are not currently available in Sweden and their acquisition is only viable for large rivers.

4.5. Guidelines

There are no Swedish guidelines on how to conduct an erosion analysis or account for river erosion in slope stability analyses, especially not if a longer time perspective and the impact of climate change is to be considered. Starting in 2020, SGI has begun to investigate the possibility of including instructions for erosion analysis in the Commission on slope stability's Instruction for slope stability investigations, report 3:95.

4.6. Mitigation measures

In order to identify the best measure to mitigate erosion one should investigate its causes, but also its ecological and river functional values and its impact on human activities, resources or health (Figure 11) [14]. Other aspects to consider are the impact area (scale) and maintenance (time).

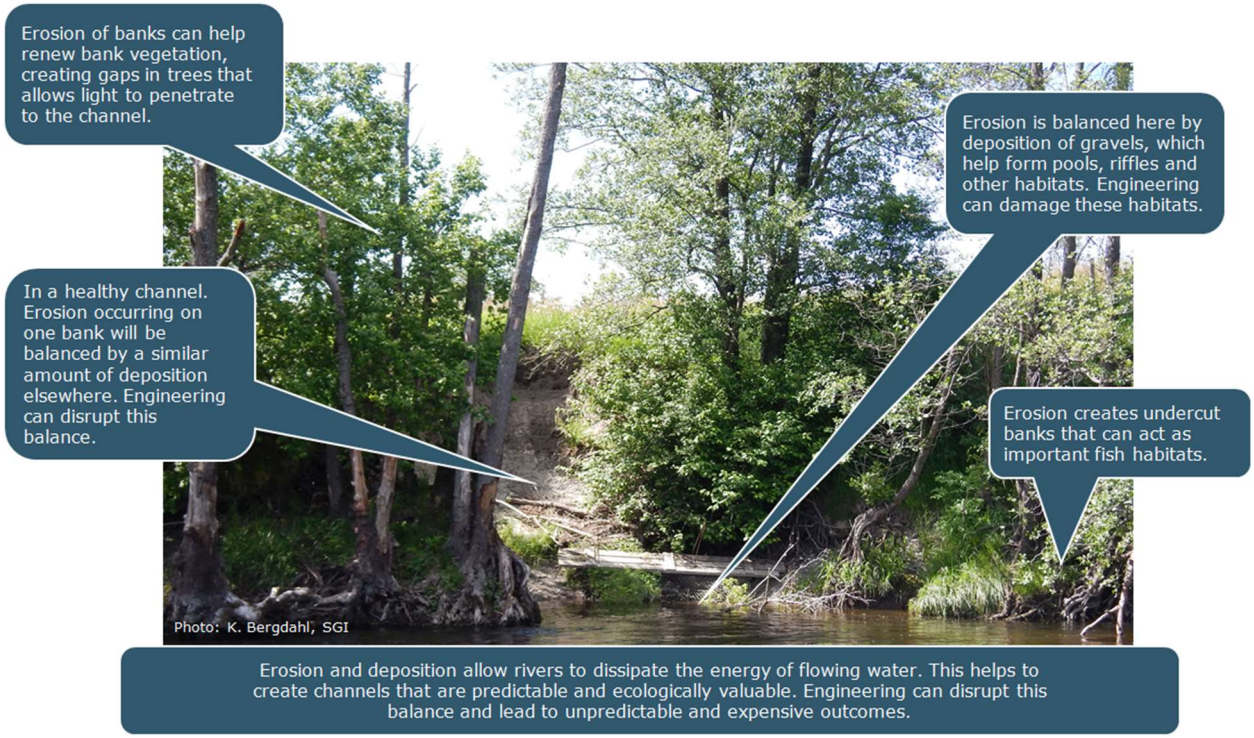


Figure 11. Ecological and functional values should be considered when assessing the need for erosion protection. (After [14]).

