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Geotextile bag revetments for large rivers in Bangladesh

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A B S T R A C T

Since the late 1990s, riverbank revetments constructed of sand-filled geotextile bags (geotextile bags) have been developed in Bangladesh in response to the lack of traditional erosion-protection materials, particularly rock. After independence in 1971 and the related loss of access to quarries, rock was replaced by concrete cubes, but those are expensive and slow to manufacture. Geotextile bags on the other hand, first used as emergency measures during the second half of the 1990s, can be filled with local sand and therefore provide the opportunity to respond quickly to dynamic river changes.

Geotextile bags also provide the potential for substantial cost reduction, due to the use of locally available resources. The use of the abundant local sand reduces transport distance and cost, while local labor is used for filling, transporting, and dumping of the 75–250 kg bags. Driven by the need for longer protection, the idea of using geotextile bags for permanent riverbank protection emerged in 2001. Eight years of experience have enabled systematic placement of geotextile bag protection along about 12 km of major riverbanks at a unit cost of around USD 2 M per km. By comparison, concrete-block revetments cost around USD 5 M per km. In addition, there are strong indications that geotextile bags perform better than concrete blocks as underwater protection, largely due to their inherent filter properties and better launching behavior when the toe of the protected underwater slope is under-scoured.

This article reports the outcome of the last eight years of development work under the ADB-supported Jamuna-Meghna River Erosion Mitigation Project (ADB, 2002), implemented by the Bangladesh Water Development Board. Besides substituting geotextile bags for concrete blocks as protective elements, the project involved development of a comprehensive planning system to improve the overall reliability and sustainability of riverbank protection works.

1. Introduction

1.1. Background

Bangladesh is one of the most densely populated countries of the world (more than 1000 persons per km^2), with few natural resources. At the same time it is one of the most disaster-prone areas with an average of about 6 major disasters annually. The country is largely situated on the fertile delta of four great rivers: Ganges, Brahmaputra, Padma and Meghna. These rivers flow through alluvial plains built up over million of years from sediments mainly derived from the unstable southern slopes of the Himalaya. The rivers are characterized by (i) very high discharges, in the order of 100,000 m^3/s in severe floods, (ii) local flow velocities exceeding 4 m/s at exposed points, (iii) deep scouring, locally exceeding 70 m in depth, (iv) great lateral instability with bank erosion rates in some places exceeding 1 km per year, and (v) an absence of rock sources for riverbank stabilization.

In this environment riverbank protection was attempted over a long period, with only limited success. A major impediment was the high cost of concrete blocks. This often limited the length of the protective works to a few hundred meters, while erosion problems commonly affect lengths of several km. In 1999 riverbank erosion became critical alongside two large irrigation projects: one situated on the right or west bank of the lower Brahmaputra (called Jamuna in Bangladesh), and the other on the left or east bank at the confluence of the Upper Meghna with the Padma – which carries the combined flow of the Brahmaputra and Ganges (ADB, 2002). In terms of average annual discharge the Brahmaputra is classified as the fifth largest river of the world, while the Padma is the third largest, only surpassed by the Congo and Amazon (Schumm and Winckley, 1994).

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Table 1
Properties of geotextiles used for bags.

Properties	Test standard	Test values
Opening size O_{90}[b]	EN ISO 12956	≥0.06 and ≤0.08 mm
Mass per unit area	BS EN 965	≥400 g/m^2
CBR puncture resistance	EN ISO 12236	≥4000 N
Tensile strength (machine direction or MD and cross machine direction or CMD)[a]	EN ISO 10319	≥20.0 kN/m
Elongation at maximum force (MD)	EN ISO 10319	≥60% and ≤100%
Elongation at maximum force (CMD)	EN ISO 10319	≥40% and ≤100%
Permeability, (velocity index for a head loss of 50 mm − v_{H50})	EN ISO 11058	$\geq 2 * 10^{-3}$ m/s
Abrasion	Following RPG of BAW, Germany, O_{90} according to EN ISO 12956 and thickness according to BS EN 9641	After test: tensile strength ≥ 75% of specified tensile strength, thickness ≥ 75% of original value, O_{90} ≤ 0.09[b] mm
UV resistance	ASTM D4355[c]	≥70% of original tensile strength before exposure

[a] In case of non-isotropic material ≥ 14 kN/m for machine direction.
[b] Based on experienced variations of test results, values should not vary more than 0.01 mm from the specified values in this table.
[c] The same requirements apply in case the ISO test is used.

1.2. Geotextile bag revetment and adaptive management

At both project sites mentioned above, concrete-block protection was not economically feasible for the protection of what was largely agricultural land. Nevertheless, relatively high investments in the areas and the high population density called for an initiative to develop more cost-effective solutions. The backbone of the new development is the use of sand-filled geotextile bags, which had been used locally for emergency protection since the mid 1990s. Based on such experience with 250 kg bags, a feasibility study recommended the use of graded geotextile bags weighing between 11 and 126 kg, which were dumped in 2002 as a launching heap along the water line of eroding riverbanks. This concept assumed that once erosion undercut the heap, the different sizes of bags would launch down the underwater slope and protect it from further erosion.

The first systematic underwater investigations raised doubts about the thickness of the cover layer achieved after launching, and consequently about the long-term reliability of the coverage. Consequently, a modified “adaptive” concept was developed, based on phased planning and implementation. This concept provides the necessary flexibility to respond in an adaptive manner to the largely unpredictable river behavior. Core principles include:

Fig. 1. A geotextile bag from the wave zone at the Bahadurabad test site on the Jamuna River. The bond between the fibers is destroyed and the bag is open. The bag was placed in early 1997, and the photo was taken in early 2005.

(i) *Erosion prediction during the dry season* to support prioritizing and budgeting for riverbank protection after the following flood season, and to initiate emergency measures at priority sites before the flood season.
(ii) *Extensive river surveys during the flood season* to identify the current channel geometry and enable prediction of the main channel locations and points of erosional attack during the following dry season.
(iii) *Phased implementation of bank protection over several years* starting with (a) optional immediate protection before the flood season, if there is an emergency situation, followed by (b) installation of main protection during the next dry season, and (c) later placement of adaptive protection to extend the existing work to deeper levels if river attack continues. Adaptive protection, which in this phased concept is a fundamental requisite for long-term stability, differs from traditional approaches where the initial design was expected to serve for a long time with only minor maintenance.
(iv) *Monitoring on a regular basis* to provide the information required for deciding on maintenance and adaptive protection.
(v) *Placement of strategic stockpiles* of geotextile bags near the riverbank, to support emergency work and reduce response times.

The main design and construction phase of the Project from 2003 to 2006 built on experience with emergency works in 2001–2002. This continued experience with geotextile bags, and associated improved understanding about failure mechanisms of riverbank protection, led to publication of updated “Guidelines for Riverbank Protection” in 2008, supported by the Bangladesh University of Engineering and Technology (BUET). By the end of

Table 2
Geotextile bag dimensions.

