Journal of Construction in Developing Countries, Vol. 15(2), 69–85, 2010

Protection Works Against Wave Attacks in the Haor Areas of Bangladesh: Analysis of Sustainability

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Abstract: Haor is the local name of the saucer-shaped, naturally depressed areas of Bangladesh. There are 414 haors in the northeast region that comprise approximately 17% of the country. These areas are submerged under deep water from July to November due to the overflow of rivers and heavy rainfall, causing them to appear like seas with erosive waves. Recently, the wave attack has drastically increased because of de-plantation and changing cropping patterns to allow for more agricultural production. The local people, government and Non-Government Organisations (NGOs) have tried many techniques to protect life and property against wave attacks. A cost comparison shows that Cement Concrete (CC) blocks over geotextile on the slope embankment is a cost-effective, environment friendly and socially acceptable method to prevent loss of life and property. However, the design rules employed by the engineers are faulty because there is knowledge gap in the application of wave hydraulics among these professionals. As a result, damage frequently occurs and maintenance costs are increasing. This study explores the sustainability of the CC blocks used in the Haor areas by evaluating two case studies with the verification of available design rules.

Keywords: Haor area, Protection works, Cement Concrete (CC) block, damages due to waves

THE HAORS

Haor is the local name of the north-eastern region of Bangladesh (see Figure 1). It constitutes approximately 17% of the country's land area and the total number of haor is about 414. This is a naturally depressed area covering 24,265 sq. km that is surrounded by small tributaries of the main rivers Surma and Kushiyara. Due to overflow of rivers and heavy rainfall from July through November, these areas are submerged in 4 to 5 meter of water and become similar to with erosive waves (see Figure 2). During dry season (December to April), the water is completely drained from the area by gravity and the area returns to fertile land for crop production. The people of this area are mostly poor farmers and fishermen and survive below the poverty level.

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THE PRESENT PROBLEMS

Haor areas face two main problems: (1) scarcity of food and (2) safety of life and property. These are briefly discussed below.

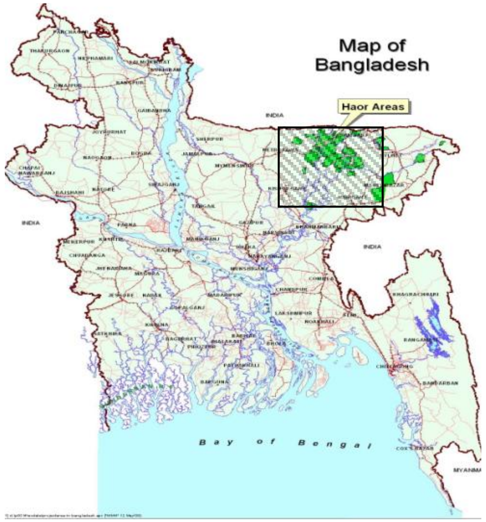

Figure 1. Location map of haor areas of Bangladesh

Source: Research.

Figure 2. View of a village in the haor area during a monsoon

Source: Research.

Scarcity of Food

In the last two decades, the residents of haor have faced problems of food scarcity and road communication within and outside haor areas. Food scarcity was due to crop damage by a flash flood from April to May. The road communication could not be developed due to a flood, a persistent problem that exists for half of the year. To solve these problems, government and Non-Government

Organisations (NGO) constructed submersible (low) dykes along the rivers and paddy fields to prevent early flash floods that occur in mid-May. These submersible dykes are approximately 1 meter in height from the surrounding lands and are located in deep water during a monsoon (see Figure 3). These dykes around the paddy field have been paved with concrete for road communication. Due to the construction of these submersible (low) dykes, the bumper production of crops has become possible. The living standard of the local people has greatly improved. However, this improvement is limited to the dry season and hardly extends past four to five months of the year.

Figure 3. Submersible concrete road (low) dykes in the haor area to prevent early flash floods

Source: Research.