5. Nature-based solutions

5.1. Riverbank protection

Compared to protection against scour, a large number of nature-based solutions are available for river bank protection. Compilations may be found at the site of the project LaRiMit [34], funded by the European Union, the analysis of EU-funded projects performed by the European Commission [64] [68] and guidelines published by various public bodies of the United States of America [20] [41] [43] [64] and Canada [19]. Compilations of case studies are less common, though some are available [21]. Within Sweden some studies have also been performed [53] [6] [54], while a catalogue was made available recently by SGI[2].

The list that follows is not exhaustive, among other reasons also because the boundaries between different methods are not always clear. Where possible, the domain of application is also discussed in terms of bank steepness, flow velocity and other in situ conditions. It should however be noted that, while some recommendations are available, the decisions always need to be site specific.

The measures found below are for the most part suitable for preventing erosion. A list of methods for the restoration of streambanks using nature-based solutions can be found in [19].

5.1.1. Turfing

Turfing is the direct application of grass with developed roots onto the slope surface. Mostly used for runoff and splash erosion, but can also be used for channel protection when the flow velocity does not exceed 1.5 m/s [34]. The slope should not be steeper than 33%. For the installation suitable site preparation must be ensured for a successful installation. The soil should be smoothed and shaped if required. The soil conditions (PH and nutrient availability) should be suitable for hosting the turf. Indigenous grasses are preferred. The contact between turf and underlying soil is important to avoid water flooding underneath the layer. A first irrigation should be provided to encourage the vegetation establishment. Maintenance includes mowing. Another possibility is the direct planning of woody vegetation, but this is not adequate for shoreline protection. Design examples can be found in [39].

[2] https://storymaps.arcgis.com/stories/ec5d69f5dcdf42e3820d01e8eb01b102

5.1.2. Live/inert fascines and straw wattles

Fascines are elongated bundles of live cuttings of woody plant material. They are placed in trenches across the slope of a bank and fastened with wooden stakes, as shown in Figure 12. They are generally separated into inert fascines (IF) and live fascines (LF). The first are used as a support measure while other vegetation takes hold, while the second are expected to take root and support the soil. They are often used for slope stabilization, because they stabilize the soil and at the same time provide additional drainage. However, they can also be used for erosion protection of riverbanks, when the flow velocities are not very large.

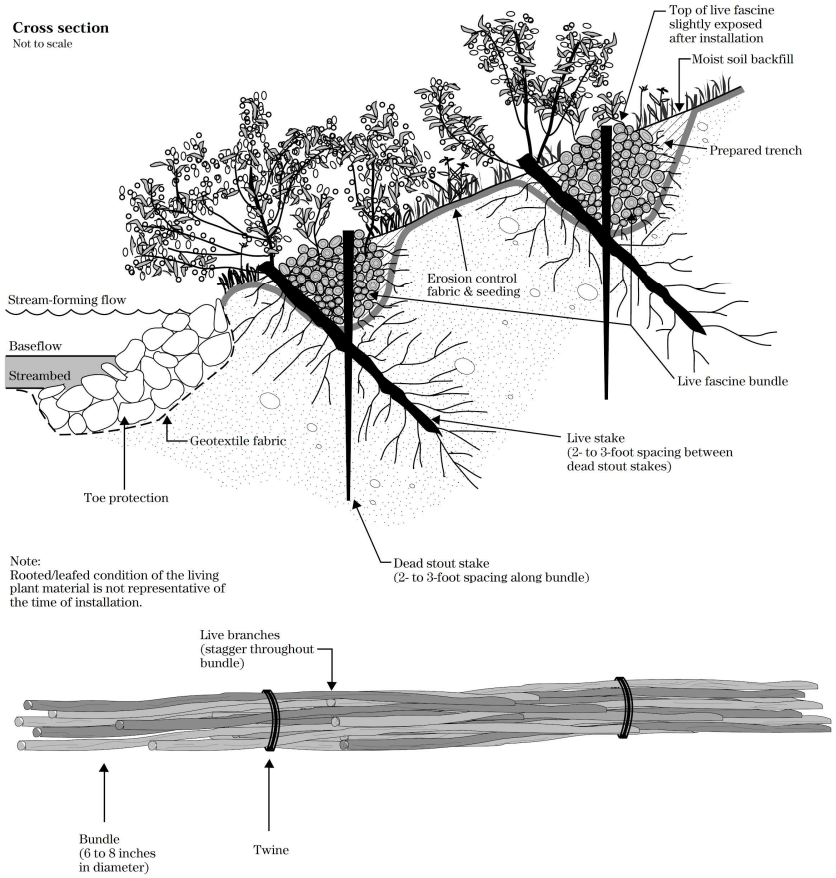


Figure 12. Live fascines after [41].

