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Optimum Geometry for Naturally Armouring Berm Breakwaters

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ABSTRACT

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A naturally armoring berm breakwater (NABB), as the name implies, is a breakwater that is built with a berm on the seaward side and derives its stability through a mechanism called "natural armoring". A series of two and three dimensional hydraulic model tests was undertaken at the Coastal Engineering Research Laboratory of Queen's University (QUCERL), Kingston, Ontario, Canada to evaluate the factors affecting the stability of NABB. The parameters that were varied in the tests included the significant wave height (H_s), wave period (Tp), lower front slope (LFS), initial berm width (Bi), number of waves (N) and the volume of material placed in the berm (V). In all tests, the characteristics of the material were held constant in order to systematically evaluate the influence of the factors mentioned above. The influence of the lower front slope of the berm on the stability and profile formation in a NABB forms the basis of this paper.

Overall, the study showed that the stability of the trunk of a NABB is influenced by the wave height, wave period and lower front slope. A breakwater section having a lower front slope equal to the natural angle of repose was found to be the most efficient section (in terms of required material volume and construction costs) for a naturally armoring breakwater.

Additional Index Words: *Berm breakwaters, breakwater geometry, naturally armoring breakwaters, reshaping breakwaters, profile development.*

INTRODUCTION

Modern breakwaters can be classified as either conventional breakwaters or unconventional breakwaters. A conventional breakwater typically consists of three or more different sizes of stones comprising three or more layers: armor, filter and core layers. Generally, this structure has a uniform seaward slope which is not expected to be significantly deformed by wave action during its life time. Therefore, this type of breakwater is called a statically stable breakwater.

A naturally armoring berm breakwater consists of two different sizes of stones: armor and core. This type of structure is usually constructed with a berm placed slightly above the still water level. Unlike a static breakwater, the seaward profile is allowed to be deformed by wave action without undermining the purpose of the structure. Therefore, this type of breakwater is called a dynamically stable breakwater. It is the movement of material which results in "sorting" and "nesting" thus maximizing inter-particle interlocking and the subsequent reforming of the profile that increases the stability of this structure.

The conventional type of breakwater is considered to have failed if there is a considerable deformation in the seaward profile of the breakwater, which can be due to breakage (in the case of concrete armor units) or movement (removal and displacement) of the armor units. The amount of deformation allowed depends on the degree of damage that the designer/owner is willing to accept during normal service. It has been observed that even after a so called failure, a conventional structure may continue to serve its intended purpose in its damaged state until it experiences a severe wave condition. This led to the idea of building a breakwater with an arbi-

Table 1. *Variables influencing stability of naturally armouring berm breakwaters.*

Wave Characteristics	Structural Characteristics	Material Characteristics	Other Factors
a) Wave height b) Wave period c) Wave groupiness d) Shape of the wave spectrum e) Number of waves attacking the structure f) Angle of wave attack	a) Lower front slope b) Initial berm width c) Berm elevation	a) Diameter (D_{50}) of the armour stone b) Uniformity coefficient of the armour stones (D_{85}/D_{15}) c) Shape of the armour stones (percentage of round stones) d) Density of armour stones e) Roughness of armour stones	a) Variation in SWL in front of the structure b) Permeability of the structure c) Flume width

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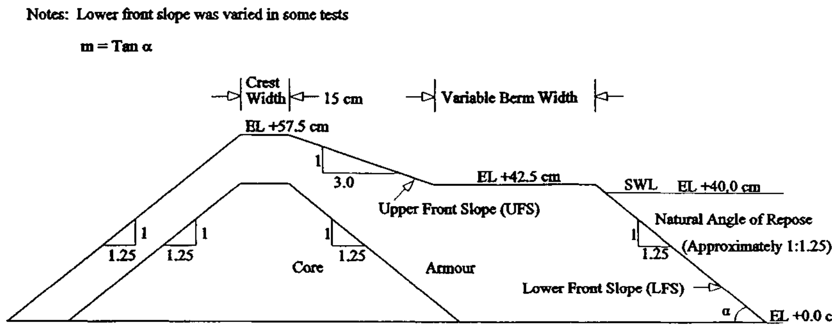

Figure 1. Model breakwater.

trary seaward slope and allowing nature to dictate the stable seaward slope without undermining the purpose of the breakwater.

Dynamically stable breakwater are given different names by different authors such as: mass armored breakwater (FOSTER and HALL, 1987), naturally armoring breakwater (HALL, 1987), sacrificial breakwater (BURCHARTH and FRIGAARD, 1987), unconventional breakwater (ANGLIN *et al.*, 1987), berm breakwater (HALL *et al.*, 1983), dynamically stable breakwater (KAO, 1990) and naturally armoring berm breakwater (SAHAYAN, 1995). In this paper, the name naturally armoring berm breakwater (NABB) will be used.

The variables which have been found to have an influence on the stability of NABB are shown in Table 1. HALL *et al.* (1983), BURCHARTH and FRIGAARD (1987), TORUM *et al.* (1988), VAN DER MEER (1988), KAO (1990), RANKIN (1993) and SAHAYAN (1995) have shown that wave height is the key parameter that influences the stability of NABB.

