Conference Paper, Published Version

Oberhagemann, Knut; Diggelmann, Philemon; Mukhles-Uz-Zaman

Understanding Falling Aprons - Experience from the Lower Brahmaputra/Jamuna River

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/100135

Vorgeschlagene Zitierweise/Suggested citation:
Oberhagemann, Knut; Diggelmann, Philemon; Mukhles-Uz-Zaman (2008): Understanding Falling Aprons - Experience from the Lower Brahmaputra/Jamuna River. In: Sekiguchi, Hideo (Hg.): Proceedings 4th International Conference on Scour and Erosion (ICSE-4). November 5-7, 2008, Tokyo, Japan. Tokyo: The Japanese Geotechnical Society. S. 302-309.

UNDERSTANDING FALLING APRONS – EXPERIENCE FROM THE LOWER BRAHMAPUTRA / JAMUNA RIVER

Knut OBERHAGEMANN[1], Philemon DIGGELMANN[2] and MUKHLES-UZ-ZAMAN[3]

[1]Northwest Hydraulic Consultants, Ltd.
(9819 - 12 Avenue SW, Edmonton, Alberta, Canada T6X 0E3)
E-mail:koberhagemann@nhc-edm.com
[2]Pöyry Hydraulics Engineer
(Hardturmstrasse 161, P.O. Box, 8037 Zurich, Switzerland)
E-mail:philemon.diggelmann@poyry.com
[3]Consulting Engineer
(House #30, App. E2, Road #16, Banani, Dhaka, Bangladesh)
E-mail:mzaman66@gmail.com

Falling aprons provide self-launching, cost-effective and fast temporary protection against sudden scour, if placed on consolidated granular soils. This article summarizes experience from the Indian Subcontinent, focusing on recent observations along the lower Brahmaputra/Jamuna River in Bangladesh.

The authors try to explain the variables affecting the slope angles after launching of the loose elements. While in general bank slopes after launching are in the order of 1V:2H, different materials and turbulence influence the slope. The critical boundary to geotechnically unstable slopes (at about 1V:2H for the fine granular soils in Bangladesh) can be surpassed when using cubical elements (concrete blocks) and in turbulent flow conditions, such as at the upstream termination points of guide bunds or the heads of spurs. Survey data indicate that slope angles in the field are generally steeper than in flume tests.

One author developed a first simplified model, which describes the beahouvior of falling aprons: (i) The natural bank slope consisting of consolidated sands is generally 1V:2H or flatter. (ii) Loose elements placed as falling apron alongside the riverbanks launch after getting undermined. Slopes angles after luanching in the relative uniform subsoil in Bangladesh depend mainly on the angularity of the elements. (iii) If repeated attack or angular flow occurs, the slope will tend to approach the borderline of stability or, in other words, its maximum angle, determined by a combination of the angles of repose of the subsoil and of the protective elements. Once the protective layer reaches the limit of geotechnical stability it eventually fails.

In summary, the commonly used falling aprons provide a useful tool if carefully applied to respond to immediate erosive attack, but do not provide long-term protection. Recently applied flexible geobags tend to show a better performance than conventionally used cubical concrete blocks, as theylaunch on flatter and geotechnically more stable slope angles and provide a denser coverage with less gaps between individual elment.

Key Words : *Falling apron, launching apron, river bank erosion, bank protection, revetments, scour, slope stability*

1. INTRODUCTION

Building infrastructure on the great alluvial plains of the Indian Subcontinent always posed special challenges. The two main concerns are lateral and vertical river instability, expressed as lateral erosion of banks and vertical scour of the bed. River courses can shift suddenly with banks eroding laterally at rates of 1 km per year or more, and local scour depths can reach over 70 m at protected points or at outcrops of cohesive material.

In such an environment, protection systems must be able to cope with or respond to sudden changes. One important problem is sudden scouring as a consequence of the construction of bank protection. A widely used response is to place protective material at or near the toe of the bank as a contingency measure, designed to "launch" down the eroding slope as the toe is undermined. This is called a falling (or launching) apron. Falling aprons are commonly placed under water, the bank slopes having been covered with stable protection down to the deepest pre-existing level (**Fig.1**).

An alternative system is to place falling apron material as a heap on the floodplain or along the upper bank near low water level, as shown in **Fig.2**. Materials used in Bangladesh due to lack of rock include concrete blocks and more recently sand-filled geotextile bags (geobags). The heaps are designed to launch down the full existing slope length and provide protection against scouring beyond the toe. The longer launching distance may be less effective.