Fascines usually consist of live cuttings bound together with untreated bailing twine, with ties spaced at 30-45 cm, in bundles of 15-25 cm diameter and 1-6 m length. The bundles themselves need to contain at least five cuttings at a minimum of 3-5 cm in diameter [43], see Figure 12. The exact dimensions are determined by the available plant material. The bundles are placed in trenches, whose spacing depends on the type of soil. For soils more prone to erosion the spacing between adjacent trenches becomes smaller. The

fascine bundles are secured every meter with dead or live stakes with a length of 60-90 cm [43] [34]. The trenches are filled with soil, without entirely covering the live fascines, to encourage rooting.

An alternative to fascines along the same principles is brush layering. In this case live cut branches and rooted plants are used. The plants are placed in excavated terraces, which are then filled with compacted soil material. Compared to fascines, brush layering provides deeper stabilization.

5.1.3. Live stakes

Live stakes are typically used for reducing the erosion along slopes or stream/riverbanks. They are fresh woody cuttings, typically with a diameter between 2,5 and 5 cm and a length between 60 and 180 cm [34]. The stakes are installed generally in a triangular pattern with a spacing between 60 and 100 cm [29]. They can be combined with other techniques, such as the fascines mentioned above. The aim is for the live stakes to take root, thus providing support to the slope. Depending on the type of vegetation and application, the reinforcing effect may reach significant depths. The method is clearly not immediately effective in controlling erosion and the time span required depends among other things on the type of vegetation used. As a rule it is deemed preferable to use indigenous plants.

5.1.4. Branchpacking

Branchpacking consists of alternating layers of live branches and compacted backfill to repair small localized slumps and holes in streambanks [43]. The method provides immediate reinforcement for the soil, though it is not usually effective in larger scoured areas. In addition, the live branches serve as tensile inclusions for reinforcement once installed. As the plants begin to grow, the branchpacking system becomes increasingly effective in retarding runoff and reducing surface erosion.

The material used are live branches with a diameter of 1-5 cm. The depth depends on the application. The branches should be long enough to reach the undisturbed soil, while the upper part remains above the surface. In addition wooden stakes are needed ranging from 1.6 to 2.6 m [41].

For installation the wooden stakes should be driven vertically into the ground at depths of 1-1.5 m on a grid of 0.3 to 0.45 m [41]. A layer of living branches is placed in the bottom of the hole between the vertical stakes. Subsequent layers of branches are installed with

the basal ends lower than the growing tips of the branches. Each layer of branches must be followed by a layer of compacted soil.

It is possible to combine this method with vegetated geogrids. Vegetated geogrids are similar to branchpacking except that natural or synthetic geotextile materials are wrapped around each soil lift between the layers of live branch cuttings [43].

5.1.5. Live cribwall

Most of the above methods are mostly suitable for slope erosion due to rainfall or for riverbank protection. Live cribwalls can be applied to areas where strong currents are present. They consist of an interlocking arrangement of untreated log or timber members in a form similar to that of a box. An example after [43] is shown in Figure 13.

The cribwall is filled with suitable backfill material. Live branch cuttings are planted that take root in the structure and extend into the slope. Once the live cuttings root and become established, they act as support for the riverbank, even after the cribwall member decay. Detailed instructions for installations may be found in [43].