Weight of bag	Empty bag size [mm]	Area of empty bag	Area of fully filled bag[a]	Volume of fully filled bag[b]	Number of bags per m^3
126 kg	1030 × 700	0.72 m^2	0.54 m^2	0.0700 m^3	14.3
78 kg	830 × 600	0.50 m^2	0.37 m^2	0.0433 m^3	23.1

[a] The area of a fully filled bag is about 75% of the area of an empty bag.
[b] The volume is calculated assuming that 1 m^3 of sand weights 1800 kg after consolidation under water. This translates into 32% voids. For comparison the loose sand fill weighs 1500 kg/m^3 and has 43% voids, but it gets denser after consolidation or compaction under water. These computations do not account for water molecules sticking to the sand grains, which adds to the weight when weighed in air.

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Table 3
Quantities of bags according to finally adopted system.

Stage	Number of bags/m^2 Number of layers	Quantities [m^3 bag/m^2][a]	Cumulative layer thickness [m]
Immediate protection (launching heap)	1 layer (2 × 126 kg)	0.14	0.14
Main protection	3 layers (6 × 126 kg)	0.42	0.56 (0.14 + 0.42)
	2 layers (4 × 126 kg)	0.28	0.42 (0.14 + 0.28)
Adaptation	Same as main protection		
Supplementary protection	1.5 layers (3 × 126 kg)	0.21	0.77 (0.21 + 0.56)
			0.63 (0.21 + 0.42)

[a] Quantities are computed based on the coverage provided by the sand in the bags. The concept basically assumes that a certain layer of sand is provided as protective layer. The thickness of the layer is computed assuming a specific weight of compacted sand of 1800 kg/m^3.

2008 a total length of about 12 km of riverbank had been protected with geotextile bag revetments with an additional 7 km under completion along a meandering tributary. Further work covering an additional length of about 10 km along the lower Brahmaputra/Jamuna River is planned for completion by mid-2011.

2. Geotextile material

2.1. Properties

Geotextile bags are fabricated from engineered geosynthetic materials produced under controlled conditions. The testing largely follows ISO. Table 1 summarizes the specified properties. Most suppliers offer polypropylene (PP) fibers.

Core characteristics are:

(i) *O_{90} for containing the sand fill.* The fine sand in the large Bangladesh rivers has a median diameter D_{50} in the order of 0.02–0.01 mm and is very uniform. The geotextile cloth must retain this fine sand.
(ii) *Abrasion test.* The top layer of geotextile bags is exposed to river drag forces and sediment transport acting on the surface of the bags. In order to confirm the long-term stability of the geotextile, an abrasion test (BAW, 1994) was introduced in a modified form by adding an additional O_{90} criterion. This test is an important element to assure stability in the given environment (Heibaum et al., 2008; Restall et al., 2002).
(iii) *CBR.* CBR expresses tensile strength and resistance to puncturing. The latter is required to cope with bamboo stakes used for berthing boats, and in combination with tensile strength, to permit lifting of bags by their corners without undue elongation or rupture.
(iv) *Permeability.* The geotextile bag and sand fill act as a filter and need to be sufficiently permeable.
(v) *Elongation.* Excessive elongation and deformation of the bags can lead to poor performance as bank protection.

2.2. Practical considerations and experience

Given the fineness of the locally available sand, the most suitable geotextile material is non-woven. The sand D_{50} of about 0.2 mm compares with the minimum available O_{90} of non-woven geotextile of around 0.08 mm. Woven material commonly has an O_{90} of above 0.1 mm, which was considered to be too porous.

The need to minimize cost indicated the use of relatively thin geotextiles. Whereas the initial specifications asked for a weight of 300 g/m^2 at a thickness of 3 mm, suppliers using continuous filament as well as staple fiber generally provided material close to 400 g/m^2. Consequently the specifications were adjusted to this value.

Fig. 2. Filling of geotextile bags.

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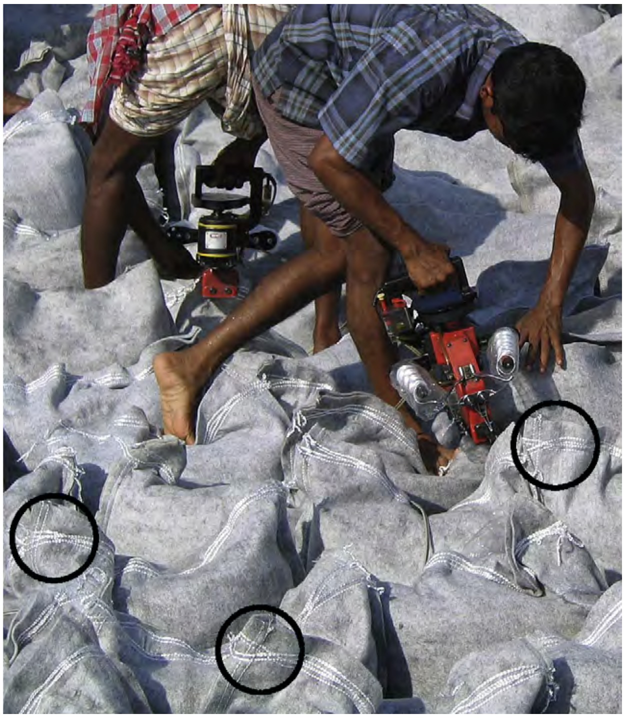

Fig. 3. Closing bags at the site with two lines of type 201 seam.

Long-term resistance to UV radiation is not a major concern, since the sand-filled geotextile bags are mostly placed under water. However, small quantities are used temporarily as wave protection between low water and floodplain level, and as such are exposed to sunlight. This protection is typically in place for not more than two years, and during that time the bags are under water for several months every year. Also during this period some fraction of the river's high sediment load is captured on the surface and protects lower fibers from direct exposure to UV light. This notwithstanding, UV stability is generally specified.

Bags used as temporary wave protection are later dumped under water as permanent protection. Extensive diving investigations indicate that stresses associated with the dumping process do not cause damage. Consequently, it can be concluded that limited exposure to ultraviolet light does not prevent the affected bags from being used for underwater protection. Also, since the underwater coverage consists of multiple layers, individual weaker elements do not significantly detract from the overall stability.

Sediment and hydrodynamic loads were initially of major concern, as the geotextile cloth must not lose its sand-tightness. Considering the high sediment load in the main rivers in Bangladesh, sediment transport could be important if sand grains continuously rub along the unprotected geotextile surface of the bags and subject it to abrasion. A simple example explains this: assuming an average flow velocity of 1 m/s, transporting sediment along the riverbank during the four main monsoon months of a year, results in 300,000 km of relative transport length during the assumed lifetime of a geotextile bag (1 m/s * 60 s/min * 60 min/h * 24 h/d * 120d * 30yrs). Even though the main attack is not always at the same level under water and the sand grains are under uplift, the resulting load could be sufficiently large to damage the geotextile in the long-run.

Restall et al. (2002) report about abrasion in the surf zone along beaches and recommend the BAW abrasion test. In addition, hydrodynamic forces from wave action can affect the internal bond, especially of continuous filament (Fig. 1).