Safety of Life and Property

The people in haor areas live in isolated settlements that are located on earthen mounds or on raised platforms. Boats are the only means of transportation during the flood season. Residents use bullock carts for transportation during the dry season. Extensive de-plantation has been occurred to reclaim the agricultural land. The cropping pattern has also significantly changed over last three decades. These alterations have increased wave attacks in the haor areas. A decade ago, wave attacks were not a serious threat to the existence of settlements. In the past, the farmers cultivated long stem paddy during monsoon that could absorb wave impacts. Presently, the land is vacant during the monsoon season and the wave height has thus increased two fold from 0.6 meter to 1.5 meter, threatening the settlement. The traditional methods are no longer adequate against wave attacks. Many villages have been washed away and the existing ones are in threat. Landless villagers are migrating to the slum areas of the nearby cities and towns, which decreases the quality of life and causes social problems in the country.

Realising this situation, the government and NGOs have been applying a wide range of materials and techniques to prevent wave attacks since 1996. The cost comparison of various techniques of erosion control against wave attack that simultaneously promote sustainability for long periods suggests that the CC blocks revetment over geotextile are the most economical solution in the haor areas (see Table 1). These techniques are both environment friendly as well as socially acceptable in their structure. However, damage has become a regular phenomenon in this region due to a knowledge gap of wave hydraulics of the design engineers and professionals. The failure mechanism is not fully understood and Hudson's formula is usually applied in these situations (Hudson, 1953). Hence, the protection plans are either under-designed or over-designed. This study analyses the design of CC blocks based on two case studies.

METHODOLOGY

The methodology consists of two parts: (1) an extensive laboratory study conducted for the verification of the applicability of the popular Dutch formula known as the Pilarczyk formula (1998) (Eq. 1, Article 3.2.1.2) on wave structure and (2) a damage study of The completed wave structures at two different locations.

Lab Experiments

The lab experiments have been conducted in the Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering at Bangladesh University of Engineering and Technology (BUET) in Dhaka. A total 325 experiments were conducted in a 21.3 meter (70 feet) long, 0.76 meter (2 feet 6 inches) wide and 0.76 meter-deep glass-sided tilting flume of the laboratory. A modern wave generator with a wave damper and a wave height meter were used during the experimentation. Data were collected through the LabVIEW system and then transferred to MATLAB software. The details of the lab experiments are not detailed in this manuscript and can be found in the Design Manual (2006).

Case Study on Damages

Two case studies are included in this study. These are (1) a wave protection embankment at Mithamain haor and (2) a wave protection work at Joydorkandi Village of the Akashi-Shapla haor.

Table 1. Unit costs of cover layer materials in the haor areas of Bangladesh

Cover Layer Materials	**Dimensions (mm)**	**Cost (US$/m²)**	**Remarks**
Traditional Methods (soft protection)	Long stem grass in bamboo frame	10.0	Not suitable. High maintenance cost, 6.6 US$/m².
Concrete blocks with geotextile.	400 × 400 ×250	20.0	Socially acceptable and environmental friendly. Low maintenance cost, 0.66 US$/m².
Cable connected blocks	300×300×150	9.6	Not feasible due to construction and maintenance problem.
Gabion fill material	500 (thick)	12.0	Not feasible due to construction and maintenance problem
Reno Mattress	400×3500×2000	13.0	Not feasible due to construction and maintenance problem
Macmat	25	10.38	Less effective than CC blocks. Unknown technology, high maintenance cost.
Brick wall	4.0 meter high (750 mm thick)	109.0	High initial cost. Maintenance cost more than CC blocks.
RCC wall	4.0 meter high (200 mm thick)	107.0	High initial cost. Maintenance cost more or The same as CC blocks.

Source: Research.

Wave protection embankment at Mithamain haor

The Mithamain haor is one of the largest haors of Bangladesh and is one of the most affected areas. An earthen embankment (2 kilometer long, 4 meter high, 5 meter wide) with a 1 meter high brick toe wall was constructed above ground level as a mitigation measure during the 1997–1998 dry season (see Figure 4). The locally available Chala grass in split bamboo woven mesh was used as protection works against wave attack (see Figure 5). The structure was not successful and failed (i.e., washed away).

