A NEW VIEW ON FALLING APRONS

by

Henk Jan Verhagen[1] , Mark van der Hoeven[2] and Bettina Thiel[3]

ABSTRACT

In a flume of BallastHam Dredging a falling apron model has been constructed and loaded by current. The tests have been done with different rock sizes, different layer thickness of the top storage of the apron and two different gradings. In summary it was found that for both the narrow graded rock layers as well as for wide graded riprap the final slope of the apron was always 1:2, while the riprap layer reached a thickness equal to d_{n50}. It was also clear from the tests that the slope did not stop the transport of sand on the slope, but retarded it considerably. The process of settlement of the riprap was that the stones did not roll over each other, but that the whole structure moved down, like on an escalator.

For the protection of the abutments of the Januma Bridge in Bangladesh also a falling apron has been applied. This apron has been designed according the standard design rules, applying also a (relatively costly) wide grading of rock. In the framework of the maintenance of the structure, yearly surveys are made of the falling apron. These surveys show that also in prototype the slopes reached a steepness of approximately 1:2. A volumetric analysis indicated that also in reality the thickness of the falling apron was in the order of only one layer of stones.

1 INTRODUCTION

In rivers and along estuaries currents can be considerable. Especially in case of large variation of river discharges or in case high tidal prisms, this usually gives the (tidal) river a very dynamic character. Channels may move to different locations. From a management point of view, this is sometimes not desired because of the location of bridge piers, quay walls, shipping routes, etc. The main flow has to be restricted to a given section. The consequence is usually that the flow starts to scour the bed; this scour can be considerable, sometimes several decades of meters deep. Eventually such scouring holes will endanger adjacent structures. In order to prevent scouring, bed and shoreline protection is applied.

The standard approach is to cover the whole slope, as well as a part of the bottom with a rock layer. This can only be done when the whole profile is available at the moment of construction. In many large, untamed rivers and estuaries the channel is not yet been formed at the place where it may cause potential danger. In such situations three potential options exist.

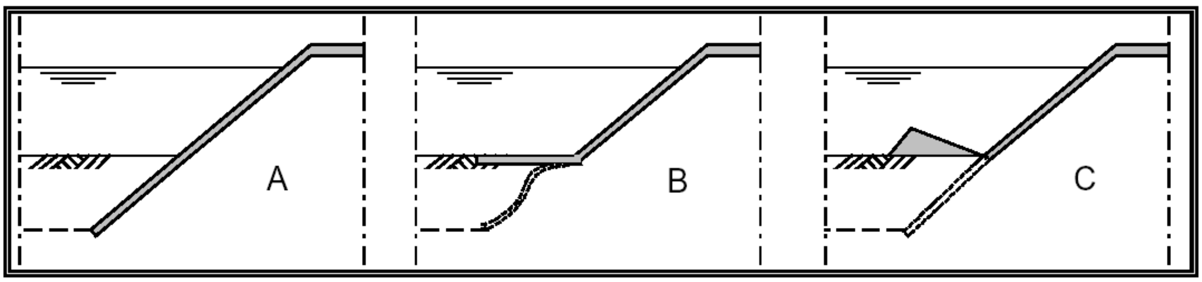


Figure 1: alternative ways of protecting a slope

The first possibility is to install the protection down to the expected scour depth and to cover it with the original bed material (A). This is a good solution, but often very expensive. When the expected scour depth is more than 25-30m below water level, technical difficulties with dredging might arise.

Another option is to cover the toe of the revetment with a flexible mattress, which can follow the scour slope and thus retain the bed material (B). Nowadays mattresses are made of geotextile for strength

[1] Associate professor, Delft University of Technology, PO Box 5048, Delft, The Netherlands, H.J.Verhagen@ct.tudelft.nl
[2] Graduate student, Delft University, present address: Ballast-Ham Dredging PO Box 8574, Rotterdam, The Netherlands, mho@ballastham.com
[3] Graduate student, Delft University, present address: University of Darmstadt, Bettina.Thiel@gmx.net

and sand-tightness, and concrete blocks for ballast. Traditionally, fascine mattresses were made of willow saplings or bamboo and ballasted with rock.

Another possible solution is the *'falling apron'* (C), which is often applied in rivers in India and Bangladesh. The falling apron is a toe protection that can adjust to scour and follow any bed erosion downwards, thus continuing to protect the toe of the bank protection. The idea is to store an amount of stones at the toe of the revetment during construction. Scour will cause the stones to roll down; preventing the formation of an erosion slope that is too steep. When the scour starts to develop, the material is launched onto the developing slope. The loose elements are assumed to cover the slope to a thickness large enough to retain the bed material.

2. HISTORY

A flexible toe protection in the form of a falling apron finds many applications in India and Bangladesh.One of these constructions is the falling apron, first applied in 1912 to protect the abutments of the Hardinge Bridge in present day Bangladesh. According of the design guidelines of SPRING from 1903 [see CBIP 1989], the thickness of the falling apron should be 1.25 times the thickness of a riprap slope revetment. Later on RAO [CBIP 1989] recommended to a thickness of 2.25 times the thickness of the riprap revetment, while SCHIERECK [2000] recommends a thickness of 5 times D_n. All these design rules were based on geometrical considerations, and not based on prototype analysis.

The covered slope of the falling apron after setting can be estimated as 1:2 for loose stones. Observations at guide banks on various rivers in India and Bangladesh [CBIP 1989] have shown that the actual slopes of launched aprons usually range from 1:1.5 to 1:3, but in some cases may even be flatter. However, in most cases the average approximates to1:2.