This paper presents the results of a study undertaken to evaluate the importance of the lower front slope (from the seaward edge of the berm to the toe of the structure, as shown in Figure 1) on the stability and profile formation of a naturally armoring berm breakwater. This is of particular interest since the angle of the lower front slope will dictate the method of construction used. Steep lower front slopes can be constructed using a "dump and push" operation where the outer slope of the berm is allowed to take up the natural angle of repose of the material. Flatter slopes will require machine placement to specified slopes. This may require the use of marine plant. The trade off is that the amount of berm recession decreases with decreasing front slope. There should exist a certain combination of berm width/lower front slope which will result in maximizing performance (stability) while minimizing construction costs which are related to material quantities and placement method. The experiments described in this paper look at the variation in berm recession with changes in the lower front slope, for both a constant initial berm width and a constant volume of armor stone.

EXPERIMENTAL FACILITIES

Test Procedure

Two-dimensional tests were undertaken in a 45 m-long, 2 m-wide and 1.2 m-deep wave flume (see Figure 2). A total of

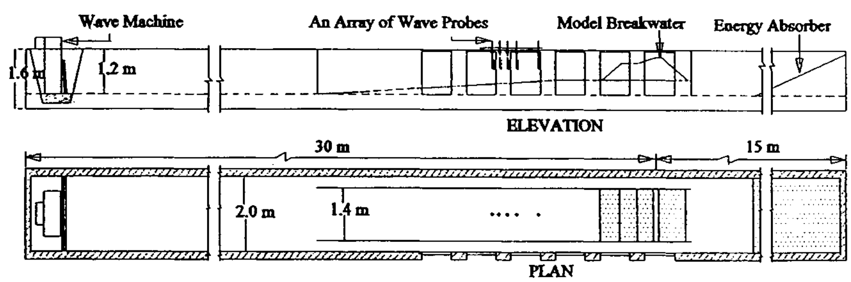

Figure 2. Layout of two-metre wave flume.

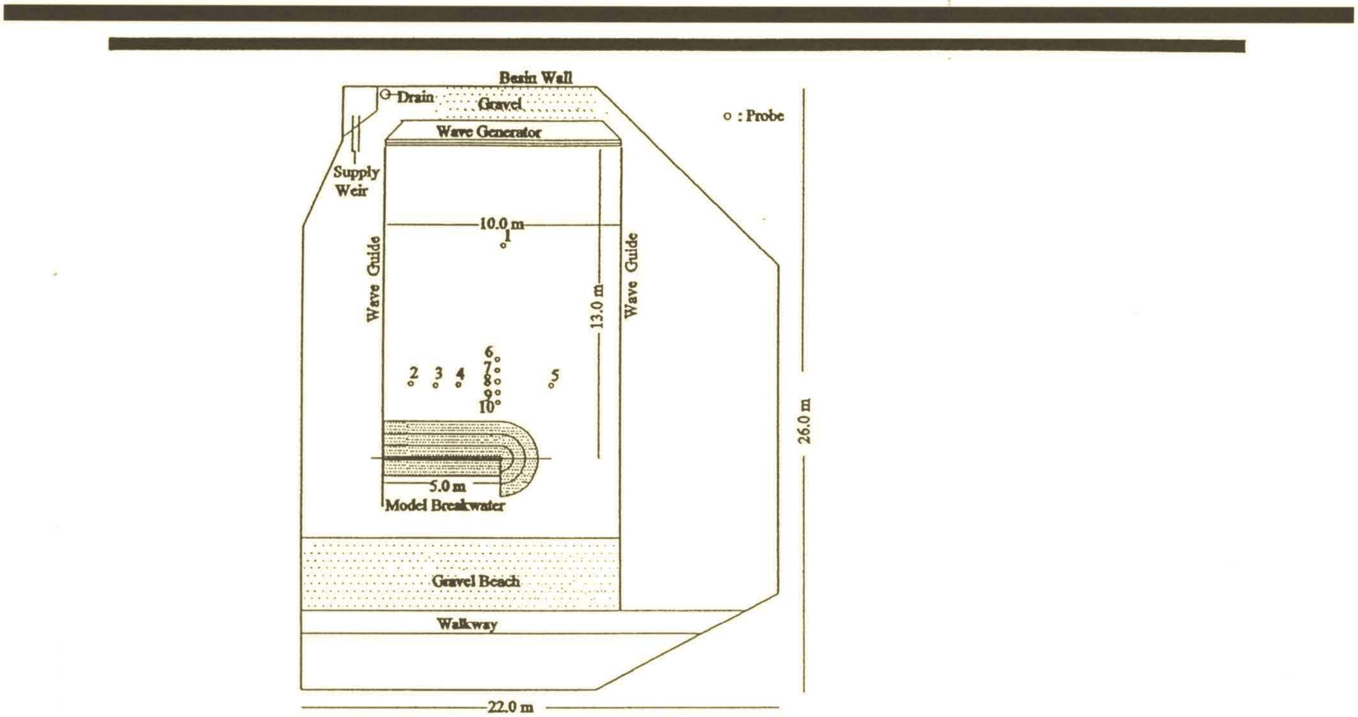

Figure 3. Layout of wave basin.

