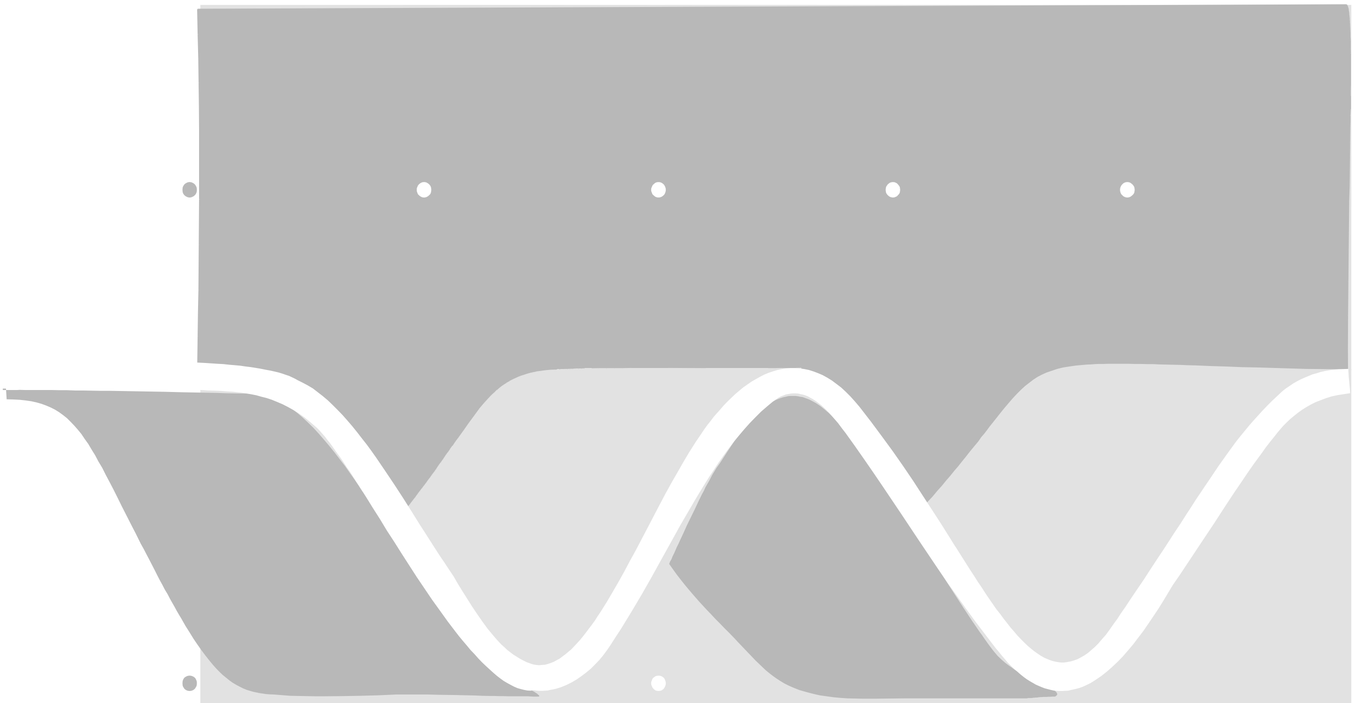

Internal Report

Falling aprons

Progress Report 2006

Research Report

December, 2006

Q4140.00

WL | delft hydraulics

Internal Report

Falling aprons

Progress Report 2006

Henk Verheij, Chris Stolker, and Mohamed F.M. Yossef

Research Report

December, 2006

WL | delft hydraulics

CLIENT:	WL | Delft Hydraulics
TITLE:	Falling Aprons – progress report 2006

ABSTRACT:

Falling aprons do not always behave as expected, e.g.: sometimes they are not launched. The reasons behind this are unknown what has to do also with the not well-known failure mechanisms responsible for correct functioning of falling aprons. In that respect it is significant that the design rules are based on geometrical considerations.
Therefore, the objective of the project is to analyze the present design rules and failure mechanisms regarding correct or incorrect functioning of falling aprons and, if necessary to propose improvements and to validate these improvements by physical tests.
In this report the activities carried out in 2006 are summarized resulting in an overview of present design rules, results of experimental and prototype results and possible failure mechanisms. The research will be continued in 2007 with describing successive events related to correct functioning of a falling apron, analyzing constructed falling aprons and to carry out laboratory tests.

REFERENCES:	R&D project within the framework of Research Funds of the Ministry of V&W on Theme 4 Infrastructural Questions

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Contents

1 Introduction

1.1 Background

Recently, a falling apron was proposed to protect banks along the River Meuse, but due to uncertainties about the correct behaviour of the falling apron the design was rejected. Moreover, a falling apron was constructed in the Hartel Canal to protect the banks against the tidal flow velocities. After a few years it was observed that the unprotected bed level was lowered with over 5 m, but that the falling apron was not fallen. It is not clear what the reason is of this non functioning although also no undermining has been observed under the falling apron.

The two examples of falling apron designs described above, more particular their non-functioning or uncertainties about it, were the reason for the Road and Hydraulic Department of Rijkswaterstaat to commission WL | Delft Hydraulics to carry out a research project within the framework of Theme 4 Infrastructural Questions of the Research funds of the Ministry of V&W.
This Progress Report presents the results of the activities carried out in 2006.

1.2 Problem definition

Uncertainty exists about the desired behaviour of falling aprons, e.g. falling aprons intend to fall if erosion occurs on levels below the apron in order to prevent instability and erosion of the bank. In literature design rules are presented based on geometrical considerations and improved by experience, but without a thorough understanding of failure mechanisms. Recent experiments in a physical model at Delft University of Technology showed that the falling apron functioned but the new protection of the bank consisted of one layer only which is insufficient in order to protect the underlying bank material.
Most falling aprons are constructed with riprap, but there is some recent experience in Bangladesh with geobags as constructing material for falling aprons. Model studies have been carried out and the first experiences with the behaviour of this type of falling aprons have been presented in literature.
In addition to the above problems, the following aspects require attention:

- Behaviour of a falling apron in areas susceptible for flow slides (common slopes below a falling apron of 1 vertical to 2 horizontal are to steep in those areas);
- Sudden transition of a fixed bank protection to a more flexible part, where a more gradual transition over a certain distance seems preferable;
- Resistance of apron material, in particular by applying geobags.

Summarizing: the reasons falling aprons do not function as assumed are not understood, and perhaps unknown mechanisms play a role.

1.3 Objectives

The objective of the project is:

> *To analyse the present design rules and failure mechanisms regarding correct or incorrect functioning of falling aprons and, if necessary to propose improvements and to validate these improvements by physical tests.*

The project will be restricted to conditions with falling aprons subjected to currents.

1.4 Summary of activities

During 2006 of the research project, the following activities have been carried out:

1. Steering committee meeting on June 20: Based on the first ideas a discussion has taken place about failure mechanisms, recent experiences at the Hartel Canal and the River Meuse.
2. Inventory of present design rules and experimental results: literature has been examined with respect to present state of knowledge. The results are presented in a memo (see Appendix A) and summarized in Chapter 2.1.
3. Literature review: a memo has been prepared for the purpose of covering the available literature concerning falling aprons (see Appendix B). A short characteristic of the literature is presented in Chapter 2.2.

2 Summary of research in 2006

2.1 Memo 1: Present state of knowledge

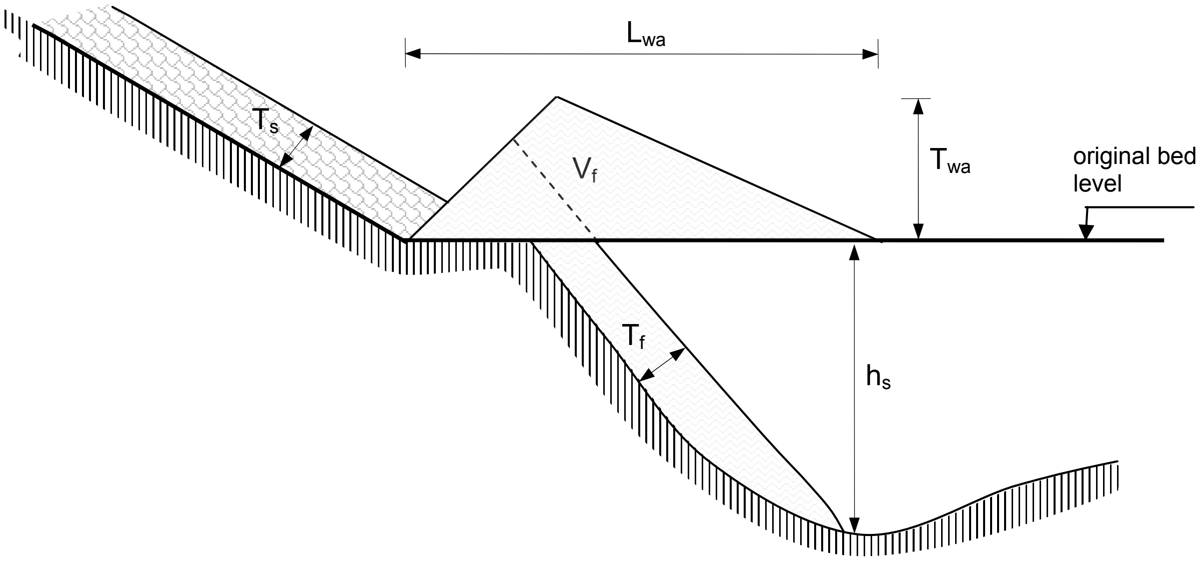
In this memo (see Appendix A) the following items were discussed in details:

1. The proposed design of the falling aprons along the Meuse river;
2. Design rules from other literature;
3. Experimental and prototype results;
4. Functioning of falling aprons.

