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CONTROL OF BANK EROSION IN THE NETHERLANDS. STATE-OF-THE-ART

Paper to be published in a Special Technical Publication of the ASCE.
An extended abstract is presented at the 3rd National Conference on Hydraulic Engineering of the ASCE, New Orleans, La, USA, Aug. 14-18, 1989

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July 1989

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CONTROL OF BANK EROSION IN THE NETHERLANDS. STATE-OF-THE-ART

CONTROL OF BANK EROSION IN THE NETHERLANDS. STATE-OF-THE-ART

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ABSTRACT: In the Netherlands protection against flooding and inland navigation have always been extremely important. Many problems related to these items, among them erosion and the protection of banks and dikes, were and are solved within the scope of various specific studies supported by experience. Recently, much more attention is paid to environmental aspects of projects and applied measures. The increased demand on reliable design methods has resulted in development of various calculation methods on hydraulic loading, morphological changes and erosion prediction, and on the other side, in preparing a set of design methods and guidelines for protection structures. The developments in these areas in the Netherlands are discussed in this paper.

INTRODUCTION

The Netherlands is a flat, low-lying country, the western part of which lies below sea level and has gradually been sinking over the years. The land is protected against flooding by dikes and kept dry by drainage stations. For this purpose, a network of canals has been built in addition to the already existing waters. Both systems are also used for water transport, irrigation, water supply and recreation. The total length of the navigable waterways is about 4370 km; rivers 841 km and canals 3529 km. Because of the navigational requirements the main Dutch waterways have been regulated already in the early stage by river structures and/or canalized. Only a small percentage of the waterways and some estuaries remain in a natural state.
Inland navigation has always been extremely important (Figure 1). During the last decades, the sizes and engine powers of inland motor vessels have increased, particularly since the introduction of push-tow units. This induced more attack on banks, more erosion and the necessity of heavier protection became evident.

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A long-term research program on these subjects has been carried out. A variety of design rules and calculation methods have been derived from small-scale model tests and were verified by full-scale tests in canals.
There has been increased public discussion on more natural waterway development in recent years. The need for that is generally recognized. Evidence of this trend underlines an initiative by the government (in 1986) to start a national project on, aptly named, "Environment-sensitive solutions for bank protection". The aim of this project is to stimulate the use of biological methods (if possible in combination with other methods) for reinforcing the waterway banks, and to prepare design methods including a maintenance strategy.
As a result of the trends mentioned above various studies on the mechanics of bank erosion and bank protection have been carried out or are still going on. They include such subjects as morphological changes of natural rivers, influence of river structures and navigation on river regime and morphology, ship-induced water movement and its interaction with banks, erosion and protection of estuary-shores, stability criteria for various protection methods (reed, cellular blocks allowing vegetation, riprap, blocks, mattresses, asphalt, indirect protection by offshore breakwaters/sills, etc.).
Previous work is concisely summarized in this paper but major attention is given to reporting on current investigations.

The state-of-the-art on past research and the general approach to erosion control of navigation channels have been published (Blaauw et el, 1984; Van de Kaa et al, 1985; PIANC, 1987a), as well as on the strategy to erosion control of Dutch estuaries (Leewis, 1983; Pilarczyk, 1986), dike protection (Pilarczyk, 1987) and mathematical tools for river engineering (Schilperoort, Wijbenga and van der Zwaard, 1985). In all these publications attention is also paid to environment-friendly solutions and the choice of the proper construction.
Regarding the treatment of coastal erosion problems useful reference can be made to the Manual on Artificial Beach Nourishment (CUR, 1987).

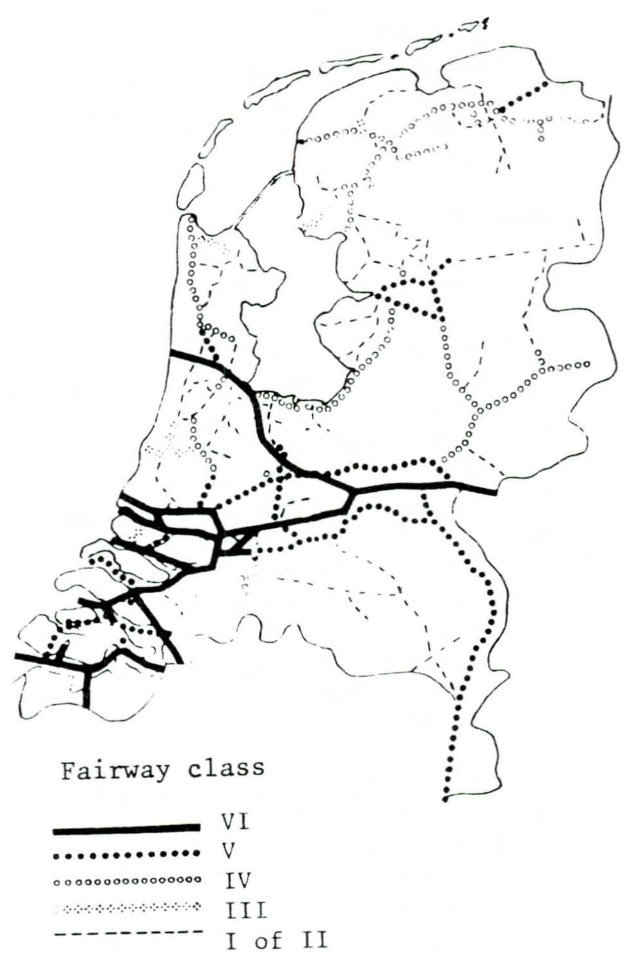


Figure 1 Main navigable waterways in The Netherlands

The mechanics of bank erosion and the stability of protective structures (incl. vegetation) subject to hydraulic loading are complex problems. The understanding of erosion processes and failure mechanisms of structures is still in a rudimentary stage, and it is not yet possible to describe many important phenomena and their interactions by theory. While laboratory investigations and practical experience provide means for gaining further understanding of interaction processes, the solution of many practical engineering problems cannot wait until complete understanding of these processes is obtained. Therefore, existing knowledge on this subject (though limited) should be systematized and made available for designers and managers in this field.

MANAGEMENT, ORGANIZATION AND GENERAL PHILOSPHY

Management on water defences incl. bank protection is characterized by its integral nature. Firstly, an integral approach to water defences is required because of the interrelationship between land use, protection measures and daily management and control. Secondly, an integral approach is required since various disciplines and techniques are involved in the analysis of coastal problems and their potential solutions; for example, coastal engineering, river engineering, economics, evironmental science, mathematical and physical modelling techniques, monitoring techniques, etc.
Because of this integral nature of the water defences incl. bank protection, the function of the management is not only to provide a proper integrated research program but also to build a bridge between research and practice. This last point is very important for the implementation of the research results.
In the Netherlands, Rijkswaterstaat (Public Works Department) plays a very important role in research into and management of erosion control for shores and banks. Especially by initiating research, managing funds and evaluating and implementation of results. Research is carried out by specialized services of Rijkswaterstaat and by external institutes (i.e. Delft Hydraulics, Delft Geotechnics, Delft University) mainly financed from government sources.
Because of the integrated nature of water defence and associated erosion problems and also the involvement of other bodies/authorities (in addition to Rijkswaterstaat), for the co-ordination and funding of research in specific fields several task committees have been created. These committees are budgetted by the Ministry of Public Works and may commission research to specialised institutes and Rijkswaterstaat.

- The Committee for Applied Research in Hydraulic Engineering (TOW) (actually, under direct supervision of specialised divisions of Rijkswaterstaat). One of the objectives is to analyse processes and to develop calculation methods for the prediction of coastal behaviour and river mechanics.
- The Technical Advisory Committee for Water Defences (TAW). The studies of this Committee increase the knowledge on environmental impacts, strength and construction of several kinds of water defences (river- and sea-dikes). The final results are presented as guidelines for design.
  Example of projects:
  - Guidelines on a method to select revetment materials for dikes and shores.
  - Guide to concrete Dyke Revetments.
  - Guidelines for River Dykes.
- The Dutch Committee on Management of Waterways (CVB). One of the objectives is to prepare the guidelines on various aspects involved in the management of waterways (i.e. nautical guidelines, guidelines on bank protection, etc.).
  Project example: - Design recommendations for bank protection of navigation fairways (CVB, 1988).

- The Dutch Centre for Civil Engineering Research, Codes and Specifications (CUR). The main objective of this centre is to stimulate the collective research in the field of civil engineering. In the CUR, experts from public authorities, contractors, consultants and research institutes are acting on the same collective-basis.
  Example of projects: - Structural aspects of environmentally acceptable banks (Manual).

The Dutch practice has learned that the best way to perform an integrated (multi-disciplinary) research project is to do so by organizing working groups or project-teams and appoint independent chairmen when all institutions involved are able to participate. Most research carried out under the above-mentioned task committees is realized by the working groups not only consisting of researchers but also of designers, contractors and local managers. It helps to identify and to define the problem, to create understanding for a chosen research strategy and to implement the results in an efficient way. This is one of the ways of building bridges between research and practice.
For solving some complex problems, the common Dutch practise is to apply a probabilistic approach and specifically the "event or fault tree" (Figure 2). To apply this method, all possible causes of failure have to be analysed and consequences determined. It has to be stressed that having quantified (even roughly) the fault tree, it is possible to pay extra attention to those mechanisms which contribute most to the overall probability of failure. Thus, this approach is an important element in the quality-control processes of the design and execution of projects.
The fault tree is also an important tool for preparing the integrated research program for erosion control projects and for objective judgement of priorities.
Taking knowledge of these recent developments can be rather beneficial, especially for the estimations of possible risks involved in realized projects and for finding the optimum between risks and investment, including research-investment.

