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Supplementary Environmental Information

North Bank Flood Defence Crest Height

Explanatory Note EX 36.2

June 2012
Revision: 0
Black & Veatch

CHERRY COBB SANDS – COMPENSATION SITE

DESIGN MEMO – OVERTOPPING

1. INTRODUCTION

Purpose of calculations – to determine required crest level of new embankment.

Client requirement – to provide a 1 in 200 year standard of protection, taking into account 100years of climate change.

2. SECTION 1 & 2

2.1 Water level and wave data

Section 1 & 2 of the embankment are subject to estuary waves entering through the breach, without being reduced due to diffraction effects.

JPA results for Little Humber are considered to be representative of the estuary waves at this point (see Diffraction Analysis design memo) and therefore these results have been used for the overtopping analysis (see Table 1).

Table 1 JPA results for Little Humber - used for overtopping analysis at Section 1

RP	Water level	Hs	Tm
20	0	0.96	3.43
20	1	0.96	3.43
20	2	0.96	3.43
20	3.5	0.94	3.39
20	3.86	0.9	3.32
20	4	0.88	3.28
20	4.23	0.8	3.13
20	4.4	0.7	2.93
20	4.41	0.7	2.93
20	4.59	0.6	2.71
20	4.75	0.4	2.21
20	4.8	0.22	1.64
20	4.81	0	0
50	0	1.01	3.52
50	1	1.01	3.52
50	2	1.01	3.52
50	3.17	1	3.5
50	3.5	0.98	3.46
50	4	0.94	3.39
50	4.14	0.9	3.32
50	4.4	0.81	3.15
50	4.41	0.8	3.13
50	4.62	0.7	2.93
50	4.78	0.6	2.71
50	4.8	0.58	2.67
50	4.9	0.4	2.21
50	4.92	0	0

100	0	1.04	3.57
100	1	1.04	3.57
100	2	1.04	3.57
100	3.5	1.03	3.55
100	3.79	1	3.5
100	4	0.98	3.46
100	4.38	0.9	3.2
100	4.4	0.88	3.28
100	4.54	0.8	3.13
100	4.8	0.7	2.93
100	4.81	0.7	2.93
100	4.91	0.6	2.71
100	4.98	0.4	2.21
100	5.01	0	0
200	0	1.09	3.65
200	1	1.09	3.65
200	2	1.09	3.65
200	3.5	1.07	3.62
200	4	1.03	3.55
200	4.14	1	3.5
200	4.4	0.93	3.38
200	4.51	0.9	3.32
200	4.74	0.8	3.13
200	4.8	0.79	3.11
200	4.96	0.7	2.93
200	4.99	0.6	2.71
200	5.05	0.4	2.21

Climate change allowances have been taken from Planning Policy Statement 25 (PPS25), table B1, for the East of England (South of Flamborough Head) area. These allowances are as follows:

1990-2025	+4.0mm/yr
2025-2055	+8.5mm/yr
2055-2085	+12.0mm/yr
2085-2115	+15.0mm/yr

The JPA results were carried out in 2007, and therefore three years of sea level rise have been taken into account to bring the water levels to current levels.

Three different water levels have been considered it the calculations :

- Current conditions - including a 12mm increase in water levels
- 50 years of climate change - including a 381mm increase in water levels
- 100 years of climate change – including a 1059mm increase in water levels

PPS25 table B2 also includes an allowance for increased storminess due to climate change - these are as follows

- 5% increase in extreme wave height up to 2055
- 10% increase in extreme wave height up to 2115

The latest EA / Defra (FCDPAG3) guidance suggests that these allowances should be included as a sensitivity test on overtopping. Therefore five different scenarios for overtopping have been considered:

1 Current Level
2 50 years sea level rise
3 50 years sea level rise + 5% increase in wave height
4 100 years sea level rise
5 100 years sea level rise + 10% increase in wave height

2.2 Overtopping calculations

Overtopping calculations have been carried out in accordance with the EurOtop manual (Wave Overtopping of Sea Defences and Related Structures: Assessment Manual, August 2007). The deterministic design equations for Coastal Dikes and Embankment Seawalls have been used to calculate the mean overtopping discharge over the embankment, (eqs 5.9 and 5.11).

The waves from the JPA analysis are offshore waves and don't take into account any shallow water effects. These waves have therefore been transformed using Goda equations (as set out in the CIRIA Rock Manual – box 4.9) to take account of shallow water effects including shoaling and wave breaking. The land in front of the embankment has been taken at a level of +1.5mAOD. The foreshore is very flat, consisting of existing mud flats, therefore the foreshore slope used in the Goda equations has been taken as 1 in 1000.

A berm of 15m width at +4.0mAOD has been included in the calculation, although this only has an effect on overtopping when the level of the berm is less than $2H_{mo}$ lower than the Still Water Level (SWL).

2.3 Allowable overtopping limits

Allowable overtopping limits have been taken from the EurOtop manual (Table 3.5) which gives limits for overtopping for damage to the defence crest or rear slope of an embankment. These limits are reproduced in Table 2 below.

Table 2 Limits for overtopping for damage to the defence crest or rear slope

Hazard type and reason	Mean discharge (l/s/m)
No damage if crest and rear slope are well protected	50-200
No damage to crest and rear face of grass covered embankment of clay	1-10
No damage to crest and rear face of embankment if not protected	0.1

Over the medium to long term, vegetation will establish on the embankment, therefore an allowable discharge of 10l/s/m has been considered when determining the required crest level.

In the period immediately after the breach, vegetation will not have fully established and therefore the overtopping due to current conditions should be kept below 0.1l/s/m.

2.4 Results

A crest level of **+7.33mAOD** is required to keep overtopping limits below 10l/s/m for the 1 in 200 year event including for the effects of 100 years of climate change (including increased wave heights). With this crest level the overtopping limits for all five scenarios tested are show in Table 3.

Table 3 Overtopping rates at Section 1 with a crest level of +7.33mAOD

Maximum Overtopping (L/s/m) for current and future conditions					
Return period (years)	Current	50 yr SLR	50 yr SLR + 5% Hs	100 yr SLR	100 yr SLR + 10% Hs
20	0.0	0.0	0.0	0.9	1.5
50	0.0	0.0	0.0	1.9	2.8
100	0.0	0.0	0.0	3.4	4.7
200	0.0	0.1	0.2	6.7	9.7

This table shows that the required crest level is quite sensitive to the wave height, and therefore this potential effect shouldn't be neglected.

This crest level is sufficient to keep overtopping under current conditions less than 0.1l/s/m.