Rao [CBIP 1989] states: “The materials of the armour on the slope of the shank and in the apron act only as ‘face wall’. The guide bank slopes should, therefore, be stable by themselves, without any external support. To ensure this, the slope should have the same ‘angle of repose’ of the material of which it is constructed. The presence of clay in the sand, (which is always found in the alluvium, of which the bed and banks of the alluvial rivers are composed), at once makes the angle of repose approximate more towards saturated clay. The wet clay mixed with wet sand, apparently acts as a lubricant between the grains of sand, so that the angle of repose of the alluvium is 18° approximating to a slope of about 1 to 3.”

The structure of the river training works for the Jamuna Bridge (finished in 1997) also included a falling apron. These works were executed by a joint venture of two Dutch dredging contractors; HAM and Van Oord ACZ (HAMVOA JV). Data is available from the execution of these works and from surveys conducted since the construction. This provides an opportunity for research on this protection method and comparisons with prototype data.

In design practice for Bangladesh, in addition to rock, alternative materials are used. Besides concrete blocks of uniform size and granular material with a very wide grading, articulated concrete mats and geocontainers are also used. The wide grading is supposed to be more sand-tight than a normal (narrow) grading, because it has a more compact granular skeleton. In all designs, the slope after the falling process is assumed to be 1:2. It is very likely that the different materials will influence the establishment of the slope and the final protection. For sand-tight materials, such as geotextile, this has already been proven by tests at WL|Delft Hydraulics [DE GROOT ET AL, 1998].

The idea is that when a layer of approximately 2.25 – 5 timed d_n has been formed, the near bed velocities (i.e the velocities near the sand bed under the falling apron) become so small, that the sand cannot be brought into motion. In fact the falling apron will behave as a geometric open filter [SCHIERECK, 2000]. The designer should realise that the desired thickness is an expectation, and the design of a falling apron only provides sufficient rock to form a layer with the “design thickness”. The real thickness formed in nature can be completely different.

In case the final thickness is more than the design thickness, there will be a shortage of rock. The stockpile is not sufficient, and rock has to be added to the system. Because of this, surveys will always be needed. In case the final thickness is less than the design thickness, it is expected that the filter will not be able to stop effectively the erosion.

Unfortunately no detailed measurements of layer thickness exist, neither in models, nor in prototype. Therefore this research was set up in order to get some more insight into the behaviour of a falling apron. Also no information is available regarding the final slope, apart from the material from Rao.

The material for the falling apron should have such a weight that it is not transported by the current, but that it only falls down the slope because of gravity. This implies that the stone weight has to fulfil the requirements of Shields or Izbash for rock stability [SCHIERECK, 2000].

3. MODEL TESTS

In a flume of Ballast Ham Dredging a falling apron model has been constructed and loaded by current. The tests have been done with different rock sizes, different layer thickness of the top storage of the apron and two different gradings. In the tests, the complete apron was submerged. In summary it was found that for both the narrow graded rock layers [VANDER HOEVEN, 2002] as well as for wide graded riprap [THIEL, 2002] the final slope of the settled apron was always 1:2, while the riprap layer reached a thickness equal to D_{n50}. It was also clear from the tests that the slope did not stop the transport of sand on the slope, but retarded it considerably.

3.1 Apron material

The size of rock in the model should be such that it is much larger than the base material. Another consideration is that the rock should be small enough to fit the flume. To investigate the falling process, there should be a real apron of stones, a few layers thick. Because of limitations on the testing facility, the choice was made to use different sizes of apron material. This meant that more tests had to be done, but at the same time produced more results that could be compared.

In the model tests little emphasis was placed on the hydraulic stability of individual stones. Transport of rock in the direction of the current was not permitted during the tests. With the aid of the Shields formula, rock sizes were determined that were stable in the current.

The space available for the apron section was 0.60m wide. With a d_{n50} of 0.01m, this meant (depending on grading and packing of material) a width of approx. 60 stones. An apron consisting of 10 layers would be 0.10m high. This is considered enough to determine the process of resettling. When the stones are coloured, this process can be visualised.

The larger their size, the fewer stones can be placed in the apron section. To compare the results for small stones of 0.01m, larger sizes were also tested. The size of the stones chosen was (d_{50}) of 0.025m and 0.045m. An option is to test different gradings in the falling apron section. The grading can be changed, while the characteristic size remains the same.

The difference in size between sand and rock should be large enough (as in the prototype); a comparison is given in Table 1.

	Sand (d_{50})	Rock (m)			Size factor
		d_{15}	d_{50}	d_{85}	
Prototype	200 µm		0.300		1500
Model 1	100 µm	0.007	0.010	0.015	100
Model 2	100 µm	0.018	0.025	0.033	250
Model 3	100 µm	0.030	0.045	0.058	450
Model 4 (mixture)	100 µm	0.010	0.033	0.046	328

Table 1: Sand and rock size

The velocities in the flume were always set in such a way that the velocity was not high enough to move the rock, but is certainly high enough to transport the sand.

3.2 Experimental set-up

The *Merwelanden Flume* at the research facility of HAM at Moerdijk was used for the tests. The tank is approx. 13m long, 1.10m wide and 1.30m high and has one glass side The first part of the flume (3m) is separated from the rest by a weir. In this part the water is pumped. The weir distributes the water over the entire width into the flume.

In the flume section two slopes, made of wood, were placed. The central, horizontal, section (5m long) consists of sand. This is the measuring area. The sand body was 0.5m high. Together with the slopes it makes a sill on which the apron can be placed.

The discharge was generated by a submersible pump, which was placed at the end of the flume. The submersible pump has a capacity of approx. 100 l/s (0,100 m^3/s) when the head difference is kept small (horizontal water displacement). This is the reason why the return-pipe for the water was placed directly on the side wall of the flume and was kept as short as possible. A diameter of 125mm was used for this pipe.

The end part of the flume has a pit with a depth of 0.50m below flume bottom. The pump was placed partly above this pit. Because of the flow conditions in this end part and the closed bottom of the pump, most of the transported sand settles in this pit. It serves as a sand trap.