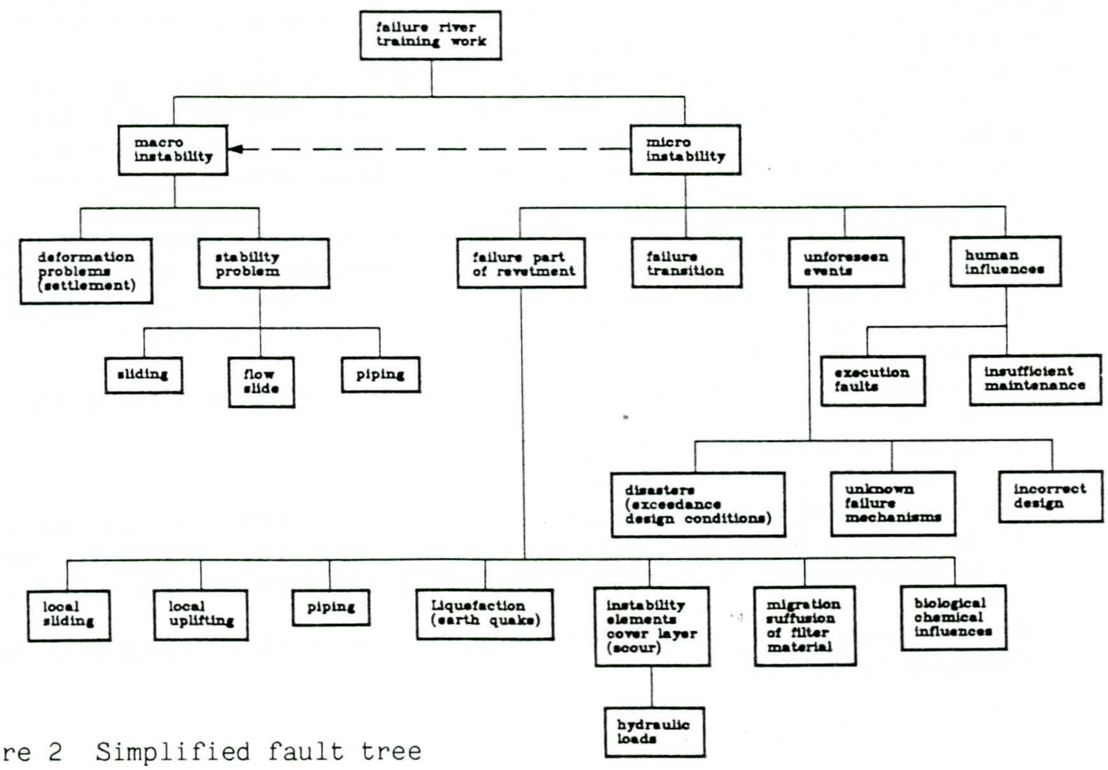


Figure 2 Simplified fault tree

BANK EROSION DUE TO RIVERINE PROCESSES

General

Land-use planning in alluvial river valleys and the choice of locations for bridges and hydraulic structures require predictions of future river planform changes and, consequently, knowledge of river-bank erosion and riverine processes. Of particular interest is the problem of stabilizing a river planform by constructing protection works at certain carefully selected locations only, allowing for solutions attractive from an economic but also an environmental point of view, as natural banks provide biotic and abiotic diversity, which are very important for riverine eco-systems (see Section Environmental aspects of river bank erosion). For this reason, some canalized streams in Germany have been changed back into more natural ones by partial removal of bank protection works (Keller and Brookes, 1983; Kern and Nadolny, 1986). For rivers in the Netherlands, De Bruin et al. (1986) have developed similar ideas, parts of which have been incorporated in the Dutch government's policy for urban and rural planning.

The understanding of the mechanisms of bank erosion along rivers is imperative for assessing the need for protective works and for the design of these works. This understanding should comprise both the riverine morphological processes that determine the erosive forces, and the soil-mechanical properties of the river banks that characterize their ability to withstand erosion.
In order to gain insight into the interactions between river-bank erosion, river flow and bed topography, and in order to develop tools for the prediction of river planform changes and their morphological consequences, research is performed at the Delft University of Technology and at Delft Hydraulics. At present this research is concentrating on the riverine processes considering both meandering and braided rivers.

Erosion problems

Bank erosion shows up in different forms: gradual recession of the banks and a consequent loss of bank vegetation or cliff development (the often steep transition between the river bank and the groyne field beach). Sometimes serious erosion occurs during floods. Factors governing erosion are, amongst others, the frequency and duration of high current velocities caused by navigation and flood.

An analysis of erosion of Dutch river banks in reaches with important push-tow navigation based on a comparison of airial photographs taken between 1975 and 1985, resulted in the following conclusions (see Table 1): almost half of the river banks in the reaches observed are protected; one-sixth of the unprotected banks do not appear to be eroded; two-third shows erosion up to 1 metre/year and one-sixth shows severe erosion of more than 1 metre/year. No conclusions can be drawn from the airial photographs about the causes of erosion. In fact, a number of factors may be responsible: the level of the lower bed, the geometry of the reach, the discharge regime, navigation. In order to decide upon the cause(s) in a particular case and to prepare the most suitable designs for erosion control measures, the river reach and its banks have to be studied as a part of the river system with its dynamic variation in water levels and water and sediment discharge.

Class: m/yr	total length		protected banks		unprotected banks	
	%	km	%	km	%	km
1: 0	52	168	44	142	8	26
2: 0 -1	40	131	5	17	35	114
3: 1 -2	6	22	1	5	5	17
4: over 2	2	6	0	0	2	6
total	100	327	50	164	50	163

Table 1 Bank erosion rates on reaches with push-tow navigation

For instance, the following phenomena may contribute to bank erosion:

- In the middle and upper reaches of alluvial rivers the lower bed may degrade because of, for example, mining activities, training works and navigation. In such cases the groyne field beach will also degrade. The slope of the beach is very small (1:30 to 1:100) because of the small size of the sediment which has settled particles there (low flow velocities). In fact, a slight degradation of the bed may eventually cause severe bank erosion.

- During floods, large quantities of water and sediment are exchanged between the lower bed and the flood plain. The water exchange occurs with large velocities, especially where there are sudden changes in the bed topography, for example at the banks. During floods groynes function like weirs, and after floods local erosion can often be observed downstream and sedimentation upstream of the groynes.

- If navigation becomes important on a river, the impact of large and heavy powered ships on the bed will increase and inevitably bank erosion will grow. The propellor race may cause bed erosion, which can indirectly affect the banks. In contrast the bow and stern waves of fast-sailing ships attack the banks directly. The immense water displacement of large ships causes heavy currents near the banks, generating large sediment transport.

The qualitative description above only indicates possible causes of bank erosion. Generally speaking only the total erosion can be observed in the field, the causes seldom being obvious.

Mechanics of river-bank erosion

River-bank erosion is a complex phenomenon in which many factors play a role: flow (discharge flow, groundwater flow, wind waves, ship waves), bed topography (undermining), sediment transport (e.g. removal of slump debris after mass failure) and bank properties (bank material weight and texture, shear strength including cohesive properties, electrochemical properties, bank height and cross-sectional shape, groundwater level and permeability, stratigraphy, tension cracks, vegetation and constructions).

At present, the numerical models under development only account for river-bank erosion due to shear stresses exerted by discharge flow. According to Blondeaux and Seminara (1985) these shear stresses can be represented well by the longitudinal near-bank shear stress, as continuity implies that the vertical component of the flow field close to the banks is driven by the perturbation of the longitudinal component, and is relatively small with respect to the latter.

Cohesive banks usually erode by mass failure, which implies that bank geometry fluctuates during bank retreat. Following mass failure slump, debris accumulates at the bank toe. The debris is removed by lateral erosion prior to further bank oversteepening or bed degradation generating further mass failures. These periodical bank geometry changes cause apparent variations in bank erodibility, thus complicating erosion laws.
However, when assuming that the debris is removed immediately from the toe, though still taking complex bank failure mechanisms into account, the time-average migration rate can be well characterized by a critical shear stress and an erodibility coefficient of the bank material at the toe (Osman and Thorne, 1988). This complies with field observations of Hickin and Nanson (1984), who found the relationship between grain sizes at the outer bend toe and bank migration resistance to be very similar to Shields' diagram. They conclude that bank migration is primarily determined by fluvial entrainment of basal sediments, after which cohesive upper sediments erode by the collapse of cantilevered overhangs.

The considerations above justify the use of a simple bank erosion law in the models, similar to relations for the erosion rate of cohesive soil samples (Ariathuri and Arulanandan, 1978):

$$\frac{dB}{dt} = E * (\tau - \tau_c) \qquad \text{for } \tau > \tau_c \qquad (2.1)$$

$$\frac{dB}{dt} = 0 \qquad \text{for } \tau < \tau_c \qquad (2.2)$$

in which dB/dt is the migration rate, E is an erodibility coefficient, τ is the shear stress exerted by the near-bank longitudinal flow component and τ_c is a critical shear stress below which no erosion occurs.
Arulanandan et al (1980) give relations to determine the erodibility coefficient and the critical shear stress of a cohesive soil. Osman and Thorne (1988) consider the approach of Arulanandan et al to be one of the most promising of the currently available methods, because calculation of erodibility and critical shear stress is based on the electrochemical properties of the soil, pore water and eroding fluid.

The presented bank erosion law has been incorporated in a mathematical model for river morphology. A linear analysis of this model with the approach of De Vriend and Struiksma (1983) indicates that the input of bank erosion products decreases transverse bed slopes, but hardly influences the wave lengths and damping lengths of flow and bed topography in natural rivers. A more important effect of an increase in bank erodibility seems to be widening of the bed and associated shallowing. This change of width-to-depth ratio leads to longer wave lengths and less damping. Ultimately, when the banks are extremely eroded, the river may become braided.

Meandering rivers

For meandering rivers tools are being developed to predict changes in planform. At the Delft University of Technology research is going on, in combination with Delft Hydraulics, to develop a mathematical model for large-scale changes in planform (Crosato and Struiksma, 1989). The 1D model, MIANDRAS, combines the approach of Johannesson and Parker (1985) with the insight gained in the Netherlands on the water movement and bed topography in curved channels

(Struiksma et al, 1985; Struiksma, 1985). Also the understanding of the occurence of natural cut-offs of meanders is improved via analytical modelling and exploring experiments (Klaassen and van Zanten, 1989). This phenomenon is the controlling mechanism, causing that the length of a meandering river does not increase, in the long run (Figure 3).
Furthermore, also at the Delft University of Technology the two-dimensional depth-averaged model RIPA is being developed. This model deals with river planform changes on a smaller scale and in fact is an extension of the work of Olesen (1987), in which more attention is being paid to the bank erosion and its effects on the two-dimensional bed topography in river bends.

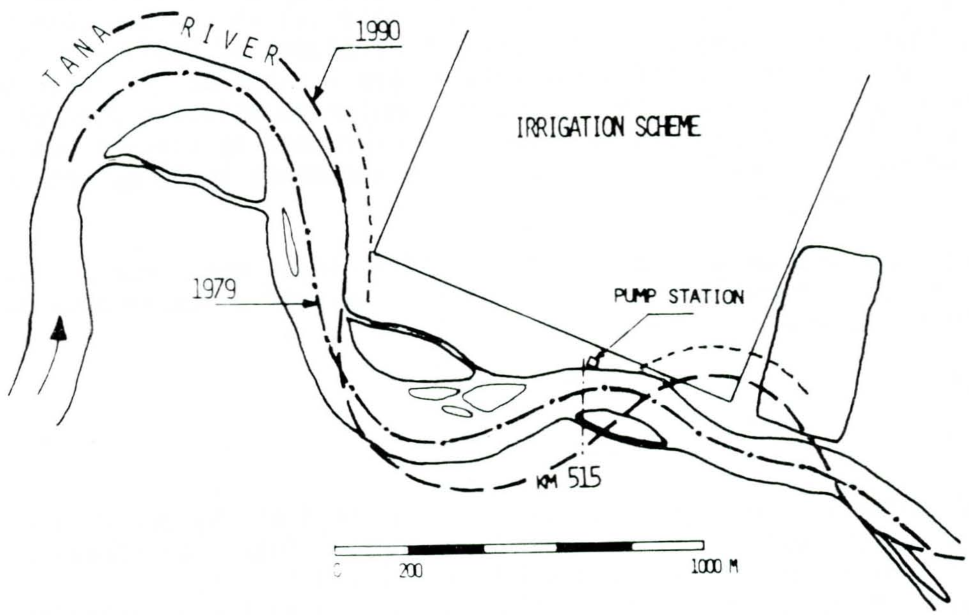


Figure 3 Example of actual and predicted planform of river

An arbitrary river geometry with a curved centre line, a non-uniform width and eroding banks requires a boundary-fitted coordinate system ('grid'). Such a coordinate system for which each segment of the boundary of the physical region coincides with some coordinate line is very convenient for the representation of boundary conditions and, therefore, has been chosen for implementation in the numerical model. After a certain amount of bank migration, a new grid must be generated, which is adapted to the new river geometry. Non-homogeneous bank erodibility can be accounted for by attributing bank properties to each bank grid-point separately. In order to retain these properties at the proper locations when generating a new grid, bank points are not allowed to shift along the banks. They only move perpendicularly to the local bank lines. This restriction implies that it is not possible to generate a purely orthogonal grid (Thompson et al, 1985).