This table also shows that there is a significant difference between the overtopping rates for the scenario where 50 years of climate change is considered, than where 100 years of climate change is considered. This is due to the increase in allowance for sea level rise per year the further into the future the allowance is considered for. As allowances further into the future are less certain, there could be cost (and material) savings if the crest level was set allowing for 50 years of climate change, with the view that the level could be raised in the future if necessary.

Table 4 below shows the required crest levels to give a Standard of Protection of 1 in 200 years for the five different scenarios under consideration

Table 4 Required crest levels at Section 1 to give SoP of 200years

Scenario	Allowable overtopping rate (l/m/s)	Required crest level (mAOD)
Current conditions	0.1	6.70
50 years SLR	10	6.15
50 years SLR + 5% increase in Hs	10	6.20
100 years SLR	10	7.23
100 years SLR +10% increase in Hs	10	7.33

This table shows that the required level to keep overtopping lower than 0.1l/m/s under current conditions is greater than the required level including for 50 years of climate change. If there is not sufficient material available to build the crest level up to 7.33mAOD, then having a crest level of 6.7mAOD could be an acceptable compromise.

Table 5 shows the overtopping rates for the different scenarios with a level of +**6.7mAOD**

Table 5 Overtopping rates with a crest level of +6.7mAOD at Section 1

Maximum Overtopping (L/s/m) for current and future conditions					
Return period (years)	Current	50 yr SLR	50 yr SLR + 5% Hs	100 yr SLR	100 yr SLR + 10% Hs
20	0.0	0.0	0.0	8.7	12.0
50	0.0	0.1	0.2	18.4	25.9
100	0.0	0.4	0.5	42.8	56.0
200	0.1	1.2	1.5	93.2	102.9

3. OUTER END OF SECTION 2

3.1 Wave heights

Wave heights reduce along the length of Section 2 due to diffraction effects. The outer limit of Section 2 is defined by the point at which incident waves at the breach are reduced in height by 50% due to diffraction. The overtopping levels will therefore be less at this point than for Section 1.

For overtopping at this section the JPA results for Little Humber have been used as a basis, with the wave heights reduced by 50%. Diffraction of the waves will also change the direction, so the waves approach the embankment obliquely, but this effect has been ignore for this calculation.

For these wave heights a crest level of +6.66mAOD is required to give a 1 in 200 year SoP including for the effects of 100years of climate change. With this crest level the overtopping limits for all five scenarios tested are show in Table 6.

Table 6 Overtopping rates at Section 2 with a crest level of +6.66mAOD

Maximum Overtopping (L/s/m) for current and future conditions					
Return period (years)	Current	50 yr SLR	50 yr SLR + 5% Hs	100 yr SLR	100 yr SLR + 10% Hs
20	0.0	0.0	0.0	0.0	0.0
50	0.0	0.0	0.0	0.2	0.4
100	0.0	0.0	0.0	1.2	2.4
200	0.0	0.0	0.0	5.8	9.8

As with Section 1 the crest level could be reduced if a lower allowance the 100 years SLR was acceptable.

Table 7 below shows the required crest levels to give a 1 in 200 year standard of protection for each of the different scenarios.

Table 7 Required crest levels at Section 1 to give SoP of 200years

Scenario	Allowable overtopping rate (l/m/s)	Required crest level (mAOD)
Current conditions	0.1	5.55
50 years SLR	10	5.55
50 years SLR + 5% increase in Hs	10	5.57
100 years SLR	10	6.62
100 years SLR +10% increase in Hs	10	6.66

Here the crest level required to give a 1 in 200 year SoP for current conditions is slightly lower than the required crest level to give a 1 in 200 year SoP allowing for 50 years of climate change. It is considered then that a crest level of 5.57mAOD (the required level to give a in 200 year SoP in 50 years time) would be an acceptable crest level if there was not enough material available to build the crest level to 6.67mAOD.

4. SECTION 3

By inspection (see figure 1 in Wave Diffraction Analysis Design Memo) the wave heights at Section 3 are similar to those at Section 2 and therefore the crest levels calculated for Section 2 will be appropriate.

5. SECTION 4 & 5

Sections 4 & 5 are exposed to lower wave heights than Sections 1 to 3. At this outline design stage these sections should have the same crest levels as Section 3, although this is something that could be optimised as the design is developed.

6. SUMMARY

To give a 1 in 200 year standard of protection with an allowance for 100 years of climate change the following crest levels should be adopted

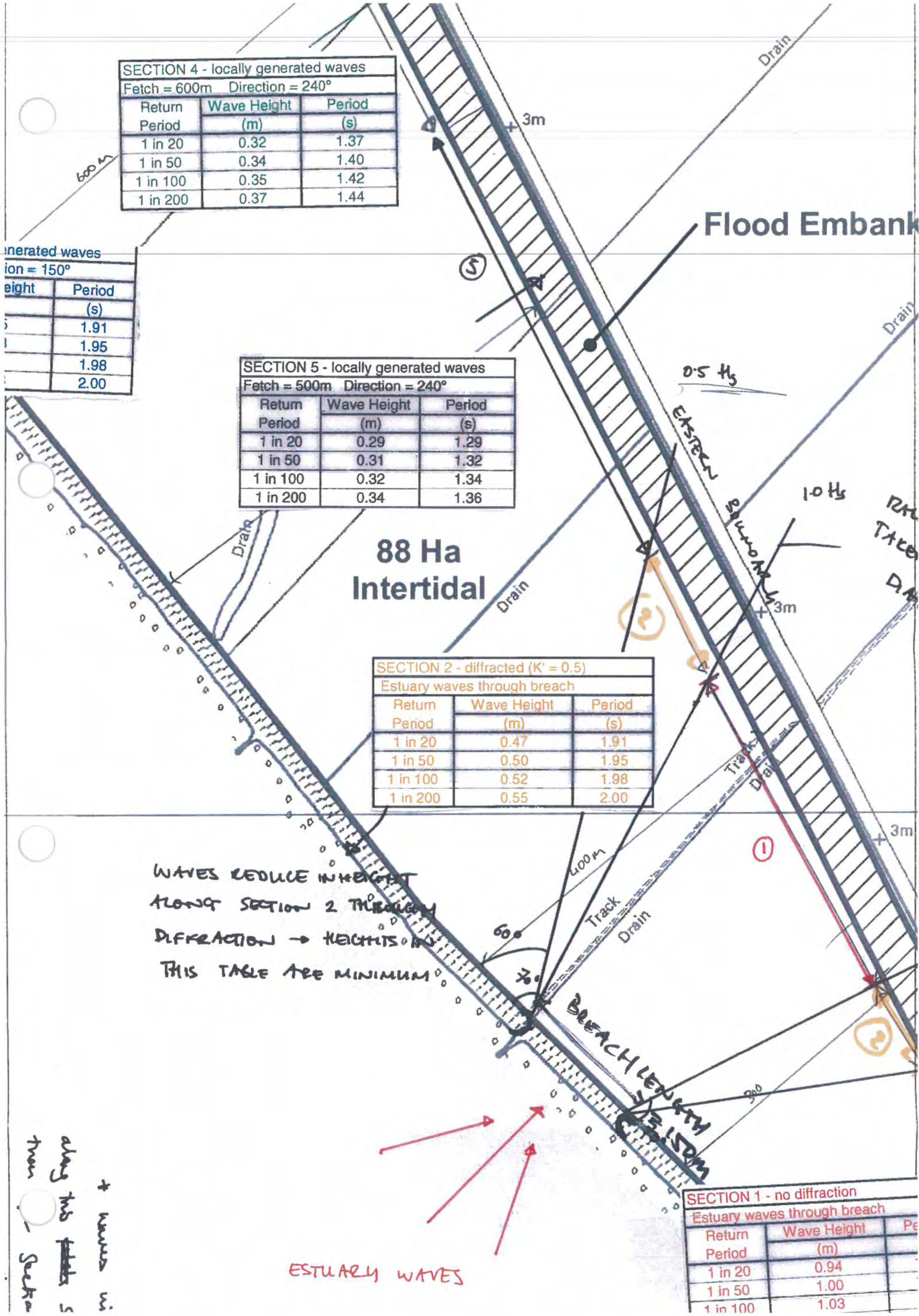
- **Section 1:** +7.33mAOD
- **Section 3-5:** +6.66mAOD
- **Section 2:** Linear transition from +7.33mAOD at boundary with Section 1 to +6.66mAOD at boundary with Section 3