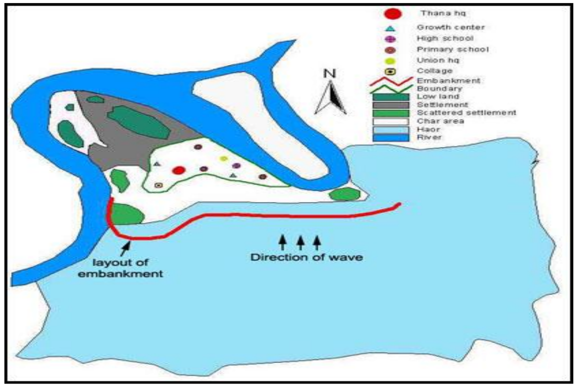

Figure 4. Layout of embankment (1998) against wave attack at Mithamain
Source: Research.

Figure 5. Protection of slope by locally available Chala grass encased in a bamboo split frame
Source: Research.

In the next attempt, the structure was rehabilitated with a 5 meter high earthen embankment with CC blocks revetment in the dry season of 1999. The base materials of the embankment are of local origin with predominantly clay soils of D_{50} between 0.026 mm and 0.045 mm (i.e, 50% of the clay soil is finer than the specified diameter). The original brick toe wall was repaired and used for the structure. A RCC guard wall of 1 m in height was installed at the crest level to minimise wave intrusion. Three different sizes of blocks were used. The lower third composed of 400 × 400 × 150 mm blocks, the middle third of 400 × 400 × 200 mm

CC blocks and the upper third consisted of 400 × 400 × 250 mm blocks. The cost of revetment and the cost of the guard wall were 48.5% and 38.5%, respectively, of the total cost of the rehabilitated protective works with a value of US$ 1800 (approx) . Since then, the structure has been protecting the villages and lives against wave attacks but damage frequently occurs.

The first damage to this new structure occurred six months after the construction in the 1999 flood, which included the entire collapse of the brick toe wall and movement of the CC blocks down the slope (see Figure 6). In the following dry season, the brick toe wall was replaced

Figure 6. Brick toe wall collapsed (under water) and CC blocks slid down slope (view in dry season, first damage)

Source: Research.

by a CC beam that was casted below the ground level and anchored to a level that matched the embankment slope of 1:2 (see Figure 7).

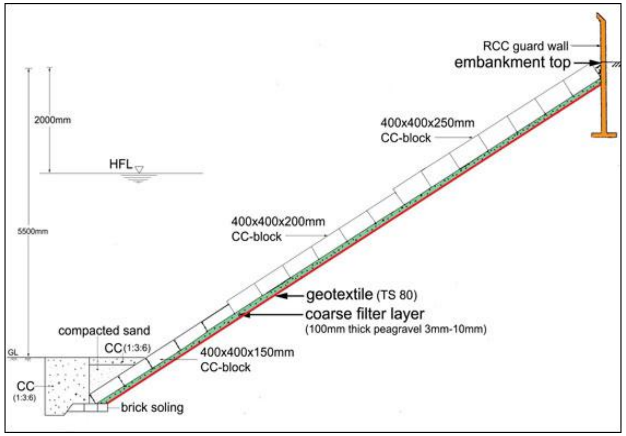

Figure 7. Cross section of the embankment with the concrete key wall (not to scale)

Source: Research.

The second set of damages occurred during the 2003 monsoon in which the CC blocks were compromised at five places because of strong wind waves. However, the damages were not severe and regular repair work restored the wall (see Figure 8).

Figure 8. A view of the CC block settlement in the upper part of the slope during the 2003 flood (second damage)
Source: Research.

The third damage occurred in August 2004 and is considered the most severe. In this storm, the water level exceeded previous maximum levels and was an event with a 120-year re-occurrence pattern. The water level was only 0.7 meter below the embankment crest level. There was continuous rainfall for seven days in the area and the run-off at the crest accumulated at the bottom of the guard wall due to a cross slope toward the wall. Breaches were created at four places along the length of the embankment due to the wave thrust at the foot of the guard wall and flood water rushed toward the countryside areas through the holes. Sand bags were dumped at these locations to minimise gushing water (see Figure 9, 10, 11 and 12). All damage occurred during a single storm on 17th August 2004. However, the toe wall was intact throughout the length of the embankment and blocks did not slide down the slope.

Figure 9. One of the breaches at the bottom of the guard wall approximately at the middle of the embankment
Source: Research.