3.3 Well graded material

From the tests it could clearly been seen that the apron follows the bed profile as it is supposed to do. At the edge of the settled apron the stones are more exposed to the flow. Here it was obvious that extra erosion had taken place, in addition to the general lowering of the sand bed, the imposed scour. It appears that the flow around the individual stones caused turbulence around them, like that around a bridge pier.

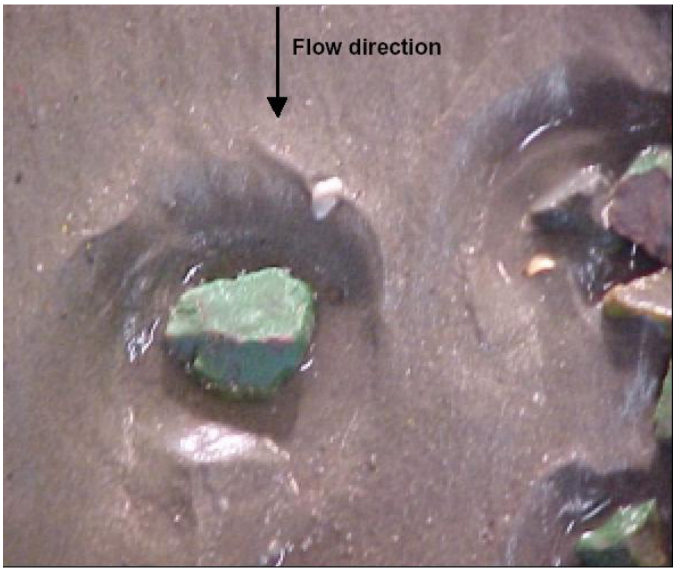


Figure 2: Erosion around an individual stone and along the apron edge (on the right)

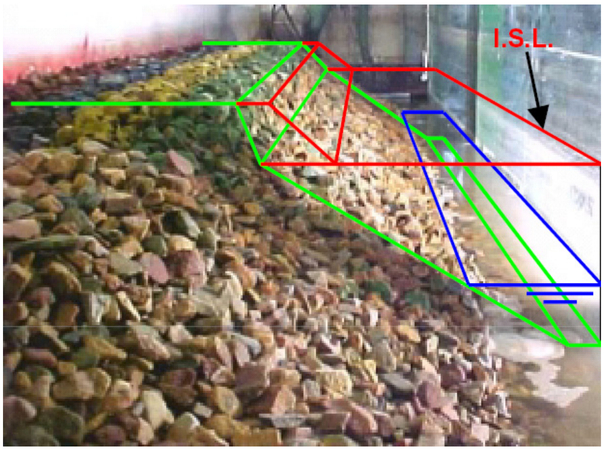
Because of this, the stones were sinking into the sand. The rock at the edge of the slope is therefore constantly ahead of the sand bed position. This mechanism causes a complete covering and therefore there is no unprotected sand slope at any moment. This is shown in Figure 2, which is the top view of the edge of the settled apron with one individual stone on the sand bed just in front of this edge.

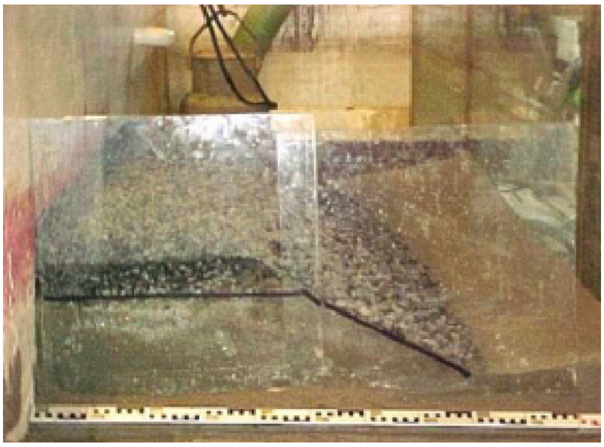
Situation before the test

Situation after the test

Figure 3: model in the flume before and after the test (25 mm rock)

The rock-layer on the establishing slope remained limited to a very thin layer. Only a single layer of rock ended up on the slope. The edge of the apron retreated only 0.10m, which implies that a very small amount of apron stone is really used. The larger part was unaffected. This was observed from analysis of the cross-sectional profiles. A difference in angle was observed between the slope were the rock lies directly on the sand and the slope of the toe of the waiting apron.





Settled apron after 420 minutes in test. In the photo the initial sand bed level (ISL) is indicated

Cross section of the apron; it is clear that the apron is only one stone layer thick

Figure 4: model in flume after erosion

The process of settlement of the riprap was that the stones did not roll over each other, but that the whole structure moved down, like on an escalator. The visualisation of this process gave a better understanding of the actual settlement and seems to contradict to the term *falling* apron. The pre-vailing idea that a sorting of the grading would occur during settlement is not found in the model.

3.4 Poorly graded material

The first series of tests were executed using well sorted material. As mentioned before, in practice fall-ing aprons are constructed using poorly sorted material. The purpose is that the material itself is able to build up a filter. In order to investigate this, also an experiment using poorly sorted material has been performed.