Summarizing, the coordinate system to be implemented is boundary-fitted, curvilinear and non-orthogonal. The set of equations is solved in the transformed space, which is inherently rectangular with a square grid. Due to the transformation some terms have to be added to the equations. These terms account for rates-of-change of grid spacing and for grid skewnesses. An economical grid generator has been developed. The transformation of equations is currently being performed (progress has been made, but not completed yet).

Braided rivers

For braided rivers an extensive study of the erosion along the Jamuna (= lower Brahmaputra) River in Bangladesh was recently carried out by Delft Hydraulics. This study used satellite images over successive years. It was found that bank erosion along such a braided river is far more difficult to predict due to the much more difficult processes. Bank erosions occur both along curved channels and along straight reaches. The bank erosion along curved channels is to some extent similar to what was observed by Hickin and Nanson (1984) for meandering rivers, notably an increase of the celerity of bank erosion with decreasing relative radius of curvature. Results are, at present, only available in limitedly distributed reports within the framework of the Jamuna Bridge Appraisal Study (RPT/NEDECO/BCL, 1989), for which the study was carried out. Another interesting aspect is the substantial reduction in outer bend scour in the Jamuna River due to the contribution of bank erosion products. Bank erosion is, on average, about 300 m/year, but can be up to 1000 m/year. The maximum depth in the outer bends is only about twice the average channel depth and independent of the relative radius of curvature of the bend.

BANK EROSION DUE TO NAVIGATION

General

For many Dutch rivers (Figure 4), the lower bed is restricted by groynes. The bed in the groyne field between two groynes may be considered as a beach, visible during low water periods. The beach and bank in some groyne fields, is often eroded. A reason for such bank erosion may be navigation, especially when large, fast ships like push-tows use the river. Therefore, it is necessary to understand the erosion process when considering the introduction of (six-)barge push-towing. With this knowledge predictions of the extent of erosion can be made and designs prepared for "environment-friendly" river-bank protection instead of traditional bank protections consisting of layers of stones or blocks laid on geotextiles. With respect to traditional bank protection the past research and the general approach to erosion control of navigation embankments have already been treated extensively in recent publications (Blaauw et al, 1984; Pilarczyk, 1984; van de Kaa et al, 1985; PIANC, 1987a). Therefore, only the new developments related to the possible introduction of six-barge push-towing are discussed.

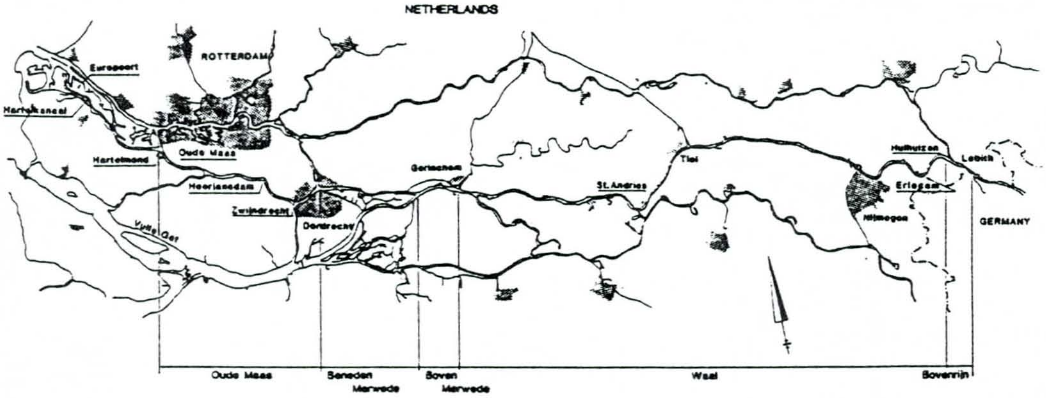


Figure 4 The Dutch sections of the River Rhine

Push-towing is a possible cause of bank erosion, of which, however, the physical processes are not fully understood. Therefore, this type of bank erosion has been investigated in field studies and in laboratory experiments. The 1986 six-barge push-tow trials were used to obtain field data of the flow field and sediment transport in groyne fields. Small-scale hydraulic tests were carried out at Delft Hydraulics to study the flow field and bank erosion which could be caused by push-towing. This research was aimed at predicting whether or not six-barge push-tows units would result in greater erosion than four-barge push-tows (Brolsma, 1988).

Flow patterns in groyne fields

The poor correlation between clearly defined examples of bank erosion and its possible causes among which navigation, resulted in carrying out a study to the erosion processes caused by push-tows, rather than to actually measure the erosion itself. With respect to the full-scale tests, the investigations were concentrated on two groyne fields, one in a straight reach and one in a bend. In a small-scale model at Delft Hydraulics on length scale 1:25, the flow pattern was systematically studied in a large and a small groyne field.
Figure 5 shows the flow pattern without navigation in a large groyne field (200 x 50 m) at a river discharge of 1450 m³/s (mean flow in the River Waal).
A vortex (eddy) develops immediately downstream of the groyne where the main current cannot make a sharp bend into the groyne field. Further downstream the main current does enter the groyne field and consequently the stream width is larger. A second eddy develops at the upstream face of the second groyne where the outflow is hampered by this groyne.
There is a continuous exchange of water and sediment across the streamline between the main flow and the flow between the groynes. The current velocities in the groyne field (0.3 m/s or less) are smaller than the velocities in the main current (1 m/s). Sediment carried by the incoming flow of water will tend to settle in the groyne field, except in the eddy downstream from the upstream groyne where the flow velocities are about 0.4 to 0.5 m/s.

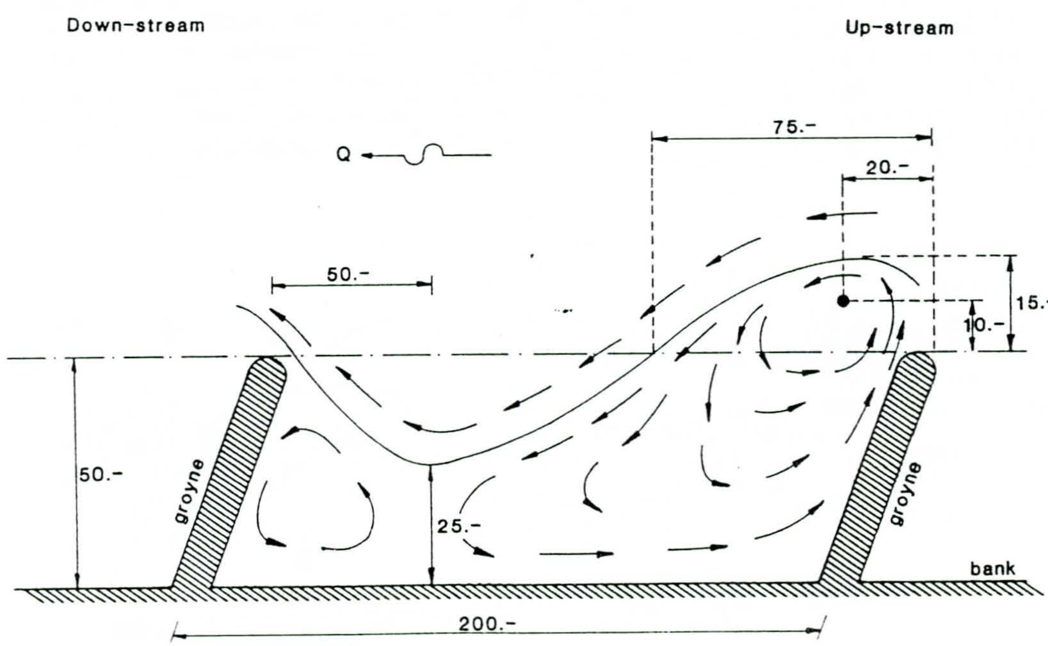


Figure 5 Flow pattern in a groyne field, no navigation (dimensions in metres)

In a shorter groyne field the incoming flow is strongly reduced and the downstream eddy does not develop and so the groyne field is dominated by the upstream vortex.
Before discussing ship-induced water movement in groyne fields, some observations should be made about the water movement around a ship in a fairway without groynes (Figure 6). When a ship is loaded the return current and the supply flow are the dominant phenomena for banks.

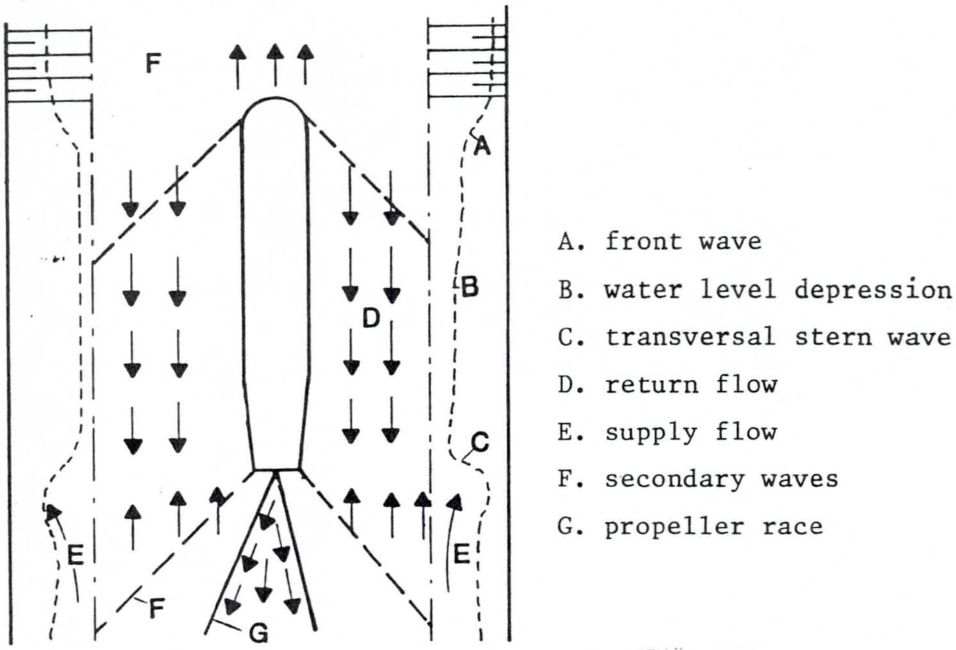


Figure 6 Water movement around a ship in fairway without groynes

The direction of the return current and the supply flow are parallel to the fairway axis. The return current is in the opposite direction to the ship's sailing direction, while the supply flow is in the same direction. The aft boundary of the water level depression caused by the return current is called the transversal stern wave and here the change in flow direction between the return flow and the supply flow occurs. Normally the propeller race has no direct impact on bank stability. The size of the secondary waves depends on ship speed and thus are only important in relation to bank erosion, when ships sail relatively fast, which is not the case with loaded push-tow units.

The effects of push-towing on the flow patterns in fairways with groynes is schematically presented in Figure 7. The discontinuities in the cross-section formed by groynes cause flow concentrations near the groynes and flows perpendicular to the fairway axis.
Three important stages can be distinguished during the passage of a push-tow unit sailing upstream. The return current is at a maximum immediately when the bow passes a groyne. The return current is furnished by water from the upstream groyne field and the groyne field alongside. An eddy develops at the groyne head and the small vortex at the downstream end of the groyne field apparently disappears entirely. As the push-tow passes by the supply flow refills the groyne field. When the stern of the push-tow passes the particular groyne field, the supply flow is forced to flow perpendicular to the axis of the fairway, out of the groyne field at the upstream groyne. The eddy immediately downstream of the groyne is transported downstream by the main current.