Figure 10. Settlement of CC-blocks the crest of the guard wall during storm wave during 17th August, 2004

Source: Research.

Figure 11. Cavities below geotextiles

Source: Research.

A damage assessment was conducted via three field visits by visual observation (1) in unopened condition, i.e. intact condition of the protective works, on 28 November 2004, (2) in open condition, i.e. blocks are removed from the original position and materials become opened, on 6 January 2005 and (3) during the repair work on 6 March 2005. Major damages occurred at 16 locations and minor damages occurred at 52 locations. The area of the major damages varied between 33 m^2 and 350 m^2 and the minor damages varied between 1.5 m^2 and 25 m^2. A total number of 16,000 CC blocks were opened for inspection and repair work.

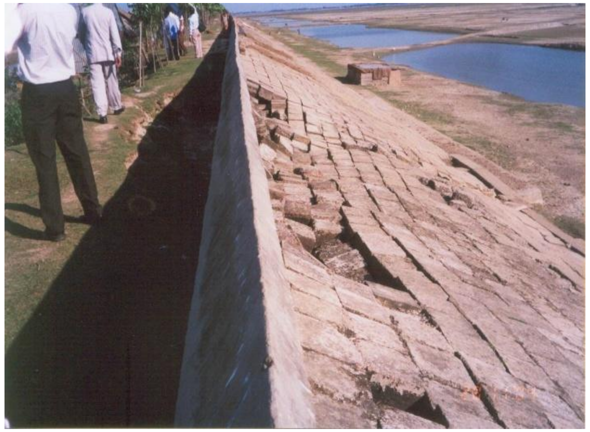

Figure 12. Cast in situ slab was found blown away and displaced

Source: Research.

The major damages occurred at the upper part of the embankment in the vicinity of the vertical guard wall at regular, horizontal intervals (see Figure 10). Each major damage site showed a substantial subsidence of soil level under the geotextile. The covering revetment blocks caved in, following the subsidence areas. The decline in soil level corresponded to a virtual loss of the soil body up to 1 m^3 that formed a wedge-shaped cavity under the revetment. The bottom of the cavity was nearly horizontal and at the same depth as the foundation of the vertical guard wall.

The geotextile appeared to be evenly sunk with the soil level and was undisturbed and undamaged. However, the geotextile did not align with the transition with the guard wall and was not properly anchored and sealed. Erosion channels were found below the geotextile at those locations (see Figure 11).

It was not clear how the transition between geotextile and guard wall had been effected. There is no evidence that there was inadequate overlapping of the respective geotextile sheets. The minor damages (i.e., individual CC blocks displaced out of the revetment) occurred at the middle and lower portions of the embankment slope (see Figure 12).

Rat holes were identified at the unpaved crest and the inner slope. However, there was no strong evidence that the piping created by the rats was deep and/or long enough to reach the geotextile, which would have thereby allowed the stagnant rainwater at crest of the embankment to wash away fine soil particles and create a void below the geotextile where the CC blocks could settle. Blocks also protruded at the middle reach at the apex of the embankment where wave attack was severe.

ANALYSIS OF DAMAGE OCCURRENCE

From these observations, the following questions arose:

(1) Is the subsidence of the soil level in the vicinity of the guard wall due to a real loss of soil material (i.e., removal/migration of soil particles)?

(2) Is the quality of the geotextile appropriately applied?

(3) Is the soil mass of embankment, especially in the upper part, properly compacted?

(4) Did all damages originate from the last monsoon period or are they partly due to failures in maintenance?

In regards to the first question, the migration of large masses of soil particles at damage sites could have occurred due to the open joints between the CC blocks and the geotextile; however, the joints were narrow and the geotextile sheets appeared to be undisturbed and undamaged with proper overlapping. The loss of soil material at the damage sites seemed to be too large to have been solely caused by the migration of soil particles.