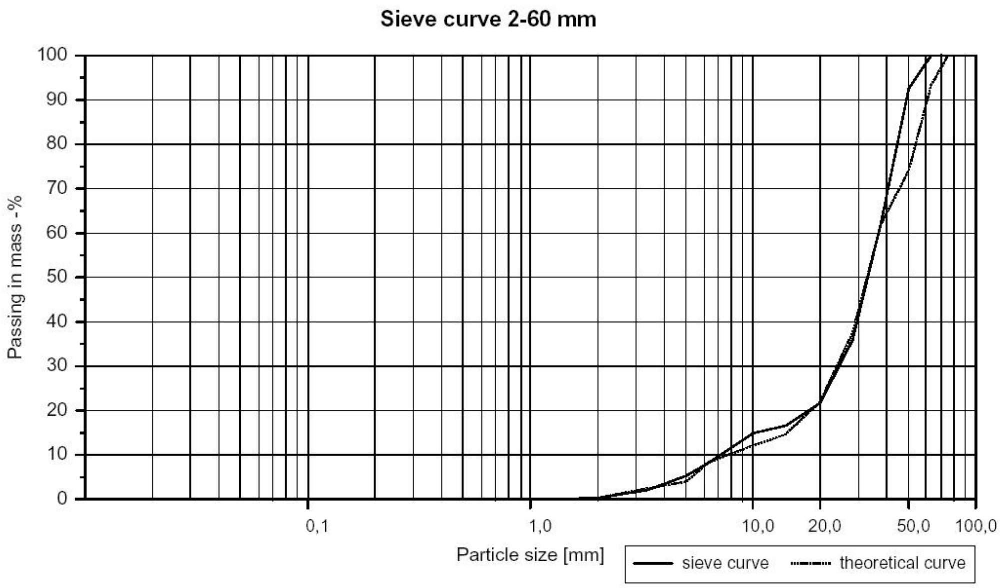


Figure 5: Sieve curve of the poorly sorted material

A shallow sieve curve was found by mixing available material with a stone variation of 2-8 mm, 8-16 mm, 15-30 mm and 30-60 mm in a certain proportion. This proportion was found by simply drawing a graph on logarithmic paper to get the values of passing in mass-%. Then the proportion of each stone variation was computed to best fit the graph.

Also this material is selected in such a way that it is not moved by the currents. The experiment is conducted in the same way as the experiments with well graded material. The observation was that the falling apron did settle in exactly the same way as the aprons with well graded material. Considering the reduction of the volume of the apron material the thickness of the protective layer cannot be very substantial. Only a layer with an average thickness of the characteristic stone diameter of d_{50} covered the slope. The smaller stones are situated in the space between larger stones. This effect can be seen in figure 6.

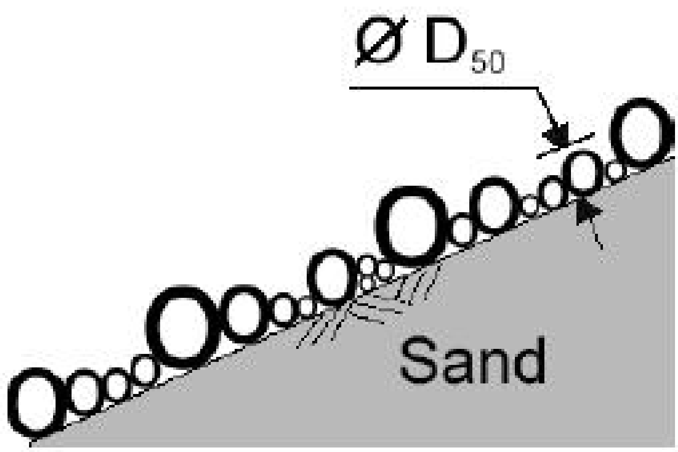


Figure 6: Schematic illustration of the protective layer with poorly graded material

Also for this experiment the average slope angle was 1:2. The experiment with the poorly graded material has been done twice (with different initial layer thicknesses). The impression was that in both cases the erosion speed with a poorly graded falling apron was lower than for a well graded falling apron. However, the differences were too small to come to final conclusions regarding this point.

The reason for the slower sediment transport may be caused by the grains itself. The space between larger grains of poorly sorted material is filled with the smaller stones. These grains are laying in a kind of protection of the larger rocks. The stones (on a slope) were already visualised in figure 6. As a small grain would reach the threshold of motion a grain which lays between larger stones grains stays longer stable in a current as a fact of this protection. As the thickness of the protective layer at falling aprons made from well sorted material is equal to the characteristic stone diameter d_{50} of the filter material the space between the stones is not as well protected as with the poorly sorted material, which leads to more sediment transport. But as the falling apron has to be a geometrically open filter, the sediment transport is in both variations (well sorted or poorly sorted) not stopped. The erosion is only slowed down.

Also it is observed that in case of the use of a poor grading the layer with a thickness of (on average) d_{n50} is much more uneven than in case of using a well graded rock. These last two points are in line with the conclusions from tests by DEGROOT ET AL. [1988]. They indicated that by insufficient supply of rock also a quite even distribution of the riprap over the sandbed was formed, but that the distance between the individual rock became more. Consequently, the erosion rate of this slope was more. However, they found that in that case the final slope became 1:3.5.

3.5 Observations from the model tests

The following observations are given here on basis of the observed and described behaviour of the apron in the model.

- The slope in the model came to 1:2 after setting.
- The setting of the falling apron was a continuous and even process.
- The flow conditions, which are not a macro instability process, dictate the setting process.
- The slope angle was not dependent on the size of stone.

- Uneven scour along a guide bund (as with attack under an angle) did not seem to jeopardise the working of the apron.
- Because of turbulent current around the individual stones, the stones 'sink' into the sand and against the surrounding stones. The layer, however thin, is therefore closely packed.
- The flow around the individual stones causes erosion around them and therefore the stones sink into the sand. Because of this mechanism, there is no unprotected sand slope at any moment.
- Applying a thicker apron does not lead to a thicker protection on the establishing slope.
- The difference between the behaviour of falling aprons made from poorly sorted and well sorted material is that the falling apron made from poorly sorted material slows down the scour development in a more effective way.
- The resulting protective layer has an average thickness of only the characteristic stone diameter of d_{50} of the granular material. However the protective layer of the poorly sorted material is not the same kind of single layer as it occurred by a falling apron made from well sorted material. The layer is in this case much more uneven resulting from the wider grading.