42 tests were carried out. The lower front slope was varied between the natural angle of repose (approximately 1:1.25) and 1:3. Three-dimensional tests were undertaken in a 26 m by 22 m and 1 m-deep wave basin (see Figure 3). A total of 5 tests were carried out with lower front slopes of 1: 1.25 and 1: 2.0. Various combinations of wave height/wave period and initial berm widths were used throughout the testing program. A summary of the 2-D and 3-D tests, including the values of the LFS other than natural angle of repose is given in Tables 2 and 3.

Table 2. *Two-dimensional tests.*

Test #	LFS	Bi (cm)	wc #	wd (cm)
23a	1:1.25 (38.7°)	50	12	40
23b	1:1.25 (38.7°)	50	11	40
23c	1:1.25 (38.7°)	50	8	40
24	1:2.0 (26.6°)	50	14	40
25a	1:2.0 (26.6°)	50	8	40
25b	1:2.0 (26.6°)	50	11	40
25c	1:2.0 (26.6°)	50	12	40
26	1:2.0 (26.6°)	50	7	40
27	1:2.0 (26.6°)	45	14	40
28	1:1.25 (38.7°)	66	14	40
29	1:3.0 (18.4°)	27.8	10	40
30	1:2.0 (26.6°)	30	14	40
31	1:1.25 (38.7°)	46	14	40
32	1:3.0 (18.4°)	09	14	40
33	1:2.5 (21.8°)	19	14	40

Initial Berm Width (Bi) = 9 cm−50 cm; Water Depth (wd) = 40 cm; Wave Climate (wc) = wc#1–#14 (see Tables 4 and 5); Uniformity Coefficient (D_{85}/D_{15}) = 1.8; Diameter (D_{50}) = 1.55 cm; Lower Front Slope (LFS) = Natural angle of repose (NAR) unless otherwise mentioned

All tests were completed using irregular waves. Profiles were measured after each segment of wave attack (approximately 3,000 waves) at the locations shown in Figure 4. An automated trailing arm profiler was used to obtain these profiles. A typical profile measured is shown in Figure 5.

Data Acquisition

Experiment control and data acquisition were carried out using a VAX-3200 computer which operates under VMS (Virtual Memory System), a digital computer and a micro computer. The software systems used for this purpose were GEDAP (Generalised Experiment Data Control and Analysis Package), RTC (Real Time Control system) as well as various FORTRAN programs. The VAX-3200 uses a built-in Digital Equipment Corporation (DEC) an-

Table 3. *Three-dimensional tests (wave angle = 0 degrees).*

Test #	LFS	Bi (cm)	wc #
3D01	1:1.25 (38.7°)	40	14*
3D02	1:1.25 (38.7°)	40	15*
3D03	1:2.0 (26.6°)	24	14*
3D04	1:1.25 (38.7°)	65	16
3D05	1:2.0 (26.6°)	49	16

15* = Peak wave height 10 cm
16* = Peak wave height 10 cm
Initial Berm Width (Bi) = 24 cm−65 cm; Water Depth (wd) = 40 cm; Wave Climate (wc) = wc#14–#16 (see Table 5); Uniformity Coefficient (D_{85}/D_{15}) = 1.8; Diameter (D_{50}) = 1.55 cm; Lower Front Slope (LFS) = Natural angle of repose (NAR) unless otherwise mentioned; Angle of Wave Attack (AW) = 0 Degrees (normally incident waves)

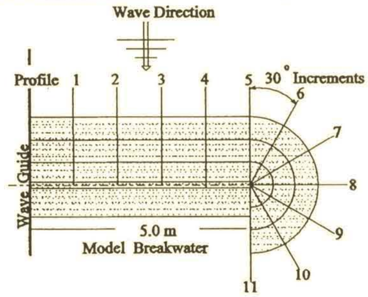

Figure 4. Profile positions.

alog-to-digital ADQ32 input board and a digital-to-analog AAV11-DA output board to collect and send signals. The GEDAP software system, developed by the National Research Council of Canada (NRCC), was used for analysing and managing data, including real-time experiment control and data acquisition functions.

Model Breakwater

The geometry of the model breakwater used in both the two-dimensional and the three-dimensional tests is shown in Figure 1. The basic geometry and dimensions of the model breakwater were determined from past experience obtained from the various tests conducted at QUCERL (KAO and HALL, 1990, RANKIN, 1993). The model breakwater had a variable lower front slope (LFS) ranging from the natural angle of repose of the material (approximately 1:1.25) to 1:3, a horizontal berm, an upper front slope (UFS) of 1:3, a 15 cm wide crest and a back slope equal to the natural angle of repose of the material.