Interestingly, material susceptible to abrasion as tested in the rotating drum test of BAW (BAW, 1994) appears to be more susceptible to unraveling under hydrodynamic (wave) loading. On the basis of extensive initial tests reported by Heibaum et al. (2008), the project adopted the BAW abrasion test (BAW, 1994) in a modified form as an appropriate testing tool to assure long-term sand-tightness.

Other factors of interest are tensile strength and CBR puncture resistance. The bags are handled manually and the worst case scenario would be to lift a full bag by its corners. This means that for a 126 kg bag all the weight would be applied to about 20 cm length of material, which translates into a unit load of 630 kg/m or 6.3 kN/m. To avoid extreme elongation the Project specified a minimum tensile strength of 20 kN/m. The CBR puncture resistance plays a role when boats approach the shore and are stopped using bamboo poles. It appears that a strong boatman can apply a force of about 100 kg or 1 kN on the bamboo, which has a diameter similar to that of the cone used for the CBR puncture test. Again to avoid local weaknesses, the Project specified a CBR puncture resistance of 4 kN. This high value means that staple fibers need to be well fabricated (needle-punched) as compared with continuous filament, which at same unit weight is characterized by much higher tensile strength and CBR values than staple fiber.

3. Geotextile bag characteristics

3.1. Dimensions and coverage

The initial concept envisaged using four different sizes geotextile bags, but this was soon revised to use only bags of a single size, or at most two sizes. It was found difficult to fill, store, and mix a larger number of bag sizes at the site. Also, the smaller 11 kg and

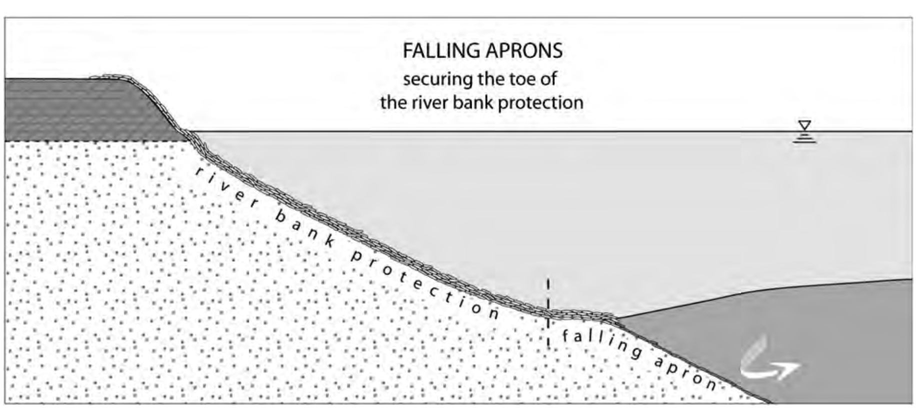

Fig. 4. The principle of falling aprons to protect against future scour (dark grey).

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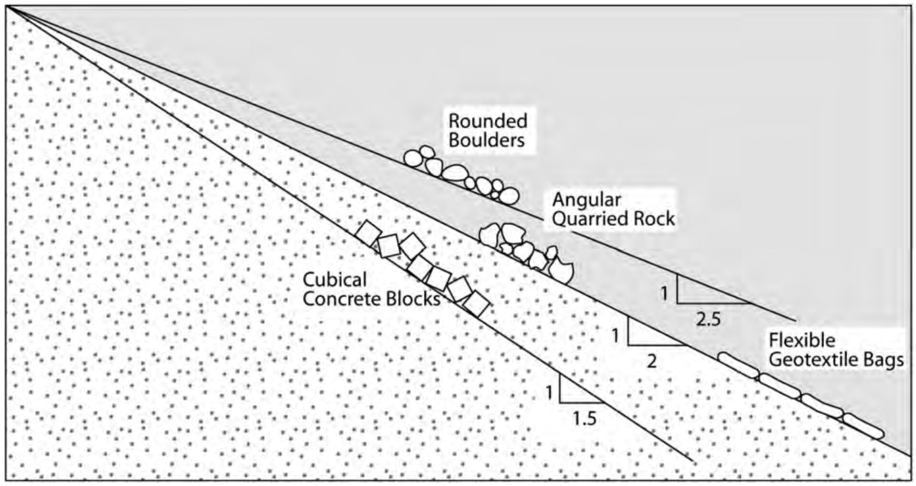

Fig. 5. Launching slopes of different protective materials (JMREMP, 2006).

36 kg bags were not stable under the higher flow velocities. Table 2 provides details of the two sizes retained for current use.

The different bag sizes can be expressed in terms of numbers of bags per square meter of protection, depending on the number of layers.

Table 3 provides details (the different stages of protection are explained in Section 4.3). In terms of areal coverage, two filled 126 kg bags or three filled 78 kg bags cover one square meter of riverbank with one layer. Completed coverage for slopes and falling aprons commonly consists of three or four layers.

3.2. Loads from dumping

The main load sustained by a geotextile bag is an impact load when it is dumped. This load, however, is relatively small (Individual Consultants, 2003, Section 3.1.2). To test bags to their maximum performance, filled bags were dropped from 10 m height onto a concrete surface. (The impact velocity from this height is around 50 km/h, whereas the theoretical maximum velocity from falling through water is between 10 and 14 km/h or 2.8–3.9 m/s depending on size.) The result of this severe test was that the geotextile experienced only very low strain (maximum measured elongation 5%), without any breaking of seams.

3.3. Manufacture

The manufacture of geotextile bags is simple and can be done in a labor-intensive manner. The sheets forming one bag are cut and folded from material coming out of the needling machines. It is practical to control the fabrication width at the machine to multipliers of the bag widths. Commonly the fold forms the bottom of the bag. After folding, the two sheets are stitched together along the sides of the bag. A type 402 seam consisting of two parallels lines of double-thread chain stitch, is appropriate. The interlocking of the two threads (upper and bobbin) prevents unraveling if the seam breaks. The seam strength is required to be above 80% of the specified material strength, which is easily achievable with high-quality thread.

3.4. Filling and closing

The bags are filled manually with local sand dredged from the river. This minimizes transport cost and consequently is a major factor for cost effectiveness. During filling one worker holds the bags upright while others fill the sand, commonly from head-baskets. Bag filling in some parts of Bangladesh is largely done by women (Fig. 2).

The use of moist sand and the limited facilities at the site result in fluctuations in weight. Systematic tests (Zellweger, 2007) indicate that the specific density can range from 1260 to 1760 kg/m^3 for 2–23% moisture content. 23% moisture content is a limit beyond which the bags start leaking water out. The average density of dredged sand sampled on the cargo ships was around 1510 kg/m^3 (ranging from 4 to 8% moisture content), while loose oven-dry sand has a density of around 1430 kg/m^3. For practical purposes a 126 kg bag should be filled to a nominal weight of around 135 kg to account for moisture content, and one of 78 kg to a nominal weight of around 85 kg.