The main conclusions were as follows:

- From the application in the prototype:
    - Some references indicate that falling aprons have functioned properly in different prototype situations.
    - Little information is available about situations when falling aprons failed to work.
    - The uncertainty about the functioning of a falling apron is still high.
    - Therefore, regular maintenance is inevitable.

- Current design rules:
    - The present design rules are all based on geometrical considerations.
    - In principle, all design equations can be simplified to $V_f = \lambda \cdot T_f \cdot h_s \cdot \sqrt{5}$, with λ being a safety factor, T_f the thickness of apron and h_s the scour depth, and assuming a final scour slope of 1:2 (vertical : horizontal).
    - The falling apron volume advised in the different design rules may vary with a factor 4, depending on the expected end thickness of the falling apron (T_f) and the safety factor.



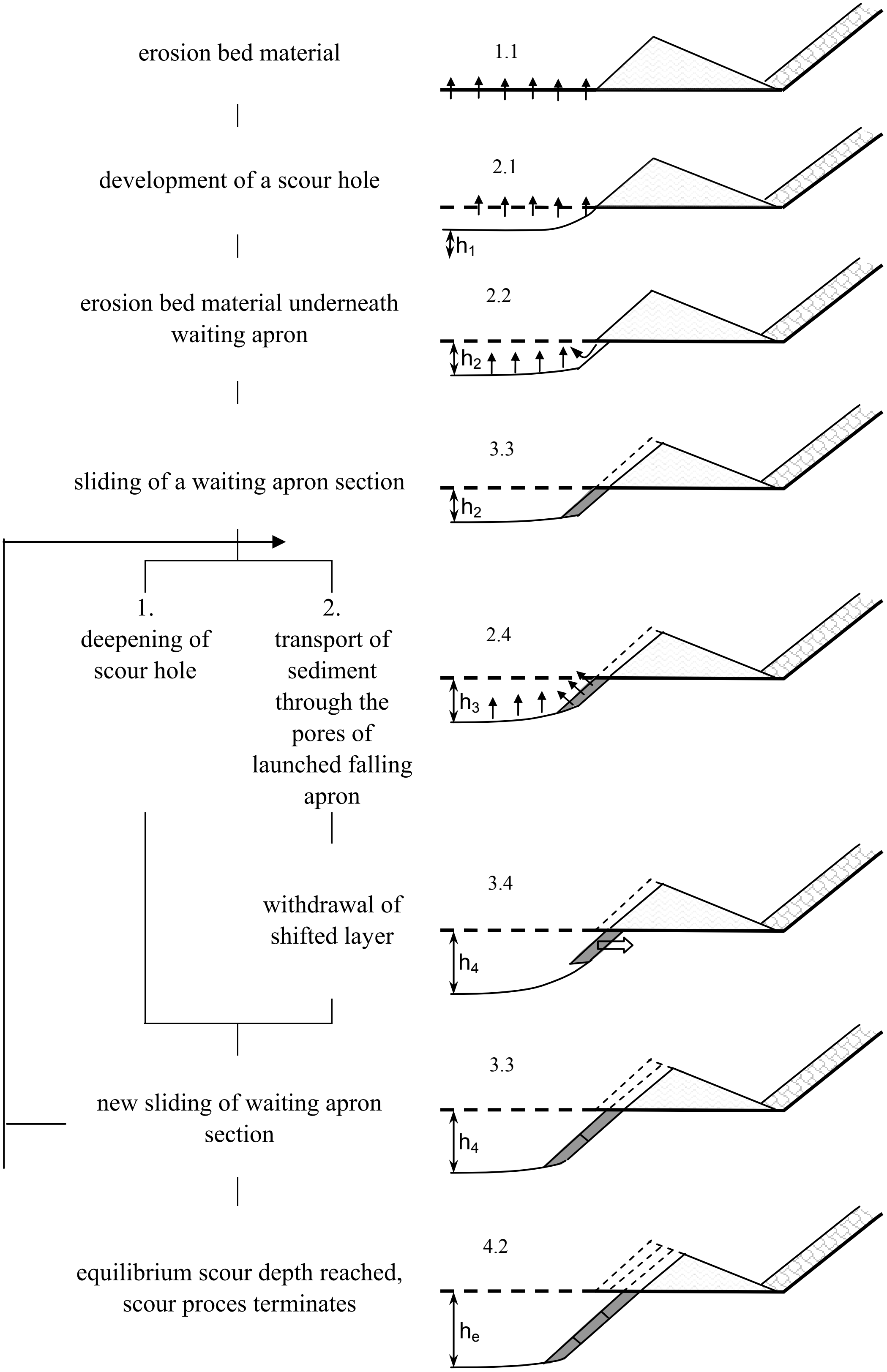
- From the results of experiments and prototype observations:
  - The slope of the scour hole is approximately 1: 2 (vertical : horizontal) (viz. 27 degrees) and the falling aprons are only launched when the apron is undermined at the toe.
  - The falling apron stones are covering the scour slope by sliding downwards and not by rolling over each other.
  - Experiments show a final thickness of about one stone layer

- The functioning of falling aprons
  - The way how falling aprons function in prototype and under different circumstances is not well understood.
  - A process or event tree may show the weak points of a falling apron and might help in improving the falling apron design rules

Based on the survey of present knowledge the following activities are recommended:

1. Extend the list of relevant processes related to the functioning of falling aprons;
2. Improve the event tree with the successive events in the development of a falling apron;
3. Describe the (failure) mechanisms which occur successively;
4. Confront the results with prototype data.

Event Tree Falling Apron



2.2 Memo 2: Literature survey

In this memo (see Appendix B) an up-to-date review of the available literature was conducted.

For the function of a falling apron a sort of controlled failure is expected to take place for the otherwise regular apron. The memo addresses in some details the failure mechanisms of riprap as a starting point to evaluate the functioning of falling aprons. The failure mechanisms can be summarised as follows:

1. Shear failure;
2. Winnowing failure;
3. Edge failure;
4. Bedform-induced failure (this can cause edge failure or total failure according to the location and extent of the riprap);
5. Bed-degradation induced failure (this can cause edge failure or total failure according to the location and extent of the riprap);
6. Sliding of riprap (coupled to edge failure);
7. Sinking of riprap (coupled with winnowing failure);
8. Rolling of riprap (this is as a seldom failure mode).

The functioning of a falling apron is to a great extent depending on undermining of the riprap layer, which can be associated to edge failure or winnowing failure. In cases of local scour (around piers or abutments) it is assumed that edge failure will always take place (if the extent of the riprap is short enough). Whereas, in cases of bank protection the situation is more complicated as bank erosion can be replaced by main channel erosion. Thus, the first step of the falling apron to function is not guaranteed to take place.

In the case of the Hartelkanaal (Hout & Blokland, 2006) the falling apron did not function as planned. After the opening of the seaward end of the Hartelkanaal to create a free route for inland navigation, main channel bed degradation took place and continued over 7 years without affecting the banks. For no apparent reason, bank erosion, which was expected to undermine the apron and consequently lead to the functioning of a falling apron, did not take place at all and the apron stayed as was originally dumped (see Figure 2-1).

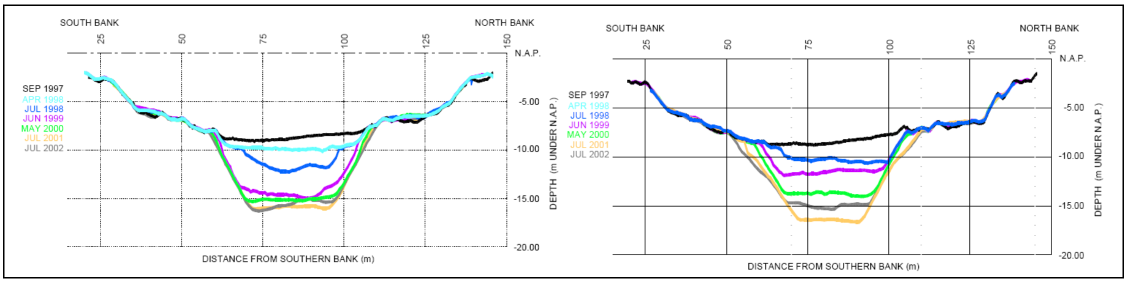


Figure 2-1: Bed level changes in the Hartelkanaal over the period 1997 – 2002; cross section 688 (left) and 694 (right) (source: Hout & Blokland, 2006).