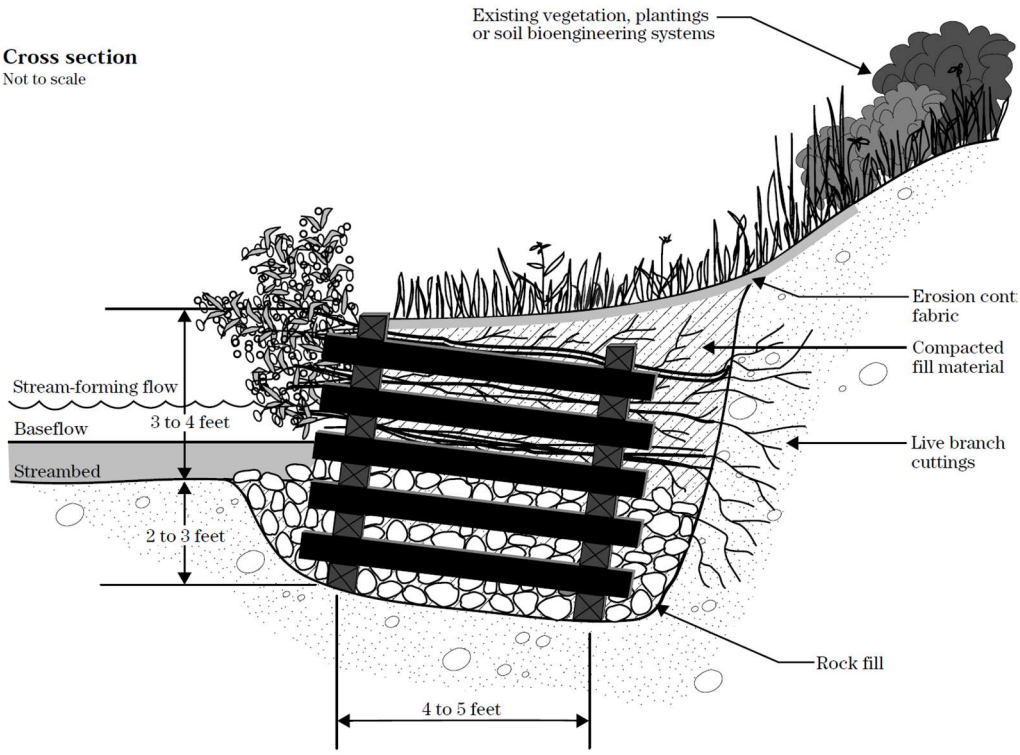


Figure 13. Live cribwall [41] .

5.1.6. Brush mattress

Brush mattresses are living branches placed close together on the slope surface to form a mattress [34]. They usually consist of 1-2 layers of branches laid in a crisscross pattern to homogeneously form a living ground cover and generally include fascines [41]. An immediate protective cover is formed over the streambank. The method is suitable for steep, fast flowing streams.

In terms of materials. Live stakes, cuttings and fascines are used. The branches are required to have a length of 2-3 m and a diameter of about 2.5 cm [41]. They should be flexible, so that their shape can conform to that of the bank. Untreated twine is used to bound the fascines and twine of wire to secure the branches. The live or dead stakes are used to secure the mattress in place. Detailed instructions for installation may be found in [36]. Compared to other solutions, this approach is more work intensive, but presents the advantage of providing immediate support.

5.2. Scour protection

As visible above, a wealth of nature-based solutions exist for riverbank protection. The situation is very different in the case of scour. The main reason for this lack is that it is not straightforward to make use of vegetation as bed protection from scour that is governed by large flow velocities. A possibility is also that the matter has received less attention. However, that may be, very little literature is available on the topic of nature friendly solution against scour. Among the works available, most refer to coast protection, for example [35]. The focus is placed on avoiding the modification of the habitat for the worse. For rivers the only relevant work was the recent publication by Tao and coworkers [60].

5.2.1. Streamlining

Modifying the shape of bridge piers has been investigated by many authors for its ability to reduce scour, for example [60]. Modified shapes are characterized by elongation in the direction of flow, often with a ‘nose’ at their base.