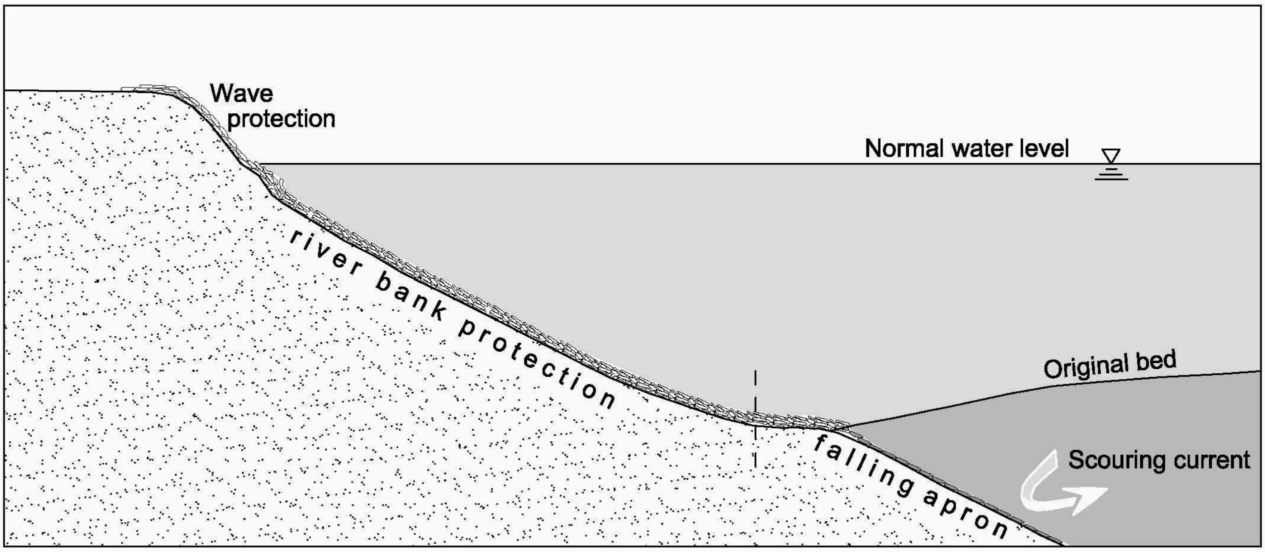


Fig.1 The principle of falling aprons

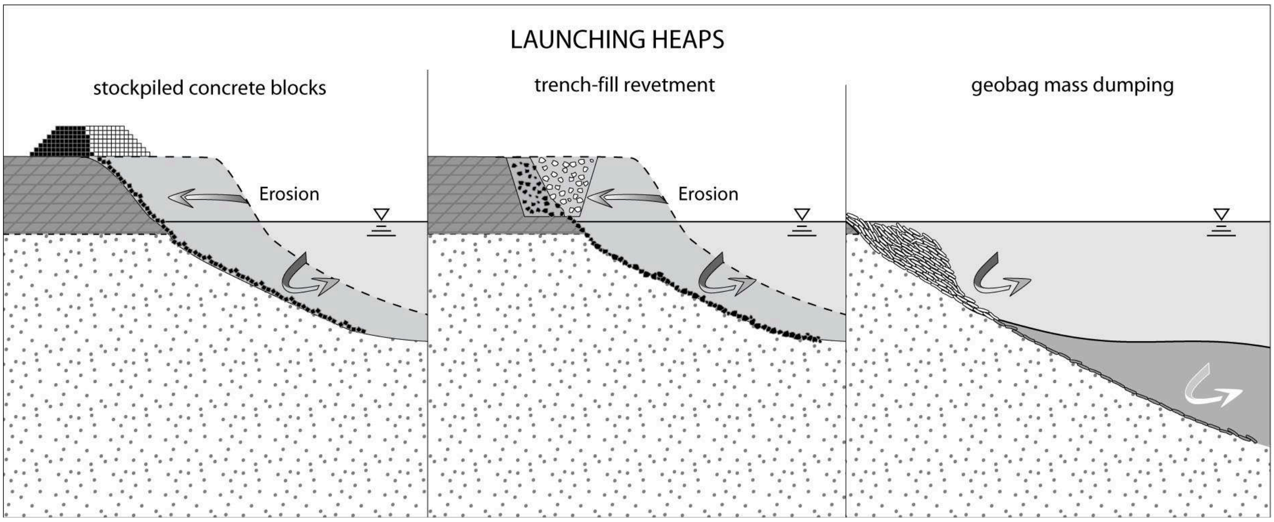


Fig.2 The principle of launching heaps

2. UNDERSTANDING FALLING APRONS

Falling aprons have two main limitations: (i) geotechnical slope stability and (ii) thickness after launching. Related issues are the angle of repose of subsoil and protective elements, the interaction between subsoil and protective elements, and the resistance of the protective elements to hydraulic forces, as explained below.

(1) Angle of repose

Design criteria for riverbank protection require the elements to be undisturbed for all design conditions. On the other hand, falling aprons are designed to slide or roll down the undermined slope in order to provide continuous coverage of the scoured bed.