At present, the bulk of research conducted on NABB has been for a geometry having the LFS equal to the natural angle of repose. Generally, the LFS is placed to the natural angle of repose of the material, as this simplifies construction of the prototype, so that a simple pushing and dumping of the material into the water can be used. The berm was located 2.5 cm above the SWL in the model (at typical model scales of 1:20 to 1:35, this translates to 0.5 to 0.75 m above the water level, which has been found to be sufficient to allow for construction). Initially, the berm also offers resistance to the wave uprush and absorbs some of the wave energy impinging on it. The upper front slope (UFS) was set at 1:3. This slope has been found to help reduce the wave runup levels and hence the height of the breakwater, which is the concern of many breakwater designers in North America. This slope is also easy to construct and is aesthetically attractive.

Model Breakwater Material

The core and the armour materials used in both two and three-dimensional tests were the same. In all tests, the influence of the core on reshaping was considered to be negligible (KAO and HALL, 1990; RANKIN, 1993). Experiments were carried out with only one gradation of armour stone which had characteristics similar to that which was recommended by

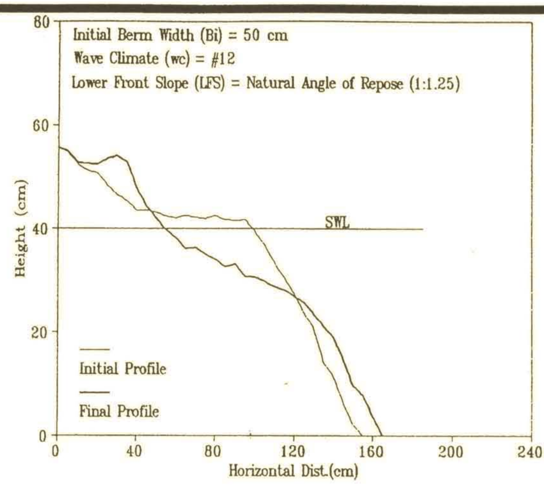

Figure 5. Measured initial and final profiles.

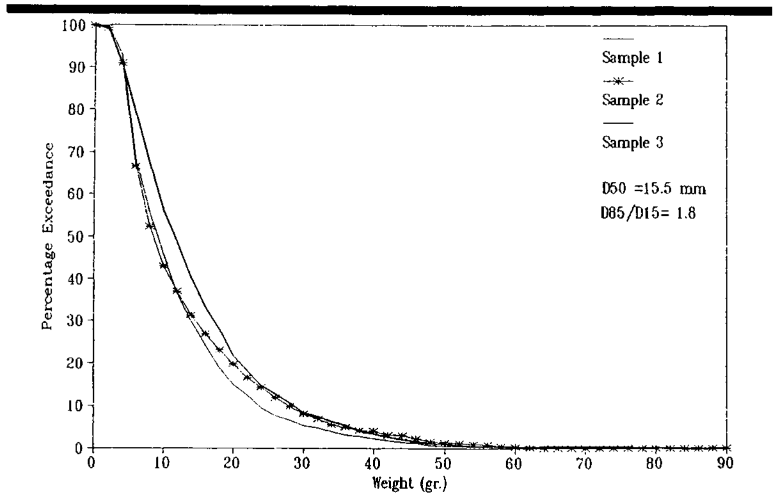

Figure 6. Gradation curves for armour units.

KAO and HALL (1990). For this study, the characteristics of the material was held constant, so that the influence of the other variables could be systematically evaluated. The armor material gradation used provides realistic simulation of obtainable material gradations produced at many prototype quarries (KAO and HALL, 1990).

The core material used throughout the tests had a D_{50} of 10.3 mm. The armor stones had a D_{50} of 15.5 mm and a corresponding uniformity coefficient, D_{85}/D_{15} of 1.8 (see Figure 6). The test material was comprised of 70% angular stones and 30% rounded stones. The inclusion of "rounded" stones in the gradation was used to simulate the field condition that may be present after a few storms due to stone motion in the armour layer. This stone motion often results in the corners being broken off some stones and a progressive rounding of the edges of the stones may occur.

Wave Climate

The test sections were subjected to various wave climates consisting of a single or several segments of specific wave height/period combinations (see Tables 4 and 5). Wave climates #14–#16 consisted of discrete segments starting with smaller waves (H_s = 6 cm) and increasing in steps of 2 cm up to 14 cm, then decreasing in increments of 2 cm to 6 cm. This approach was used to simulate the growth and decay of waves during a simulated storm. This has been shown to influence the development of the stable profile of a NABB (HALL *et al.*, 1983; KAO and HALL, 1990). The majority of the tests were undertaken with wave climates #14 and #15.

In both the two and three-dimensional tests, waves were synthesised, generated and sampled at the location of the structure before the structure was constructed. This allowed for consistent determination of the incident-wave character istics interacting with the test sections. All instruments used for acquisition of data were calibrated on a regular basis. The model breakwater was considered to have failed if recession of the berm progressed beyond the toe of the upper front slope, as shown in Figure 7. This criteria is selected based on