According to [28], the shape of the nose of a pier or an abutment can have up to a 20 percent influence on scour depth. Streamlining the front end of a pier reduces the strength of the horseshoe vortex, while streamlining the downstream end of piers reduces the strength of the wake vortices. The shape effect becomes negligible when the flow forms an angle to the symmetry axis of the pier that is larger than five degrees.

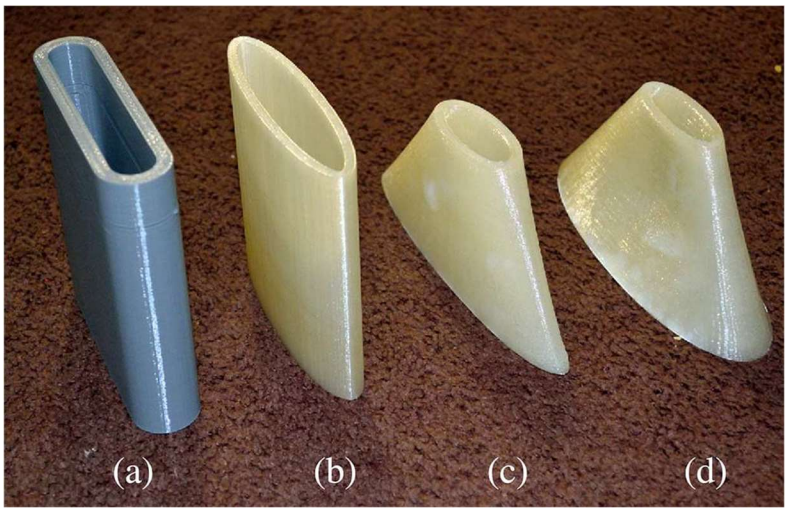


Figure 14. Streamlined pier shapes investigated in [60]. (c) was found to be the most efficient.

The method is attractive, in that it requires practically no maintenance after construction, though the more complicated shape may lead to somewhat increased construction costs. The main disadvantage is that any advantage originating in the modified shape of the pier is quickly lost when the angle of flow deviates from the predicted one, even by small angles [28].

5.2.2. Effects of bacteria

Two types of phenomena can be considered in this category. The first is the presence of biofilms and the second is biocementation. Biofilms are created by bacterial communities and show increased elastic deformations in tension or shear compared to natural soils. Biocementation is linked to an increase of the soil's cohesion due to the production of calcite from the bacteria [44].

The effect of biofilms on scour was considered in [44]. While some benefit was observed, this was mostly in delaying the erosion, rather than inhibiting it. Excessive biofilm growth is further linked to adverse ecological effects, as noted in the same work, so that their use for riverbed stabilization should be subject to detailed studies of potential effects on the local ecosystems and may require continuous monitoring and maintenance.

Biocementation has not been generally considered as a solution to scour. The only available reference in that respect seems to be [60]. Biocementation in general has however been investigated by a number of authors for sand [33] [71] [25], clayey sand [8] and clay [13] [31] either for its own sake or for other applications, for example protection from wind erosion [71].

Biocementation requires the material to be mixed with the bacteria, as well as a food source for the bacteria as a rule. This means that for use as a protection measure against scour, the soil should be treated, something that presents several technical difficulties. Moreover, the treatment introduces the bacteria into the ecosystem, so that careful consideration is required in advance to assess how this could affect the ecosystem balance.

Overall, while the method presents a degree of promise, it is still in its infancy. Before large-scale application in a natural ecosystem is possible, many questions need to be answered and solutions to a large number of technical challenges need to be answered.

6. Erosion problems for Trafikverket's assets

Trafikverket is responsible for the design and maintenance of a large variety of infrastructure projects with links to erosion, ranging from heavily trafficked bridges over rivers to bridges over streams or roads next to creeks with a rather small traffic load. Riverbank erosion is relevant to the whole range of project sizes, while scour erosion, especially when considering the scour around bridge foundations, is mostly relevant to bridges with more than one span, linked to larger rivers, rather than streams or creeks. Due to the characteristics of the Swedish landscape and the relatively low population density of many regions, most projects both in construction and maintenance fall within the second category.