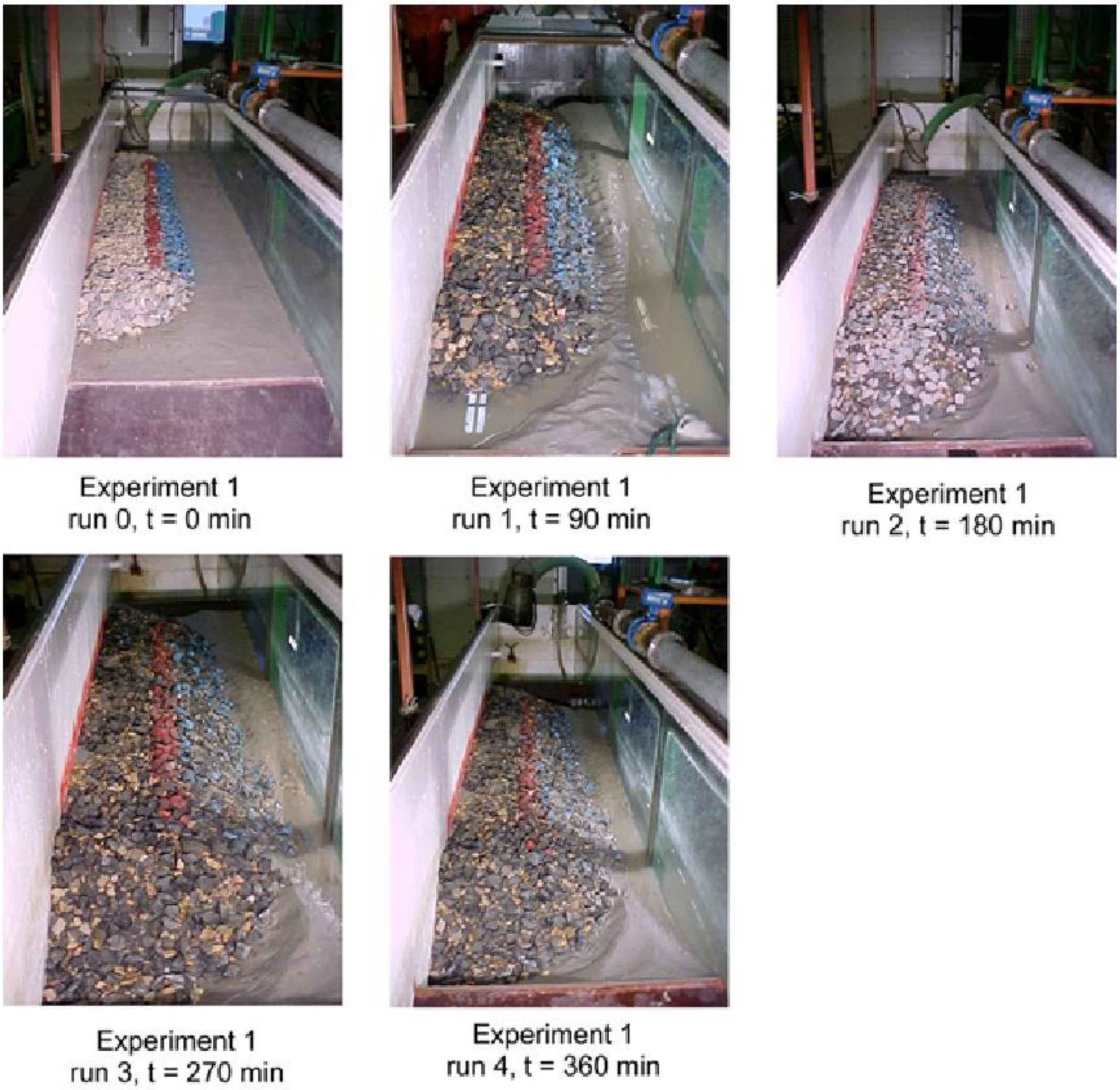


Figure7: Several steps in the experiment using the poorly graded material

4. PROTOTYPE

4.1 General

For the protection of the abutments of the Jamuna Bridge in Bangladesh also a falling apron has been applied. This apron has been designed according the standard design rules, applying also a (relatively costly) wide grading of rock. In the framework of the maintenance of the structure, yearly surveys are made of the falling apron. These surveys show that also in prototype the slopes reached a steepness of approximately 1:2. A volumetric analysis indicated that also in reality the thickness of the falling apron was in the order of only one layer of stones.

4.2 Mica

During the construction of the river training works for the Jamuna Bridge, special geotechnical aspects were encountered. During excavation works near the toe of the riverbanks, shallow landslides occurred. The reason for this was that the sand contained mica. MUNDEGAR [1998] did research on the behaviour of sand containing mica. Mica particles, which have a plate-like shape, have an enormous influence on the behaviour of the sand.

It was shown that the presence of sand-size mica plates within sand increases its void ratio, modifies its volume change characteristics and introduces a collapse potential, particularly when under low stress and when sheared in extension. Extension loading under low stress occurs at the toe of a slope being excavated by dredging or by scour.

Shear testing with different mica percentages showed that for low percentages of mica, the sand dictates the failure. Between 20% and 40% lies the transition. In the study the pure sand was found to have an internal angle of shearing resistance of about 30º compared with 24º for the 40% mica sample. The mica also increases the porosity of the sand.

5. RESULTS FROM THE INVESTIGATIONS

In this chapter a general overview of the observed apron behaviour is presented. It summarises the behaviour of a falling apron as observed in this study. The considerations are given in a qualitative way and should apply for both model and prototype. The three aspects that are discussed are:

- Setting result
- Filter function
- Durability

5.1 Apron dynamics

In the model it was found that the rock size did not influence the steepness of the slope. In both the model and the prototype situation, the slope after setting is 1:2 (27º). This angle should be flat enough to prevent macro instability of the slope. Ground mechanical collapse mechanisms were not observed in the model or prototype. The size of the model was too small for these kinds of failure modes to occur.