A key parameter in the mechanics of a falling apron is the angle of repose of the apron elements. Unprotected banks in non-cohesive consolidated sandy material erode to slopes of about 1V:2.5H or $\beta = 22°$, which corresponds to the angle of repose (or angle of internal friction) of the soil. This angle is at the borderlie of geotechnical stability. When bank protection is applied there is an interaction between the cover layer and the underlying soil, especially when bed scour at the toe of the bank starts undermining the protected slope. In this case, river erosion steepens the bank slopes until the protective elements start moving. This interaction depends on the angle of repose of the protective material as well. Inglis1) tested different materials on a tilting board with the following range of angles of repose: (i) rounded boulders laid on similar stones: 37° or 1V:1.3H, (ii) angular quarry rocks laid on similar stones: 40° or 1V:1.2H, and (iii) rounded boulders laid on Ganges sand: 31° or 1V:1.7H

The angle of repose of the protective material defines the maximum slope angle possible. With increasing grain size the angle of repose converges to approximately 1V:1.2H or 40° 2). A physical explanation for achieving only single layer coverage after launching relates to the angle of repose. Cover layer elements such as rock riprap or concrete cubes have steeper angles of repose than fine sandy subsoils, so that they slide more readily over the subsoil than over each other, and at flatter angles. Consequently launching always starts with cover elements sliding over the subsoil. Hypothetically it is possible to achieve multiple layer coverage if the angles are steep enough, but in that case the subsoil fails geotechnically by slip circles or sheet failure.

(2) Geotechnical instability

Geotechnical slope instability is a common immediate reason for failure of riverbank protection – following under-scour at the toe. In the consolidated granular soils commonly found along the banks of major rivers in Bangladesh, slopes of 1V:2H are at borderline stability. In unconsolidated char (temporary island) soils, slopes must be 1V:3.5H or flatter for stability. Whereas the first can be protected with falling aprons, the second cannot, as the slope would fail before the material launches. Placement of a falling apron would even increase instability by adding to local overloading.

(3) Thickness after launching

In the first period of falling apron application up to about 1940, the initial apron thickness was derived by estimating the maximum depth of scour and the desired thickness of the underwater slope coverage. This approach assumes that provided a sufficient amount of stones is placed initially, the falling apron builds a uniform thickness consisting of several layers after launching. Bell3), Spring4), and Gales5)6) all used this principle. Spring and Gales assumed 1V:2H slopes after launching.

On the basis of model tests, Inglis1) challenged the assumption that the underwater thickness could be determined from the amount of launching material (**Fig.3**). He wrote: *"…the … idea that the thickness of the layer of stone remaining on a slope after an apron launched could be regulated by the distribution of stone in the apron had been shown by experiments to be incorrect."*

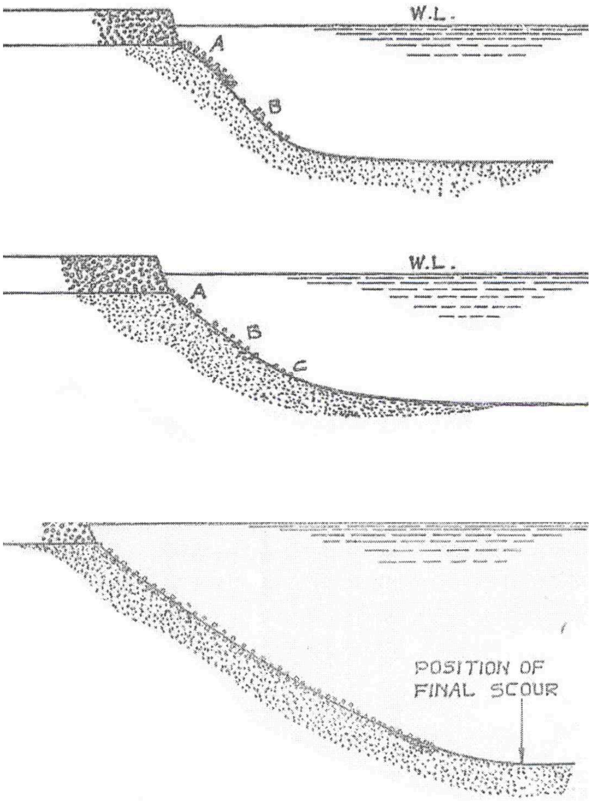
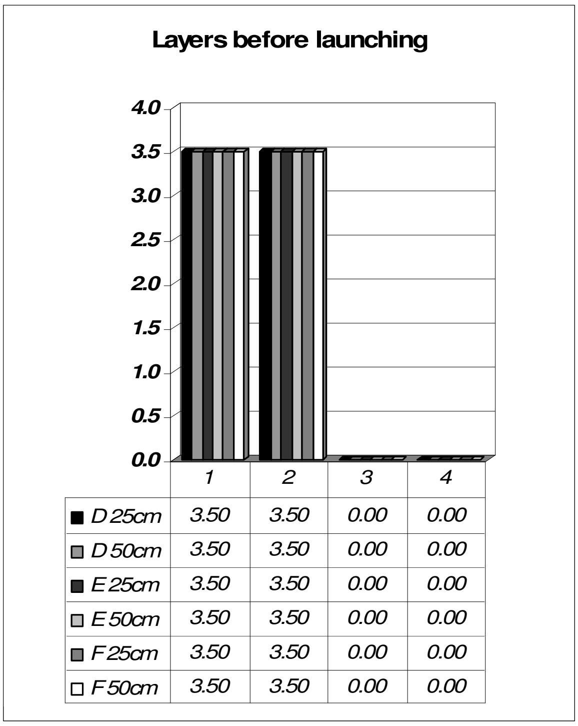
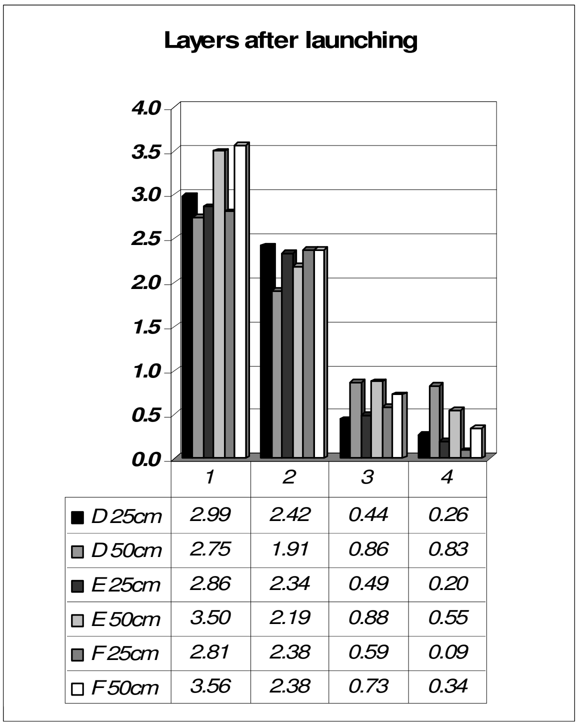