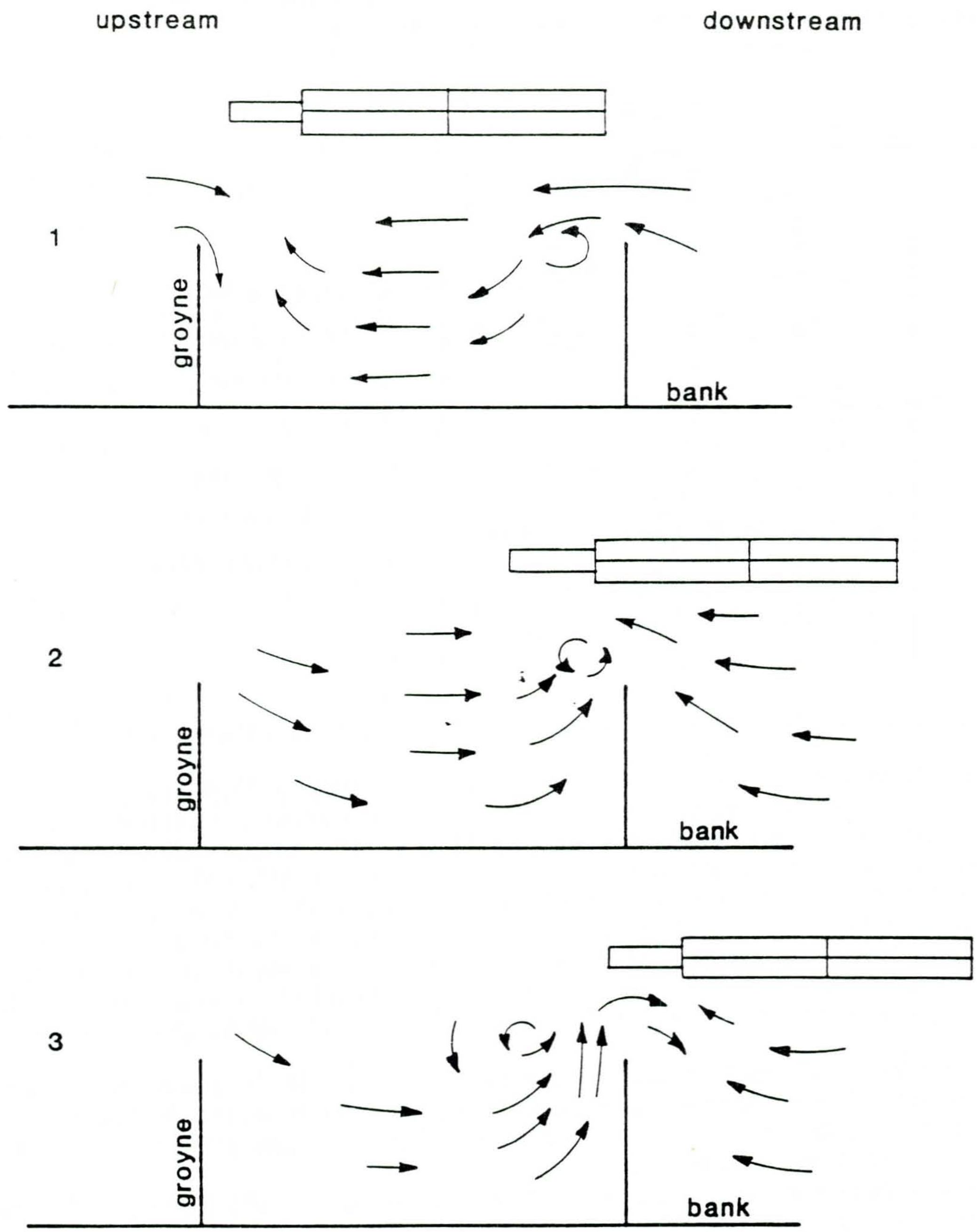


Figure 7 Flow pattern in a groyne field during passage of a push-tow unit

The following conclusions could be drawn from the model investigations and the field measurements:

- Push-towing induces large velocities, especially immediately downstream of the groynes. The magnitude of the velocities depends on ship dimensions, ship speed, distance between push-tow unit and groyne, and barge draught.
- The maximum current velocity in small groyne fields are less than in large groyne fields, because of the smaller effect of the supply flow.
- When the river discharge increases, the river cross-section also increases and this causes a reduction of the return current and supply flow and thus a reduction of the flow velocities.
- Field experiments in 1983 indicated that, whereas push-tow units tended to produce a considerable increase in the flow velocities in the groyne field, the largest self-propelled ship (about 2000 tons) had very little effect.

Erosion and sedimentation in groyne fields

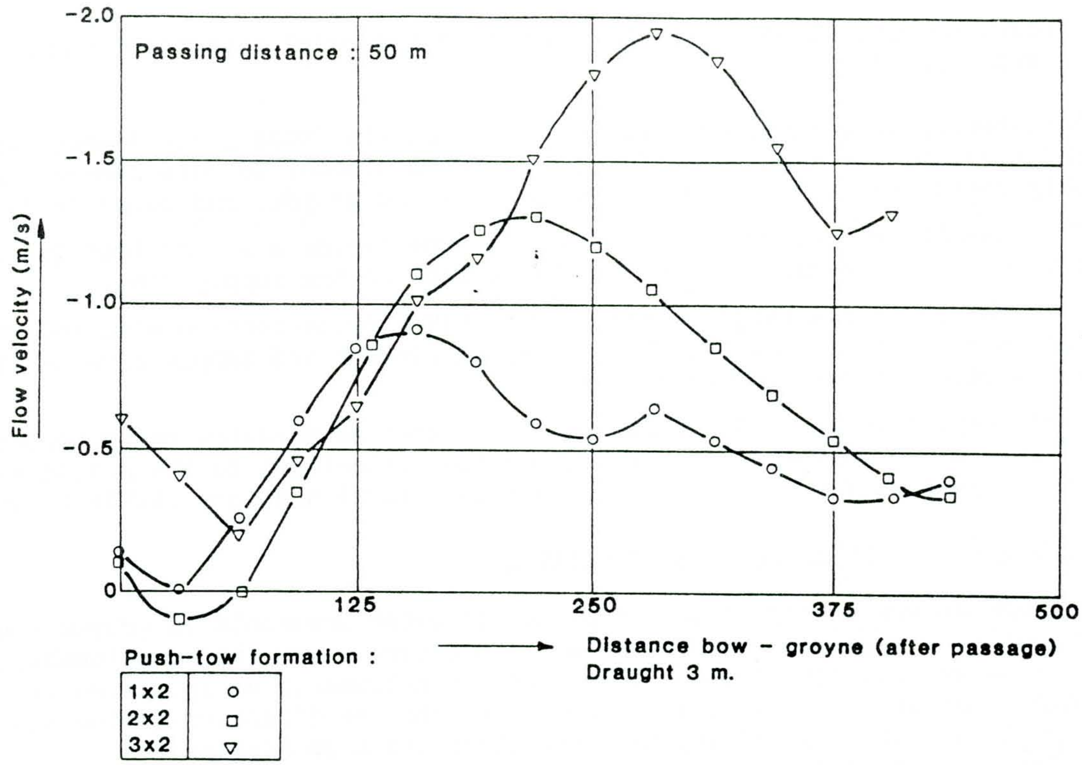
A thorough understanding of the ship-induced water movements in groyne fields is essential for predicting bank erosion. However, since the relationship between flow and sediment transport is highly non-linear, and in curved flow, the direction of the flow does not coincide with the direction of the sediment transport, measurements of sediment transport are also necessary.
Therefore, field observations have been carried out in the two pilot groyne fields as well as tracer experiments in the small-scale model. The findings of these erosion studies were as follows:

- Four and six-barge push-tow units induce increased sediment transport out of the groyne field, especially immediately downstream of the groyne head, caused by the increased intensity of the eddy at the moment the stern passes.

- The amount of sediment transported out of the groyne field, as a result of the passage of a six-barge push-tow unit, was 1.5 to 3 times larger than that with a four-barge push-tow unit. Of the transported material very little returns. The rate of return is larger for a four-barge push-tow unit than for a six-barge push-tow unit.

- Calculations with a conceptual mathematical model based on the insight obtained indicated small erosion rates for the groyne beach, both in the case of four-barge and six-barge push-tow units. As is to be expected the six-barge push-tow unit produces a somewhat larger erosion rate. Other erosion-producing phenomena appear to be dominant because of the small flow velocities. This is a continuing process which is only disrupted by passing push-tow units.

- Field observations made in the large groyne field indicated an aggradation (or recovery) capability of about 0.1 m per year, assuming no navigation, floods and low-water bed degradation. In contrast, the shorter groyne field does not have much recovery capability.



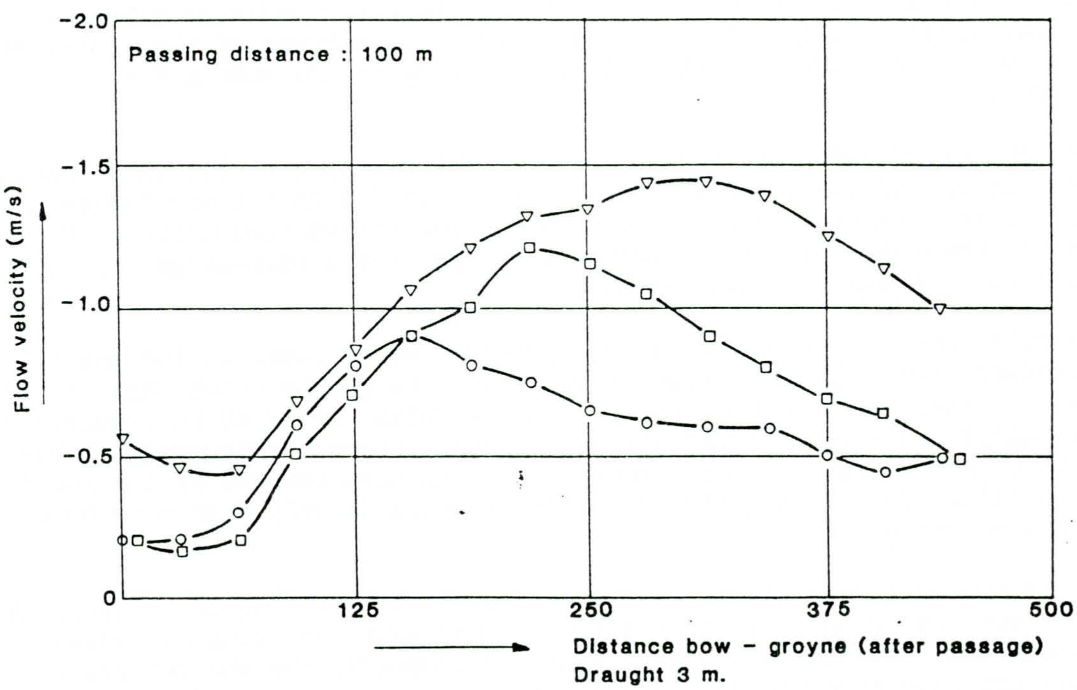


Figure 8 Flow velocities, push-tow unit passing at 50 m and 100 m from groyne field

Conclusions

Push-tow navigation causes erosion in groyne fields. The erosion rate, however, is low. Six-barge push-tow units almost certainly will cause more erosion than four-barge push-tow units. The erosion starts immediately downstream of the groyne heads, and will extend to the river bank. Eventually the bank will collapse. The rate of bank erosion due to push-towing depends also on the recovery capability and local sediment transport of which more information is required. Consequently, the rate of bank erosion cannot be predicted yet.