At the Jamuna Bridge the recorded scour depths (below the falling apron level at PWD –15m) are also not deep enough to expect flow slides in front of the apron. It was opserved in prototype that flow slides occurred during construction along slopes steeper than 1:3. For the settled apron with a steepness of 1:2 this could have consequences on the stability. However, at the time the height was still modest.

In Figure 7 the setting process due to scour at four different times is shown. The single layer is located at the edge of the waiting part of the apron. When the bed material is eroded, the rock on the slope *slides* downward and more material from the waiting part is drawn upon. At all times, the top of the slope coincides with the outer edge of the waiting part of the apron.

Theoretically the rock should be stable on a slope of 1:2, both statically and hydraulically. With the, modest, flow velocity in the model even the grading 8/16mm is theoretically stable. This sliding can therefore only be explained by erosion of the sand layer directly under the rock layer. Apparently, the gradient inside the rock layer is high enough to transport the sand. When this transport takes place, the sand grains in the top layer lose contact with surrounding grains and loss of friction will result. The rock layer can slide into this fluidised sand-water mixture layer, thus following the subsiding riverbed.

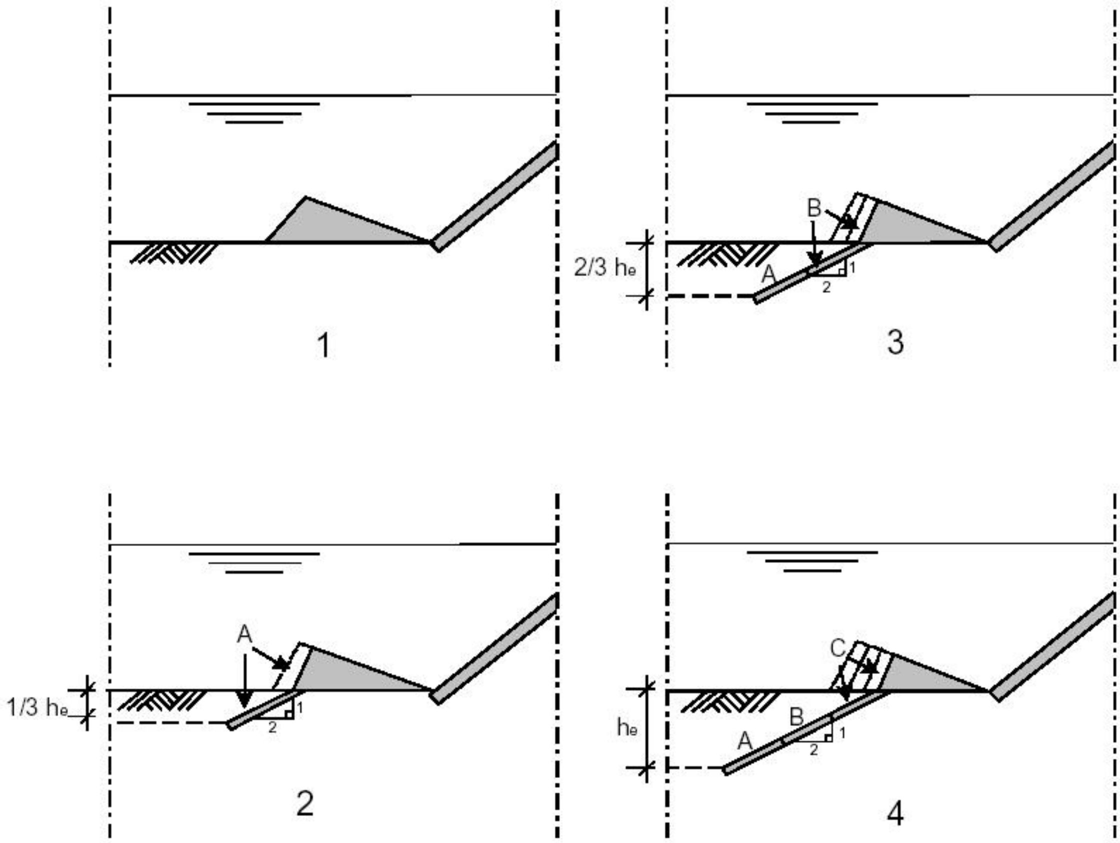


Figure 7: Settling process of the apron

In Figure 8, the expected and the observed setting results are presented (not to scale). For both situations the slope is approximately 1:2. The difference is found in the layer thickness and the location of the slope. In both situations, an equilibrium depth is assumed, which is drawn in the figures. When this depth is reached, the flow velocity is expected to be under the critical value and the transport of bed material stops.

The layer thickness, which was expected to be 5 times d_{50} (A) remains limited to a single layer (B). A consequence of this single layer is that only a small amount of apron material is really used. The greater part of the waiting apron remains unaffected

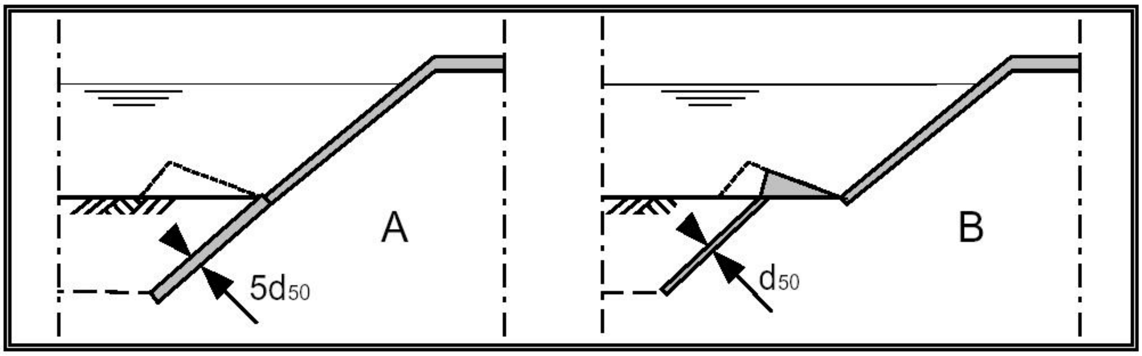


Figure 8: The expected (A) and the observed (B) sellting result

The developing slope was expected to start from the toe of the constructed slope downwards. In Figure 8, these slopes are drawn in line, but of course a flatter or steeper constructed slope is also possible, depending on the design. As far as the macro-stability is concerned, the observed setting has an advantage. In the observed situation, a horizontal part is still present, this being by means of 'waiting' part of the apron. This can be compared with a berm in a breakwater or dyke. The stability for slip circle failure is influenced positively by this 'berm'.