Fig.3 Inglis1): launching process of falling aprons covering the slope in single layer

More recent studies in Bangladesh confirm that launching results in single layer coverage. The two Flood Action Plan study components FAP 17) and FAP 218) conducted extensive model studies on falling aprons. **Fig.4** from FAP 21 shows the distribution of layers of concrete blocks before and after launching. (References "D" to "F" indicate different revetment sections along the bank, D being the most upstream and "F" the most downstream.) Two concrete block sizes were tested, 25 cm and 50 cm. The coverage on the launched slope is less than one layer thick. FAP 17) describes the launching process and the coverage after launching: "*About one layer of blocks covered the eroded slope below the apron setting level.*" It adds: "*The natural process of self-armouring the slope by the launching apron therefore seems to be favouring one layer of blocks. However if more blocks are present for launching* *and the slope steepens due to extraction or erosion of sand one would believe that the natural process would continue with more layers of concrete blocks until the sand is covered to a degree preventing further sediment transport and erosion of the sand.*" We should add that steepening could violate geotechnical slope stability and lead to slope failure, independent of the quality of the protective layer.



	1	2	3	4
■ D25cm	3.50	3.50	0.00	0.00
▨ D50cm	3.50	3.50	0.00	0.00
■ E25cm	3.50	3.50	0.00	0.00
▨ E50cm	3.50	3.50	0.00	0.00
▨ F25cm	3.50	3.50	0.00	0.00
□ F50cm	3.50	3.50	0.00	0.00



	1	2	3	4
■ D25cm	2.99	2.42	0.44	0.26
▨ D50cm	2.75	1.91	0.86	0.83
■ E25cm	2.86	2.34	0.49	0.20
▨ E50cm	3.50	2.19	0.88	0.55
▨ F25cm	2.81	2.38	0.59	0.09
□ F50cm	3.56	2.38	0.73	0.34

Fig.4 FAP 21[8] model tests - layer thickness before and after launching. The concrete blocks were placed along the toe in two parallel segments named 1 and 2 and launched down the slope after scouring. Here they were counted again in two segments named 3 and 4.

(4) Filter properties

For practical reasons falling aprons are often built from fairly uniform-size elements and placed on fine sands. The elements often have no filter properties and cannot prevent percolation of underlying sand ("winnowing"). Thus single-layer coverage after launching is not durable due to lack of a filter (**Fig.5**). The more uniform the protective elements the greater is the probability of loss of subsoil.