It is considered that allowing for the effect of 100 years of climate change is very conservative as future sea level rises are uncertain.

If there is not sufficient material available from the site to construct embankments to the required crest level, it is considered that allowing for 50years of climate change would be an acceptable solution. The required crest levels to give a 1 in 200 year SoP for this scenario are as follows:

- **Section 1:** +6.70mAOD
- **Section 3-5:** +5.57mAOD
- **Section 2:** Linear transition from +6.7mAOD at boundary with Section 1 to +5.57mAOD at boundary with Section 3

Allowable overtopping limits have been taken as 0.1l/s/m for current conditions (unvegetated slopes) and 10l/s/m for future conditions (assuming that vegetation has established on the crest and slopes).



SECTION 4 - locally generated waves

Fetch = 600m Direction = 240°

Return Period	Wave Height (m)	Period (s)
1 in 20	0.32	1.37
1 in 50	0.34	1.40
1 in 100	0.35	1.42
1 in 200	0.37	1.44

...nerated waves

...ion = 150°

...eight	Period (s)
	1.91
	1.95
	1.98
	2.00

SECTION 5 - locally generated waves

Fetch = 500m Direction = 240°

Return Period	Wave Height (m)	Period (s)
1 in 20	0.29	1.29
1 in 50	0.31	1.32
1 in 100	0.32	1.34
1 in 200	0.34	1.36

SECTION 2 - diffracted (K' = 0.5)

Estuary waves through breach

Return Period	Wave Height (m)	Period (s)
1 in 20	0.47	1.91
1 in 50	0.50	1.95
1 in 100	0.52	1.98
1 in 200	0.55	2.00

SECTION 1 - no diffraction

Estuary waves through breach

Return Period	Wave Height (m)	Pe...
1 in 20	0.94	
1 in 50	1.00	
1 in 100	1.03	

CHERRY COBB SANDS – COMPENSATION SITE

DESIGN MEMO – WAVE DIFFRACTION ANALYSIS, REV1

Rev1 - Updated following DK's comments to look at the effect of sea level rise and currents on the proposed protection measures. Also considers the use of Open Stone Asphalt as an alternative to Armorflex, and provides further detail of the protection requirements if a berm is not constructed.

1. INTRODUCTION

The purpose of these calculations is to determine the likely wave climate at the site and determine the required protection for the new set-back embankment.

1.1 Site topography

The site is to have a level at +1.5mAOD. It is proposed to have a 15m berm in front of the embankment at a level around +3.5mAOD to 4.0mAOD to provide protection to the defence in the first year following the breach.

1.2 Water levels

Table 1.1 Water levels

Level	mAOD
LAT	-3.8
MWLS	-3
MLWN	-1.3
MSL	+0.3
MHWN	+1.9
MHWS	+3.4
HAT	+4.1
1 in 20 year	+4.81
1 in 50 year	+4.92
1 in 100 year	+5.01
1 in 200 year	+5.05

- Astronomical tide levels have been taken from the Tide Charts for Immingham.
- Extreme tide levels have been taken from the JPA analysis for Little Humber.

2. WAVES

Waves from two sources can reach the new defence

1) Waves from within the estuary entering through the breach
2) Locally generated wind waves caused by wind blowing across the site

2.1 Estuary waves

Various studies have previously been carried out to numerically determine wave climates within the Humber estuary. The two sources that have been reference in this study are:

- ABP Research 2007: The Humber Tidal Database and JPA of large waves and high water levels
- JBA Consulting Report: South Humber Channel Marine Studies: Hydrodynamic, wave and sediment study

No analysis has been carried out specifically at the compensation habitat site, therefore waves at the breach point have been taken from the JPA analysis carried out at Little Humber, a site approximately 4km up the estuary from the proposed breach point at Cherry Cobb Sands. Little Humber is considered to be representative of Cherry Cobbs Sands as it is on the same side of the estuary with similar fetch and offshore topography.

The wave climate from the JPA results at Little Humber also compares favourably with the predicted wave fields presented in Figure 16 and 17 of the JBA Consulting report, and also with hand calculations of wind generated waves from the south east, south west and north east calculated in accordance with the wave hindcasting equations presented in the Coastal Engineering Manual.