What the literature did not address is a clear definition of a working falling apron and the process by which it would be guaranteed to achieve an acceptable level of protection by a falling apron.

3 Planned activities for 2007

The survey of consulted existing literature made clear that:

1. The mechanisms resulting in a falling apron as supposed are not fully understood;
2. Present design rules are not based on a theoretical approach but on geometrical considerations and they do not guarantee the falling of a falling apron.

Therefore, the following activities are recommended:

- To improve the event tree which describes all relevant successive events related to the functioning of falling aprons;
- To describe the (failure) mechanisms and develop design rules and confront the results with prototype data;
- To analyze constructed falling aprons and the reason why they functioned the way they did, e.g. as expected or not;
- To carry out physical tests to increase the insight into the mechanisms.

This research project is expected to be completed in 2007 with an end product of a scientific publication in the form of a conference paper; if possible it will be extended to a journal paper.

A Present state of knowledge

CONTENT:

A.1 Introduction

This memo is a literature survey on the present state of knowledge with regard to the topic of falling aprons. It deals with the available knowledge on the functioning of a falling apron and the present design rules associated.

Two definitions for a falling apron are cited first. Webster's dictionary defines a falling apron as:
"*A covering of loose stones or blocks laid on the berm of a river embankment to protect it from erosion. The stone from the apron gradually falls and goes on covering the slope as scour takes place and this process is called; launching*".
CUR (1995) defines a falling apron as:
"*a ridge of stone, dumped at the toe of a revetment, with the stones supposed to move in downward direction when sour develops in front of the toe, covering the entire downward slope*".

A.2 Design of falling aprons along the Meuse river

Introduction
Motivation for the research on the functioning of falling aprons was, amongst others, the rejection by the KRM (Kwaliteitsgroep Riverontwerp Maaswerken) of the Royal Haskoning design of the bank protections along the Meuse river (Grensmaas) near Meers. Falling aprons were an important aspect of this design. Although the written substantiation of the rejection is not discovered yet, oral communication point in the direction of the large uncertainties associated with the design. These uncertainties, however, do not necessarily concern the (functioning of) the falling aprons merely, but are probably also related to the river and model bound uncertainties. Nevertheless, for the following two reasons insight in the background of the Haskoning design of the falling aprons along the trajectory of the Meuse is very interesting:

1. It gives an indication of the present engineering approach of the design of falling aprons, which is well likely to be the current state-of-the-art
2. It may give insight in the uncertain aspects.

The sources consulted are the following:

a) Royal Haskoning (2001). Proefproject Meers; Principe-ontwerp rivierkundige werken op basis van DO – Meers, de Maaswerken, maart 2001.
b) Rijkwaterstaat (2003). Ontwerpershandleiding Granulaire Oeververdedigingen (Grens)Maas, 22 september 2003
c) Royal Haskoning (2005). Bodem- en oeverversterkingen Grensmaas, Ruw theoretisch ontwerp, eindrapport, 25 mei 2005

Background design
Within the framework of the Maaswerken, river enlargement works were being carried out in the Meuse river near Meers with the purpose of lowering the flood levels. The risks associated with hydraulic effects of the works was the possible damage to a levee upstream of the enlargement trajectory and the diminishing of the cover layer of a pipeline at the downstream side. The levee was located closely to the outer bend of the river, which made bank protection necessary.

Yet, the river enlargement works as well as the design of the protections aimed at minimizing the necessary fixation of the river to allow for maximum natural dynamics. Compared to the present situation, the flow attack will increase after realization of the enlargement works and heavier protections than in the present situation will be required. From Royal Haskoning (2001) it appears that, for the present situation, already local falling aprons were applied, with a width of 1 m.

Based on gradients of the flow velocities in the flow direction the equilibrium scour depth along the banks was estimated. The maximum scour depth calculated appears to be 5 m. Based on this expected erosion pattern toe protections were allocated and where considerable erosion was estimated a falling apron was adopted. In practice all toe protections were carried out as falling aprons, with the purpose to prevent undermining of the adjacent protected banks.

For the design of the protections Haskoning adopts its own design methodology (not available), of which a part has been reported by Rijkswaterstaat (RWS, 2003) (not the falling apron part). The considerations with respect to the falling aprons are based on experiences at the Jamuna Multipurpose Bridge in Bangladesh and the handbook “Manual on River Behaviour and Control” of the Central Board of Irrigation and Power, India (1971).

Composition of the falling apron
To enable the falling apron to slide along with the arising scour no sand tight filter is applied underneath the waiting apron layer. The falling apron should contain a wide gradation of rip rap, so that after launching a kind of filter can emerge. A range of 1 – 200 kg was recommended in this case, while the wide gradation should be mounted well-mixed. A density of the stones of 2650 kg/m3 was assumed.

Dimensions waiting apron
The necessary apron thickness on the scour slope is $2 \cdot D_n$. From the angle of repose of the natural bed material (1:1) the thickness of the waiting apron section should therefore be $\sqrt{2}$ times the required thickness.

This indicates that the width of the waiting apron equals the horizontal distance between the toe of the bank and the expected deepest point of the scour hole. In this case (scour slope 1:1) the width equals the scour depth itself. Toe scour up to around 0.5 m doesn't require a falling apron as it is being assumed to be part of natural variation of the bed. The report of Haskoning (2001) does not mention which criterion is used to determine the weight or size of the rip-rap stones for the falling apron. From Rijkwaterstaat (2003) it is well possible that the equation of Pilarczyk is being used.

Practical considerations
To ascertain for a reliable connection between the bank protection and the falling apron a so-called buffer is being applied. The buffer also realizes a smoothing of the tow line, when looked at from a top view. The buffers and falling aprons are placed outside the tow line on the nearly horizontal part of the alluvial bed. On average the buffer has a width of 2 m and consists of rip-rip 40-200 kg with a filter underneath. When discontinuities in height occur in the transition between the bank protection and the buffer and/or the buffer and the falling apron, this is being filled-out on the section with the thinnest layer.

In the transition between different longitudinal bank protection sections a 50 m long transition section is applied with the characteristics of the upstream section. At the end, the bank protection continues for an additional 50 m, which does not apply for the falling apron and the buffers.

End notes
It is remarked that in Haskoning (2005) no falling apron design is elaborated. However, report is made of a revaluation of the safety factor applied on the bank protection from 1.3 to 1.5, as a result of a reassessment of the uncertainties associated with the Meuse river stretch considered.

A.3 Design rules from other literature

A.3.1 References

The following additional literature was found on falling aprons:

CUR (1995). "Manual on the use of Rock in Hydraulic Engineering", Ministry of Transport, Road and Hydraulic Engineering division, Directorate-General for Public Works and Water Management, the Netherlands

De Groot, F. J. Lindenberg and R. Jorissen. (1988). "Gedrag van een bodemverdedigingsrand bij een over- en langstrekkende stroom", WL | Delft Hydraulics report, November 1988, Q0771.

FAP21 (2001). "Guidelines and Design Manual for Standardized Bank Protection Structures", Bank Protection Pilot Project FAP 21, Government of Bangladesh, Ministry of Water Resources, Water Resources Planning Organization, December 2001.

Fredsøe, J., B.M. Sumer and K. Bundgaard, (2001) Scour at a riprap revetment in currents. 2nd IAHR Symposium on River, Coastal and Estuarine Morphodynamics, 10-14 September 2001, Obihiro Japan.

Hossain, M.M., K.M. Salzar Hossain and M.A. Faheem Sadeque (date unknown). A laboratory study on Falling Apron around Abutment. <unclear if this paper has been published>.

Mosselman, E. (2006). “Bank protection and river training along the braided Brahmaputra-Jamuna river, Bangladesh”. In: “Braided Rivers”, International Association of Sedimentologists, Blackwell Publ. (to appear: 2006)

Melvile, B.W. and S. E. Coleman (2001). “Bridge Scour”. Water Resources Publications, LLC

Melville, B.W., S. van Ballegooy, S. Coleman and B. Barkdoll (2006). Countermeasure Toe Protection at Spill-Through Abutments, Journal of Hydraulic Engineering ASCE, march 2006

Neill, C.R. (1973), “Guide to bridge hydraulics”, Published for Roads and Transportation Association of Canada by University of Toronto Press. Editor: C.R. Neill.