The filtering problem has led to recommendations for widely graded material. A mixture of sizes leads to some kind of armouring, with the finer material plugging the gaps between larger elements. Inglis[1] reported about mixtures: "*When the discharge was raised the apron launched in the usual way; and sand was sucked out from between the stones as in other experiments. After a time, however, the larger stones sorted themselves out .... so that the mixture afforded somewhat better protection ....*" USACE[9] states: "*Widely graded ripraps are recommended because of reduced rock voids that tend to prevent leaching of lower bank material through the launched riprap. Launchable stone should have* $D_{85}/D_{15} \geq 2$*.*"

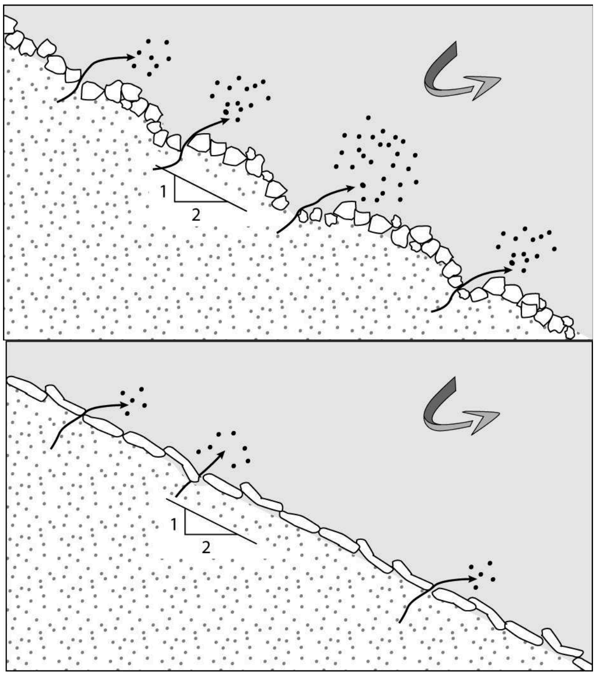


Fig.5 The single layer coverage of falling aprons does not provide a stable filter against the fine subsoil and sand is drawn through the interstices

(5) Interaction between river slope and protective elements

Falling aprons work well only where placed on non-cohesive granular material. Inglis[1)] states: *"…falling aprons should never be used where the angle of repose of the underlying material is steeper than that of the stones to be laid in the apron, or where there are layers of coherent material in the bank or in the bed above the level of maximum scour."* Two main difficulties occur when the upper slope consists of

(i) more cohesive strata that form steep banks (**Fig.6**). The upper photo shows the failure of pitched rock on clayey soil, and the lower one shows that even a higher pile of concrete blocks does not cover the steeper cohesive bank properly but leaves an unprotected gap above the low water line.

(ii) recently deposited, very loose sands that are not geotechnically stable at the launched angle (ref. Chap. 2.2).

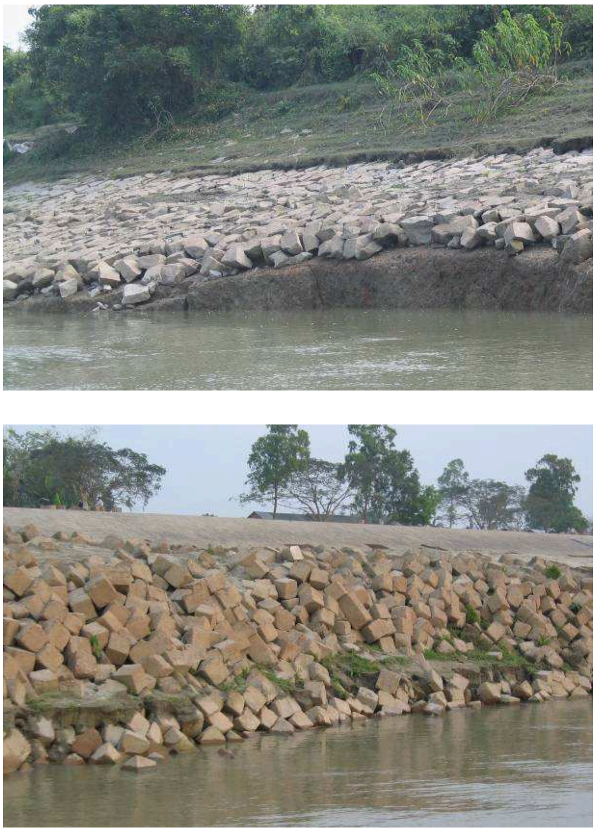


Fig.6 Steep cohesive banks cannot be covered with falling aprons

It is often assumed that protected river slopes after launching are about 1V:2H, but model tests mostly with parallel flow along the bank indicate a range from about 1V:2.5H for round boulders to 1V:1.5H for cubical concrete blocks (see Inglis[1)] and FAP 21[8)]. Quarried rock and geobags (sand-filled geotextile bags) produce slopes of about 1V:2H. These slopes are near the boundary of geotechnical stability along consolidated riverbanks, but can also be found at greater depth underlying unconsolidated soil strata. The latter implies that deeply placed falling aprons are likely to be more successful when they launch on more consolidated soils.

Survey data from the lower Brahmaputra/Jamuna River in Bangladesh indicate that slope angles in the field are generally steeper than in flume tests. Since 1995 various types of bank protection have been built using materials ranging from quarried rock to geobags. River channels in this large braided river can attack the bank at angles ranging up to 90°, even during the dry season. Also, erosion upstream of protective work can lead to outflanking and cause flow to erode soil from behind the protection work. Associated large-scale turbulence results in rapid scour rates and causes steeper slope angles under the launching materials. Diggelmann[10)] found that slope angles of 1V:1.5H are possible with all investigated materials, depending on the angularity of flow and the severity of the turbulence (**Table 1**).