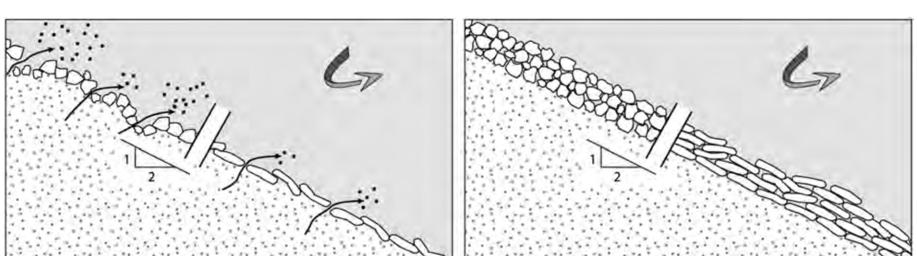

Fig. 6. Conceptual behavior of different thicknesses and different materials.

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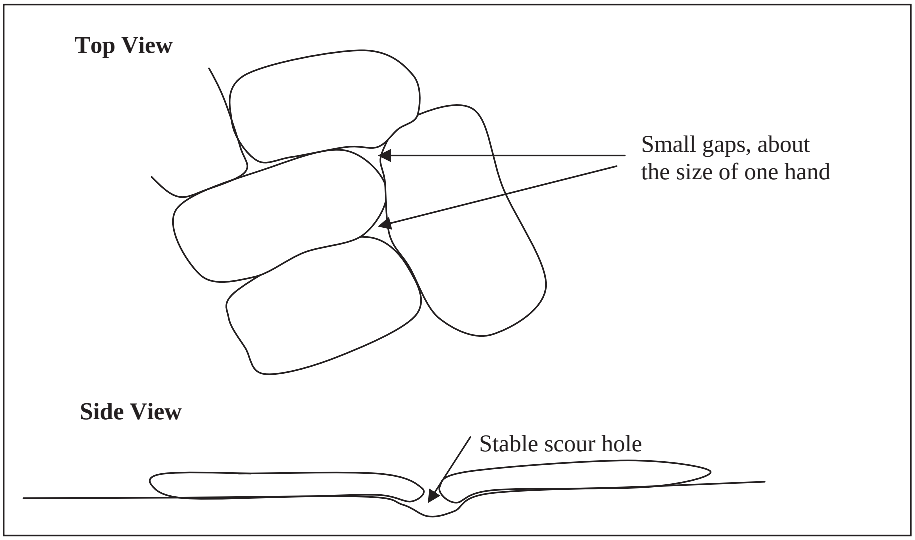

Fig. 7. Single coverage with geotextile bags, leaving small stable holes in the underlying sand.

At the site the top of the bag is closed with two type 201 seams (two parallel single-thread chain stitch) – see Fig. 3. One double line runs straight and the other forms an arch, crossing the straight seam at the ends for better interlocking. Care needs to be taken that the bags are not filled too fully and that the hand-held sewing machines are operated through the sand fill.

3.5. Use as protective elements

Geotextile bags as protective elements have to satisfy four main criteria:

(i) *Stability against flow and wave attack.* This aspect is discussed in detail in Section 3.6.
(ii) *Filtration.* The geotextile must provide a filter to prevent loss of fines through gaps between the bags. This type of failure is commonly referred to as winnowing failure (Melville and Coleman, 2000, section 9.5.1). It can be prevented by using multiple-layer coverage.
(iii) *Launching.* Riverbank protection in the large Bangladesh rivers cannot be placed initially to the deepest potential scour levels. Dredging is normally limited to depths of 20–30 m, whereas deeper scour holes can exceed 50 m water depth. Consequently, a self-launching toe protection, usually called a falling apron, is always provided (Fig. 4).
The falling apron needs to provide a geotechnically stable slope along the toe. Hard materials, such as quarried rock, boulders, and concrete blocks all launch on characteristic slopes – generally, the more rounded the material, the flatter the slope Model tests and field investigations confirm that geotextile bags also launch to a certain slope. Fig. 5 shows the commonly accepted slopes after launching. A related problem is that all launching materials provide only single-layer coverage. Here bags perform better than hard materials because the sand fill can adjust locally, leading to smaller gaps between individual elements (Figs. 6 and 7). Model experience with launching is demonstrated in Figs. 8 and 9. (NHC, 2006). The model tests investigated a falling apron consisting of 126-kg geotextile bags placed to a thickness of 0.8 m to provide coverage for future toe scour. During the model run the bed scoured 6.2 m deep and the apron launched. The launched geotextile bags covered an 8.2 m wide slope, measured horizontally from the beginning of the falling apron at the toe of the upper slope to the end of the last launched bags (under water).
(iv) *Longevity*. Riverbank protection is commonly designed for a life of 30–50 years, it being understood that maintenance

Fig. 8. Model of lower bank slope with initially installed falling apron.

Fig. 9. Launched apron of Fig. 8.

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Table 4
Expected lifetime of geosynthetics.

Expected lifetime	Description	Reference
>100 years	For believers: summary of geotextile properties for hydraulic and coastal engineering	Pilarczyk, 2000
50 years	For non-believers: summary of geotextile properties for hydraulic and coastal engineering	Pilarczyk, 2000
>20 years	No specifications	Restall et al., 2002
30–110 years	Long-time behavior of geotextiles used in landfills	Müller Rochholz, 2002
50 years	Non-woven geotextile bags in dike revetments	Van de Burg, 2002
>35 years	Non-woven geotextiles in dike revetments as filters at the Mittellandkanal in Germany (the tested needle-punched geotextile did not show weaknesses or problems after 35 years)	Heerten and Saathoff, 2004

will be required during this period. Estimating the lifetime of geotextile bags is difficult, given the widely varying loads and conditions and the fact that overall experience with geosynthetics is limited to around 55 years (Carthage Mills, Faure et al., 1999). Nevertheless, field investigations have been made about changes in material properties, comparing material properties after several decades with original properties at the time of construction (Saathoff et al., 2007). Probably the earliest investigations were conducted in the 1980s with materials used for coastal protection in the later 1950s. Little degradation was reported, and given the improved production facilities and processes since then, it can reasonably be expected that future life expectancy will be greater.

Table 4 shows some examples from the technical literature, with life expectancies ranging from 35 to 110 years. Some documented tests suggest that geotextiles protected from weather and sunlight may last for one or even several centuries. A conservative assumption of a lifetime of three to five decades, combined with multiple-layer coverage, seems to provide reasonable confidence in reliable long-term performance for the envisaged life-time of 30 years.

3.6. Stability

Physical hydraulic modeling (NHC, 2006) at 1:20 scale indicated that geotextile bags of 126 kg are stable to depth-averaged velocities of around 3 m/s, and that only a few bags would be displaced at velocities as high as 4.5 m/s. The hydrodynamic stability of stones, concrete blocks and geotextile bags can be assessed by the equation (Stevens, 2006):

$$\frac{u^2}{2gk\Delta} = C\cdot F$$

Here u = velocity of the water over the stone; g = acceleration due to gravity = 9.81 m/s^2; $k = (V_0/A)$ effective thickness of the element; V_0 = volume of element; A = area over which hydrodynamic forces act

$$\Delta = \frac{(\gamma_s - \gamma)}{\gamma}$$

γ_s = density of the particles; γ = density of water; C = coefficient; F = adjustment factor to account for issues not directly addressed in the analysis.