Pilarczyk, K.W. (1990). “Design of seawalls and dikes – Including overview of revetments”. In: “Coastal protection” Proceedings of the short Course on coastal Protections, 30 June – 1 July 1990, Delft University of Technology, Editor: K.W. Pilarczyk, Balkema, Rotterdam, ISBN 90 6191 127 3, pp. 197-288

Pilarczyk, K.W. (1998). “Other design considerations” In: “Dikes and revetments; Design, Maintenance and Safety Assessment”. Editor: K.W. Pilarczyk, Balkema, Rotterdam, pp. 407-428

Schiereck, G.J. (1998). “Soil water Structure interactions” In: “Dikes and revetments; Design, Maintenance and Safety Assessment”. Editor: K.W. Pilarczyk, Balkema, Rotterdam, pp. 101-112

Schiereck, G.J. (1992). “Introduction to Bed, bank and shore protection; Engineering the interface of soil and water”, Draft report.

Schiereck, G.J. (2001). “Introduction to Bed, bank and shore protection; Engineering the interface of soil and water”, Delft University press, Delft, The Netherlands.

Te Slaa, B. (1995), River training works for a bridge across the BrahmaputraRiver, Bangladesh. In: River, coastal and shoreline protection; Erosion control using riprap and armourstone, Eds. C.R. Thorne, S.R. Abt, F.B.J. Barends, S.T. Maynord & K.W. Pilarczyk, Wiley, pp. 695-715

Thiel, B. (2002). Behaviour of a falling apron made from ‘poorly sorted’ material, M.Sc-Thesis, Technische Unversität Darmstadt / Delft University of Technology, Delft, April 2002.

Van der Hoeven, M.A., (2002). “Behaviour of a falling apron”, M.Sc. thesis, Delft University of Technology, Delft, January 2002.

Verhagen, H.J., M. van der Hoeven and B. Thiel (2003). “A new view on falling aprons”, COPEDEC VI, 2003, Colombo, Sri Lanka.

A.3.2 Synonyms and definitions

The literature provides other words as synonyms for falling apron, like:

- Launching apron
- Windrow
- Toe apron
- Launched windrow rock
- Longitudinal stone fill
- Longitudinal stone toe
- Launchable stone
- Supporting toe
- Rubble toe
- Boulder rip-rap
- (anti-) Scour aprons

Other apron related words are defined below:

- Waiting apron:
  Unused apron in a falling apron structure, waiting to be launched.

- Launched apron:
  In general, literature defines launching or launched apron as an exact synonym for falling apron (CUR1995, Websters dictionary). However, Mosselman (2006), as well as Schiereck (2001), make a distinction in falling apron, as being loose rock, and launching aprons as being interconnected or coherent, like a mattress block mat.

- Wedge shape
  Regarding the shape of the waiting apron section, there are some discrepancies in definition of a 'wedge shape". The term is probably introduced by Spring in 1903 (CBIP, 1983). Van der Hoeven (2002) interpret this term as being the shape of the apron section when making a vertical cross-section of the riprap rubble and seeing that the thickness gradually reduces to zero (see fig. 1A). However, Hossain (date unknown) defines the "wedge shape" of the apron section around an abutment from a top-view angle (see fig. 1B), with the wedge shape pointed in downstream direction.

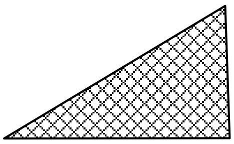


Fig. 1A

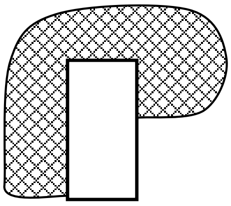


Fig. 1B

A.3.3 (Empirical) design rules

Toe scour is probably the most frequent cause of riprap failure (Melville, 2003). Toe scour undermines the slope and initiates progressive geotechnical slope failure. The primary function of falling apron is to cover the scour slope with a course material, thus preventing the scour to proceed. Secondary function of a falling apron is that it provides a toe weight which improves slope stability (Te Slaa, 1995).
To the present day, design rules for falling apron are primarily based on geometrical considerations (Verhagen, 2003). However, more insight in the functioning of falling apron can be obtained from physical experiments, like those of De Groot (1988), Van der Hoeven (2002) and Thiel (2002) and from field monitoring of FAP21/22 (2001).

Basically, the present design rules for falling aprons amounts to an apron volume enough to cover the entire scour slope with a thickness of 2 to 5 times D_{50} (imperfect filter) increased with 25 – 50% to apply for uneven distribution of the stones, containing more or less uniform (well sorted) or well-graded rock (depending on the reference) with a stone size that is capable of entailing the current forces according to requirements of for example Shields or Izbash . Additional design recommendations are, stones with high density (>2500 kg/m^3) to contribute to a better falling process (Schiereck, 2001), not laid on geotextiles and/or fascines as the falling apron will not be flexible enough to follow the scour slope in longitudinal direction (CUR 1995).

Design rules found in previous mentioned literature are summarized below, subdivided in volume/thickness of waiting apron, length of waiting apron section, grain size, grading, density, form of waiting apron section and thickness of launched apron layer. The parameters presented are explained in the appendix.

First, a table is presented which relates the desired thickness of the protection as a function of the stone diameter.

Table 1. Thickness of the launched apron

Thickness of launched apron				
Reference	(design) rule	design rule uniformed for a slope 1:2	Remarks	Based on
Schiereck (1992) Pg 12.12	$T_f = 5 \cdot D_{50}$	$T_f = 5 \cdot D_{50}$	More than normal thickness (2-3·D$_{50}$) since there is no filter layer	Geometrical considerations
CBIP (1989)	$T_f = 1.25 \cdot T_s$	$T_f = 2.5 \cdot D_{50}$	Recommendation of Spring in 1903. Source: Van der Hoeven (2002) and Verhagen et. al. (2003)	
CBIP (1989)	$T_f = 1.5 \cdot T_s$ at the toe (transition with slope revetment) to $T_f = 2.25 \cdot T_s$ at river side	$T_f = 3\ to\ 4 \cdot D_{50}$	Recommendation of Rao. Source: Van der Hoeven (2002), and Verhagen et. al. (2003)	
Melville & Coleman (2001) pg. 336	$T_f = 1.5 \cdot T_s$	$T_f = 3 \cdot D_{50}$	Volume of launchable stone should be sufficient to give a thickness after launching of 1.5 times the design thickness to the expected depth of scour.	
Haskoning (2001)	$T_f = 2 \cdot D_n$	$T_f = 1.7 \cdot D_{50}$.		

From Table 1 it can be concluded that the desired thickness varies between 1.7 and 5 times the stone diameter (assuming $T_s = 2\ D_{50}$ and $D_n=0.85\ D_{50}$).

Based on this requirement the volume, thickness and length of the waiting apron can be estimated, see Table 2 and 3.

In principle, all design equations can be simplified to:

$$V_f = \lambda \cdot T_f \cdot h_s \cdot \sqrt{5}$$

with λ being a safety factor and assuming a final slope of 1:2 (vertical : horizontal).

Table 2. Volume of the waiting apron

Volume or layer thickness of waiting apron				
Reference	(design) rule	design rule uniformed for a slope 1:2	Remarks	Based on
Schiereck (2001) Pg 282	$V_f = (5\ to\ 7) \cdot h_s \cdot D_{n50}$ (m^3/m^1)	$V_f = (4.25\ to\ 5.95) \cdot h_s \cdot D_{50}$	an extra quantity of 25% is recommended for uneven distribution during process of falling (25% affirmed by Maynord in discussion) The length of the scour slope seems to be taken equal to the scour depth when using 5 instead of 7.	Geometrical considerations
Te Slaa (1995) pg. 714	$V_f :: 5 \cdot D + 25\%$	$V_f = 14 \cdot h_s \cdot D_{50}$	see also CUR (1995)	Geometrical considerations
CUR (1995) pg. 8-45	$V_f = h_s \cdot T_f \cdot \sqrt{5}$ with $T_f = 1.25 \cdot \left(5 \cdot D_{65}\right)$	$V_f = \left(\alpha \cdot 14\right) \cdot h_s \cdot D_{50}$	- 5·D_{65} for uneven distribution - x1.25 as extra quantity uneven distribution *25%) - x $\sqrt{5}$ for length along slope with gradient of 1:2	Geometrical considerations
FAP21 (2001) pg. 5-20	$V_f = 1.5 \cdot D_n \cdot \sqrt{5} \cdot h_s \cdot C_{fa}$	$V_f = (4.2\ to\ 5) \cdot h_s \cdot D_{50}$	assuming scour slope gradient of 1:2 D_n is block size (1.5·D_n is the proposed layer thickness after scouring without voids). h_s as vertical distance between base level of falling apron at time of construction and deepest point of the expected design scour hole. C_{fa} = flow attack coefficient: 1.5 (moderate flow attack), 1.75 (strong flow attack).	Geometrical considerations
FAP21 (2001) pg. 5-21	$T_{wa} = \left(5\ to\ 8.5\right) \cdot D_n$	$V_f = (9.5\ to\ 16.15) \cdot h_s \cdot D_{50}$	Without voids	Geometrical considerations