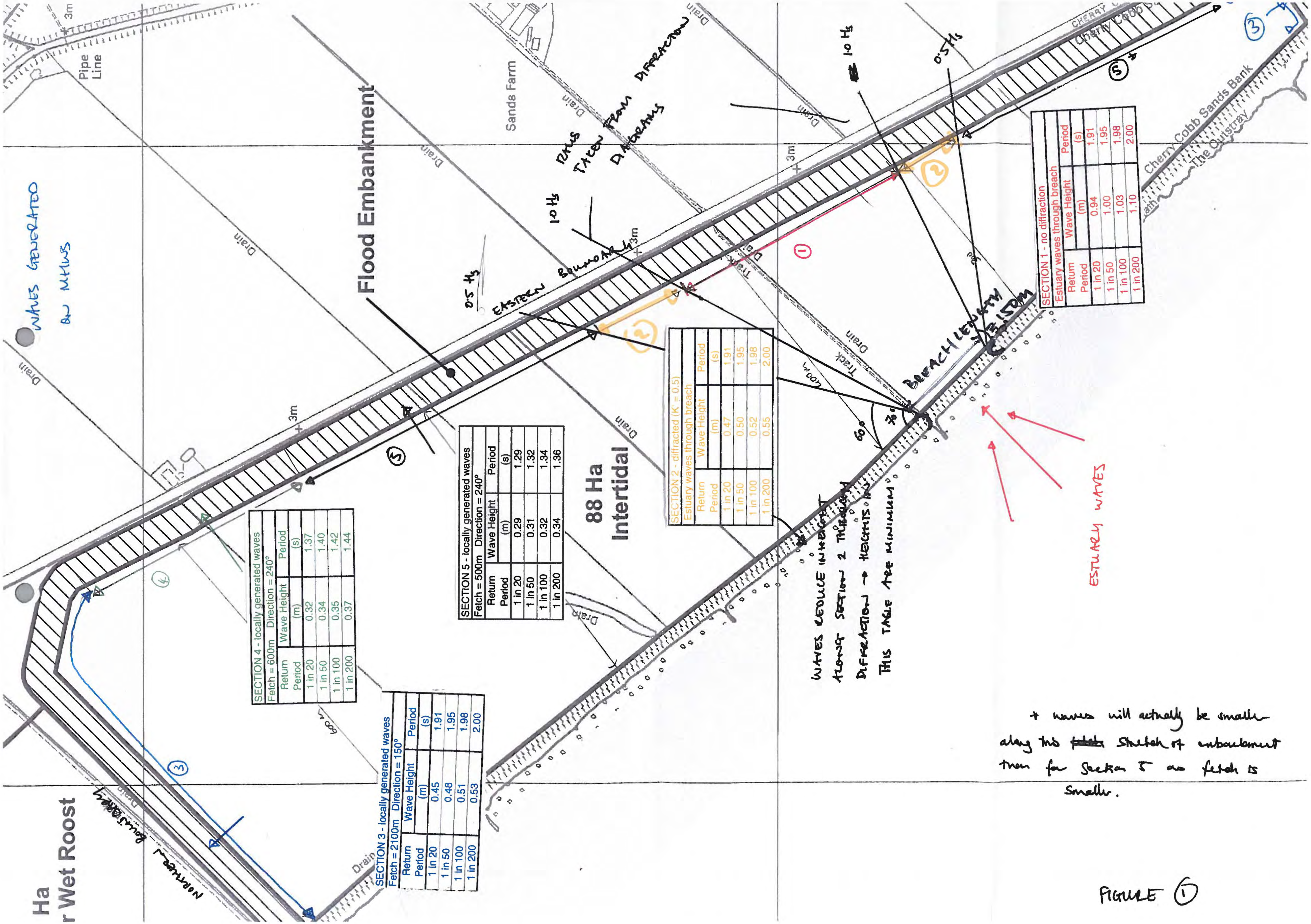
The estuary waves at the breach point have been taken to approach normal to the breach (±30º). Diffraction analysis has been carried out using the diffraction diagrams presented in the Shore Protection Manual. The stretch of embankment opposite the breach point is the most exposed, as waves here are not reduced through diffraction.

2.2 Locally generated waves

The northern boundary of the site is exposed to local waves generated by wind from the SE blowing across the length of the site (2100m fetch for the 88ha option, and 2500m for the 110ha option). The eastern boundary is exposed to local waves generated by wind from the SW blowing across the width of the site (fetch between 300 and 600m). The eastern boundary will also have waves generated by a south easterly wind running parallel to the defence.

The wave heights and period for these locally generated waves have been calculated using the hindcasting equations presented in the Coastal Engineering Manual.

Figure 1 shows the wave heights expected along the length of the embankment. Along Sections 1&2, estuary waves are the most critical, and along Sections 3 to 5 the local waves are the most critical.



SECTION 1 - no diffraction
Estuary waves through breach

Return Period	Wave Height (m)	Period (s)
1 in 20	0.94	1.91
1 in 50	1.00	1.95
1 in 100	1.03	1.98
1 in 200	1.10	2.00

SECTION 2 - diffracted (K' = 0.5)
Estuary waves through breach

Return Period	Wave Height (m)	Period (s)
1 in 20	0.47	1.91
1 in 50	0.50	1.95
1 in 100	0.52	1.98
1 in 200	0.55	2.00

SECTION 3 - locally generated waves
Fetch = 2100m Direction = 150°

Return Period	Wave Height (m)	Period (s)
1 in 20	0.45	1.91
1 in 50	0.48	1.95
1 in 100	0.51	1.98
1 in 200	0.53	2.00

SECTION 4 - locally generated waves
Fetch = 600m Direction = 240°

Return Period	Wave Height (m)	Period (s)
1 in 20	0.32	1.37
1 in 50	0.34	1.40
1 in 100	0.35	1.42
1 in 200	0.37	1.44

SECTION 5 - locally generated waves
Fetch = 500m Direction = 240°

Return Period	Wave Height (m)	Period (s)
1 in 20	0.29	1.29
1 in 50	0.31	1.32
1 in 100	0.32	1.34
1 in 200	0.34	1.36

+ waves will actually be smaller along this ~~fetch~~ stretch of embankment than for Section 5 as fetch is smaller.

FIGURE 1

3. EMBANKMENT PROTECTION

3.1 Berm

The purpose of the berm is to provide protection to the embankment in the first year following the breach, before vegetation has had time to establish.

A berm provides the following advantages:

- Protects the toe of the embankment which is the critical area for wave attack as if the toe is undermined this could result in slippage and catastrophic failure of the embankment.
- Aids vegetation establishment, as greater area above the intertidal zone.
- The upper slopes will only be affected by waves in storm events with water levels greater than MHWS
- Wave breaking on the upper slopes will be reduced as a majority of the waves will break on the berm
- Waves that reach the upper slopes will be reduced in height as they will be depth limited by the presence of the berm

It is proposed that a berm is constructed along the whole length of the new embankment, although there could be an argument that the waves reaching Sections 4 and 5 are sufficiently small that a berm is not necessary.

3.2 Vegetation – medium to long term protection

A vegetated slope can withstand wave attack for the following conditions (taken from Enkamat design manual – original reference, Waterloopkundig Laboratorium, Erosiebestendigheid can grassland als dijkbekleding,Delft, 1996):

(a) Waves less than 0.4m

- Good turf – not damaged in period of 1 to 2 days
- Poor turf - holes up to 0.2m to 0.4m depth develop in 24 hours

(b) Waves between 0.4m and 1.0m

- Good turf - only slight damage in a period of 1 to 2 days, vegetation itself damaged within 24 hours
- Turf in poor condition – severe damage and large holes up to 200mm within 36 hours.