Two remarks are made here concerning these observations:
- The observed setting behaviour is only an anticipated final situation.
- Although the macro-stability for the slope as a whole (apron and constructed slope) is influenced positively, the slope at the edge of the waiting part is steep. Here a considerable amount of apron material per m^1 is present. Small instabilities might occur, which would lead to more apron material falling on the slope.

The observations at the Jamuna Bridge do not seem to contradict the setting observed in the model. Here also the waiting (horizontal) part of the apron can be seen and also at the Jamuna Bridge, the slope angle stays limited to 1:2.

As far as the anticipated final situation is concerned, both in the model and in the prototype, more setting can be expected. This setting could occur because the equilibrium depth is not reached, or because sand material is transported through the single layer. Also a more severe flow condition could occur. When it is assumed that the equilibrium depth is reached, no more transport of the bed material takes place. Two possibilities then remain:
- The transport of bed material stops *and* the transport of sand through the rock layer stops because the gradient is below the critical value. A stable situation is reached (until the flow conditions are again more severe).
- The transport of bed material stops, *but* there is still transport of bed material through the rock layer. When this happens, the rock layer will subside and more rock from the waiting part will reach the slope until the transport stops.

In a real situation the probability always exists that the stable situation is loaded by more severe flow conditions. This could result from a higher discharge or because of a more direct attack of the apron by a river branch. However, because of the natural character of the river, the load could also decrease. This should be realised when interpreting the outcome of this study; the apron is an extra protection for the maximum possible flow conditions that may occur from time to time. It is not likely that the apron will be heavily loaded constantly.

5.2 Filter function

The setting behaviour of the apron, which was observed in the model, has a significant influence on the soil retaining function. Two different aspects are mentioned here:
- Single layer on the slope
- Continuous setting process

In the model, only a single layer of rock was found on the developed slope. Slope protection by a single layer does not comply with the normal filter rules [SCHIERECK, 2000]. Here it was stated that for geometrically open filters, the layer thickness should be such that the gradient inside the apron is smaller than the critical value. With only a single layer this condition can not be assured.

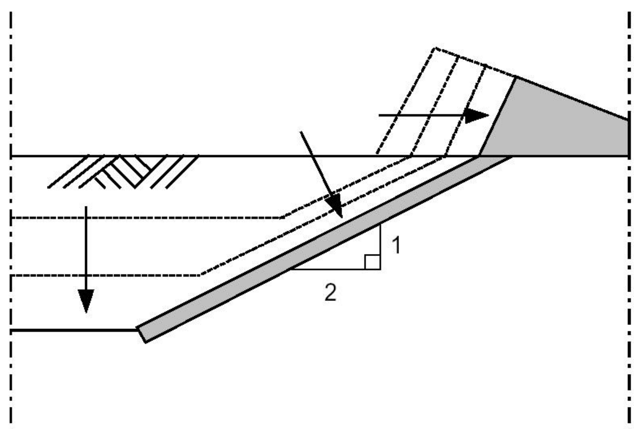


Figure 9: Retreat of slope

As seen in the model and described in the previous section, the developed slope retreats with the edge of the waiting part of the apron. In Figure 9 it can be seen that the slopes at different intervals lie parallel. The slopes are linear, which means that the setting is even over the entire slope. The fact that the complete slope retreats implies that sand is transported *through* the apron.

It can therefore be stated that the apron does not fulfil its function to retain the bed material. However, the erosion of sand is slowed down significantly (relative to the erosion of the unprotected bed). Another important feature is that this single layer seems to distribute the erosion evenly over the entire slope. Instead of steep scour hole slopes, the slope stays limited to 1:2.

The setting process, as observed in the model, is expected to have an influence on the final grading of rock on the slope. When a wide grading is used with a very fine fraction, these fines are washed out easily. This washing out is in fact the idea behind the application of wide gradings. However, in the filter design it is expected that a layer of about 5 times d_{50} will cover the scour slope. If then some fine material is washed out from the top layer, a filter structure will develop.

One can imagine that when the individual stones in a cross-section reach the slope one by one, *all* the grains that are small enough could theoretically be transported with the current. Instead of a thick layer with larger rock in the upper layer and more fines underneath, only the rock that is stable in the current will remain on the slope. In addition to this, it has been observed that apron material is only launched onto the slope when the current is eroding the toe (scour) or when sand is transported through the covering layer. Both mechanisms are only present during the higher flow velocities and thus the fines are likely to be transported.

5.3 Durability

It was observed in the model and seen on the survey results from the Jamuna Bridge that the apron settles nicely and uniformly over the slope. This is one of the outstanding features of the falling apron protection. The setting will take place at the most protruding part along the guide bund and therefore the face wall of the apron will always be flat. Thorough site investigations should be made to ensure that there are no clay layers, which will disturb this even setting process.

When the equilibrium scour depth is reached, a single layer of granular material will cover the slope. This will not sufficiently retain the soil. But when still sufficient apron material is stored in the waiting part, this will not endanger the protective function. When sand is transported from under the slope cover, the rock will subside. The above lying material will then shift downwards and fill the hole. Here, the sand transport is stopped and it will take place at another location where the cover layer is not sand-tight. The slope will retreat and more rock will reach the slope from the waiting stack of material.