These observations on riverbanks protected with quarried rock and concrete cubes indicate the following features of falling aprons under repeated attacks at various angles:

(i) A natural bank slope consisting of consolidated sands is generally 1V:2H or flatter. After the falling apron is undermined and first launches, the slope will settle at approximately the same value, as observed at Bahadurabad and Ghutail (**Table 1**).

(ii) If repeated attack or angular flow occurs, the slope will tend to its maximum angle, determined by a combination of the angles of repose of the subsoil and of the protective elements.

(iii) If angular flow hits the bank to impinge on the launched apron directly, more fine subsoil will be washed through the gaps of the covering elements than in parallel flow conditions.

(iv) Repeated attack leads to repeated loss of fines and wider gaps between the protective elements as they sink in locally. The protected slope will steepen, reach the geotechnical stability limit, and eventually fail. Then the requirement of geotechnical slope stability limits the use of falling aprons.

Location	Period	Material	# of surv.	Min	Max	Aver	Attack
Jamuna Bridge	2006	Quarry rocks	12	1.52	1.8	1.64	angular
Bahadurabad 1. attack	1997-2003	Concrete Cubes 40-45 cm	9	1.76	2.39	2	parallel
Bahadurabad 2. attack		CC 40-45 cm	16	1.39	1.92	1.62	repeated
Bahadurabad 1. attack		CC 35-45 cm	5	1.81	2.04	1.93	parallel
Bahadurabad 2. attack		CC 35-45 cm	12	1.32	1.72	1.51	repeated
Ghutail 1. attack	2000-2005	CC 30-35 cm	3	1.9	2.11	2	parallel
Ghutail 2. attack		CC 30-35 cm	4	1.56	1.71	1.6	repeated outflanked
Ghutail 1. attack		CC 40-45 cm	3	1.77	2	1.86	parallel
Ghutail 2. attack		CC 40-45 cm	4	1.54	1.71	1.64	repeated outflanked

Table 1 Summary of observed slopes in the lower Brahmaputra/Jamuna at revetment structures

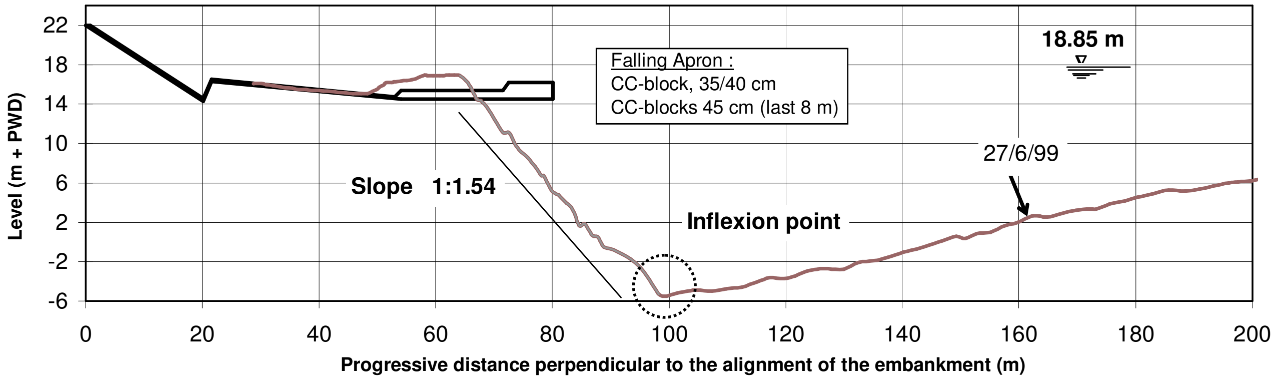


Fig.7 Cross section with concrete (CC) blocks measured at Bahadurabad FAP 21/22[8]. The inflexion point is at the toe and provides the starting point for measuring the slope angles