Table 4. *Wave climates #1–#13 (wc #1–#13).*

wc #	H_s (cm)	T_p (s)	Duration (min.)	Spectra	Groupiness Factor
1	6	1	50	Jonswap	0.8
2	6	1.2	60	Jonswap	0.8
3	8	1	50	Jonswap	0.8
4	8	1.4	70	Jonswap	0.8
5	10	1	50	Jonswap	0.8
6	10	1.2	60	Jonswap	0.8
7	10	1.6	80	Jonswap	0.8
8	12	1	50	Jonswap	0.8
9	12	1.2	60	Jonswap	0.8
10	12	1.4	70	Jonswap	0.8
11	12	1.8	90	Jonswap	0.8
12	12	2.0	100	Jonswap	0.8
13	14	1.6	80	Jonswap	0.8

H_s = Significant Wave Height (Expected), T_p = Peak Period of the Wave Spectrum (Expected)

Table 5. *Wave climates.*

wc #	Segments
14	wc#1, wc#3, wc#6, wc#10, wc#6, wc#3, wc#1
15	wc#2, wc#4, wc#7, wc#11, wc#7, wc#4, wc#2
16	wc#1, wc#3, wc#6, wc#10, wc#13

Table 6. *Summary of the test result for constant initial armour volume.*

Test #	Be (cm)	Br (cm)	Bi (cm)	Ve (cm²/m)	wc #	m	Remarks
31	33	13	46	306.1	15	1:1.25	Safe
30	28	2	30	220.1	15	1:2.0	Safe
33	17	2	19	154.8	15	1:2.5	Safe
32	12	−3	9	106.2	15	1:3.0	Failed

Be = Eroded berm width; Br = Remaining berm width; Bi = Initial berm width; Ve = Eroded volume (per unit length)

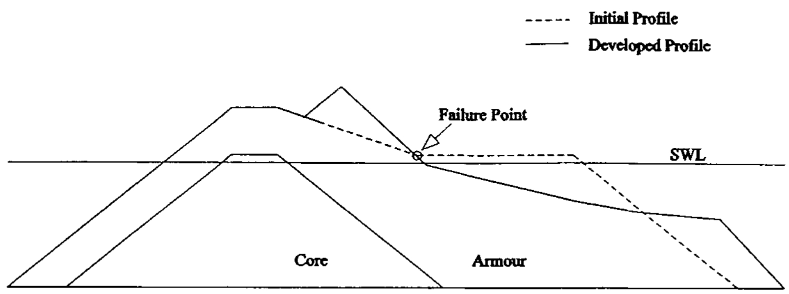

Figure 7. Failure criterion.

past experience obtained over the past two decades and because it has been observed that if the berm recedes into the upper slope, the upper slope may fail by a sliding failure, exposing the core stone along the crest.

GENERAL OBSERVATIONS

In the case of the two-dimensional tests, only one profile was recorded after each wave segment, as erosion of berm was uniform across the entire width of the flume. For the three dimensional tests, profiles were measured along the trunk at 1m intervals from the wave guide, and around the head at 30 degrees increments (see Figure 4).

Two-Dimensional Tests

For the test sections constructed with the lower front slope equal to the natural angle of repose, during the attack of the first few waves of the first segment of the design storm, it was observed that no matter how small the waves were, the edge of the berm was rounded off and stones rolled along the lower front slope. The majority of these stones rolled down the slope and came to rest in the vicinity of the toe of the test section.

In the case of milder lower front slopes (1: 2. 0 and 1: 3), the edge of the berm was rounded off and stones rolled along the slope but were retained either on the slope or were moved close to the toe of the test section. The extent of rounding depended on the magnitude of the wave parameters and the steepness of the lower front slope (LFS).

The movement of the outer edge of the berm ceased after the first 50 to 100 waves, and stones moved to and fro about the still water level (SWL). Since the wave trains were random, when the larger waves in the train attacked, material was moved up the slope with the uprushing jet and down the slope during the downrush. During wave downrush, material was moved down the slope and stones which could not find any stable position along the slope continued to move down towards the toe. During the first few waves of the second segment and consecutive segments, the rounding off did not occur as in the first segment because the slope in the area of the SWL was flatter because of the rounding off that had occurred. The motion of material can be described by familiar

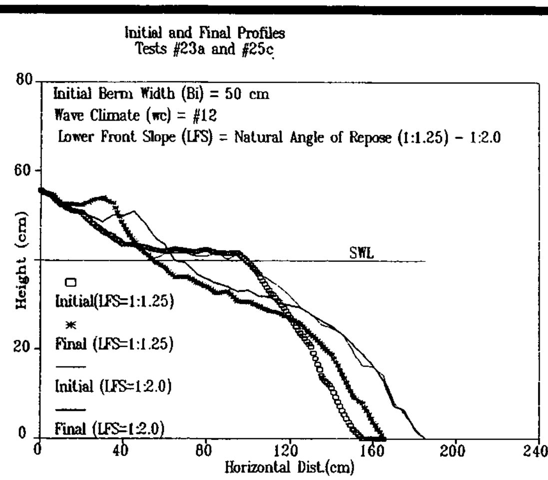

Figure 8. Influence of lower front slope on eroded berm width.