ENVIRONMENTAL ASPECTS OF RIVER BANK EROSION

General

In the long history of river bed regulation, the main rivers in the Netherlands have been transformed from rivers that meandered freely in a broad flood plain to one fixed in a single channel with less sharp bends and contained in a flood plain reduced in width. This also holds for the branches of the River Rhine, which is one of the main navigable waterways. The river flows in an almost flat landscape and consequently, builds up its own flood plain by sedimentation. The annual fluctuations are moderate compared to other rivers. Most of the discharge comes from precipitation in the catchment areas in the upper river reaches in Germany, particularly in winter and spring. In summer the Alpine region contributes with meltwater.

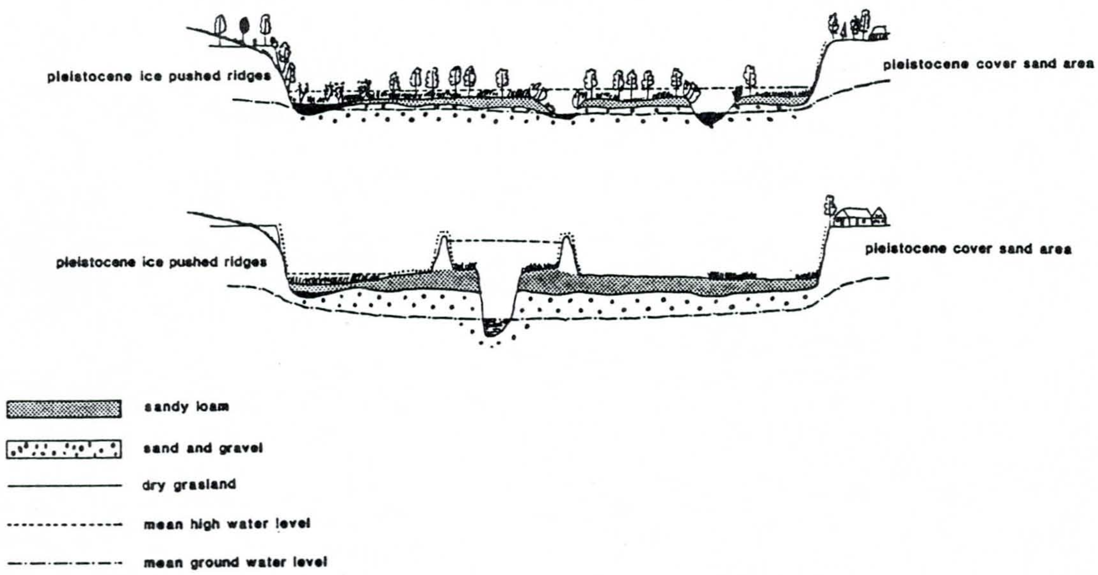


Figure 9 Cross-section of the Rhine, 1000 AD (above) and 1900 AD (below)

Every reach of the river has its own environmental features with corresponding plant and animal communities composed of general and specific species. The loss of natural environment has been considerable, since centuries ago human acitivities started to influence the river (Figure 9). Up to the 19th century this influence only consisted of diking activities and river training works in order to prevent flood disasters and to improve navigation. Nowadays, severe water pollution and intense navigation also play a role. The result of this all is that in the flood plain natural forests of willow and poplar were replaced by pastures, crests of high natural levees were flattened and banks were smoothed.

Abiotic diversity

In the present situation the low-water channel has sufficient capacity to contain the river water most of the time without inundating the pastures on the higher grounds between the dikes. High discharges now flood this restricted flood plain only once or twice a year. Summer dikes have been constructed in most areas to prevent summer inundation. These dikes also prevent polluted water entering the summer polder. The low-water channel is bordered by beaches, groynes and other artifical bank protection structures composed of bitumen, concrete, riprap, blocks and geotextiles. At high discharges the border is formed by the natural levees or winter dikes (Figure 10).
Geomorphological features such as old meanders, steep slopes, old and young natural levees, shallow and deep water pits and man-made clay pits, dikes and other structures create a very complex, continuously changing landscape.
In places where old natural levees of flood plains are exposed to the eroding forces of the current, steep slopes are created. This is a natural phenomenon that can be seen in most river landscapes. However, in the present Dutch river landscape the natural phenomenon of steep and high slopes on river banks is almost totally absent.

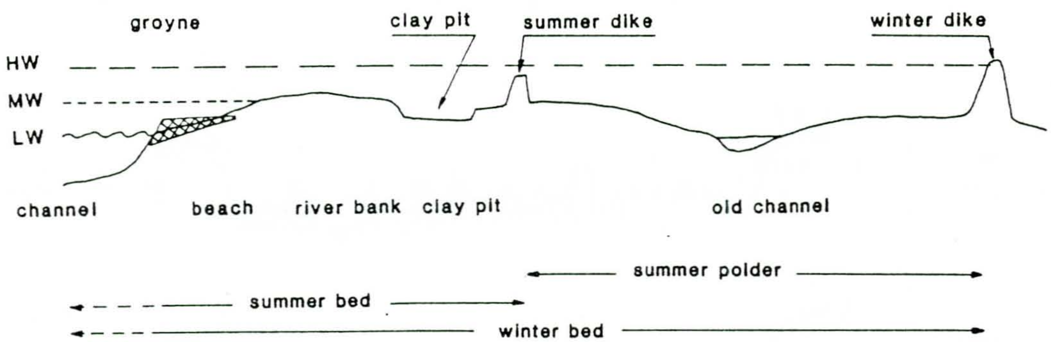


Figure 10 Schematized section across an active flood plain

In the past the river banks were more varied and to a certain extent covered with vegetation. Nowadays, however, the overall picture is one of almost bare sand beaches, except in the transition zone to the estuarine, where there is still a marsh land vegetation.
The young soils of the river banks are to some extent calciferous, in particular the soils in front of the summer dikes. Their composition varies from coarse sand and gravel in the deeper subsoil, to alternating layers of sand and clay and also thick clay packets.
Higher areas are dryer and more ripened and homogenized by the activity of soil fauna and show less hydromorphic features because of lower groundwater levels. Former river beds or cut-off meanders, have slowly turned into marches with organic soils. Hydrological factors play a very important role in the distribution of organisms in the river bank system. Compared with dry ecosystems the variations in time and place are great. Most dramatic, for example, is the periodic inundation of the river bank which only a specialized selection of organisms can survive. In addition, the water quality of the River Rhine deteriorated to a minimum. Recently, a slight recovery has taken place. The effects of pollution are severe because many polluting agents, such as

heavy metals and polycyclic aromatic organic substances, become bound to clay mineral deposits and stay in the system for a long time. In the short term, the accumulation of poisonous substances in the organisms of the food chain are more serious.

Biotic diversity

Nowadays, the low-water channel borders are almost completely without vegetation, because of the turbulent water motion generated by navigation and the sand movement. The higher grounds are less exposed to eroding forces and carry a permanent vegetation cover. The impact of the water regime on nature is very decisive and governs the presence or absence of organisms in the flood plain and on the river banks.

In early spring when most organisms hibernate, the effect of flooding is minimal, but in summer, flooding can be disastrous for many plants that are flowering or setting seeds and some animals species can suffer under oxygen depletion.

There is a relation between the organism and the mean duration of annual flooding. At the water line, species can be found which are resistant to high flow velocities (reed, willow). Some species are tolerant to inundation because they possess aerial canals in their stems (reeds, bulrushes). Others have short life cycles to avoid the flooding season. Organisms most sensitive to flooding are found on the crest of the natural levees and on dikes.

Biotic diversity is also related to soil diversity. Clay soils do not dry out quickly since they contain very fine particles and retain ground water better than sandy soils. Permanently water-saturated soils are less aerated or unaerated and so only marsh land species can grow.

The mean duration of flooding is a measure for expressing the sensitivity of living organisms or the chance they can be found at a particular place. It is also an excellent way to describe different environments with specific biotic compositions. On this basis the environment of the river bank is divided into five more or less separate zones with their own features corresponding to possible life forms and abiotic phenomena and processes:

zone 1: permanently under water
zone 2: frequently flooded in summer
zone 3: sometimes flooded in summmer
zone 4: very seldomly flooded in summer
zone 5: never flooded in summer.

Protection and restoration

A new environmental equilibrium had to be reached along the rivers

The activities up to now already caused a substantial loss of habitat variation, which in turn has reduced the number of species which a river can support. A more recent negative influence is caused by the intensification of agriculture, which has resulted in the increased application of biocides and the transformation of extensively used land cropped for hay and rich in species to agro-industrial pasture with a poor species composition. Thornbush-hedges which have contributed enormously to the ecological infrastructure of the river landscape have, at the same time, been replaced by barbed wire. Cattle water holes rich in amphibian and insect life have lost their function and disappeared. In addition cattle treading has damaged the sandy soils of beaches and dunes rich in plant and animal species.

All these aspects have contributed to the growing awareness of the grave situation of the environment and governmental and public willingness to take action.

The contents of some pollutants, for instance, have already been decreased.

The willingness of the Dutch Government to take action is there and plans are being developed and have been partially worked out already. Consultation with other Rhine-countries has resulted in agreements to limit discharge of wastes into the river, to improvements in industrial installations and to prohibit or alter industrial processes as much as possible. At present, inventories of the river banks are being made. This will give information on the current abiotic and biotic diversity and the spatial differentation and quality of types. A monitoring network will gather information on fast or slow changing ecological processes, identify external influences and assist the interpretation of the experimental results.

The aim for the near future is to clean the river to such an extent that re-introduction and spontaneous repopulation of organisms takes place. Restoration of the abiotic environment so as to improve the possibilities for living creatures that belong in a river (bank) ecosystem is a more distant aim. Within the restrictions of river management and costs, preparations are being made and ideas have been presented to restore the variation and quality of the biotic and abiotic environment, which can keep itself in equilibrium. A first stage is the construction of nature-restoring types of bank protection. Little is known about appropriate methods for protecting river banks and, at the same time, for giving nature a chance. Experimental structures properly managed and maintained, are needed to evaluate possible solutions. Growth of willow forests at river banks and creation of less dynamic shelter areas between groynes seem possible. More toleration of land loss could diminish the amount of the artificial solutions. Adequate connection of the river with cut-off bends or isolated sand-pits could restore spawning places for fish and offer new habitats to macro fauna and marsh vegetation.

Conclusions

A substantial loss of plant and animal habitat has taken place, due to river bank erosion, enforced wave action on unprotected beaches and artificial bank protection constructions that suppress natural processes.
To prevent further degradation of the natural environment with its specific flora and fauna elements and the particular river landscape, measures are necessary. The willingness of government and public is growing and has already resulted in plans to enlarge natural developments, in measures to reduce pollution and attention for biotechnical bank protection solutions.