The loss of material through the geotextile can be explained by analysing the soil type and geotextile properties. Sieve analysis of the three soil samples of the base materials of the embankment show that the soils are 0.045 mm, 0.026 mm and 0.048 mm, respectively and the soils are predominantly clay soil with D_{50} between 0.026 mm and 0.045 mm. The grain sizes of the filled earth vary at different heights because the soils have been collected at different depths of the same borrow pit. The soil at the base consists of sand (D_{50} varying between 0.15 mm to 0.53 mm) with approximately 13% to 30% silt whereas the soils at the top and upper middle are predominantly silt and clay with D_{50} varying from 0.02 mm to 0.03 mm.

A geotextile separating the blocks from the clay subsoil must be geometrically sealed and the geotextile is considered sufficiently stable (CUR, 1995) if,

$$O_{90}(\text{geotextile}) < 10D_{50}(\text{base}) \text{ and } O_{90}(\text{geotextile}) < D_{90}(\text{base}) \text{ and } O_{90}\ (\text{geotextile}) < 0.1 \text{ mm.}$$

In the present case, the TS_{80} geotextile has been used whose O_{90} = 0.08 mm. The value of O_{90} of geotextile is therefore less than 10 D_{50}(base) (i.e., O_{90} (geotextile) (0.08mm) <10D_{50} (0.2 mm-0.3 mm) and also O_{90} (0.08mm) < D_{90}(base)). The D_{90} of the soil varies between 0.17 mm and 1.4 mm. All the criteria of the stability of the geotextile are fulfilled and hence, loss of materials through geotextile is not feasible.

Examination of the guard wall construction procedure revealed that the remaining soil mass was loosely filled up to the crest level without proper compaction (see Figure 13) under the assumption that the water level would seldom reach that height.

Figure 13. Construction of RCC guard wall with earth filling that was not compacted

Source: Research.

The process of uneven settlement of soils below the geotextile had been possibly occurring for several years.

Rain water infiltrated the ground and reached below the foundation of the guard wall, which created cavities and a channel. Because of this, the CC blocks revetment lost contact with the soil and arching occurred. These changes could not be seen from the surface and hence could not be checked during regular inspection work. During the extreme flood on 17 August 2004, the water level reached near to the foot of the guard wall. The soil became further saturated and the wave impact caused heavy loads of water that lead to a disastrous settlement of the soil over a large area.

Therefore, the main causes of the major damages of block settlement were due to locally improper compaction of the upper part of the embankment that led to the widespread settlement of the soil.

STABILITY OF INDIVIDUALLY PLACED BLOCKS

The stability of the blocks has been assessed using the Pilarczyk formula (1998) and design curve developed by Delft Hydraulics, Tu Delft (2006). The Pilarczyk formula (1998) can be written as:

$$\frac{H_s}{\Delta D} = \psi\phi\frac{\cos\alpha}{{\xi_{op}}^{b}} \qquad \dots (1)$$

where, the parameter $H_s/\Delta D$ is the stability parameter, ξ_{op} is the surf similarity parameter, Hs is the significant wave height, Δ is the relative density of the concrete, D is the layer thickness, Ψ is the system upgrading factor, Φ is the stability factor for initiation of motion (= 2.25), α is the slope of the dyke/revetment and b is the exponent related to the interaction process (0.5<b<1).

The surf similarity parameter ξop is given as:

$$\xi_{op} = \frac{\tan\alpha}{\sqrt{H_s/L_{op}}} \qquad \dots (2)$$

Where, H_s/L_{op} is the wave steepness and $L_{op} = gT_p^2/2\pi$.

The waves in the haor areas are irregular and do not break in the foreshore. For analysis, the boundary conditions on 17 August 2004 have been considered with a wind speed of 65 km per hour (18 m/s) with a 2-hour storm duration. The fetch length (F) was calculated to approximately 20 km with the wind blowing from the south direction. The density of the concrete material (ρ_s) has been included as 2240 kg/m^3. The depth of water (d) at the toe was 4.8 meter.