In this way, the erosion of sand is slowed down significantly and the stability of the slope is secured. Besides this, it was noticed that the flow conditions in rivers like the Ganges and Brahmaputra show extreme fluctuations. The scour depth, with the attendant need for a falling apron, are therefore not present year-round and not every year. Only during the periods with high flow velocities, does the probability of scour exist. During the period 1998-2001, the apron at the Jamuna Bridge was attacked only once This seems to agree nicely with the observed behaviour. When the toe is attacked by scour, an even covering of the slope appears. This might not be sandtight, but it does slow down the toe erosion.

Another aspect of the durability is the existence of macro-stability along the revetment or guide bund. On the basis of model and prototype, it can be stated that the steepness of the slope stays limited to the angle of repose of the bed material in the flow condition present at location. This includes the secondary influences and will be in the order of 1V:2H for sand. When the soil conditions are well known, this should not give a problem relating to the stability of the slope as a whole.

However, problems relating to micro-stability could occur, especially when the constructed upper slope consists of a thick filter layer or sand-tight mattress, with a very low permeability. If the water level in the river drops quickly, a steep groundwater gradient will be present in the bund. Because of the open structure of the covered apron slope, the water can flow out in this part of the slope and transport of sand through the apron could occur.

The most probable failure mechanisms are summarised. It can be stated that the falling apron does not fulfil its functions if the following events occur:

- Hydraulic instability of rock in the current (transport).
- Presence of clay layers which will form steep slopes.
- Usage of all material present in the apron and the uncovering of the toe of the constructed slope. When this happens, the scour will continue at the toe of the constructed slope, eventually leading to slope failure.

- Apron material, which does not easily *launch* is used. The scour slope should be covered with a layer of material at all times.
- Flow slide due to a high and steep slope.

6. CONCLUSIONS

It seems that the present design rules are too conservative with regards to the amount of rock, which is needed to let nature create a good falling apron (difference with the test is a factor 5). However, it also became clear that the falling process did not create a sand-tight slope protection, but a protection that slowed down erosion considerably. For many applications slowing down the erosion is sufficient, but in some cases only slowing down the erosion is not sufficient. In those cases it is questionable, if a falling apron should be applied without financial provisions to thicken the layer in a later stage. The process itself takes care that the full sand surface is covered with stones, no unprotected spots have been observed. Sufficient supply has to be available; otherwise, the resulting slope protection becomes too open.

The following conclusions can be drawn concerning the setting process and setting result:

- A falling apron settles evenly and over the entire slope. In the model, the scour hole slope was covered with rock at all times.
- The slope angle is approximately 1:2. This seems to hold for both model and prototype and agrees with the expected steepness described in the literature.
- The resulting protective layer stays limited to a single layer of granular material.
- The rock size does not influence the angle of the slope.
- Applying a thicker apron does not lead to the formation of a thicker protective layer on the slope. It will however slow the retreat of the apron edge.
- When the falling apron is constructed in the form of a wedge towards the river, more material is stored at the outer side. This will retard the retreat of the apron at the beginning of the setting process.
- The slope protection is not sand-tight. Because of the single layer and the relatively large rock used, the openings between the rock are such that the layer cannot retain the sand.
- The slope protection retards the transport of bed material through the layer. Although not sand-tight, the protective layer will limit the transport of sand from under the layer.
- After reaching an equilibrium depth, the larger part of the falling apron is still unaffected. This extra buffer quantity will be necessary, however, when a greater depth occurs or when a river branch is adjacent to the revetment.
- The falling apron is a flexible protection, which can adapt to flow conditions when the river attacks at an angle. In the upstream part of the model the apron was attacked at an angle. Here, the setting was also even and showed the same behaviour.
- When it is necessary to replenish a falling apron, the extra volume of rock should be dumped on the horizontal part of the apron. The setting mechanism can then distribute the rock over the slope. Because of the relatively steep slope of 1:2 and the modest rock layer on the slope, trying to place the extra quantity directly on the slope is not considered an option.

For the design practice the following conclusions can be drawn:

- Wedge-shaped design is recommended above a rectangular cross-section. More material in the riverside of the apron slows the retreat and therefore keeps the scour hole slope at a larger distance from the revetment.
- The use of a wide grading is expected to lead to high losses and therefore is not considered a good option. The design consideration of applying a wide grading which should form a filter structure (fines washing out from the top layer) is not valid when the rocks in the apron reach the scour hole slope one by one. However, when using a wide grading the erosion rate may be somewhat lower.
- A falling apron always requires maintenance, but how often will depend on the frequency of its attack.

7. ACKNOWLEDGEMENTS

The authors wish to thank the invaluable support of Ballast-Ham Dredging. Apart from financial support to the second and third author, the company made also available their research flume for performing the tests as described in this paper.

8. REFERENCES

CBIP [1989] River behaviour management and training, CBIP, New Delhi, India

DEGROOT, F, LINDENBERG, J, JORISSEN, R. [1988] Gedrag van een bodemverdedigingsrand bij en over- en langstrekkende stroom; Delft Hydraulics report Q771

MUNDEGAR, A.K. [1998], Engineering in micaeous sands: the practical significance of mica content, In: *Ground Engineering*, Nov. 1998, p34-36.

SCHIERECK, G.J [2000] Introduction to Bed, Bank and Shore protection, Delft University Press, Delft, The Netherlands

THIEL, B. [2002] Behaviour of a falling apron made from 'poorly sorted' material, M.Sc-Thesis, Technische Universität Darmstadt/Delft University of Technology

VANDERHOEVEN, M.A. [2002] Behaviour of a falling apron, M.Sc.Thesis, Delft University of Technology