(c) Waves 1.0m to 1.4m

- Good turf - may yield in 15 to 24 hours but if on a stable (clay) subsoil no major damage expected
- Poor quality turf – may yield in short period 'several' hours (2 to 3?)

It can be seen from Figure 1 that the maximum significant wave height that is expected at the new defence line is 1.1m. The upper slope of the embankment is only likely to be exposed to this wave for a maximum period of around 4 hours (taken from an assumed tidal curve for a 1 in 200 year storm), therefore once the vegetation is established this will provide more than adequate protection against the incoming waves.

3.3 Short term protection

It is likely that due to programming requirements the breach will occur before vegetation has established, and therefore the embankment will be more susceptible to damage in the short term. It also might not be possible to cultivate vegetation in the intertidal zone – although once the salt marsh has established, this will provide support to the lower slopes.

It is considered to be quite high risk to leave the embankment totally unprotected, as it is possible for waves of up to 0.94m to reach the embankment at Section 1 in the 1 the 20 year event, which has a 5% probability of exceedance in any one year.

Possible embankment reinforcement measures are discussed below:

(a) Enkamat (or other turf reinforcement systems)

Enkamat is an open three dimensional synthetic mat consisting of randomly placed filament of nylon. It performs two functions:

- Provides temporary protection to the bare soil and encourages the development of vegetation
- Prevents loss of seeds due to wave and current action
- Permanently reinforces vegetation so can withstand higher loadings that vegetation on its own

Pre-filled Enkamat (A20) is filled with bitumen bound mineral chippings – the permeability and the capacity for vegetative growth are preserved, but the filling increases the resistance of the mat to high hydraulic loadings under water where a vegetative cover is not present . (Pre-grown enkamat is also available).

Although Enkamat is primarily used as a protection system against currents and erosion due to rainfall, it does also provide protection against small waves. Unvegetated Pre-filled Enkamat can withstand frequent wave attack with a height H_s of between 0.2 and 0.3m (Enkamat Design Manual).

(b) Armorflex

Armorflex is a concrete block revetment system, consisting of an interlocking matrix of concrete blocks connected by a series of cables to form a mat. The blocks can be cellular which encourages plant growth.

There are three different sizes of Armorflex, capable of resisting waves with H_s between 1.0 and 1.6m when laid on a slope of 1in3 and blinded with a sand / gravel mixture after installation, (Armorflex Design Manual, based on Delft Hydraulics Laboratory Report M1910).

(c) Open Stone Asphalt

Open stone asphalt is an open structure mixture formed using crushed stone bound by a bituminous mortar. It is a permeable structure and therefore is particularly suitable for environments where waves, tidal flows and other differential loads are combined with current attack. As it is an open structure there is the potential for vegetation to grow through the openings if they are large enough.

4. SECTION 1 DESIGN

Figure 2 shows a schematic of the embankment, including the berm.

4.1 Lower slope

Waves that pass through the breach reach the lower slope of the embankment without being reduced through diffraction effects. These waves will then break on the lower slopes. On a spring tide the lower slopes can be exposed to wave action for a period of time in excess of 4 hours, and for a much longer period (up to 8 hours) on a 1 in 200 year surge tide.

The waves that can reach the lower slopes on return periods are shown in Table 4.1 below.

Table 4.1 Waves at Section 1

SECTION 1 - no diffraction		
Estuary waves through breach		
Return Period	Wave Height (m)	Period (s)
1 in 20	0.94	1.91
1 in 50	1.00	1.95
1 in 100	1.03	1.98
1 in 200	1.10	2.00

These waves are taken from the JPA analysis for Little Humber and can be generated on water levels around MHWS. Below this water level, wave heights are depth limited, and on water levels higher than this, the wave heights for the specific return period start to reduce.

These wave heights are too great to be withstood by an unvegetated slope, and it is considered that it is too high a risk to leave the embankment unprotected in the short term as the 1 in 20 year event has a 5% probability of exceedance in any one year, and waves of this height could potentially reach the slope for a period of up to eight hours on a surge tide.

It is proposed that Armorflex 180, which can withstand a H_s of 1.3m and a H_{max} of 1.8m should be used on the lower slopes for Section 1.