In order to better understand and map both the usual practices within Trafikverket and the current and future needs, a series of meetings with employees was organized and the conclusions drawn are summarized below.

6.1. Scour protection

Scour protection is relevant for bridges and may concern the abutments or the piers. While the origin of the problem is the same in the two cases, different guidelines are to be applied. As a rule within Trafikverket for piers [66] is used, while for abutments [58] is applied. The recommendations of the two documents do not fully coincide.

Issues with river scour adjacent to the piers are relevant for larger bridges with more than one span. These are encountered when crossing larger rivers and, though representing the more cost intensive projects, they do not represent the largest number of projects, which are related to much smaller structures. While accidents involving scour have been known to happen, they are few and far apart and are usually linked to defective design.

Bridges are inspected every 6 years with divers checking for scour. Scour damage in the area of the piers is repaired. Currently the bulk of maintenance required concerns old bridges where the protection against scour needs to be renewed and bridges built in the '60s, where concrete was used for protection without the use of hydrophobic agents, leading to poor quality results. A different but commonly encountered problem is related to small, single span bridges, when heavy flows are observed as a result of extreme rainfalls, especially in the south-west of Sweden. In such cases the water can reach the level of the deck, subjecting as a result the bridge to high horizontal loads. Large bridges are not often affected in the same way, because extreme rainfalls usually

take place over a limited geographic extent and as a consequence do not affect as strongly the discharge of large rivers.

In terms of methods used for protection against scour, the most common is crushed stone, as is the case also for the protection of riverbanks against erosion. For older bridges it is also common that the area of the abutment is covered with masonry, a method that however is not currently used in new structures.

For scour in the area of the piers nature-based solutions are not widely available as discussed in the previous section. Around bridge abutments effort is as a rule made to limit vegetation as much as possible to facilitate maintenance and access. Larger plants could cause damage with the roots and the minimum distance acceptable is of the order of 2 m. While larger vegetation is avoided, the same is not true of grass. In current practice it is at times preferred to crushed stone for aesthetic reasons but is generally not used as protection against erosion. On the whole, when it comes to protection against scour, nature-based solutions are not currently implemented.

6.2. Riverbank protection

Trafikverket is responsible for a wide range of assets for which riverbank protection against erosion is significant, for example for roads in the vicinity of rivers or streams and for the riverbank in the vicinity of bridge abutments. Due to the geography and the population distribution of Sweden, the large majority of the projects, both in terms of construction and maintenance, concern smaller structures in the vicinity of streams, rather than large rivers. Such streams generally exhibit meandering, can show a high seasonal variability in terms of the flow discharge and often have significant ecological value, including some Natura areas. This creates special challenges in the design of the erosion protection from an environmental point of view.

The currently commonly used guidelines [66] require little input and make use of safety factors to ensure that the protection is adequately dimensioned. From interviews with a number of Trafikverket's employees, it appears that the common consensus is that these guidelines lead to measures that are adequate in terms of safety. No significant problems with high maintenance needs or with accidents were reported. On the other hand, it was generally agreed that the approach currently in use tends to be overly conservative. As the material used is not of high cost, this is not a significant financial issue. The material used in the vast majority of cases is crushed stone. Because of the granulometry required, it can be hard to source at the required sizes, especially for maintenance projects, where it is not practical to order long in advance. Compared to material required for erosion protection, material for construction is much more readily

available. While crushed stone works well for erosion protection, it does lead to environmental issues especially in the smaller streams, where the larger fraction of crushed stone may be so large that it inhibits the movements of fish up and down stream when the water level is at its lowest. An example is shown in Figure 15., courtesy of Stefan Johansson. In such cases in the last years rounded stones are used for the top layer of the protection, to avoid injury to fish and other fauna moving up and down stream, but even in this case the size of the stones can pose a problem.



Figure 15. Erosion protection in a small stream at low water, courtesy of Stefan Johansson.