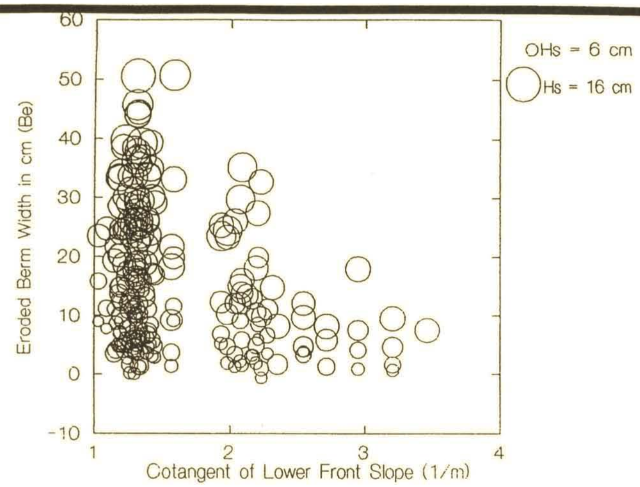

Figure 9. Influence of lower front slope on eroded berm width.

terms such as rocking, rolling and lifting. It was noted that most of the stones were moved by rolling action only, thus most of the reshaping was due to rolling. It was also observed that, during the impact of some of the larger waves, occasionally a few smaller stones were thrown on to the upper slope or beyond the leading edge of the crest. Also, no movement of stone from the region near the toe of the test sections was observed.

Three-Dimensional Tests

In the three-dimensional tests, the portion of the test section below the SWL was not visible, therefore, only observations above the SWL were made. Special attention was merited around the head of the breakwater. The basic stone motion followed the same trends observed in the two-dimensional tests as far as the trunk was concerned. It was also noted that along the trunk, erosion of the berm was not totally uniform however, the difference in eroded berm width was less than 5 per cent and, taking into consideration material variability, can be considered within the accuracy of this test series. Around the head, the basic stone motion was slightly different. Unlike in the two-dimensional tests, stones did not roll down the slope much; rather, they moved up the slope. Profile changes around the head were highly variable.

INFLUENCE OF LOWER FRONT SLOPE

The extent of reshaping can be described easily by measuring the eroded berm width or eroded volume of material. The eroded berm width would indicate, according to the failure criteria, whether the breakwater is stable or not. Therefore, in order to qualitatively describe the test results, the

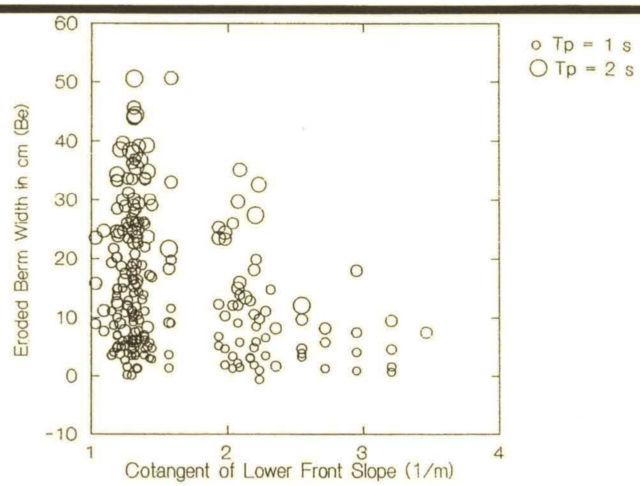

Figure 10. Influence of lower front slope on eroded berm width.

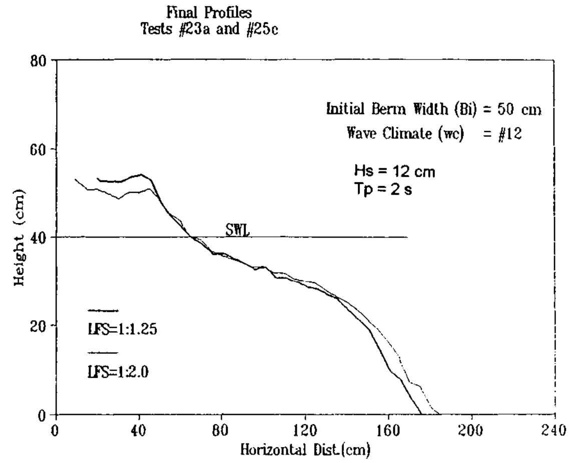

Figure 11. Influence of lower front slope on developed profiles.

eroded berm width measured during various tests will be compared.

Profile Variation With Lower Front Slope

Initial and final profiles were plotted together to evaluate the effect of LFS on the recession of the berm. Figure 8 provides an example of this comparison. The tests had lower front slopes equal to the natural angle of repose and 1:2. Figure 8 shows that the milder the slope, the smaller the recession of the berm. It should be noted that in these two tests, the breakwater models had the same initial berm width and they were subjected to the same wave climate. However, the volume of material placed on the berm was different.

SAHAYAN (1995) has shown that wave height and wave period significantly influence the eroded berm width. The eroded berm width was found to increase with increasing wave height or wave period. In these tests, this trend was not affected by the LFS. In order to verify this, all the data from 2-D and 3D tests were plotted together in Figures 9 and 10. Figure 9 shows that increasing wave height increases the eroded berm width. Similarly, Figure 10 shows that increasing wave period increases the eroded berm width. The size of the circle indicates the magnitude of wave height/wave period. Both figures show that the higher the wave height/wave period, the more severe the berm recession. The scatter in the plots is due to different boundary conditions involved in the tests.