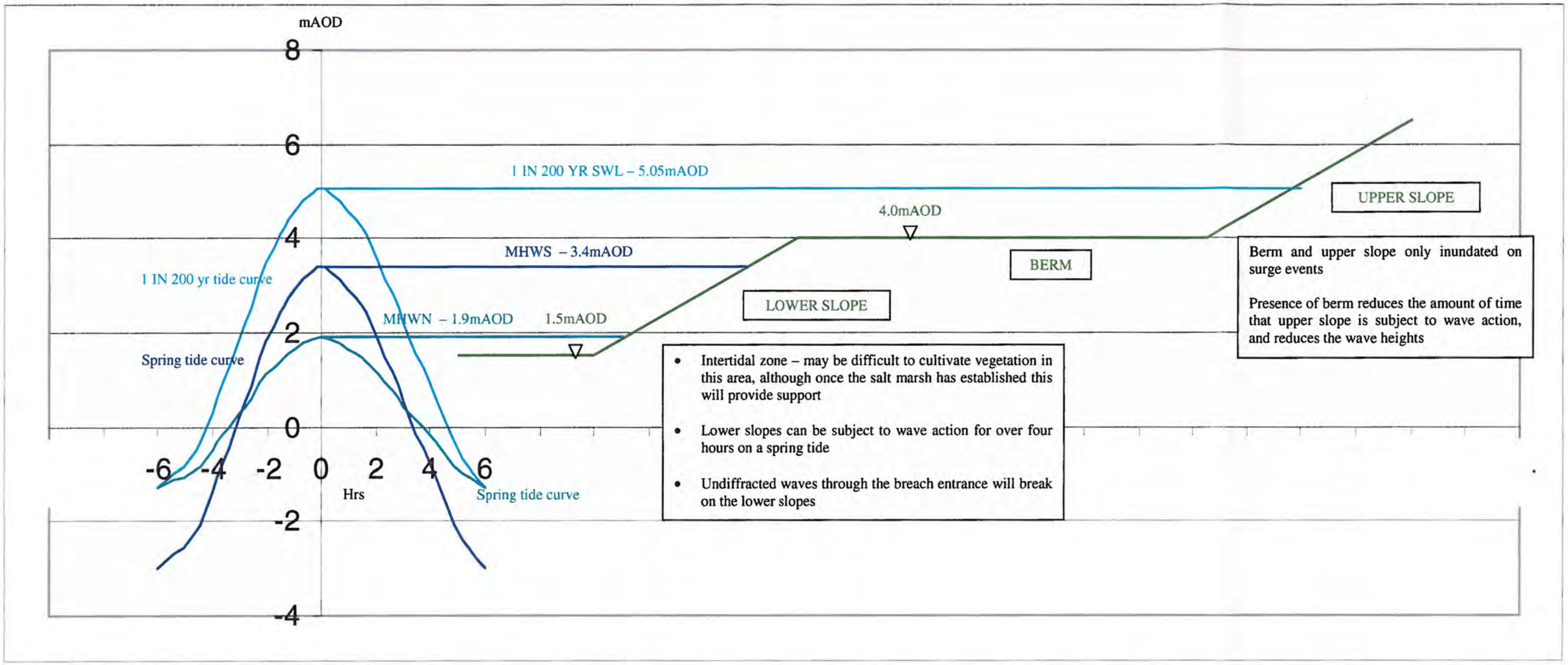
4.2 Upper slope and berm

The presence of the berm reduces the wave height that the upper slopes are exposed for, and the time that the upper slope is exposed to wave action. Table 4.2 below shows the waves that can reach the upper slopes and the time of exposure to that particular wave height based on the JPA results for Little Humber.

Column [1] and [2] show the return period and exceedance probability of a particular event. Columns [3] to [4] show the JPA wave data. Column [6] shows the maximum water depth over the berm, based on a berm level of +4.0mAOD. Column [7] gives the maximum wave that can travel over the berm, taken as the minimum of either the maximum depth limited wave (taken as 0.8x water depth) or the maximum wave from the JPA analysis. Column [8] gives the exposure time, based on an assumed surge tide curve. High water is taken as the water level from the JPA analysis, and low water is taken as MLWN, as a storm surge acts to flatten the tidal curve, resulting in a higher low water than might otherwise occur.

Table 4.2 Wave heights reaching upper slope of Section 1

[1] exceedance prob	[2] Return Period	[3] Water level (mAOD)	[4] Hs (m)	[5] T_m (sec)	[6] water depth over berm	[7] max wave height Hs (m)	[8] time of exposure (hrs)
5%	20	2	0.96	3.43	-	-	-
5%	20	3.5	0.94	3.39	-	-	-
5%	20	3.86	0.9	3.32	-	-	-
5%	20	4	0.88	3.28	0	0.00	0
5%	20	4.23	0.8	3.13	0.23	0.18	1.67
5%	20	4.4	0.7	2.93	0.4	**0.32**	2.33
5%	20	4.41	0.7	2.93	0.41	**0.33**	2.33
5%	20	4.59	0.6	2.71	0.59	**0.47**	2.67
5%	20	4.75	0.4	2.21	0.75	**0.40**	3.00
5%	20	4.8	0.22	1.64	0.8	0.22	3.17
5%	20	4.81	0	0	0.81	0.00	3.17
2%	50	2	1.01	3.52	-	-	-
2%	50	3.17	1	3.5	-	-	-
2%	50	3.5	0.98	3.46	-	-	-
2%	50	4	0.94	3.39	0	0.00	0.00
2%	50	4.14	0.9	3.32	0.14	0.11	1.33
2%	50	4.4	0.81	3.15	0.4	**0.32**	2.33
2%	50	4.41	0.8	3.13	0.41	**0.33**	2.33
2%	50	4.62	0.7	2.93	0.62	**0.50**	2.83
2%	50	4.78	0.6	2.71	0.78	**0.60**	3.17
2%	50	4.8	0.58	2.67	0.8	**0.58**	3.17
2%	50	4.9	0.4	2.21	0.9	**0.40**	3.17
2%	50	4.92	0	0	0.92	0.00	3.17
1%	100	2	1.04	3.57	-	-	-
1%	100	3.5	1.03	3.55	-	-	-
1%	100	3.79	1	3.5	-	-	-
1%	100	4	0.98	3.46	0	0.00	0.00
1%	100	4.38	0.9	3.2	0.38	0.30	2.17
1%	100	4.4	0.88	3.28	0.4	**0.32**	2.33
1%	100	4.54	0.8	3.13	0.54	**0.43**	2.50
1%	100	4.8	0.7	2.93	0.8	**0.64**	3.17
1%	100	4.81	0.7	2.93	0.81	**0.65**	3.17
1%	100	4.91	0.6	2.71	0.91	**0.60**	3.17
1%	100	4.98	0.4	2.21	0.98	**0.40**	3.33
1%	100	5.01	0	0	1.01	0.00	3.50
0.50%	200	2	1.09	3.65	-	-	-
0.50%	200	3.5	1.07	3.62	-	-	-
0.50%	200	4	1.03	3.55	0	0.00	0.00
0.50%	200	4.14	1	3.5	0.14	0.11	1.33
0.50%	200	4.4	0.93	3.38	0.4	**0.32**	2.33
0.50%	200	4.51	0.9	3.32	0.51	**0.41**	2.50
0.50%	200	4.74	0.8	3.13	0.74	**0.59**	2.83
0.50%	200	4.8	0.79	3.11	0.8	**0.64**	3.17
0.50%	200	4.96	0.7	2.93	0.96	**0.70**	3.33
0.50%	200	4.99	0.6	2.71	0.99	**0.60**	3.50
0.50%	200	5.05	0.4	2.21	1.05	**0.40**	3.50



mAOD
8
6
4
2
0
-2
-4
-6
-4
-2
0
2
4
6
Hrs
1 IN 200 YR SWL – 5.05mAOD
MHWS – 3.4mAOD
MHWN – 1.9mAOD
1.5mAOD
4.0mAOD
1 IN 200 yr tide curve
Spring tide curve
Spring tide curve
UPPER SLOPE
BERM
LOWER SLOPE
Berm and upper slope only inundated on surge events
Presence of berm reduces the amount of time that upper slope is subject to wave action, and reduces the wave heights
• Intertidal zone – may be difficult to cultivate vegetation in this area, although once the salt marsh has established this will provide support
• Lower slopes can be subject to wave action for over four hours on a spring tide
• Undiffracted waves through the breach entrance will break on the lower slopes

This table shows that wave heights are significantly reduced on the upper slopes compared with the lower slopes, and the time of exposure is also reduced (3-4 hours exposure compared with 8 hours exposure on the lower slopes). It is proposed that Enkamat A20 is used on the upper slopes to provide protection in the short term – this can withstand frequent wave attacks with a H_s up to 0.3m. Although the design manual is not specific about the maximum wave heights Enkamat can sustain over a short period of time, it is considered that this value will be higher than the 0.3m. Wave heights in bold in Table 4.2 show where wave heights of greater than 0.3m can reach the upper slopes. These increase with a decreasing exceedance probability and range between a 0.47m wave for the 1 in 20 year event and a 0.7m wave for the 1 in 200 year event. The upper slopes are only exposed to these waves for a period of up to 3.5 hours (based on the 1 in 200 year surge tide), which will not be a regular occurrence; therefore it is considered that Enkamat A20 will be sufficient to provide protection to the upper slopes.