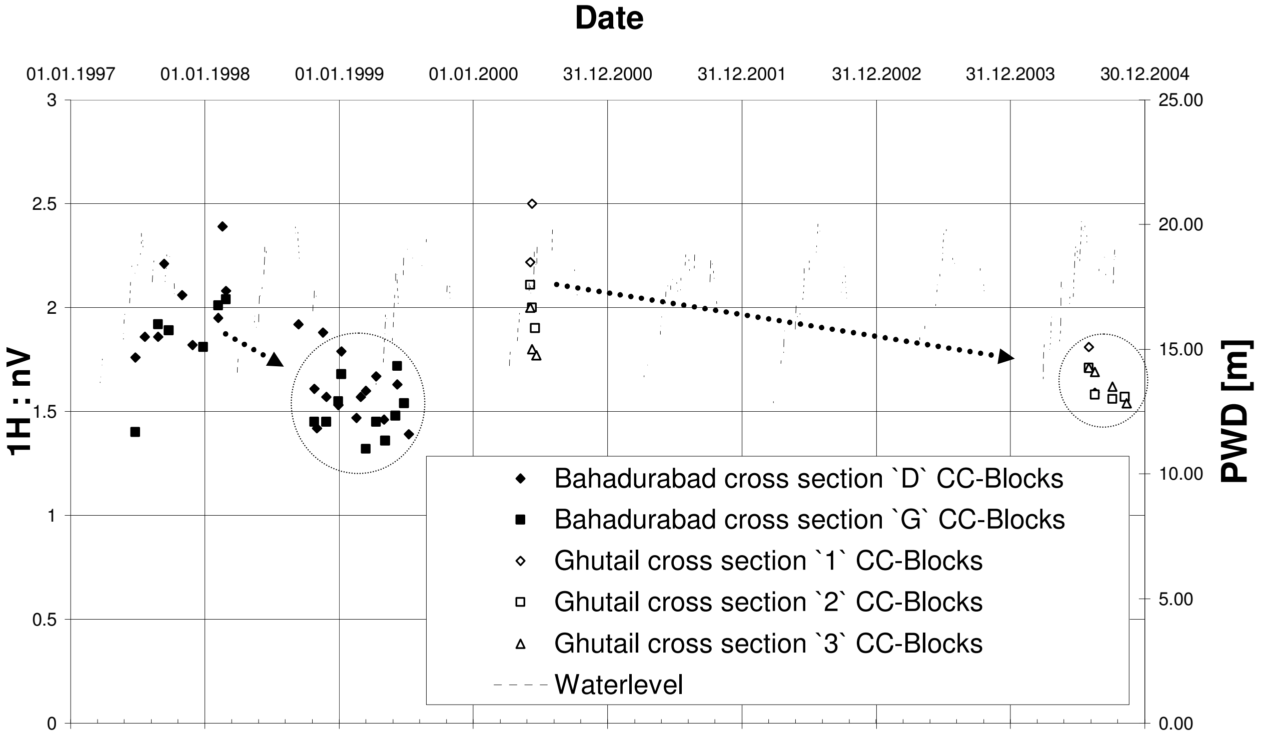


Fig.8 Development of water levels and slope over time

3. SIMPLE MONITORING MODEL

Diggelmann[10)] developed a simplified model to assess the failure risk of falling aprons, based on systematic investigations of their behavior under repeated attacks and the use of simple monitoring tools. The model compares existing slopes and the severity of flow attack with experience about geotechnically stable slopes. This simplified model reduces the risk to diving investigations under adverse conditions, at the moment the only reliable way to check the consistency of the slope coverage. More specifically, the model is based on the average slope angle between the flood plain and the inflexion point at the toe. **Fig.7** and **Fig.8** show examples of the measured slope and the systematic plotting of slope angles over many years. **Fig.9** shows the characterization of several slope angles into clouds, and their steepening over time (cloud 2). This indicates critical conditions. Finally the slope angles become flatter (cloud 3), which indicates failure. Typically, a damaged slope (**Fig.10**) has a more rounded bottom with no definite inflection point. **Fig.11** illustrates four development steps from eroding bank, through initially launched apron and critically steep apron, to final failure; the underlying observations are described in chapter 2.5.

An additional indicator of critical slopes is the distance of the inflection point from a fixed position at the bank or on the floodplain. Combined with knowledge of the development history at the site, shorter distances under scouring conditions indicate steeper slopes and a higher risk of failure.

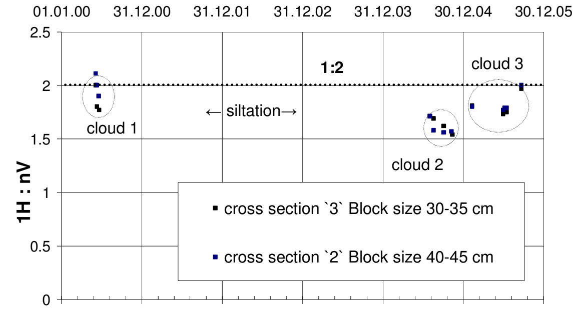


Fig.9 Development of slope angles at the same cross sections, protected with concrete blocks of different size

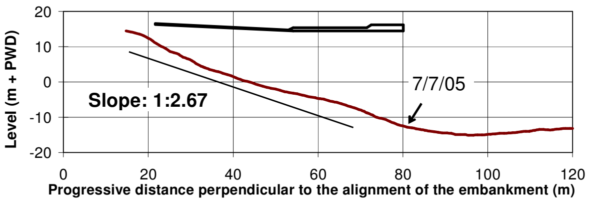
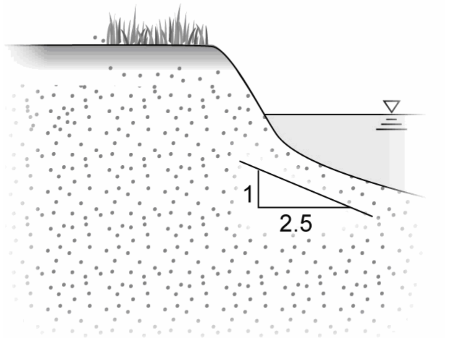