A protective element is at the threshold of motion when the left hand side of the above equation equals the product C·F. When the flow velocity increases such that the left hand term exceeds C·F, then the protective element may move. Increasing C·F with the left hand term unchanged indicates increased stability of the element. The equation is of a form first developed by Isbash (see Przedwojski et al., 1995).

In Fig. 10, a large C·F coefficient means that for a given degree of stability, the effective thickness k ($=V_0/A$) of the material can be smaller than for a material with a small coefficient. For the sizes and weights tested on a slope of 1V:1.5H, the geotextile bags have the highest C·F coefficients and the coefficients for different bag types

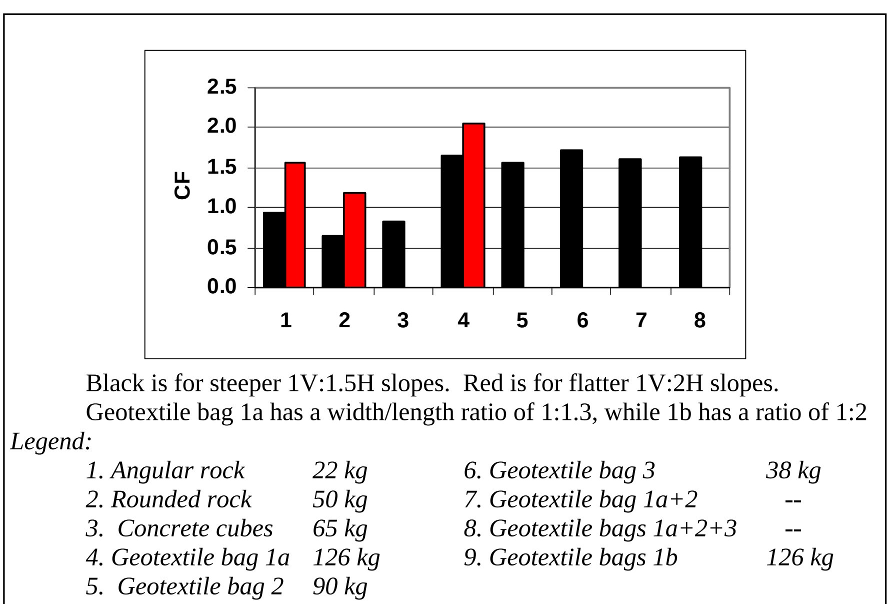

Fig. 10. C.F coefficient required for displacement of protective elements on slopes (Stevens and Oberhagemann, 2006).

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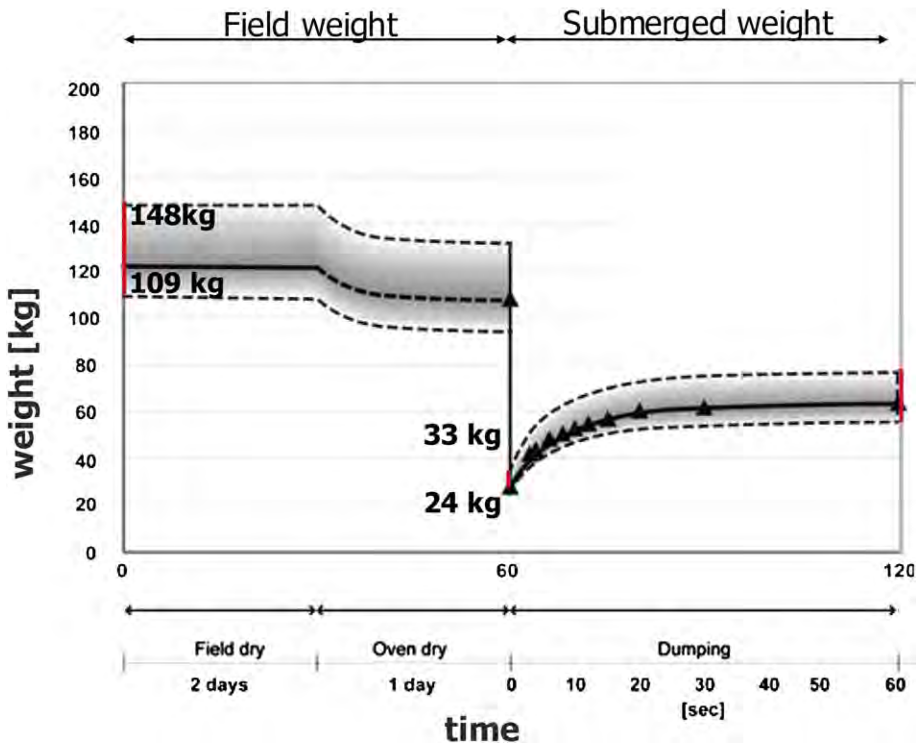

Fig. 11. Development of initial submerged weight depending on the moisture content of the sand fill (Zellweger, 2007).

are nearly the same. Rounded stones have the lowest coefficient. Angular rock is much better than rounded stone. Concrete cubes are intermediate between angular rock and rounded stones.

Neill et al. (2008) report the successful use of a common formula for riprap to dimension geotextile bags.

The stability of geotextile bags under water has been further confirmed through diving inspections. Some diving was done during major flow attack, with surface velocities surpassing 1 m/s. The divers are able to "climb" down the protected slope by holding on to the bags. The extra load of the diver's drag does not move the bags, not even the lighter 78 kg bags. Even under velocities at the limit of diving, it was found very difficult to move 78 kg bags under water, meaning to turn them, and it was impossible to lift them. In contrast, the lighter 36 kg and 11 kg bags were easily moved or even lifted, and could be displaced by the flow. This is the main reason to discourage their use, so as to avoid gaps in the protection.

Systematic submergence tests show quite a range of bag weights in the field and during initial submergence (Zellweger, 2007). The submergence tests show that a 126 kg bag reaches a submerged weight between 62 and 70 kg after two minutes (Fig. 11).

As bags are dumped from barges with the intention to form a uniform coverage of the riverbank under water, their dumping behavior plays an important role. This is difficult to observe and monitor, as the river water is murky and does not allow visual inspection. To obtain initial information, individual bags were dumped into a 6 m deep swimming pool in different positions, and