Volume or layer thickness of waiting apron				
Reference	(design) rule	design rule uniformed for a slope 1:2	Remarks	Based on
Melville & Coleman (2001) pg. 336	$V_f :: 1.5 \cdot T_s$	$V_f = 6.7 \cdot h_s \cdot D_{50}$	Volume of launchable stone should be sufficient to give a thickness after launching of 1.5 times the design thickness to the expected depth of scour.	Geometrical considerations
Neill (1973) Pg. 127	$T_{wa} = 2 \cdot D$	$V_f = 4.4 \cdot h_s \cdot D_{50}$	It is mentioned on pg. 136 that “launching aprons do not perform well on cohesive channel beds where scour occurs in the form of slumps with steep slip faces. In such cases bank revetment should be continued down to the expected worst scour level, and the excavation then refilled”.	Geometrical considerations
Royal Haskoning (2001)	$T_{wa} = a \cdot 2 \cdot D_n \cdot$	$V_f = 3.8 \cdot h_s \cdot D_{50}$	a = $\sqrt{2}$ for slope 1:1 a = $\sqrt{5}$ for slope 1:2 Haskoning mentions an additional safety factor of 1.3 to 1.5 for thee Meuse.	Geometrical considerations

Table 3. Length of the waiting apron section

Length of waiting apron section			
Reference	(design) rule	Remarks	Based on
CUR (1995)	$L_{wa} = 1.25 \cdot h_s$	It is not clear whether L_{wa} is horizontal length or length along slope	Geometrical considerations
Melville & Coleman (2001) pg. 368	$L_{wa} = 1.5 \cdot h_s$	For guide banks at bridge crossings	Geometrical considerations
CBIP (1989)	$L_{wa} = 1.5 \cdot h_s$	Recommendation of Inglis, after Van der Hoeven (2002)	Geometrical considerations
FAP21 (2001) pg. 5-21	$L_{wa} = 0.7 \text{ to } 1.0 \cdot h_s$	It is remarked that for FAP21 the apron structures consisted of a combined launching (upper part, interconnected structure like a mattrass) and falling apron (lower part, loose stones), with the length of the launched apron section being 20 m as a dimension of the standardized protection structure.	Geometrical considerations
Neill (1973) Pg. 127	$L_{wa} = 1.5 \cdot h_s$		Geometrical considerations
Royal Haskoning (2001)	$L_{wa} = b \cdot h_s$	b = 1 for slope 1:1 b = 2 for slope 1:2 etc	Geometrical considerations

In addition to the above design recommendations information has been found on grain size, grading, rock density and apron shape. Tables 4 to 7 summarize this information.

Table 4. Grain size

Grain size			
Reference	(design) rule	Remarks	Based on
Melville & Coleman (2001) pg. 369	$D_r = 0.0418 \cdot u^2$	For launching apron at guide banks. Based on the Indian Roads Congress (1985)	

Table 5. Grading

Grading			
Reference	(design) rule	Remarks	Based on
Schiereck (2000) Pg 282	fairly uniform	To create an imperfect filter: a perfect filter would hinder erosion through the stones, resulting in an uncontrolled drop of the apron after some time.	
Royal Haskoning (2001)	wide gradation and Well-mixed	So that after launching a kind of filter can emerge	

Table 6. Density of the stones

Density			
Reference	(design) rule	Remarks	Based on
Schiereck (2000) Pg 282	High (>2500 kg/m^3)	Contributes to a better falling process	
Royal Haskoning (2001)	2650 kg/m^3		

Table 7. Form of the waiting apron section

Form of waiting apron section			
Reference	(design) rule	Remarks	Based on
CBIP (1989)	Wedge shape. Thickness at the toe equal to thickness of slope revetment and increasing towards the river.	Recommendation of Spring in 1903. after Van der Hoeven (2002)	
Royal Haskoning (2001)	Uniform thickness		

A.4 Experimental and prototype results

Flume experiments on the behaviour of a falling apron, or falling apron-like structures, were carried out by De Groot et.al. (1988), Van der Hoeven (2002) and Thiel (2002). De Groot et.al. examined the behaviour of the edge of a bed protection in case of toe scour due to parallel and/or perpendicular flow. Two bed protections were involved; riprap and a block mat. Even though De Groot did not investigate an actual falling apron, the structures involved are falling apron-like with the waiting apron consisting of only one rock layer. Van der Hoeven and Thiel tested a real falling apron of riprap, scaled to flume dimensions. Both tests are comparable, but Van der Hoeven focused on well sorted (more or less uniform) riprap, while Thiel focused on 'poorly sorted' (graded) riprap.

Most prototype information originates from applications of falling aprons in Indian rivers (Pilarczyk, 1998), where they were already applied at the beginning of the 20th century (Van der Hoeven, 2002). Also, different solutions for protection of strongly retreating banks along the actively braiding Brahmaputra-Jamuna river in Bangladesh were developed and tested during the ten year long Flood Action Plan (FAP21/22) Bank Protection and River training Pilot Project (Mosselman, 2006; FAP21/22, 2001). At two locations, e.g. a 800 m long section at Bahadurabad and a 550 m long section at Ghutail, different combinations of systems and materials for cover layers and filter layers were applied, all consisting of a launching apron and a falling apron. The launching aprons were made of dumped CC blocks, riprap and different types of mattresses over geotextile filters. The falling aprons comprised CC blocks, riprap, geo-sand containers, stone-filled gabion sacks and selected boulders. Mosselman (2006) concludes that the bank retreat was effectively stopped by the revetment structures.

Lessons from these experimental and prototype applications are separated in the tables below.

Table 8. Thickness of launched apron in experimental tests

Thickness of launched apron			
Reference	Result	Remarks	Based on
Van der Hoeven (2002) Verhagen (2003)	$T_f = D_{50}$	Well sorted material $(\sigma_g = 1.35 - 1.43)$	Experiments
Thiel (2002) Verhagen (2003)	$T_f = D_{50}$	Poorly sorted material $(\sigma_g = 2.14)$	Experiments
De Groot (1988)	$T_f < D_{50}$	Due to the fact that too little apron material available Riprap (D_{50} = 0.046 m - stabile according to Izbash) Material quite uniform $(\sigma_g = 1.34)$, comparable with Van der Hoeven (2002)	Experiments

Table 9. Slope after launching in experimental tests

Slope after launching			
Reference	Result	Remarks	Based on
Van der Hoeven (2002)	1:2		Experiments
Thiel (2002)	1:2		Experiments
CBIP (1989)	1:3 – 1:1.5	Out of Van der Hoeven (2002)	Prototype observations
Schiereck (1992)	1:2		Geometrical considerations
De Groot (1988)	1:4 – 1:3.5		Experiments

Observations from the experiments are the following:

- The slope of the scour hole is approximately 1: 2 (vertical : horizontal) (viz. 27 degrees) and the falling apron will only be launched when the apron is undermined at the toe.
- The falling apron stones are covering the scour slope by sliding downwards and not by rolling over each other.
- Experiments show a final thickness of about one stone layer.

Considering the above observations it may lead to the conclusion that a falling apron functions by means of sliding of layers along the scour slope and not with rolling downwards of individual stones, because sliding occurs at a slope angle that is smaller than the angle of repose for stones (30 to 40 degrees; see Figure 2 and 3).

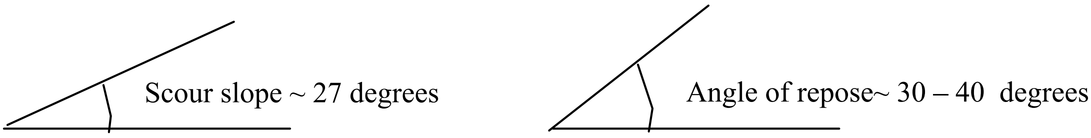


Figure 2. Slope after launching in experimental tests

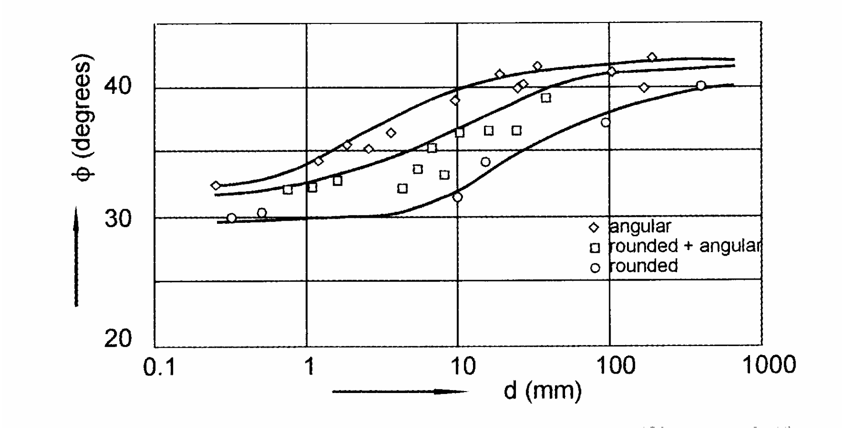


Figure 3. Angle of repose for non-cohesive materials (Schiereck, 2001)

Another related remark is whether or not a falling apron thickness of more than 1 layer will develop. If the thickness of the launched apron will not exceed 1 layer, designs should take into account that during the lifetime of the structure regular maintenance will be required because erosion of the bank will continue and never stop.