INTEGRATED RESEARCH ON REVETMENTS

General

Numerous types of revetments have been developed in the past for shores and for banks of navigation channels to prevent erosion by waves and currents (i.e. riprap, blocks, asphalt, etc.). The reason for this was the increase of the problem in respect to the defence of the shores (i.e. more rigid safety requirements for seadikes) and banks of navigation channels (i.e. increase of size and speed of motor vessels), as well as the high cost and shortage of natural materials. The fact that design rules are still limited in quantity has stimulated new investigations in the area of riprap, artificial blocks and bituminous revetments, as well in the area of geotextiles.
Problems which arise due to these developments, require solutions which often only can be found by specific in-depth multidisciplinary studies (Figure 11).

In order to control the future seadikes and bank protection problems, the Dutch Ministry of Transport and Public Works (Rijkswaterstaat) assigned Delft Hydraulics and Delft Geotechnics to carry out a systematic research into these areas. On the base of the analysis of practical design problems and the gaps in the existing knowledge, the required research programme had been determined (Figure 12). This programme follows the general SOWAS-concept as outlined in Figure 11; it includes the integration of two fields (banks and dikes) as well interdisciplinary integration (SOil-WAter-Structure).
The basic programmes have been carried out by means of small-scale models. However, it has to be pointed out, that a small-scale hydraulic model for navigation purposes needs still a lot of space. In the scope of the bank protection research programme, for example, the hydraulic model of an inland navigation fairway on scale 1:25 has been built in a 40 x 90 m^2 shed to observe the induced water motions and their erosive effects on the banks.

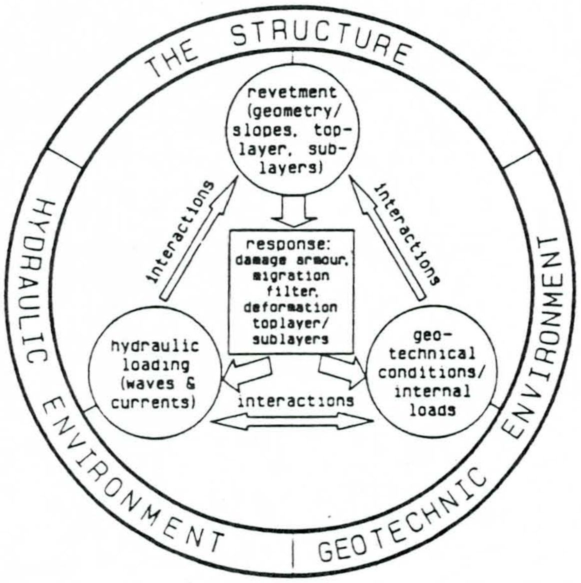


Figure 11 Soil-water-structure interaction for revetments

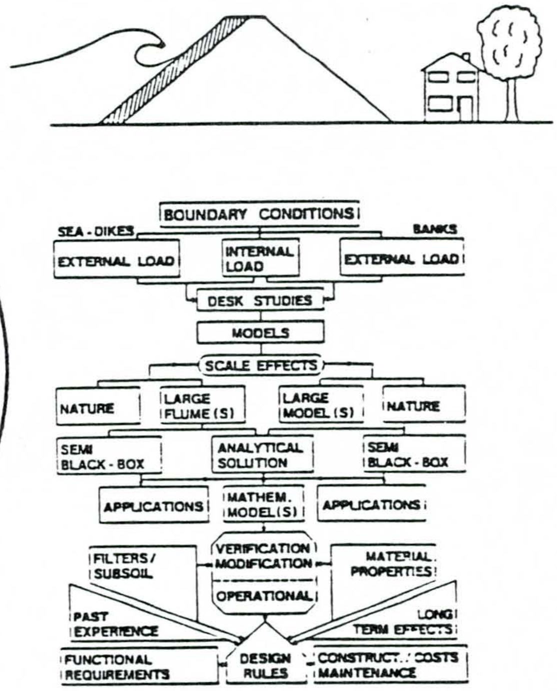


Figure 12 Sea-dikes and bank protection research approach

Since model research has certain inherent technical restrictions known as scale effects, required additional information has been obtained by means of prototype investigations i.e. the Delta-Flume and some prototype locations in respect of the sea-dikes problems, and the Hartel Canal (Rotterdam area) with test embankments in respect to bank protection problems of navigation channels. The result of the prototype tests, in combination with the model results and the calculation methods (incl. mathematical models) developed within the framework of the systematic research on dike protection (Delft Hydraulics and Delft Geotechnics, 1989) and systematic research on bank protection (Delft Hydraulics, 1988) extended with knowledge gained from practical experience, had led to the preparation of guidelines for reliable dike and bank protection designs. The aim of the total research effort was to develop such design criteria that the amount of maintenance and construction costs of new revetments is minimized.

Research aspects and research means

In general, to be able to determine the dimensions of involved protection layers of revetments the following design research-aspects have to be taken into consideration:

A) Research on characteristic/representative load
   A1 - water motion due to wind waves, currents and ship movements
   A2 - geotechnical load (gradients) due to the water motion (A1)

B) Research on characteristic/representative strength
   B1 - strength of toplayer
   B2 - strength of sublayers
   B3 - geotechnical strength (i.e. sliding)

To solve problems involved in A) and B) various research means are available, viz.:

a) Evaluation of past experiences (lessons from practice)
b) On-site investigations on existing and/or test revetments, i.e. prototype measurements in the Hartel Canal (Pilarczyk, 1984)
c) Calculations and mathematical models (desk studies)
d) Small-scale physical models
e) Large-scale models, i.e. Delta Flume.

The physical and mathematical models are very suitable for basic research within a wide range of boundary conditions and for the development of general design rules, while on-site investigations, evaluation of experience and large-scale (prototype) tests are needed for verifying the final results (design rules). In the scope of the discussed research programmes all the above-mentioned research methods have been applied. The general research strategy for both programmes and their interactions is presented in Figure 12. The main difference in approach to the problem between these two investigations lies in the fact that for the seadikes the large Delta Flume has been used for prototype tests while for the bank protection problems the 'in-situ' prototype tests have been carried out. (Large-scale models to help solve bank protection problems are not a reasonable solution). Another point of difference is that the boundary conditions related to banks cannot be reproduced mechanically as is the case for wind-waves with a wave generator, but they have to be induced by ship movement.
Besides the difference in reproducing of the hydraulic load both programmes involve some common aspects regarding stability of the toplayer and the sublayer. The integration of both programmes had taken place by means of mathematical models which had to fulfil both requirements. These mathematical models, called STEENZET, (Bezuyen et al, 1987; Burger, 1988) and DIPRO (CUR, 1989) might become important tools in the design of revetments of dikes and of banks of navigation channels.
The technical description of the projects and the results discussed above can be found in the references. However, to illustrate the SOWAS-concept on the technical level, the integration of the soil, water, and structural processes into one conceptual stability model will be repeated below (de Groot et al, 1988).

General stability approach (SOWAS-concept)

The phenomena which may be relevant can be divided roughly according to the three components of the system: water, soil and structure. The interaction between these components can be described using three Transfer Functions (see Figure 13).

I. The Transfer Function from the overall hydraulic conditions (e.g. wave height H, mean current velocity U) to hydraulic conditions along the external surface, i.e. the boundary between free water and the protection of soil (e.g. external pressure P_{ex}).
II. The Transfer Function from the hydraulic conditions along the external surface to those along the internal surface e.g. the boundary between protection and soil. The hydraulic conditions along the internal surface can be described as the internal pressure P_{int}.
III. The structural response of the protection to the loads along both surfaces.

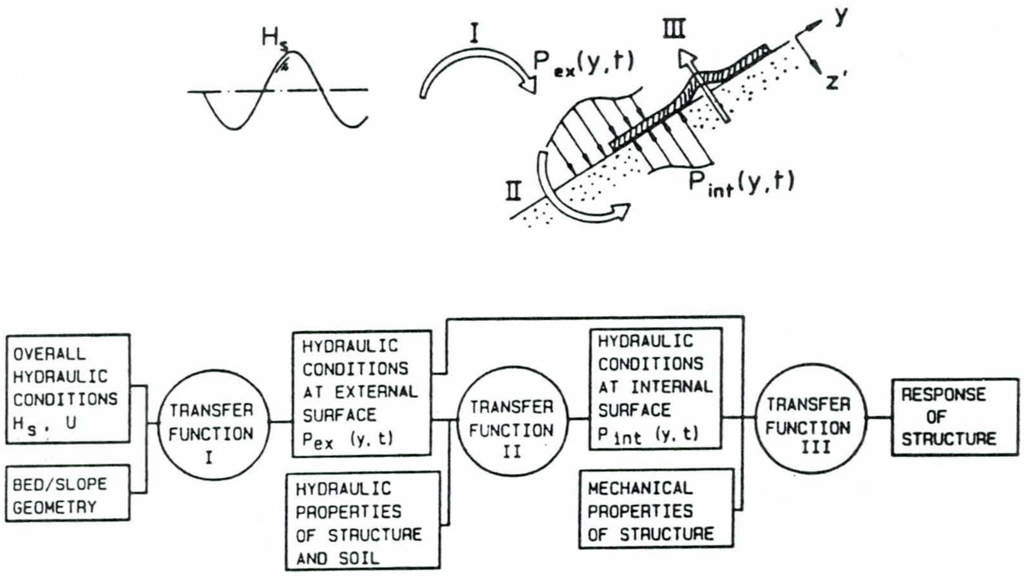


Figure 13 Schematic presentation of the three transfer functions

Information about these functions can be obtained by means of measurements in nature and (scale) model tests. If quantitative knowledge of the physical phenomena involved is available, or if there is enough experience at hand, then mathematical models or empirical formulae containing information are referred to as "models".
All three Transfer Functions can be described in one model, or individually in three separate models, depending on the type of structure and loading. The distinction between the three functions serves here mainly as a framework to describe the different phenomena that are important for the modelling.

Based on the extensive past research on various protection systems it is possible to present the load-strength relationships of these systems in the more uniform way as it will be presented in the next sections.

Overview of practical design formulae

a) current attack, civil engineering structures (Pilarczyk, 1989)

A general formula:

$$\Delta_m D_n = \phi\, K_T \frac{0.035}{\psi_{cr}} K_h \cdot K_s^{-1} \frac{\bar{u}^2}{2g}$$

in which: D_n = thickness of protection unit [m], Δ_m = relative density of protection unit [-], ϕ = stability factor [-], K_T = turbulence factor [-], K_h = depth factor [-], K_s = slope factor [-], ψ_{cr} = critical shear stress parameter [-], $\bar{u}$ = mean velocity [m/s], g = acceleration of gravity [m/s²].

The strength parameters Δ_m en D_n can be calculated with:

for rock: $D_n = (M_{50}/\rho_s)^{0.33}$ or $D_n = 0.85\, D_{50}$ and $\Delta_m = \Delta\, (\rho_s - \rho_w)/\rho_w$

for mattresses (gabions, sand-mattresses, etc.): D_n = d (= average thickness of mattress) and $\Delta_m = (1-n)\Delta$

with M_{50} = 50% value of the mass distribution of the stones [kg], ρ_s = specific weight of rock [kg/m³], ρ_w = specific weight of water [kg/m³], n = porosity of stone or sand [-] (approximately 0.4).