In order to evaluate whether the developed profile for Tests 23a and 25c (see Table 2) were identical, the profiles were transposed so that their origins (intersection of developed profile and SWL) coincided (Figure 11). These two tests were selected because the only difference between these tests was

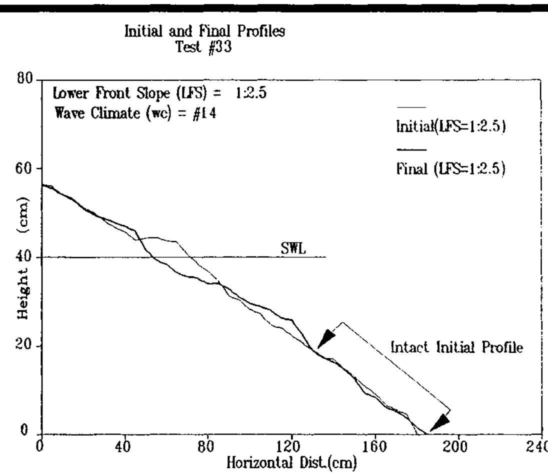

Figure 12. Influence of lower front slope on eroded berm width.

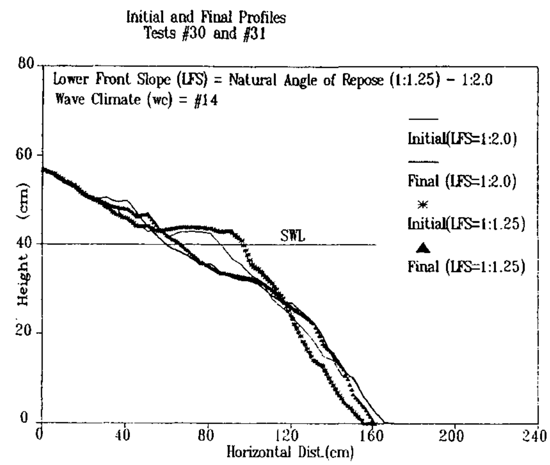

Figure 13. Influence of lower front slope on eroded berm width.

the lower front slope. Figure 11 shows that the profiles through the area of the SWL are very similar. However, the developed profiles along the berm and below the SWL differ slightly. In this region, the shape of the developed profile depends on the initial slope. For the case of LFS = 1:2.5, the lowest part of the developed profile retained the initial shape (see Figure 12). This is because the armour units that were unstable around the SWL rolled down the slope until they became statically or hydraulically stable. Below a certain threshold depth (1.5 to 2 Hs below the SWL), water particle velocity considerably reduces and hence armour units become hydraulically stable. For the case of LFS = natural angle of repose, even though units may be hydraulically stable, gravitational forces predominate, causing stones to roll further down the slope. For the case of a milder slope, the down slope component of the gravitational force is reduced so the statical stability increases and hence units are retained on the slope itself, as illustrated in Figure 12.

Constant Volume of Materials (V)

Mention was made earlier that tests compared in Figure 8 had different volumes of material. That is, if initial berm widths are the same, a breakwater with milder LFS will require larger volume of material, which will ultimately increase the construction cost. Therefore, tests were also undertaken keeping a constant volume of armor material in the berm, in order to evaluate the influence of LFS for a constant volume of placed material.

During preliminary tests, it was found that a lower front slope of 1:2.0 and an initial berm width of 30 cm provided adequate stability when it was subjected to wave climate #14.

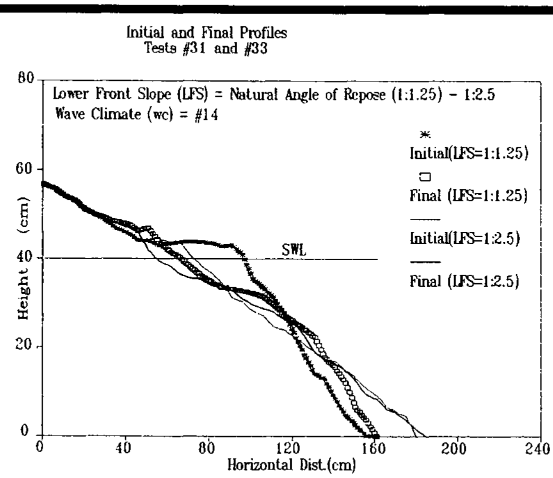

Figure 14. Influence of lower front slope on eroded berm width.

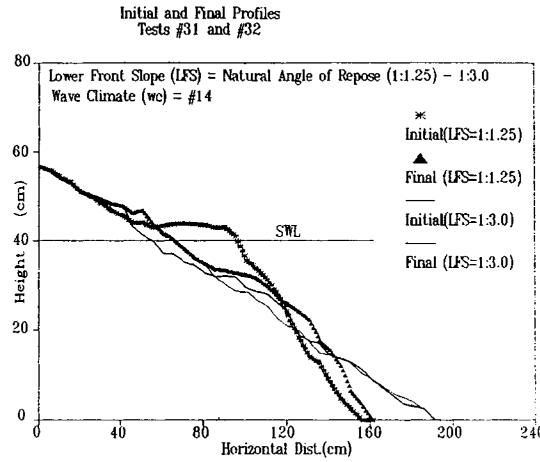

Figure 15. Influence of lower front slope on eroded berm width.