A.5 Functioning of falling aprons

From the previous elaboration it appears that the design rules for falling aprons is primarily based on geometrical considerations, e.g. the volume you need is what you dump possibly increased with a safety factor. Little information is available and incorporated in these equations on the different processes that take place when a falling apron comes into action. Although prototype applications indicate that falling aprons work, as it was proven that the bank retreat was effectively stopped (f.i. Mosselman, 2006), little information is available about exactly how it stopped the erosion and how the falling apron was distributed along the scour slope in time. Most information about the individual process involved can be obtained from literature describing experimental test on falling aprons or regular revetments. The information however is often very fragmented and not directly general applicable. Therefore, information from various articles should be combined in order to obtain a more overall picture of the functioning of a falling apron. This is aimed at by developing a kind of an event tree, in which the different successive steps are described from an initial falling apron to the stage at which the falling apron did its work and stopped the scour to evolve any further. A correct view of the successive processes may show the weak points of a falling apron and might help in improving the falling apron design rules. At first, the different processes involved are enumerated, which is done with the following successive general process steps. Hereafter the event tree can be build.

Flow attack → Sediment response → Falling apron response → Flow response
↑____↓

These general process steps are divided in the possible sub-processes enumerated below.

Process associated with a falling apron

1. Flow attack
1.1 Uniform flow
1.2 Large secondary or spiral flow (occurring in bends and at frontal flow attack of the bank)
1.3 Horseshoe vortices around individual apron stones, causing undermining, toppling and sinking of the individual stones (Fredsøe et.al., 2001)

2. Sediment response
2.1 Sediment will disappear at the toe
2.2 Sediment will disappear underneath the toe
2.3 Sediment disappears through the stones of the waiting apron (in case of uniform gradation (Schiereck, 2001),
2.4 Sediment disappears through the stones of the launched apron
2.5 Sediment will be moved (and deposited) sideward and in longitudinal direction (Fredsøe et.al., 2001),
2.6 Geotechnical instability of the soil
2.7 Liquefaction or flow slides

3. Falling apron response
3.1 Rolling of the stones
3.2 Sliding of the stones
3.3 Sliding of falling apron sections
3.4 Withdrawal of apron layer
3.5 Macro-instability

4. Flow response
4.1 Due to higher bed roughness above the rip-rap (falling apron and/or bank protection), the flow will tend towards the smoother middle section of the river. This causes less flow attack on the stone bed, but perhaps more flow attack on the sandy bed and larger toe scour.
4.2 Evolving scour holes will enlarge the conveyance capacity of the river and subsequently the flow velocities will decrease.

Process numbers 1.1, 2.1, 2.2, 2.4, 3.3, and 3.4 are combined in the event tree in the appendix which, for an important part, is based on information from Verhagen et.al. (2003). This event tree should be extended with the other processes in the future.

A.6 Conclusions and recommendations

From the literature survey the following conclusions can be drawn.

Prototype results and designs:

- Some references indicate that falling aprons have functioned properly in different prototype situations.
- Little information is available about situations when falling aprons failed to work.
- The uncertainty about the functioning of a falling apron is still high.
- Therefore, regular maintenance is inevitable.

Present design rules

- The present design rules are all based on geometrical considerations.
- In principle, all design equations can be simplified to $V_f = \lambda \cdot T_f \cdot h_s \cdot \sqrt{5}$, with λ being a safety factor and assuming a final scour slope of 1:2 (vertical : horizontal).
- The falling apron volume advised in the different design rules may vary with a factor 4, depending on the expected end thickness of the falling apron (T_f) and the safety factor.

Experimental and prototype results

- The slope of the scour hole is approximately 1: 2 (vertical : horizontal) (viz. 27 degrees) and the falling aprons are only launched when the apron is undermined at the toe.
- The falling apron stones are covering the scour slope by sliding downwards and not by rolling over each other.
- Experiments show a final thickness of about one stone layer.

Functioning of falling aprons

- The way how falling aprons function in prototype and under different circumstances is not well understood.
- A process or event tree may show the weak points of a falling apron and might help in improving the falling apron design rules

The following is recommended as future activities:

- Finalize the literature survey.
- Extend the list of relevant processes related to the functioning of falling aprons.
- Improve the event tree with the successive events in the development of a falling apron.
- Describe the (failure) mechanisms which occur successively.
- Check the results with data.

Symbols

D_i = Grain size diameter where i% of the grain mass has a smaller diameter (m)

D_{n50} = Median nominal grain size diameter $(m_{50}/\rho_s)^{1/3}$ (m)

D_n = nominal grain size diameter

L_{wa} = Length of a falling apron

T = Thickness (m)

T_f = Thickness fallen or launched apron (m)

T_{wa} = Thickness waiting apron (m)

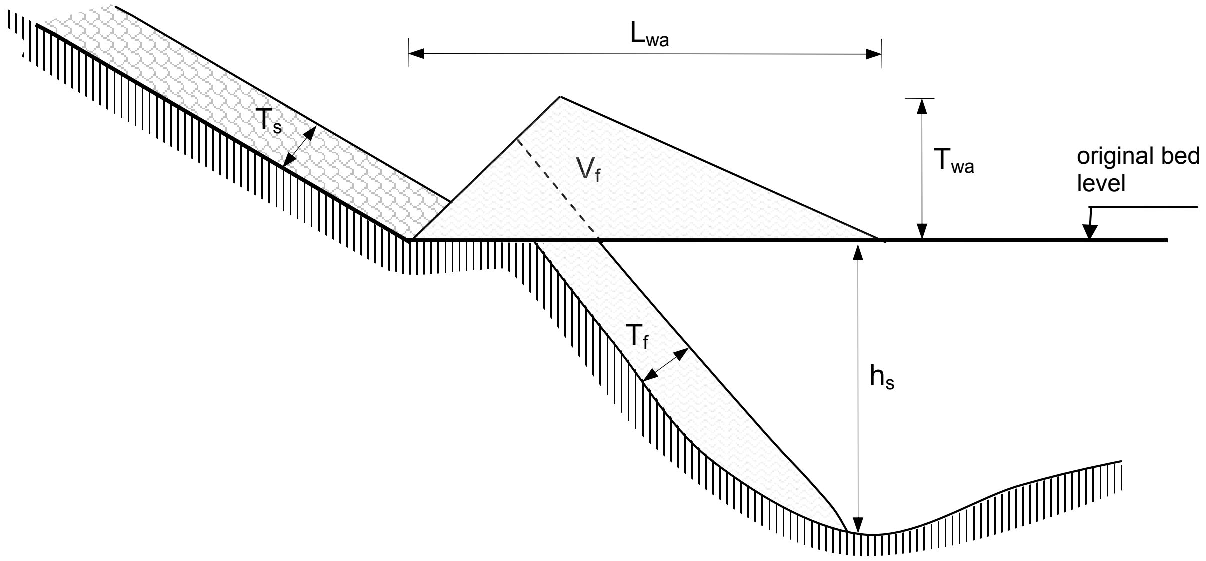
T_s = Design thickness of a slope revetment (m)

h_s = Scour depth (m)

u = Mean flow velocity (m/s)

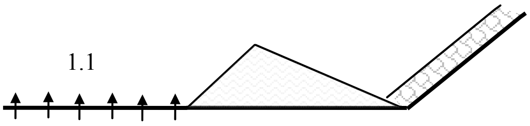
V_f = Volume of falling apron per linear metre protected longitudinal length (m^3/m)

σ_g = Geometric standard deviation: $\sigma_g = \left(D_{85}/D_{15}\right)^{\frac{1}{2}}$; the larger σ_g becomes the less uniform the material is (rule of thumb: $\sigma_g > 2$ is graded).