With the above boundary conditions, the Sverdrup-Munk-Brettschneider (SMB) method was applied for estimating Hs, Ts and T_p (SPM, 1984; CPM, 2002). Considering that wave attack occurs perpendicular to the structure, the wave parameters have been found using the following formula (Schiereck, 2001):

$$\frac{gH_s}{u^2} = 0.283 \tanh\left[0.53\left(\frac{gd}{u^2}\right)^{0.75}\right] \tanh \frac{0.0125\left(\frac{gF}{u^2}\right)^{0.42}}{\tanh\left[0.53\left(\frac{gd}{u^2}\right)^{0.75}\right]} \quad \ldots (3)$$

and

$$\frac{gT_p}{u} = 2\Pi \times 1.2 \times \tanh\left[0.833\left(\frac{gd}{u^2}\right)^{0.375}\right] \tanh \frac{0.077\left(\frac{gF}{u^2}\right)^{0.25}}{\tanh\left[0.833\left(\frac{gd}{u^2}\right)^{0.375}\right]} \quad \ldots (4)$$

The wave parameters calculated were:

H_s= 0.90 m, T_s= 3.7s, T_p= 4.07s, $L_{op} = \frac{gT_p^2}{2\pi} =$ 25.84 m.

From laboratory investigations, the values of Ψ and b of the Pilarczyk formula (1998) (Eq. 1) were calculated as 2.0 and 0.67, respectively. The surf parameter (ξ_{op}) was calculated as 2.68 and the stability parameter ($Hs/\Delta D$) was 2.90 for the Mithamain case with the CC blocks of 0.25 meter thickness (D). From the produced design curve, it is now evident that CC blocks are in the unstable zone (i.e., under designed) (see Figure 14).

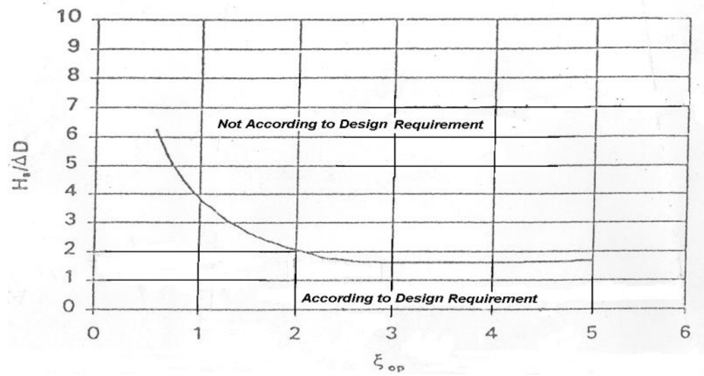

Figure 14. Design curve developed through experiments
Source: Design Manual (2006).

Therefore, the blowing away and protrusion of the CC blocks at the middle of the embankment slope were mainly due to the instability of the individual CC blocks.

WAVE PROTECTION WORK AT JOYDORKANDI VILLAGE AT THE AKASHI-SHAPLA HAOR

Joydorkandi village is an isolated village situated along the bank of the Dhamadia River (see Figure 15). The village extends in the east-west direction across 3 km and has a narrow strip of area 300 m wide. The east and south side of the village face toward Akashi-Shapla haor. These areas are most vulnerable to wave erosion.

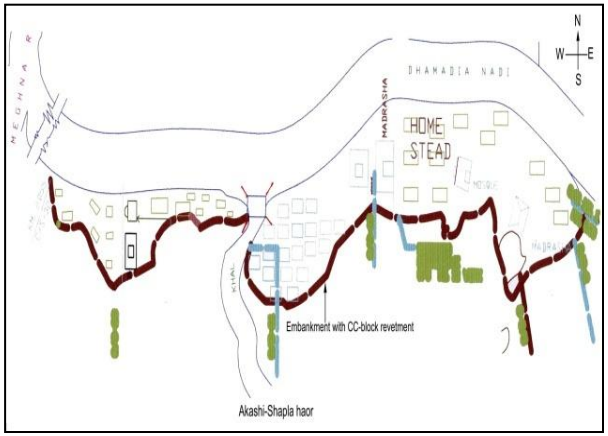

Figure 15. Map of the Joydorkandi village protection work in the Akashi-Shapla haor area

Source: Research.

As a protection measure, a 2820 m-long embankment with a CC block cover layer over the geotextile was designed (see Figure 16).