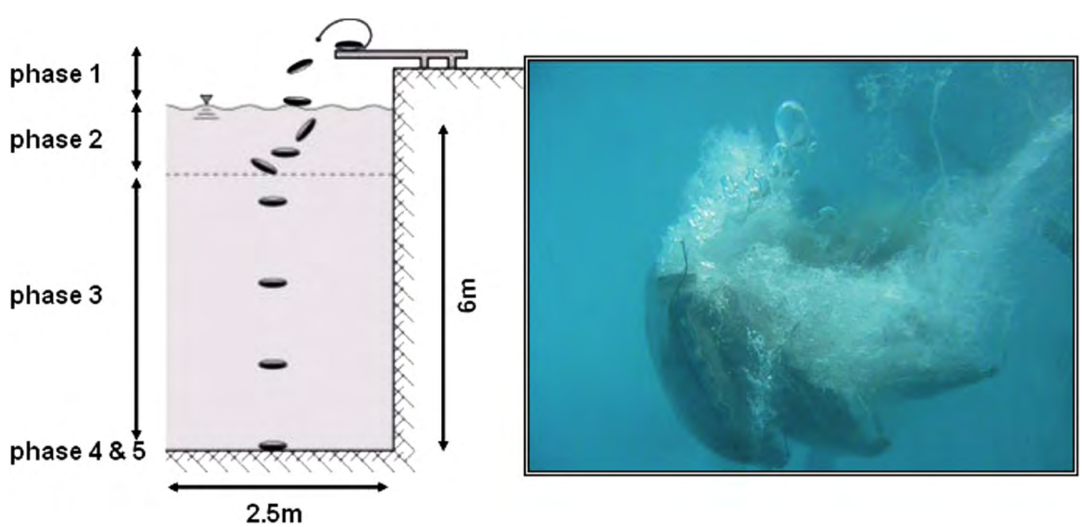

Fig. 12. Schematic of sinking behavior of dumped geotextile bags, and photo of dropped heap of three bags during the initial sinking process (Zellweger, 2007).

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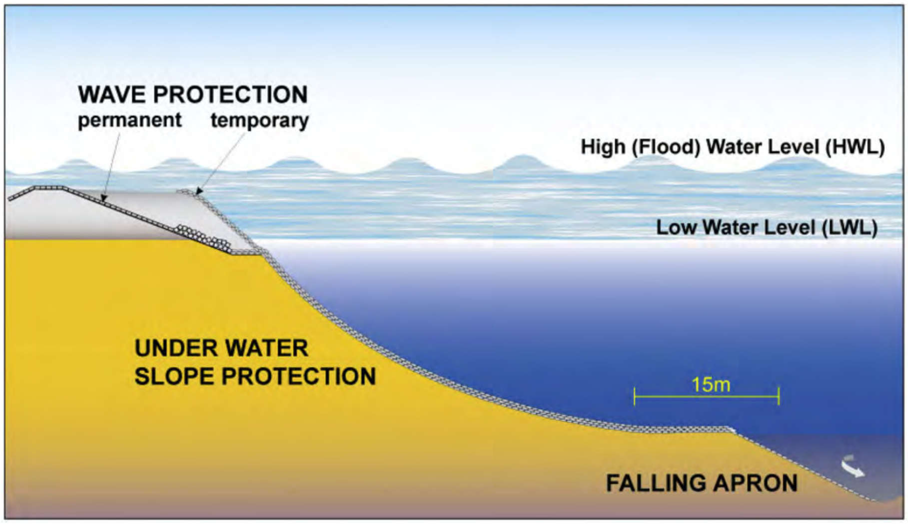

Fig. 13. The three elements of geotextile bag revetments.

the dumping was filmed from the surface and under water. No matter what the initial orientation of the bags (vertical or horizontal, flat or on edge), they always ended up sinking in a flat orientation (Fig. 12). During this process air left the bags mostly at the seams. Bags of 78 and 126 kg weight sink at a velocity of around 2 m/s. After 1–1.5 min, visible air bubbles stop leaving the bags. More systematic research is ongoing on the sinking behavior of geotextile bags (Oumeraci, 2008)

Physical hydraulic model tests (NHC, 2006) indicated that bags dropped in flowing water tended to cluster and that it was difficult to achieve an even coverage. Diving investigations after dumping, however, show that regular multiple-layer coverage can be achieved through consistent and systematic dumping from barges.

4. Geotextile bag revetments

4.1. Definition of elements

Revetments consist of three main elements (Fig. 13):

(i) Slope protection under water to prevent erosion of the riverbank;
(ii) Slope protection above low water level to prevent wave erosion as well as current erosion during the flood season between low water and floodplain levels. The temporary wave protection consists of geotextile bags and is placed to allow the completion of resettlement and land acquisition along the stabilized banks prior to excavation of the upper slope and placing of permanent protection.
(iii) Toe protection in the form of wide falling aprons to prevent undermining of the slope protection by river-bed scour.

The wave protection normally starts under water, with a berm to reduce the load on the bank and to increase the safety factor for geotechnical slope stability.

Launching geotextile bags provides another important advantage: they launch on geotechnical stable slopes. The major rivers in Bangladesh, especially the lower Brahmaputra (called Jamuna locally) is in a process of widening and as such constantly erodes old consolidated floodplains. Geotechnically stable slopes are in the order of 1V:2H (Fedinger, 2004, 2006). Geotextile bags placed as a heap along the bank launch during undercutting to form a similar slope, whereas the more angular concrete blocks need steeper slopes to launch, in the order of 1V:1.5H, which are not geotechnically stable. This makes geotextile bags an ideal tool for immediate emergency response at critically eroding reaches.

4.2. Phased construction of revetments

Revetment work in the large rivers of Bangladesh can only be implemented in a phased manner, because of rapid changes and great variability in river morphology that allow bank erosion to be predicted no more than one year ahead. The Project distinguished three main phases as shown in Figs. 14–16: (i) mass dumping along the eroding riverbank before the monsoon season, when needed as emergency response to protect valuable infrastructure; (ii) main protection dumped from the river after the monsoon season, and (iii) adaptive protection extending the work by dumping to greater

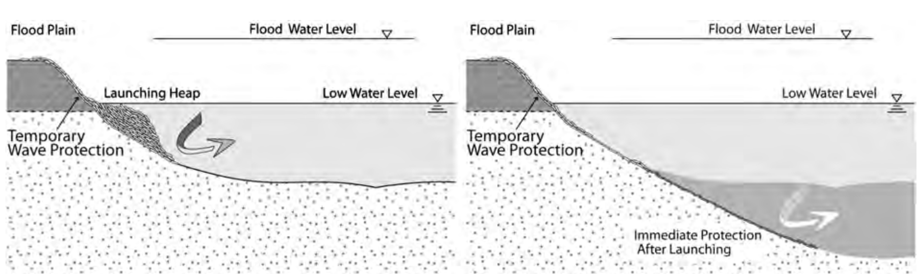

Fig. 14. Emergency protection through mass dumping of a launching heap along the bank.

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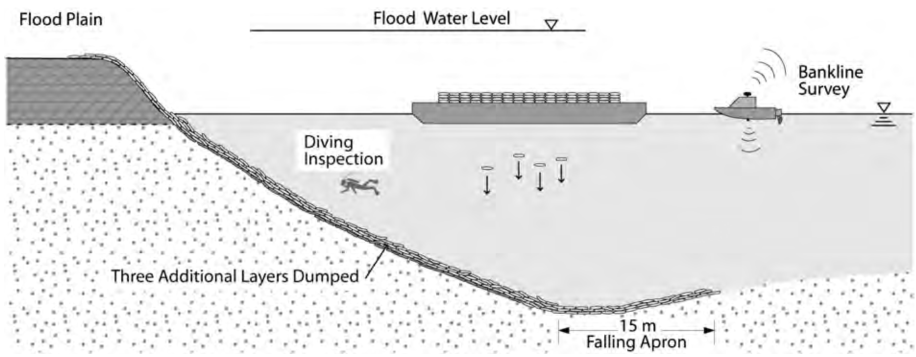

Fig. 15. Main protection through dumping of additional layers.