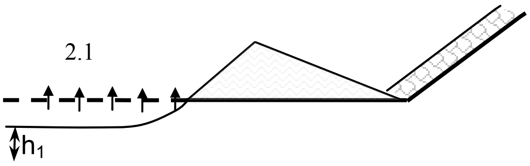


Event Tree Falling Apron

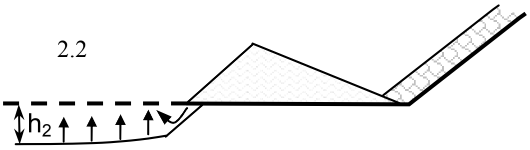
erosion bed material



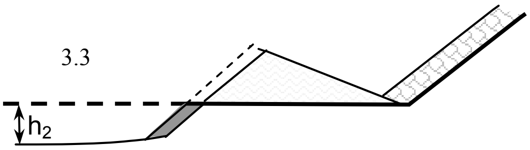
development of a scour hole



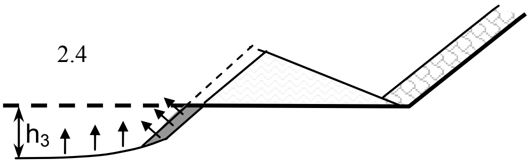
erosion bed material underneath waiting apron



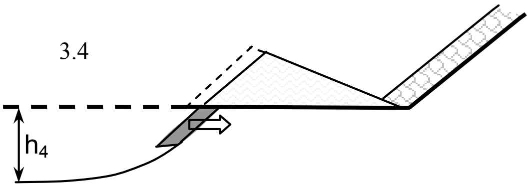
sliding of a waiting apron section



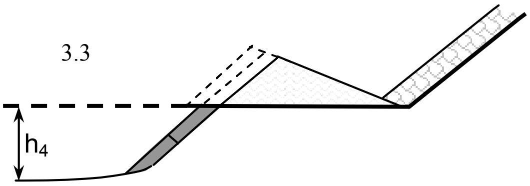
1. deepening of scour hole
2. transport of sediment through the pores of launched falling apron



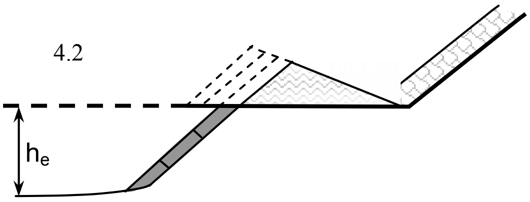
withdrawal of shifted layer



new sliding of waiting apron section



equilibrium scour depth reached, scour proces terminates



B Literature survey

This memo gives an overview of the state of the art literature with respect to *falling aprons*.

Riprap failure mechanisms

For the function of a falling apron a sort of controlled failure is expected to take place for the otherwise regular apron. In this section we try to shed some light on the failure mechanisms of riprap. Several researchers discussed the stability of riprap and its failure mechanisms.

(Y.-M. Chiew, 1995) presented a thorough analysis of riprap failure mechanisms at bridge piers. His experiments were conducted with a pier of diameter 0.070 m inserted in an almost uniform sand of size 1 mm. The riprap sizes investigated were 2.6, 4, and 4.85 times larger than the sand. The extent of riprap was defined by the diameter and the riprap thickness. All tests involved an approach flow depth of 0.20 m for clear-water conditions.

Three failure modes were identified:

1. Shear failure, where the riprap is unable to withstand the downflow and the horseshoe vortex associated with the pier scour mechanism;
2. Winnowing failure, where the underlying finer bed material escapes through the voids of the riprap; and
3. Edge failure, where riprap material at the interface to the bed material slides into the scoured surface.

In his paper (Y.-M. Chiew, 2002), Chiew summaries research on the use of riprap protection. He describes in great details the failure mechanisms related to pier scour. He adds the following two failure mechanisms:

4. bedform-induced failure, which refers to the destabilization of the riprap layer due to its interaction with the propagating bedforms (see as well Melville, van Ballegooy, Coleman, & Barkdoll, 2006).
5. bed-degradation induced failure, this type of failure occurs under conditions where general bed-degradation takes place.

When investigating riprap failure at circular bridge piers, Unger & Hager (2006) defined three distinct failures modes, namely:

1. Sliding a mode occurring once the outer riprap rows are damaged due to the formation of a scour surface between the bed sediment and the riprap; any element from an inner riprap row may possibly fail by sliding into the scour surface.
2. Undermining as the typical failure mode occurring for a riprap diameter much larger than the bed sediment. In this case, the critical riprap element is not moved horizontally, but sinks into the bed sediment. This condition is less severe than sliding, because a residual protection is guaranteed after failure has occurred.
3. Rolling as a relatively seldom failure mode, if the ratio between the riprap size to the sediment size is close to unity, so that the inner riprap members may roll away by jumping over the outer riprap rows due to the high velocity close to the element perimeter.

Gisonni & Hager (2006) reported that for selected conditions another sliding process was observed, they defined it as *failure mode 3*. For spurs of extremely small length and small relative height, the second spur was subjected with an almost plane jet originating from the overflow of first spur. This jet impinged onto the second spur and caused downflow, similar to abutments or piers. Instead of generating an interface scour along the riprap periphery towards the channel axis, a downflow scour upstream of the second spur developed eventually so intense that the riprap element located upstream close to the river bank slid into the downflow scour hole.

The case of the Hartelknaal (non-falling apron)

Hout & Blokland (2006) give an overview of a case study where falling aprons were applied in the Hartelkanaal in Rotterdam. In this case the falling apron did not function; the scour did not lead to the falling of the apron and consequently, the main stream experienced excessive erosion. The design of the apron for bank protection was based on maximum bed degradation that reaches NAP -15 m; it was predicted that it will be reached over some 10 years.

Riprap design:

The design of the top layer of the apron protection was based on a quasi-probabilistic calculation of movement of stones. The hydraulic loads which were taken into account were a combination of maximum ebb-current, seiche current, and return current caused by a full loaded push barge combination sailing in the upstream direction, eccentric from the canal axis. The return current under the bow of the barge was taken into account (about two times larger than the mean return current around the ship). We need to mention here that the navigation-induced current considered as design load might be bit exaggerated. The stability of the stones was calculated using the Shields-parameter. It was found that in a situation without ships, a rubble layer of standard sort 80-200 mm would be stable. In combination with a return current, at the slope and also at the 20 m width toe protection, the movement of stones is almost none. Only in more negative scenario where the current velocities are higher than the expected value, substantial movement of stones occurs. Under some circumstances in these scenarios one passing ship can move almost all stones in the upper layer. Accordingly, They used a rubble top layer that consisted of broken stone standard sort 80-200 mm. They used a filter only for the first 5 m of the apron (see Figure 1).

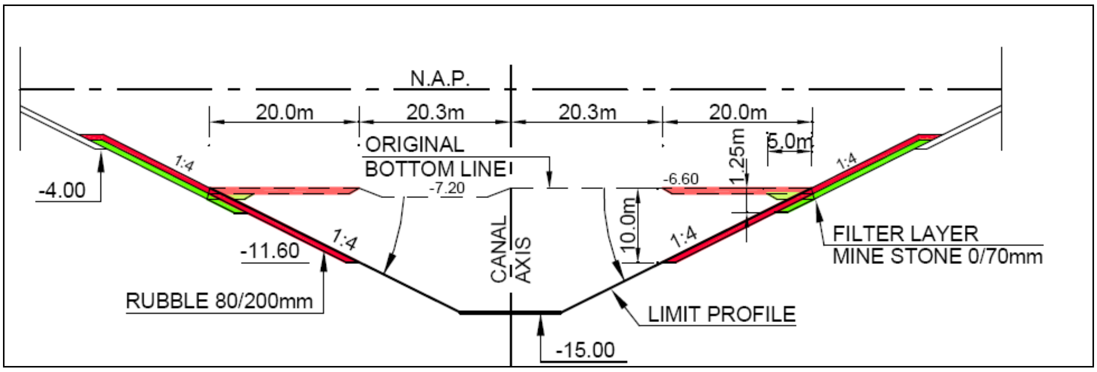


Figure 1: Design of the slope and toe protection with predicted settlement of toe for the Hartelkanaal in Rotterdam according to Hout & Blokland (2006). Note the discrepancy between the side slope (1:4) and the dimensions (10m:20m). Note the discrepancy between the side slope (1:4) and the dimensions (10m:20m), we think 10m is to be replaced by 5m.

The falling apron:

They assumed two mechanisms would lead to the functioning of the falling apron. Firstly, what they called *imperfect filter* where the underlying finer bed material escapes through the voids of the riprap. This is referred to as Winnowing failure by several researchers (see for example Y.-M. Chiew, 1995; 2002 ; Melville et al., 2006). Secondly, what they called *falling apron mechanism*, from their description it became clear that they were referring to toe failure (see for example Barkdoll, Melville, & Ettema, 2006; Y.-M. Chiew, 1995; Y.-M. Chiew, 2002). They however indicated that the settlement in this case would involve sideward movement of stones. Consequently, this would reduce the layer thickness and thus intensifies the imperfect filter mechanism. It was expected that, with the relatively large layer thickness used for the slopes, the falling apron mechanism would dominate the imperfect filter.

Field observations:

From the field observations given in Figure 2 we can see that the development of very steep side slope adjacent to the toe of the apron takes place in few months. Right from the start of the scour process, the side slope got very steep (around 1:1.6). The toe protection did not settle as it was expected. The top of the eroded slope moved only for few meters towards the canal banks. The reason why the toe protection did not settle at all, or only a small part settles with the erosion of the bed, is not clear at this moment. In 2003, the unprotected bed of the main channel was fixated to prevent it from further erosion.