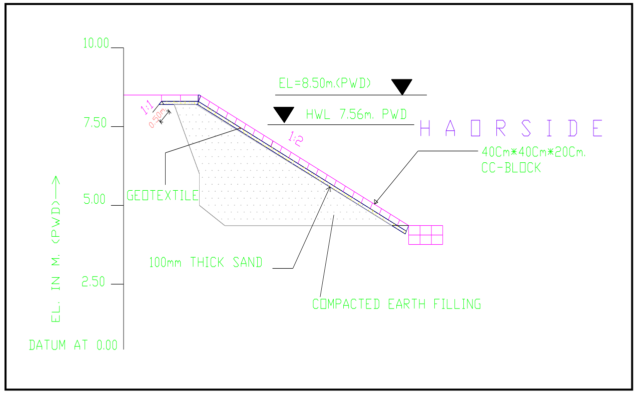

Figure 16. Cross section of Joydorkandi village protection embankment

Source: Research.

The filling of the embankment was conducted in the dry season of 2005 (March-May) with local soil. Out of a target length of 2820 meter, only 500 meter was constructed in the first phase up to the periphery of the existing mound of the residents' homesteads. A field inspection revealed that the procedure for the chronological filling of soil in 150 mm layers with compaction was not followed. Instead, geotextile was laid over the slope after nominal dressing. The slope was steeper than the design slope of 1:2. Because the CC blocks were in double layers, the toe structure was not buried below the ground level and was laid above the ground surface (see Figure 17).

Figure 17. Toe structure above ground level
Source: Research.

PERFORMANCE DURING THE FIRST FLOOD

Three months after the work was completed, damages occurred under normal flood conditions in July 2005 when the depth of water at the toe was 2.5 meter. There were settlements of the CC block revetment in more than 20 locations with each covering an area between 2 and 5 m^2 in a saucer shape. The failure points were located near the middle of the slope surface (see Figure 16). It was reported by the villagers that during wave attack, muddy water emerged from the damaged points and the CC blocks were removed from those affected points. The earth underneath the blocks had shifted and lumped in the geotextile (see Figure 18). Geotextile was also found wrapped, bulged and distorted. In the open condition, the overlapping of joints was found to be inadequate.

Figure 18. Lumping of soil in the geotextile due to wave suction
Source: Research.

The design of the CC block revetment was conducted using Pilarczyk's formula (1998) with an arbitrary choice of data on boundary conditions (i.e., significant wave height and wave period). The geotextile was appropriately installed without any soil analysis and construction was completed with inadequate compaction of the soil. Even with all these lapses, the embankment sustained the wave attack with severe damages.

LINKING BETWEEN DESIGN, PERFORMANCE AND SOCIAL IMPACT

The above two case studies are examples of the categories of damages of wave protection embankment in the Haor areas of Bangladesh.

The design of the CC block revetment at Mithamain was conducted by the Hudson's formula (1953), which is applicable to only the displaced stones. The structure has not been washed away completely because of its safety and use of geotextile.

The design of CC blocks for wave protection at the Joydorkandi Village was completed using the proper formula but with empirical data and improper compaction. The structure sustained waves because of the combined use of the CC blocks and geotextile.

Fortunately, even with poor design and improper construction of wave protection walls using CC blocks, these embankments have saved lives and property and have brought a significant change in lifestyle to the haor areas. A tremendous moral boost in residents' perceptions of safety of lives and properties is occurring. Homesteads are growing and the settlements are rapidly expanding. The value of the land is substantially increasing and submersible concrete roads are coming into existence. These areas are also gaining commercial importance through cold storage facilities and poultry farms. The tree plantations along the embankment are adding to the natural beauty of the area and promoting environmental quality and recreational importance. Flood damages have been minimised and ponds and ditches have become suitable for pisciculture. The marriage values of the young girls and boys are improving and the areas are attaining higher social status.

CONCLUSION

The following conclusions are made from the present study:

(1) The traditional soft protection (bamboo mat with Chala grass) is not effective against wave attacks in the Haor areas of Bangladesh.

(2) Even with under-designed conditions and the practical limitations of the CC block revetment structures with geotextile, this infrastructure has served

the purpose of saving lives and property of residents because of the resistant property of geotextile.

(3) The construction of the protection infrastructure should be completed at a time before the next wave attack. Dependence on the natural process of soil compaction of embankment during the following monsoon and rehabilitation in the dry season is a serious lapse in the construction procedure, which increases maintenance cost.

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