It should be noted that the exposure time is based on the length of time that the water level is higher than the berm, and therefore it is unlikely that the maximum significant wave height will act over the length of time the lower slopes are exposed.

There could be the potential for the higher return period events (1 in 100 and 1 in 200 year) to cause damage to the Enkamat in the unvegetated state, as wave heights of up to 0.7m could reach the upper slope, which is much greater than the unvegetated Enkamat can sustain. Waves breaking on the lower section of the upper slope could result in undermining and slippage of the crest. It the wave attack was sustained this could result in failure of the embankment. The consequences of failure are significant, as the land behind the embankment is around +2.5mAOD, which is significantly lower than the flood level.

The presence of the berm acts to reduce the length of time that wave attack can occur, meaning that the likelihood of a sustained attack at the toe of the slope is significantly lowered compared to the situation where the berm is in place.

It is considered therefore that the risk of damage resulting in complete failure of the embankment is low for the following reasons:

- the short time period over which the wave attack can occur should ensure that the waves cannot act long enough to cut through the slope entirely;
- the Enkamat provides a small level of protection, acting to reduce the amount of material that can be washed away;
- the probability of an event occurring that might cause some damage is only around 1% in a given year (for the 1 in 100 year event) and 0.5% for the 1 in 200 year event.

It is therefore considered that it would be more cost effective to accept that some damage may occur, and repair it, rather than providing more robust temporary protection on the upper slopes.

The final profile of the upper slope should be determined to reduce the likelihood of failure of the embankment, such as using a flat slope, and wide crest.

4.3 Solution without berm in place

Without the berm in place the likelihood of failure increases, as waves up to 1.1m in height can directly attack the toe of the embankment for a sustained period of time (up to eight hours). Vegetation is unlikely to be cultivated on the lower slopes, and therefore a robust permanent protection system would have to be implemented. In this situation it is proposed that Armorflex 180, that can withstand significant waves up to 1.3m in height be used, up to the 1 in 200 year extreme water level (+5.05mAOD). An alternative could be to use Open Stone Asphalt with a thickness of 240mm.

5. SECTION 2 DESIGN

5.1 Lower slopes

Waves reaching section 2 are reduced in height by up to 50% through diffraction at the outer limits of the section. The minimum wave heights that can reach the lower slopes of section 2 are shown Table 5.1 below.

Table 5.1 Waves at end of Section 2

SECTION 2 - diffracted (K' = 0.5)		
Estuary waves through breach		
Return Period	Wave Height (m)	Period (s)
1 in 20	0.47	1.91
1 in 50	0.50	1.95
1 in 100	0.52	1.98
1 in 200	0.55	2.00

Although these wave heights are reduced compared with section 1, wave heights greater than 0.55m can reach the embankment for periods of in excess of 4 hours, and therefore the risk of damage to an unprotected embankment before vegetation has established is quite high.

It is considered that Armorflex 180 should be used to protect the lower slopes on section 2 as for section 1.

5.2 Upper slopes and berm

By inspection, waves reaching the upper slopes of Section 2 will be lower than those that reach the upper slopes of Section 1, therefore Enkamat A20 will be sufficient to provide the required protection.

5.3 Solution without berm in place

As for Section 1 if a berm were not to be constructed, Armourflex 180 should be placed up to a level of +5.05mAOD (extreme 1 in 200yr water level).

6. SECTION 3 DESIGN

6.1 Lower slopes

Section 3 is exposed to locally generated waves blowing from the south east across a 2.1km fetch for the 88ha site option, and 2.5km fetch for the 110ha site option. Waves that can reach the lower slopes are shown in Table 6.1.

Table 6.1 Waves at Section 3

SECTION 3 - locally generated waves				
Fetch = 2100m Direction = 150º			Fetch = 2500m	
Return Period	Wave Height (m)	Period (s)	Wave Height (m)	Period (s)
1 in 20	0.45	1.91	0.49	2.02
1 in 50	0.48	1.95	0.53	2.06
1 in 100	0.51	1.98	0.55	2.10
1 in 200	0.53	2.00	0.57	2.12

These waves are generated by wind speeds equal to the return periods in the table, and can be generated on water levels around MHWS. For water levels lower than MHWS, waves will start to become depth limited, and for water levels higher than MHWS (storm events), lower wave heights will be associated with the same return period events.

The lower slopes could be exposed to these wave heights for periods in excess of 4 hours (the time the water level is higher than +1.7mAOD on a spring tide) and therefore would be at risk of damage if unprotected. The berm in this situation acts as a sacrificial toe – if the berm is undermined by the waves then the material will slump leading to a flat slope at the toe of the embankment (see figure 3 below).

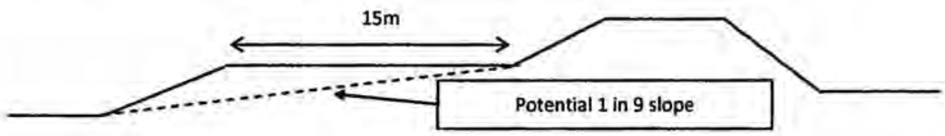


Figure 3: Potential form of berm if undermined through wave action

As the waves at Section 3 are around half the height of the waves at Section 1 it is considered that the presence of the berm provides adequate protection against the toe of the embankment being undermined, and therefore no further protection is required in the short term.

6.2 Upper slopes and berm

By inspection the waves reaching the upper slopes will be significantly smaller than those in Table 6.1 for the same return period events, as the water levels would have to be higher in order for the upper slopes to be exposed to wave action. Also the period of time the upper slopes would be exposed is shorter than the lower slopes, therefore it is considered that Enkamat A20 provides sufficient protection against wave actions, before vegetation has had time to establish.

Leaving the slope totally unprotected is not sufficient in the short term, as the consequences of the upper slope and crest failing are severe, and leads to unacceptable risk.

6.3 Solution without berm in place

Without the berm in place the likelihood of failure increases, as waves up to 0.6m in height can directly attack the toe of the embankment for a sustained period of time (up to eight hours). Vegetation is unlikely to be cultivated on the lower slopes, and therefore a robust permanent protection system would have to be implemented. In this situation it is proposed that Armorflex 140, that can withstand significant waves up to 1.0m in height be used, up to the 1 in 200 year extreme water level (+5.05mAOD). An alternative to

Armorflex could be the use of a 100mm thick layer of Open Stone Asphalt, which would be sufficient to take a sustained wave attack with a significant wave height of 0.6m.