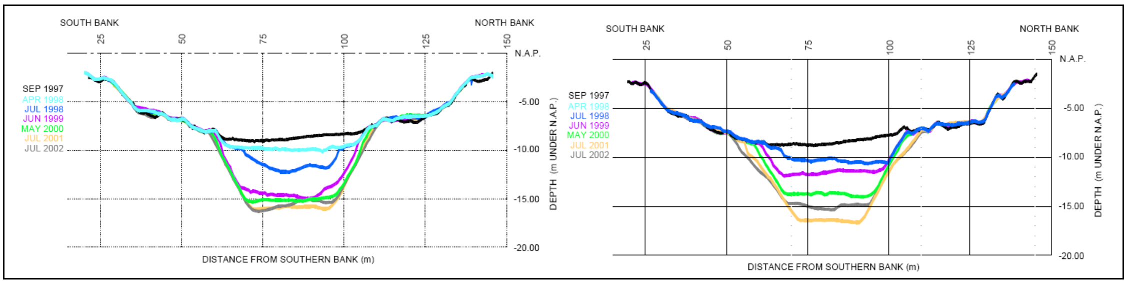


Figure 2: Bed level changes in the Hartelkanaal over the period 1997 – 2002; cross section 688 (left) and 694 (right) (source: Hout & Blokland, 2006).

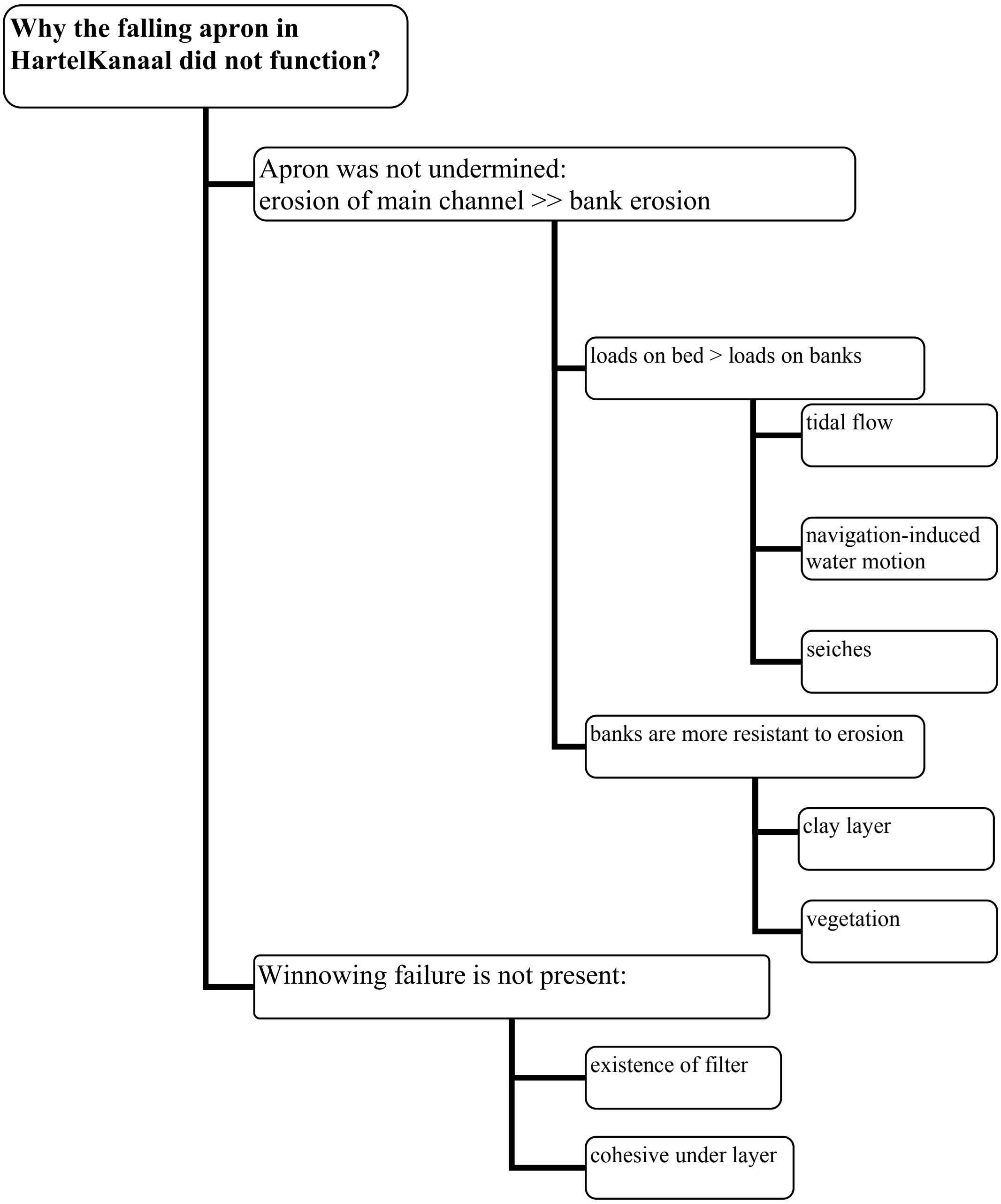


Figure 3: Design tree for the identification of the reason behind the failure of the falling apron in the Hartelkanaal.

Discussion

In the case of the Hartelkanaal the falling apron did not function as planned. Main channel bed degradation took place and continued over 7 years without affecting the banks. For no apparent reason, bank erosion, which was expected to undermine the apron and consequently lead to the functioning of a falling apron, did not take place at all.

In order to evaluate the reason way the apron did not function we need further to evaluate the following aspects:

- What was the under laying soil composition; in this paper little information is given about the soil composition of the bed and banks where the apron was applied. It was briefly mentioned that clay layers are present.
- What was the deviation of the design load from what has been observed during the period 1997-2002? It was mentioned briefly that the measured velocity was found to be lower than predicted. No mention about seiche current and the *exaggerated* navigation-induced current.
- Why the main channel bed erosion was much higher than bank erosion.

The case of the Jamuna River (adaptive falling apron using geobags)

Oberhagemann, Stevens, Haque, & Faisal (2006) presented a case study where falling apron using geobags was applied successfully in the Jamuna River. The river bed at the project can be characterised by fine and very fine sand, with median diameters of 0.1 to 0.3 mm.

In geobags revetment, the geobags form a thin layer over the natural (unprepared) bank slope. No filter is required. The design calls for placing geobags only below low-water level. Above low water, concrete blocks or other hard material are used to provide the additional stability to resist wave attack and to guard against vandalism.

In a laboratory experiment model 90-kg geobags were dropped into a 10-m depth of water flowing at 1.7 and 3.3 m/s (scaled-up prototype values). It was difficult to achieve complete coverage even when the bank was visible and bags were dropped to cover an observed bare spot. Bags tended to cluster in random piles surrounded by bare patches. Mixtures of bags achieved more precarious coverage.

In the feasibility study it was conceived that a heap of geobags of different sizes placed along the bank just below low water would launch when undercut by erosion and covers the eroding area with a 0.9 m thick layer of protection.

Diving investigations of the first implemented works of the same project indicated that this did not fully happen. Geobags indeed launched down the slope and protected the bank from further erosion. The launching, however, does not result in multiple layer coverage as assumed. The coverage was either by single bags or sometimes lumpy with bare patches. The smallest bags disappeared. Clearly adaptations were needed. The implementation concept was modified to arrive at a stable multiple layer coverage.

For predominantly construction purposes, single-size geobags are favourable so only 126 kg bags were used. The protective system was to remain geobags revetment protection below low water level and concrete blocks or interconnected systems such as grout-filled mattresses above low water.

A multi-step implementation system combining a fast response to erosion threat and an optimized use of geobags has been developed and implemented that has provided satisfactory protection. The system involves the following procedures:

- Immediate Protection: Fast response to river erosion was provided through mass dumping of bags along the eroding bank, allowing the bags to launch down the slope. The result is a commonly one-bag thick cover layer, which substantially reduces erosion rates but is not stable in the long run. During this initial stage only temporary wave protection above low water level, consisting of geobags, was provided.

- First level protection: A three-bag layer was placed over the launched bags making, on the average, a four-layer thickness on the slope after completion of this first level protection. In addition, a thin and wide falling apron for the expected future scour is placed at the toe of this protection.
- Adaptation: The response to the protection results in toe scour along the revetment. For this purpose falling aprons were placed along the toe. These falling aprons may have to be upgraded later to first level protection.
- Second level protection: The River reacts to the bank protection during the initial years and there are changes to the overall morphology. Settlements and adjustments of the unprepared uneven bank will occur. Scour might reach deeper levels and the falling apron at the toe starts deploying. The second level protection is designed to improve the protective layer of first level protection and subsequent adaptation works and to arrive at a more uniform surface. It is planned to place 1.5 layers of bags after reaching deepest scour depths.
- Maintenance: Regular maintenance is a long-term operation during the lifetime of the protective system. The normal maintenance is expected to start about 5 to 10 years after implementation and after completion of second level protection to deeper scour levels.

This system proved to be successful, to date more than five million geobags have been deployed.

Lessons learned from this case:

- Falling aprons initially fall in a one-layer protective layer, which is often not enough to guarantee sustainability.
- The multi-step implementation system (*adaptive technique*) which was applied in this case appears to be efficient.

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