The different K-factors follow with:

$K_h = 2/(\log 12h/k_r)^2$ for a logaritmic velocity profile or
$K_h = (h/D_n)^{-0.2}$ for a not-fully developed velocity profile
$K_s = \cos\alpha\, (1-\tan^2\alpha/\tan^2\theta)^{0.5} = (1-\sin^2\alpha/\sin^2\theta)^{0.5}$
K_T = 0.67 (low turbulence, uniform flow); K_T = 1.0 (normal turbulence, rivers); K_T = = 2.0 (high turbulence, local disturbances, outer bends), with h = water depth [m], $k_r = D_n$ (smooth units, i.e. concrete blocks) or $k_r = 2D_n$ (rough units, i.e. rock), α = slope angle [°], θ = angle of interval friction [°].

The following remarks can be made. Firstly, the factor K_h can be neglected if in stead of $\bar{u}$ the bottom velocity u_b is substituted. Secondly, the factor K_s only holds for bank and shore slopes. For a bed slope a different value should be used. Finally, the value of 2 for K_T should only be applied if due to difficulties in defining the local mean velocity, the average mean velocity is applied.

The following values of the stability factor ϕ are recommended:

ϕ = 1.25 for exposed edges of loose units
ϕ = 1.0 for exposed edges of block-mats and/or mattresses
ϕ = 0.75 for continuous protection of loose units
ϕ = 0.50 for continuous protection of block-mats and/or mattresses

with ψ_{cr} = 0.035 for rock and ψ_{cr} = 0.06 ÷ 0.10 for gabions.

Examples of exposed edges are: bed protection at scour holes (particularly in the case of two-directional current i.e. ebb and flood), edges of a toe protection, transitions between adjacent revetment systems, connections between mats or mattresses.

b) wave attack, civil engineering structures (Pilarczyk, 1989)

The general formula is:

$$\phi_f \frac{\cos\alpha}{\xi_z} \leq \frac{H_s}{\Delta D} \leq \phi_o \frac{\cos\alpha}{\sqrt{\xi_z}}$$

with: $\xi_z = \tan\alpha/(H_s/L_o)^{0.5} = 1.25 \cdot T_z/H_s^{0.5} \cdot \tan\alpha$

in which: $\phi_f = \phi_o$ = stability factors [-], H_s = significant wave height [m], T_z = average wave period [s], L_o = wave length [m], D = thickness of protection unit [m], α = slope angle [°], Δ = relative density [-].

The general equation is valid especially for placed/pitched stones and blocks, more in particular: the left side for free blocks/stones (ϕ_f) and the right-hand side for old revetments (ϕ_o) with natural friction and/or interlocking.

The following values of the parameters ϕ_f and ϕ_o are recommended:

ϕ_f	ϕ_o	type of revetment
2.0	2.5	poor quality (irregular) pitched stone
3.0	3.5	good quality (regular) pitched stone
3.5	4.0	natural basalt and less permeable (closed) blocks
4.0	5.0	relatively permeable blocks (open area 5 ÷ 20%)
5.0	6.0	closed blocks on good quality and smooth clay-surface

It should be emphasized that in the case of the first four types of revetment a granular sublayer is required. In the case of blocks on a geotextile on a sandy subsoil, the applied wave height should be less than 1.5 m, because of the danger of liquefaction.

For block-mats and grouted/interlocked systems on a granular sublayer the right-hand side of the general equation can be applied. Values for ϕ are:

ϕ = 3.5 - blocks connected to geotextile by pins
ϕ = 4.0 - grouted blocks connected by geotextile
ϕ = 4.5 - cabled closed blocks
ϕ = 5.0 - cabled open blocks; grouted concrete prism (basalton)
$\phi \geq$ 6.0 - grouted cabled blocks; properly designed mechanically interlocked blocks

The edges of the adjacent block-mats, if not properly connected, should be treated as free blocks ($\phi \approx 3$).
In all cases, experience and sound engineering judgement play an important role in applying these design rules, or else mathematical or physical testing can provide an optimum solution.

For other revetment systems, such as riprap, grouted aggregates (riprap, bitumen grouting), gabions (incl. gabion mattresses), open stone asphalt, fabric (geotextile) mattresses the general wave-design equation has been changed slightly:

$$\frac{H_s}{\Delta_m D_n} \leq \psi_u \cdot \frac{\phi}{\sqrt{\xi_z}}$$

with ψ_u = upgrading factor (ψ_u = 1.0 for riprap and $\psi_u \neq$ 1.0 for other revetments systems).

Depending on the type of revetment different values for Δ_m and ϕ should be substituted. For D_n should be applied a value based on M_{50} or in the case of mattresses the value of d. The value of ψ_u can vary between 1.5 and 3.0 depending on the type of revetment and for ϕ a safe value is 2.25.
Also more sophisticated formulae have been developed. For instance, for plunging waves ($\xi_z \leq 2.5$) attacking slopes protected with loosely materials taking into accont duration of wave attack, damage level and permeability of sublayer and subsoil (van der Meer and Pilarczyk, 1984):

$$H_s/\Delta D_n < 6.2.p_b^{0.18}.(S_b^2/N)^{0.1}/\xi_z^{\frac{1}{2}}$$

with p_b = permeability factor with p_b = 0.1 for the practically impermeable core (i.e. sand-/clay-body), and p_b = 0.5 for the permeable (granular) core (i.e. breakwaters), N = number of waves [-], S_b = damage level [-]

A physical description for S_b is the number of cubical stones with a side of 1 x D_n, eroded over a width of 1 x D_n. The "no-damage" criterion is generally applicable when S_b is between 1 and 3 stones eroded.

c) biotechnical revetments (Klein Breteler et al, 1988).

Due to the recent trend to environment-friendly solutions for bank protection, research is started on combined systems (artificial protection consisting of cellular revetment blocks allowing vegetation), which may be applied in the situations with hydraulic loadings exceeding the value of the natural resistance of particular vegetation especially in the first stage of growing (just after planting).
Cellular revetment blocks combine the merits of a closed revetment and a revetment of loosely packed materials: permeable enough to prevent the occurrence of high uplift pressures, and the individual blocks support each other against severe wave attack. Thus, the advantages are high permeability, a high stability against wave attack, a low block weight, and last but not least, the holes allow the growth of vegetation (Figure 14).
The aim of the ongoing research is the derivation of equations predicting the erosion of hole fillings, because for the stability of the slope protection and the establishment of a vegetation it is of vital importance that the material in the holes does not erode completely. Studied aspects are water motion, geometry of holes and characteristics of hole filling.

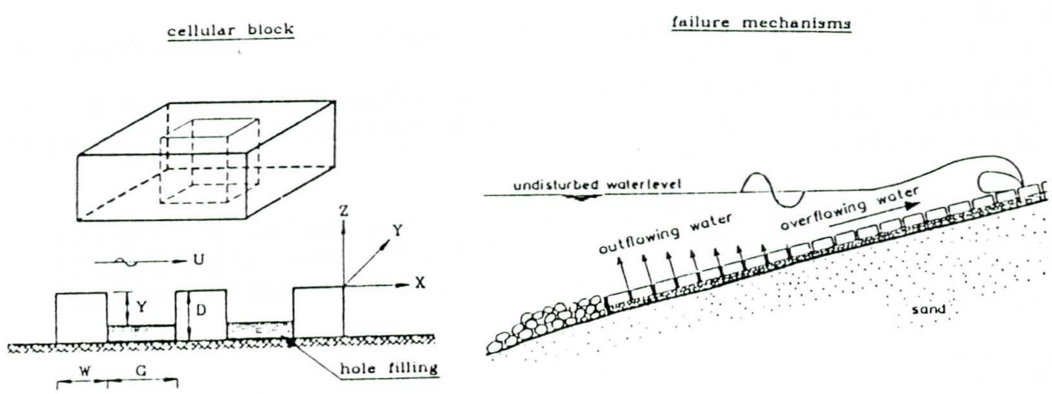


Figure 14 Cellular concrete block revetment

In the case of a bank protection along a navigable waterway the main attack is caused by ship waves. As a first result the following equation could be derived (Figure 15):

$$Y/G = c\,(z_{max})^{0.5} \cdot \log(N+1) \qquad (D_{50} \approx 0.15 \text{ mm})$$

with c = 0.7 for sand and c = 0.5 for black earth, G = hole width [m], Y = maximum erosion [m], z_{max} = height of ship wave [m], N = number of ship passages [-].

Along sea dikes wind waves cause the main attack. Depending on the size of the holes the failure mechanism is outflowing water (small holes) or overflowing water (large holes). Of course, the loads on sea-dikes will be too high for a vegetation, however erosion of hole filling is not allowed because of instability of subsoil. The tests resulted in the equations:

$$G > 100 \text{ mm: } Y/G = 0.2\,(H/D_{50})^{0.33} \qquad (D_{50} \approx 5\text{-}25 \text{ mm})$$

$$G < 100 \text{ mm: } Y/G = 25\,(H/D_{50})^{0.33} \cdot (D_{50}/G)^{1.5}$$

G = hole width [m], Y = maximum erosion [m], H = wave height [m], D_{50} = diameter hole filling [m].
Note: The first equation is also valid for small holes above the still water line.

The main conclusion of the research carried out up to now, is that cellular blocks can be applied along inland waterways and coasts. A safe design approach is to apply blocks with a hole width less than half the block thickness.

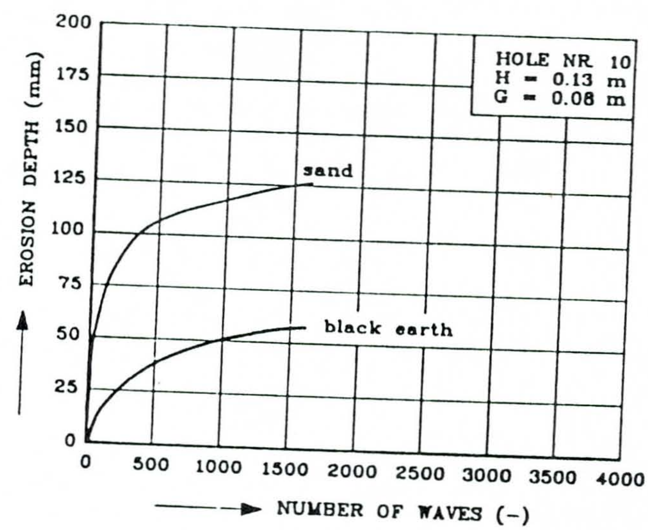


Figure 15 Erosion depth vs. number of waves

CHOICE OF MEASURES

In general the choice of a proper measure for a particular case is related to the functional requirements and the cost-benefit optimalization. The latter needs preparation of various technical alternatives satisfying the functional requirements.
Regarding the bank protection, to predict when and which measure is desirable, it is essential to have a proper understanding of the hydraulic loading (waves, currents, water stages, sediment transport etc.), the current morphological processes and the possible interactions/response due to possible measures including ecological response.

The actual state of knowledge on all these aspects it not always sufficient for solving these problems. However, due to the gradually increasing knowledge on the measures already used and the morphological and ecological response to them, the possibilities of better prognosis and choice of proper measures are also gradually increasing.
It is important that already at an early stage of the preparation of hydraulic schemes, the main view point be formulated that purely civil engineering measures are not always necessary. Taking into consideration the knowledge of natural processes and availability of materials, it must be possible in most cases to build appropriate ecological shore/bank protection and to control the erosion processes.
By involving biological elements (vegetation) in the solution some reduction in cost may also be achieved. In the case of sandy shores, the dynamic principles should be used instead of fighting against nature (e.g. sand replenishment).
The choice of protective measures today also depends on a weighing-value of functions of the area considered. Such functions are recreation, fishery, nature (biological value), navigation, etc. Thus, before choosing a measure the following aspects have to be analysed (Pilarczyk, 1986):

- what does society want to do with this area (destination of the area)?
- what kind and what amount of erosion is likely to happen without taking measures? (not taking any measures is one of the basic alternatives)
- is doing nothing responsible/desirable?
- if not, how can the erosion be fought or stopped?