Berm recession was 30 cm meaning that the structure was stable with no reserve stability. The volume of armour material placed in the berm was calculated (volume of armour units per unit length of the breakwater). Keeping this volume as constant, the initial berm widths for test sections having LFS of 1:1.25 (natural angle of repose), 1:2.5 and 1:3.0 were found to be approximately 46 cm, 19 cm and 9 cm respectively.

These three test models were subjected to the same wave climate as the model with 1:2 lower front slope. Figures 13, 14, and 15 were plotted to compare the performance of the 1:2.0, 1:2.5 and 1:3.0 slopes with the natural angle of repose, given a constant armour volume. These figures show that the eroded berm width, eroded volume of material and deposited (on the berm or on the upper front slope or on the LFS) volume of material vary with the LFS. The figures also show that eroded berm width (or the eroded volume of material) decreases with decreasing slope. In these four test, only the breakwater which had a 1:3 LFS had failed according to the criterion mentioned in Figure 7. For the case of a constant volume of material, the criterion used to infer relative stability was the width of the remaining berm. The greater the remaining berm width, the more stable the breakwater was considered (since remaining berm width can be construed as reserve stability). It should be noted that in the above four tests, the initial berm widths were not the same although the placed volume of armour was. It can be intuitively argued that a wider berm could absorb more energy and therefore the eroded berm width can be reduced. However, SAHAYAN (1995) has shown that the initial berm width does not significantly influence the eroded berm width.

These experiments showed that the cross-section having a

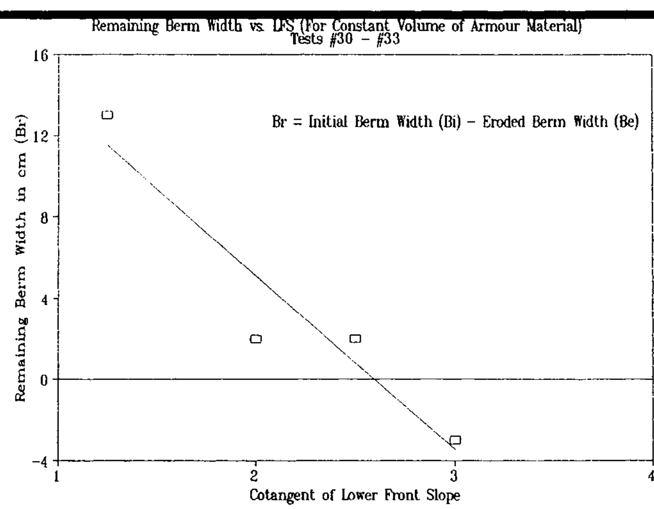

Figure 16. Remaining berm width vs. lower front slope.

lower front slope equal to the natural angle of repose had the greatest berm width remaining at the completion of the test (Figure 16). However, for that particular test section, the eroded berm width and the volume of eroded material was greater than values measured for the other test section (see Table 6). This can be explained as follows: at a certain distance below the still water level, the armor units become static, rather than dynamically active. This distance increases as the lower front slope becomes steeper, leading to an increase in the volume of armor units that are dynamically active.

Since the remaining berm width was greater for tests having a lower front slope equal to the natural angle of repose, it can be concluded that a berm breakwater constructed with the front slope set equal to the natural angle of repose would be the most economical section to construct, since it requires less stone and all stone can be placed with a simple land-based dump and push operation.

CONCLUSIONS

The initial, as constructed, lower front slope of a berm breakwater influences the reshaping of naturally armouring berm breakwaters. For tests undertaken in which the initial berm width was held constant (thus the volume of placed material increases with decreasing slope), it was found that the total eroded berm width and eroded volume of material reduces with milder slopes.

The development of the reshaped profile was also influenced by the initial lower front slope. In particular, the initial profile below approximately 1.5 H_s will be retained if the lower front slope is less steep than the natural angle of the repose of the material. However, this depends on the severity of the wave climate as well.

However, the disadvantages of constructing a NABB with a front slope milder than the natural angle of repose are that a larger bed area is required and a larger volume of material will be required which will significantly increases the cost of construction. Additionally, special placement techniques may be required to achieve the flatter initial profile (a simple dump and push operation cannot be used). Based on observation made in tests undertaken with a constant volume of placed material, the structure constructed with the front slope set at the natural angle of repose was found to be the optimum section, since considerable reserve stability was retained compared with the test sections having flatter front slopes. This combined with the lower construction costs that can be achieved by constructing the initial front slope at the natural angle of repose, lead to a more economical structure.

In areas where stone quality may be of concern, it should be noted that the extent of stone motion observed decreased with as the initial front slope became flatter, thus it can be surmised that less stone motion will result in less degradation of the armor stone. This could ultimately lead to a longer expected service life of the stones.

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