Fig.10 Typical damaged falling apron with concrete blocks measured at Ghutail FAP 21/22[8)]

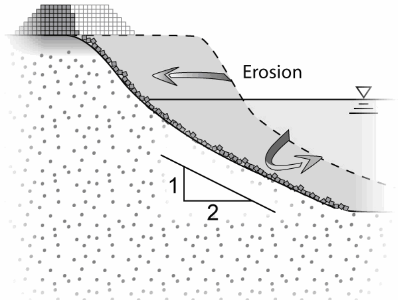
4. CONCLUSION AND OUTLOOK

Systematic monitoring alongside many different types of riverbank protection in Bangladesh has allowed development of a better understanding of the requirements for stable riverbank protection. One fundamental element is toe protection using the falling apron principle. USACE[9)] states: *"Toe scour is probably the most frequent cause of failure of riprap revetments."*

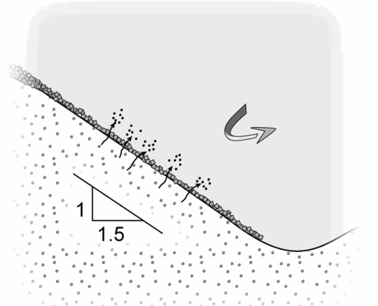
The main conclusion that can be drawn is that the commonly used falling aprons provide a useful



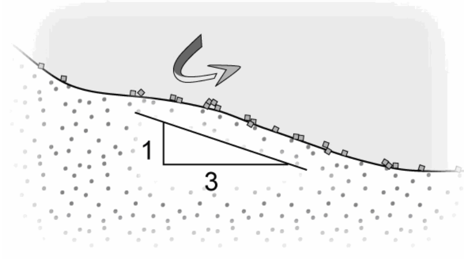
Natural slope



First erosive attack



Steepest slope



Failure, no inflexion point

Fig.11 Schematic model explaining the development of falling aprons tool in response to immediate scouring, but do not provide long-term protection. They form a single layer coverage that can withstand flow forces for some time even though it does not provide a filter to the fine underlying granular material. The more aggressive the erosive attack, for example angular, the faster the slope protected by falling aprons steepens and the earlier the failure of the falling aprons occurs, either through insufficient supply or through sudden geotechnical failure.

Future research needs to provide more detailed understanding and guidance, starting for example with the development of a flow diagram for the successful use of falling aprons and introducing different types of protective materials, such as the more recently used geobags. Specific uncertainties relate to the behavior of graded vs. uniform material, hard vs. flexible materials (rock or concrete vs. geobags), difficulties in modeling the behavior of falling aprons in distorted scale models, and the optimal shape and size of launching elements.

ACKNOWLEDGMENT: The authors express their thanks to the ADB supported JMREMP11) project, implemented through the Bangladesh Water Development Board under the Ministry of Water Resources, for the opportunity to conduct research on the performance of falling aprons and to present this paper.

REFERENCES

1) Ingles, C.C. : The design of falling apron, chapter 9, Library of Institution of Civil Engineer, London, United kindon, 1949.
2) Bezzola, G.-R. : Lecture Scripture River Engineering (Flussbau) Edition WS 05/06, Swiss Federal Institute of Technology, ETH Zurich, 2005.
3) Bell, J.R. : The Continuous Bund and Apron Method of Protecting the Flanks of Bridges for Rivers in the Panjab (India). Technical Paper No. 2B, Simla, 1890.
4) Spring, F.J.E. : River Training and Control by the Guide Bank System. Technical Paper No. 153, prepared for Railway Board, Government of India, New Delhi, 1903.
5) Gales, R.R. : The Harding Bridge over the Lower Ganges at Sara. Institution of Civil Engineers (UK) Paper No. 4200, November, 1917.
6) Gales, R.R. : The Principle of River-Training for Railway Bridges, and their Application to the Case of the Hardinge Bridge over the Lower Ganges at Sara. Institution of Civil Engineers (UK), Paper No. 5167, December, 1938.
7) FAP 1 : River Training Studies of the Brahmaputra River: Report on Model Studies. Prepared for Bangladesh Water Development Board, March, 1993.
8) FAP 21 : Flood Action Plan, Bank Protection Pilot Project, Technical Report No. 4: Falling Apron Investigation. Prepared for MoWR, WARPO, March, 1995.
9) USACE : Hydraulic Design of Flood Control Channels. Engineer Manual 1110-2-1601, U.S. Army Corps of Engineers, 1991.
10) Diggelmann, P. : Experiences with Falling Aprons in Bangladesh. Swiss Federal Institute of Technology (ETH) Zurich, Diploma Thesis, unpublished, February, 2007.
11) JMREMP : The Adaptive Approach to Riverbank Erosion Management (REM). In Mid-term Review Report prepared for Bangladesh Water Development Board, 2006.