To arrive at a choice it is necessary to proceed systematically. In The Netherlands the so-called policy-analysis is often recommended for this purpose. The principle of this method is that no decision is taken during analysis; only the pro and contra arguments for different solutions are collected and properly weighed against each other.
The final choice is left to the proper authorities.
The example of this approach for Dutch estuaries is given by Pilarczyk (1986).

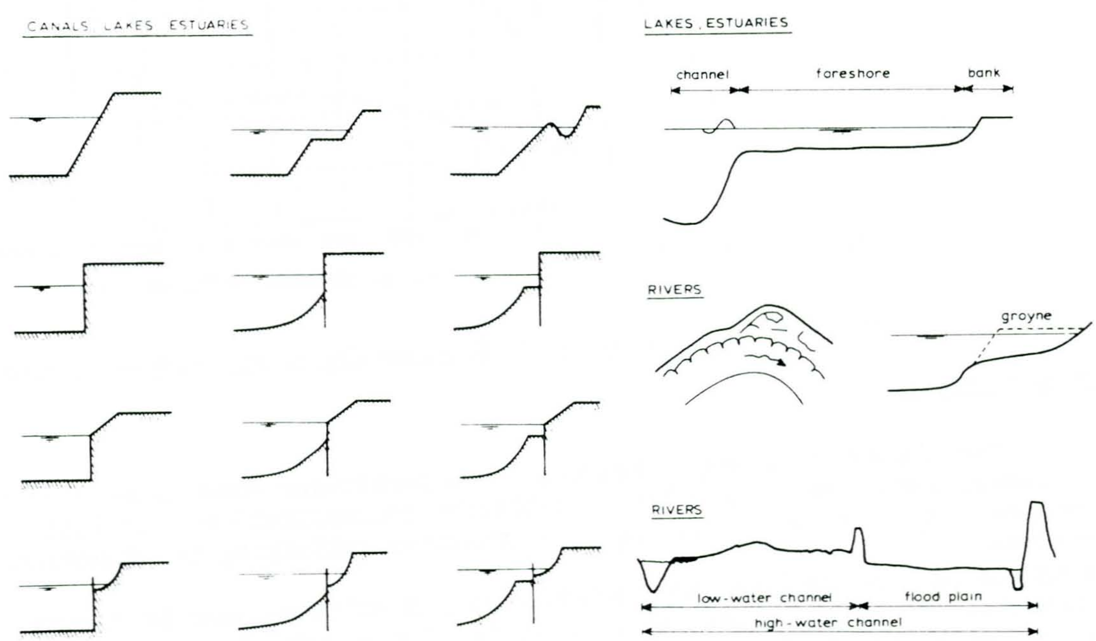


Figure 16 Basic forms of bank protection in The Netherlands

The method to select the revetment materials for covering dikes and banks is prepared by TAW (1988). Requirements have been formulated which, in general, have to be met by various materials. Selection criteria have been derived from these requirements for different local situations. By including the costs of construction and maintenance in the selection procedure, a conscious decision concerning the materials (incl. environmental aspects) to be used can be made, based on qualitative as well as economic grounds.
It is recommended to make the choice of protective systems by a group of the involved specialists so that the subjective aspect can play the least possible part. For the different aspects weighing factors can be made so that a more objective choice may be possible.

The basic forms of banks in the Netherlands are shown in Figure 16. In the case of wide rivers and channels with no space-restriction, the common way of protection is an indirect protection by groynes and sills parallel to the bank. The crest level of a sill is determined by the water level and the transmission of waves related to the type of vegetation on the land-side. The most common vegetation for larger rivers is reed. For smaller rivers there is a larger diversity of water plants because of lower hydraulic loading or better water quality.
However, the cross-section of most navigation channels in the Netherlands is only restricted for navigation purposes and defined by the nautical guidelines (classes of traffic, see PIANC (1987a)), while the land along the channels is in private hands.
In such cases the realization of the environment-friendly solutions needs a special attention and can often be more costly than a standard solution. An example of such a situation with some alternatives is given in Figure 17.

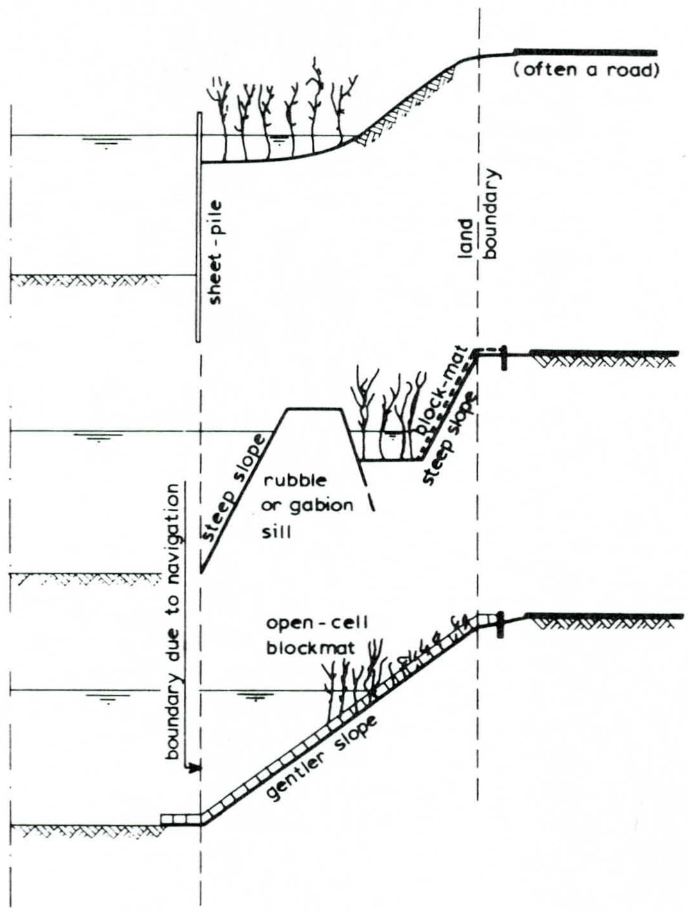


Figure 17 Examples of environment-friendly solutions for restricted waters

In general the installation costs of the environment-friendly measures are lower than the standard measures but the maintenance costs are higher and need another approach. However, recent Dutch studies have indicated that, on average, the environment-friendly solutions need not be more expensive than the traditional solutions, if both installation- and maintenance costs over the life-time of construction are properly taken into account. A legal problem can arise when, for example, the installation costs are subsidized by some central authorities and the maintenance costs are not. In such a case the local authorities will prefer a more expensive traditional (rigid) solution with less maintenance.

SHORT OVERVIEW OF CURRENT RESEARCH

The following studies are being carried out (and their end date):

- Reed as bank protection. Damping of wave attack (1989)[4]
- 2DH-numerical model of morphological changes and river bank erosion (1991)[4]
- Influence of soil type on erosion through cellular blocks (1989)[2]
- Desk study on scour at groynes (1989)[1,2]
- Geotechnical aspects of slope protection (1990)[3]
- Influence of berm on hydraulic loading on a bank (1989)[2]
- Prototype inventarization on growth of vegetation in open block-mats (1990)[1]
- Physical description of hydraulic loading between the groynes (1990)[1,5]
- Guidelines for clay specifications for grassmats (1990)[1]
- Guidelines for vegetation for river-dikes (1991)[1,5]
- Conceptual models on behaviour (and failures) of dikes and banks (1990)[5]
- Rational maintenance and management of river and channel banks (1990)[5]
- Computer program on design of navigation embankments (1989)[2,5]
- Computer handbook on scour in hydraulic engineering (1989)[1,2]
- Handbook on rock in hydraulic engineering (incl. river training works) (1991)[5]
- Manual on constructive aspects of environment-friendly (biotechnical) bank protection (1991)[5]
- Evaluation of vegetation requirements for bank protection (1990)[5]
- Manual on filter constructions in hydraulic engineering (1990)[5]
- Manual on application of alternative materials in civil engineering incl. environmental aspects (1991)[5]
- Numerical tools for maintenance and management of hydraulic structures (1989)[2]
- Decision models for operation management (1989)[2]
- Conceptual model on erosion rate of unprotected banks along navigable waterways (1991)[2,5]

CONCLUSIONS AND RECOMMENDATIONS

- The current knowledge and available (mostly 1D) mathematical tools for treatment of bank erosion are still not adequate for solving more complicated practical treatment of problems. Still more research is needed on that especially related to two-and three-dimensional treatment of problems.
- The present mathematical tools are important for sensitivity studies and for making a proper choice from alternative solutions.
- Because of the complexity of the river morphology and the mechanics of bank erosion for some specific problems, physical scale modelling is still the only investigation tool.

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1 Rijkswaterstaat, 2 Delft Hydraulics, 3 Delft Geotechnics,

4 Delft University, 5 Cooperative research incl. international cooperation.

- The current knowledge on erosion and sedimentation processes due to interaction of natural currents, waves and water stages and protective structures is still in a rudimentary stage and it is not yet possible theoretically to describe many phenomena and their interactions.
- The natural resistance of various types of vegetation against hydraulic loading is still not sufficiently evaluated, especially regarding the soil and the conditions after planting, and the methods of their (temporary or permanent) protection.
- The "technical optimum" goal for a bank protection should be transformed into a "social-economic optimum". It should include not only technical and economic aspects but also nature, landscape, environment, recreation, employment, etc.
  This means an evolution from just a bank protection to a multi-functional water-land transition.
- A proper balance between construction, inspection and maintenance, in terms of direct and indirect costs and effects, should be aimed at.
- The costs of environment-friendly solutions/measures seem often high compared with the maintenance costs of rigid protective structures. However, a cost-benefit analysis, including capital investment, will often turn out in favour of environment-friendly solutions.
- A review of the available data on erosion control indicates the lack of a central (international) data-bank, both for laboratory as on-site data. In general, the monitoring-data from the existing/realized schemes is rather scarce.
- Nowadays, ship-induced water motion can approximately be predicted for different traffic situations for schematized waterways. The same holds for the erosion of cover layers and filters for the common protective materials. The state-of-the-art on these subjects was already published. However, for more complicated geometries of waterways and banks supplementary research incl. physical modelling is still needed.
- A probabilistic approach for the design of a bank protection is important to obtain insight into the different "limit states" of structural stability. The state-of-the-art was published by PIANC (1987b). The event or fault tree can also be a useful tool for programming research and defining the priorities, and scheduling available budget.
- Computer models are under development to describe the water motion and to check the stability of banks. Existing techniques are only able to solve schematized situations satisfactorily.
- For research subjects of more general (national or international) interest it is preferable to organize collective research projects where all the proper authorities are involved. It increases the financial possibility of the project, its effectiveness and stimulate the implementation.
- It is important that the existing (international) knowledge on erosion control be systematized and made available for designers and managers in this field. This existing knowledge seems to be rather limited from a national point of view but it can be much more than we expected when it is integrated internationally into one homogeneous unit.
- Because of the complexity of the problems and the shortage of national research-funds, international co-operation, especially in the common fields of problems, should be further stimulated. International organizations as IAHR, PIANC or ASCE Task Committee on River Mechanics can play an important role in the realization of this aim.

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