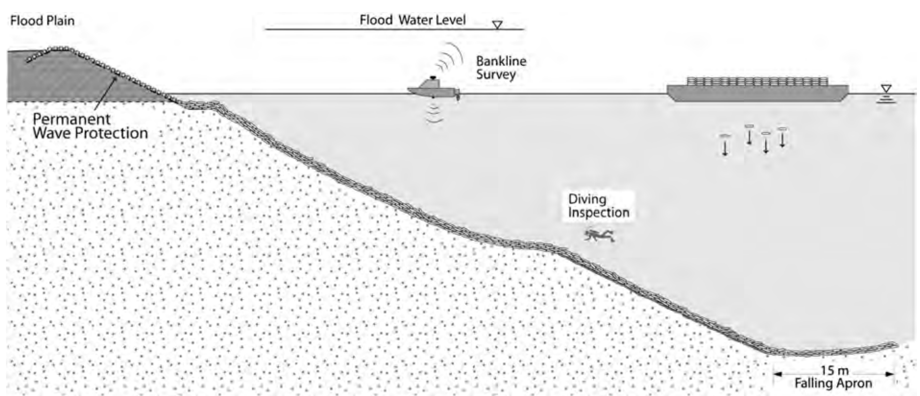

Fig. 16. Adaptive protection through dumping to greater depths.

depths, if erosion continues and threatens to undermine the existing work. This phased approach has additional advantages with respect to arranging for land acquisition and population resettlement along densely populated banklines (Oberhagemann et al., 2007; Ragsdale et al., 2008).

4.3. Performance

In the Project referred to herein, geotextile bag revetments constructed in the above three stages have been applied along about 12 km of banks in the largest rivers of Bangladesh. Systematic dumping from the surface, even allowing for flow displacement, results in complete coverage of the underwater bank slopes with multiple layers, as has been confirmed through diving.

While the bags are initially soft, the sand consolidates after a few months so that the bags later feel as hard as concrete. The surface of the bags often retains an undulated pattern resulting mainly from impact (Fig. 17). Over time, bags develop some bio-skin, consisting of algae where light penetrates and other life forms elsewhere (Fig. 18). This coverage provides extra protection against abrasion and suggests that the bags may last longer than expected.

In some cases and as a result of consolidation of the sand fill, the sand volume reduces while the geotextile volume remains the

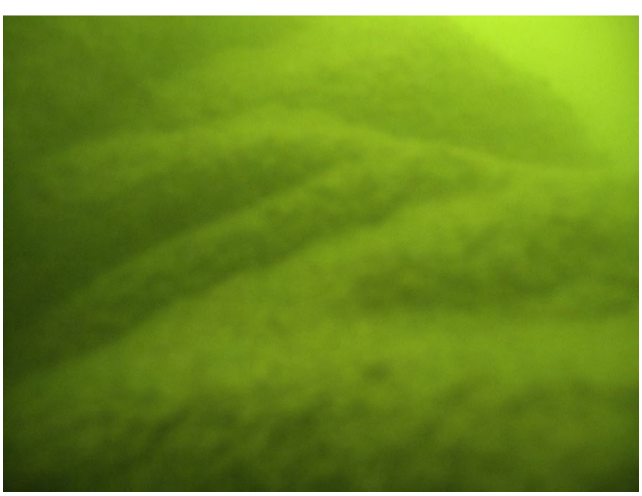

Fig. 17. Observed undulations of geotextile bag surface under water.

Fig. 18. Life forms using the geotextile bag as substrate on which to grow.

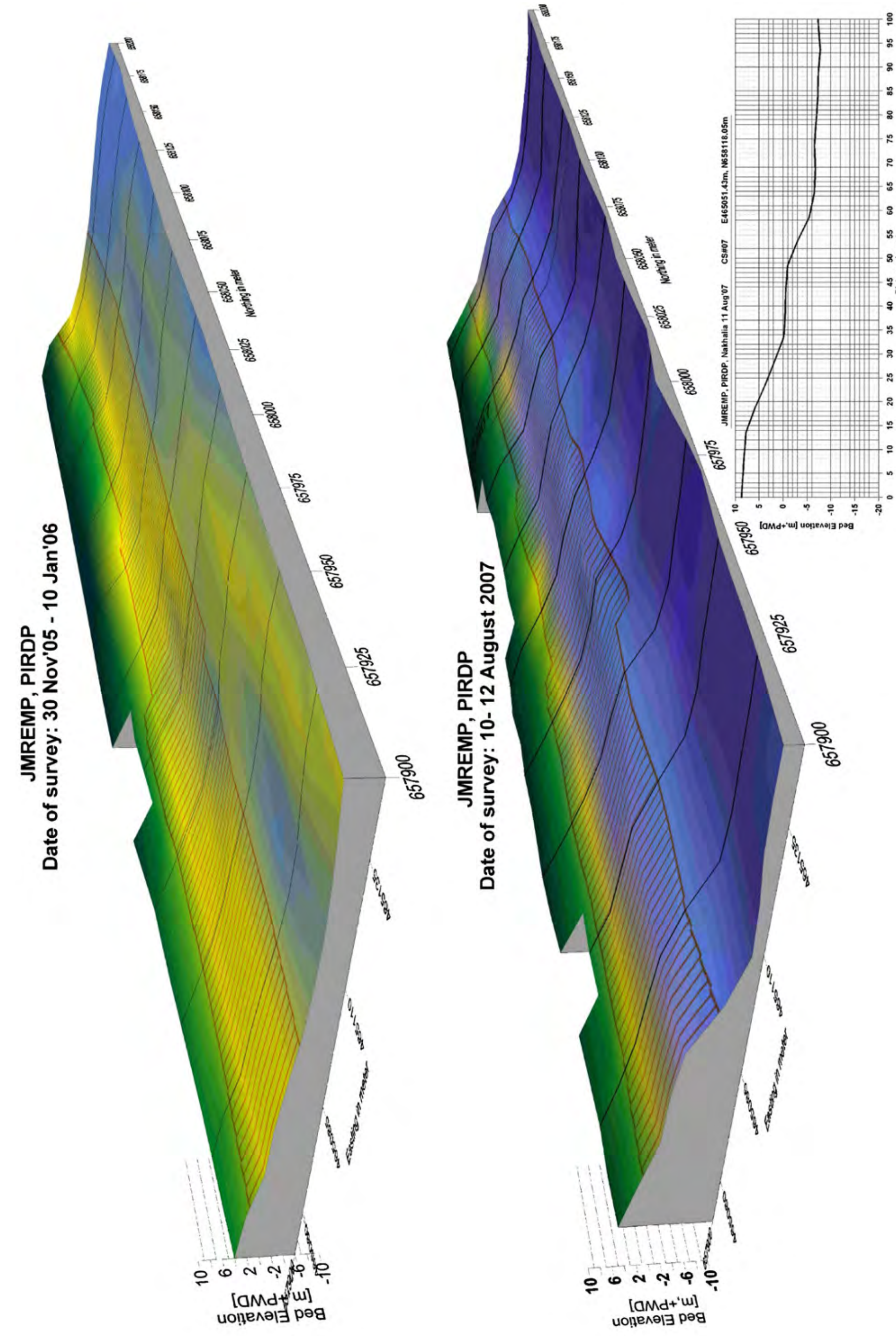

Fig. 19. Experience with launching behavior of geotextile bags.

same, so that full bags above water turn into partly filled bags under water. As a consequence some corners can become loose and start flapping in the flow. However, this is not often observed during diving. So far there are no signs of fatigue and this is not expected to play a major role, since the geotextile is quite thin and not as susceptible to fatigue as thicker material.