Current guidelines [66] are based on experiences and rely on flow velocity, with some correction and safety factors that are incorporated in the parameters used for the calculations. Following the guidelines result in functioning protection, erring on the safe side. Recently, an effort was made to optimize the design [8] [9]. The result includes the use of a number of additional factors, such as the local turbulence. Although physically sound, the suggested design poses a problem, because in most cases the required input is not known and measurement is time and resource consuming, meaning that it is not feasible for all but the largest projects. This is also true of detailed modeling, which can provide an assessment of the required input, but in turn requires input such as sediment characteristics and riverbed morphology.

Nature-based solutions are not yet widely used and dedicated guidelines do not yet exist, though there is significant interest within Trafikverket. While grass is often used for aesthetic reasons and larger plants are used to provide shelter for fauna, the present

report is only concerned with nature-based solutions as protection against erosion. In the near past, salix cuttings have been used for slope and riverbank stabilization in combination with crushed stone and coconut mats. In addition, vegetation is more and more often used up to the middle flow level, with crushed stone only used below it, whereas in the past crushed stone was used for the entire hydraulic radius. Such methods, which depend on the plants taking root, may be more difficult to apply in maintenance projects, when a swift solution is required. Application is still possible but may require the use of auxiliary temporary measures, depending on the season. Timber sheetpiles, at times back anchored, have also been used with success. As the material is not living, maintenance is required, but a replacement is not expected to be necessary for a period of twenty years. At that point the timber can be replaced at a not very high cost. The application of nature-based solutions is limited by the lack of clear guidelines, lack of experience of the contractors with similar techniques and only partial communication of past experiences within Trafikverket.

7. Conclusions & Recommendations

7.1 Conclusions

Erosion is a complex physical phenomenon involving a large number of different aspects. As such, its modelling and the prediction of its evolution are particularly difficult and require a large quantity of input data for reliable prediction. For most practical purposes, however, it is sufficient to predict the likelihood of erosion taking place, in order to design and install suitable protection measures.

Scour in the area of bridge piers is relevant for larger bridges with more than one span. For this type of problem, no issues with the current guidelines have been observed according to the discussions with Trafikverket employees. The current bulk of work involves maintenance of older bridges, where the protection needs to be renewed. The application of nature-based solutions, with the exception of pier shape, has not been considered yet within Trafikverket, but presents significant difficulties in the specific case, as the area of interest is underwater and solutions involving vegetation are not suitable for large flow velocities.

Concerning erosion in riverbanks, the current recommendations are found to be adequate in terms of protection but are often overly conservative. While this does not pose a financial problem, as the costs involved are not particularly high, it creates environmental problems for smaller streams. There, the large size of crushed stone foreseen inhibits the movement of fauna up and down stream. Furthermore, the common use of crushed stone to the high flow level is aesthetically displeasing and environmentally unfriendly. The use of optimized protection requires a significant amount of information on the flow velocity and turbulence. The collection of such data is however not possible for maintenance projects, where time is of the essence and not financially viable for all but the largest projects.

7.2 Recommendations for further research

Large rivers

In order to assess the susceptibility for erosion and subsequent failure of natural clay slopes near large river systems, such as the Göta älv, an integrated approach of hydrodynamic modelling and geotechnical stability analysis is required. It would be prudent to develop a more comprehensive approach for this type of analysis that includes the salient details of modelling the stability of natural quick clay slopes as well as the erodibility of fine-grained cohesive sediments.

Small streams

Possible solutions that could be investigated include the possibility of using nature-based solutions down to the low water level, in which case the root system should be able to cover or stabilize the flow area. The use of nature-based solutions should be extended to the largest degree possible in general for environmental considerations. To achieve this, experience on previous projects within Trafikverket should be collected and analyzed and guidelines including those solutions should be compiled using a combination of experiences and fundamental understanding of the processes involved. One of those processes includes the (in situ) assessment of the additional reinforcement from root systems, see e.g. [37].

An effort to collect experience on existing projects several years after the completion of the projects is currently ongoing at SGI. It would be useful to follow up projects performed by Trafikverket to collect information on their state, both concerning the success of the protection installed and the progress of erosion in locations that were not protected over some years.

Literature

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BIG – Branschsamverkan i grunden
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