Apart from the stability of the cover layer, geotextile bags fulfill the requirement of launching as toe protection on geotechnically stable slopes. River surveys confirm this behavior: for example, geotextile bags placed at the end of 2006 started launching after the river deepened during the high 2007 flood. Bathymetric surveys show that slopes after launching are around 1V:2H even where the falling apron was placed on recently deposited, unconsolidated sands at the bankline. Fig. 19 depicts an example from the lower Brahmaputra/Jamuna River. The upper figure is a survey conducted in 2005 as as-built survey and the lower one dates from 2007 after launching. The hatched area shows the area of original placement through controlled dumping; the cross section shows the launching after the channel in front of the apron deepened. Diver observations indicate that even though the coverage after launching consists of only a single layer of geotextile bags, the gaps between bags are on no more than hand size. The plastic behavior of launched bags through adjustment of the sand fill apparently keeps the gaps small and reduces the loss of underlying fine material. This observation supports the value of geotextile bags as flexible riverbank protection even in the extreme case of their use as a falling apron on unstable developing slopes.

After two high flood seasons (2004 and 2007) no failures were found and the protection appeared to have performed well, even though it had been dumped on the existing riverbank without any dredging operation to flatten or smoothen the slopes.

5. Conclusion and outlook

5.1. State of knowledge

The state of knowledge as of 2009 can be summarized as follows:

1. Geotextile bags launch down the slope when the river erodes the bank under a launching heap or a falling apron. Slopes after launching are approximately 1V:2H, according to field observations and model tests. Diving investigations indicate that the gaps between adjacent launched bags are small, less than hand size. These observations make geotextile bags suitable for providing erosion protection on banks consisting of consolidated sandy soil.
2. Geotextile bags of the dimensions used in the described Project provide stable elements for long parallel slope protection or revetments along riverbanks. (Flow velocities along revetments are generally less than half those at exposed corners or spur heads, as indicated by physical model tests from 2006).
3. Geotextile bags of 126 kg filled weight are stable against near bed velocities of up to 2.9 and 2.6 m/s on slopes of 1V:2H and 1V:1.5H respectively. This corresponds to depth-averaged velocities of more than 3 m/s. Bags of 90 kg are stable for slightly lower velocities. These values are well above those observed at the two subproject sites.
4. Geotextile bags provide high stability against currents. The main reason is the substantial difference in shape: flexible geotextile bags lying flat on the bank show high resistance to flow forces. Also, bags are flexible and over time form a smooth layer, so that they do not project into the flow and generate local turbulence. The USACOE, 1991 compares different hard materials[2] and states that creation of heaps from uncontrolled underwater dumping must be avoided.
5. So far there are no generally used formulas for calculating the resistance of geotextile bags to flow forces, as exist for riprap. Existing formulas require adaptation to reflect the specific characteristics of geotextile bags. Neill et al. (2008), Stevens (2006), and Pilarczyk (2000) make some suggestions. For present purposes, 126 kg geotextile bags are considered to be stable as revetments for a depth-averaged flow velocity of 3 m/s, based on studies and investigations mentioned earlier.
6. Geotextile bags with smaller length/width ratios (1.3) are better for launching than more elongated shapes.
7. Geotextile bags dumped in fast flowing water (1.7 m/s and 3.4 m/s in model tests) tend to cluster and not provide an even coverage. This has been taken into account in the design by dumping three layers of bags, which is 50% greater than the theoretical minimum of two layers (USACOE, 1991).[3]

5.2. Outlook for future

This first large-scale application of geotextile bags as bank protection without other materials has provided encouraging results, and in some places has indicated superior behavior compared with more conventional materials – especially concrete blocks. Nevertheless there is a clear need for future systematic monitoring and evaluation of their performance and for accompanying research. Currently planned research relates to:

(i) *The optimal shape of the bags*, which presently have a length/width ratio of around 1.3. Physical hydraulic model studies with longer bags of ratio 2 clearly indicated less satisfactory behavior. Perhaps square bags could perform even better.
(ii) *More systematic studies of dumping behavior*, to identify the scatter at the bottom of the river and the lower part of the bank. In this respect there could be opportunities for cost savings, as at present 50% more bags are dumped than theoretically required.
(iii) *Follow-up of long-term behavior*, by testing bags after ten years under water and comparing their key properties with those specified and tested at the time of procurement.
(iv) *Systematic testing of abrasion*, and correlating of abrasion resistance with the mass per unit area of the geotextile material might provide important insights into the lower limit of geotextile material to be used for geotextile bags.

Overall, geotextile bags combine the functions of filter and protective element, which provides clear advantages. Conventional applications using two components, a filter plus a ballast or cover layer, require more construction effort and are more limited in application. For example, fascine works consisting historically of willow bundles but now largely replaced by geotextile sheets, cannot be placed in flowing water along eroding riverbanks. The multiple-layer placement of geotextile bag revetments makes them durable even if part of the upper layer is destroyed or damaged.

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The authors express their gratitude to be involved in the design development process of a major new development initiative to provide stability to the lives of the large number of poor people living along the banks of the big rivers in Bangladesh, and permanently haunted by the risk of erosion resulting from the general widening tendency of these rivers. The development of the technology was not possible without the teamwork of a group of colleagues from the Bangladesh Water Development Board, consultants, and ADB. The driving forces for design development were the former Director General Mukhles-uz-zaman, the Project Director Md Sharif Al-

[2] Chapter 3.2, p. 3-1: "*a. Stone shape*. Riprap should be blocky in shape rather than elongated, as more nearly cubical stones "nest" together best and are more resistant to movement. The stone should have sharp, angular, clean edges at the intersections of relatively flat faces. Stream rounded stone is less resistant to movement, although the drag force on a rounded stone is less than on angular, cubical stones. As rounded stone interlock is less than that of equal-sized angular stones, the rounded stone mass is more likely to be eroded by channel flow. If used, the rounded stone should be placed on flatter side slopes than angular stone and should be about 25 percent larger in diameter".

[3] Chapter 3.2, p 3–4: "(2) The thickness determined by (1) above should be increased by 50 percent when the riprap is placed underwater to provide for uncertainties associated with this type of placement. At one location in the US Army Engineer Division, Missouri River, divers and sonic sounders were used to reduce the underwater thickness to 1.25 times the dry placement thickness."

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