7. SECTION 4&5 DESIGN

7.1 Lower and upper slopes

Section 4 and 5 are subject to smaller waves than the other sections as they are well behind the front embankment which provides protection against estuary waves, and have a much smaller fetch for locally generated waves. Table 7.1 and Table 7.2 show the waves at Section 4 & 5.

Table 7.1 Waves at Section 4

SECTION 4 - locally generated waves		
Fetch = 600m Direction = 240º		
Return Period	Wave Height (m)	Period (s)
1 in 20	0.32	1.37
1 in 50	0.34	1.40
1 in 100	0.35	1.42
1 in 200	0.37	1.44

Table 7.2 Waves at Section 5

SECTION 5 - locally generated waves		
Fetch = 500m Direction = 240º		
Return Period	Wave Height (m)	Period (s)
1 in 20	0.29	1.29
1 in 50	0.31	1.32
1 in 100	0.32	1.34
1 in 200	0.34	1.36

As these waves are much smaller than the other sites, it is considered that Enkamat A20 is sufficient to provide protection to the embankment without vegetation. The presence of a berm reduces the likelihood of failure by undercutting of the slope, and therefore would be good practice to include if there was sufficient material available. As the wave heights are relatively small, it would be feasible to develop a design without a berm in this area that did not require substantial permanent protection.

8. EFFECT OF CURRENTS

As the compensation site fills up over the tidal cycle, the embankments are subject to tidal currents. On a high spring tide (occurring approximately 7 times a year) these currents could reach speeds of up to 1.4m/s acting along a 700m length of the embankment opposite the breach, for a time period of approximately 10minutes. Currents of a lower speed will occur on smaller tides, and larger currents on surge tides. This current affects parts of Sections 1, 2 and part of 5, and will act on the lower slopes.

8.1 Sections 1 & 2

It is proposed that the berm and lower slope of Sections 1 and 2 be protected by Armorflex 180 to provide resistance against wave attack. The methods described in 'River and channel revetments – a design manual', show that loose concrete blocks of 80mm thickness can resist currents of 1.4m/s. Armorflex 180 is 120mm thick and therefore will be able to resist the currents that occur due to the breach.

This design method does not take account of combined wave and current action, as this is an area where little research has been undertaken. It is considered though that the Armorflex 180 blocks have enough reserve capacity to withstand combined wave and current attack, especially as the Armorflex blocks are interlinked using cables which increases the stability compared with loose blocks (the equations relating to interlinked blocks show that they only need to be 10mm thick in order to resist currents of 1.4m/s), and therefore it is considered that the Armorflex will be robust enough to resist the currents and any combined wave action that could occur over the 10minute period when the currents are at their highest.

8.2 Section 5

The proposed solution for Section 5 to resist wave attack is either an unprotected berm, or the lower slopes without a berm, but protected with Enkamat A20.

The simplified design method as presented in the Enkamat design manual has been used to determine whether an unprotected slope or Enkamat A20 is sufficient to provide resistance against 1.4m/s currents.

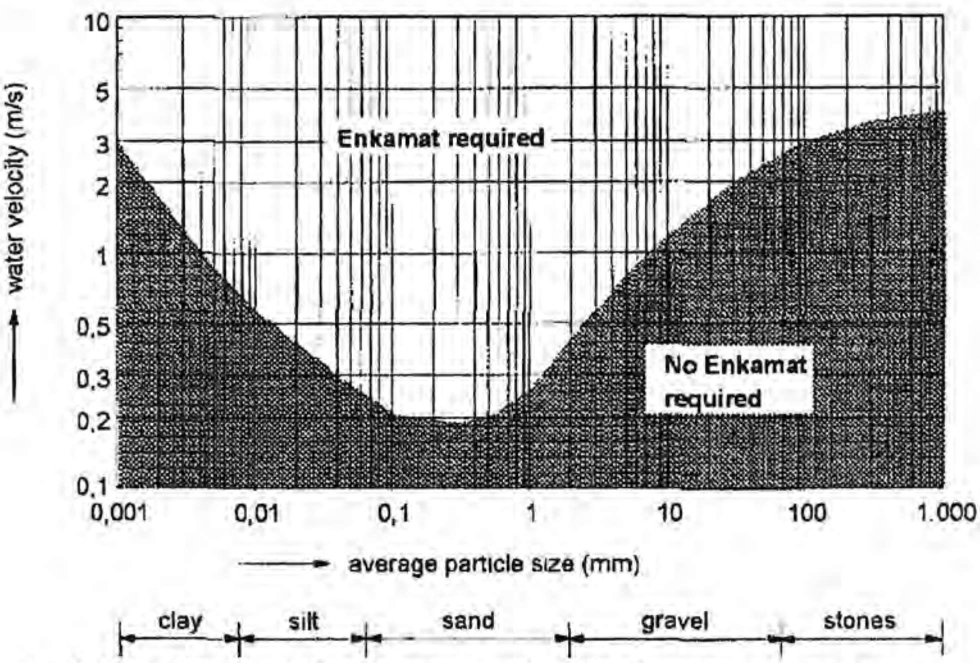


Figure 5.1 Critical flow in relation to mean grain size diameter and soil type.

Figure 5.1 from the Enkamat design manual indicates whether protection is needed on embankments to resist currents. The embankment will be constructed from the local materials that are to be excavated to create the compensation habitat area. This material consists of marine and estuarine alluvium deposits, which comprise of fine grained sands and silts. It is assumed that all particle sizes are less than 1mm. The figure above shows that this material would be subject to erosion under a 1.4m/s current (and any current greater than around 0.2m/s) and protection should be provided.

Figure 5.3 from the Enkamat design manual shows that for a 1.4m/s current, Open Enkamat + chippings would be sufficient to provide the required protection.

If an unprotected berm is used as protection for section 5, this could therefore be subject to erosion due to the current that is generated immediately following the breach. As this current will occur for a limited time only (10 minutes at a time, around seven times a year), it may be considered that as the berm is sacrificial, a small amount of erosion will be acceptable, as it is unlikely to result in total undermining and collapse of the embankment. If any particularly strong currents do cause more substantial damage then it could be that it is more preferable to repair this, than provide a more robust protection system.

However if it is considered that this risk is too great, or too costly to have to repair any damage caused by the currents, then Open Enkamat (such as Enkamat 7220) with chippings should be considered on the lower slope over the length of the section where high currents are anticipated to occur.

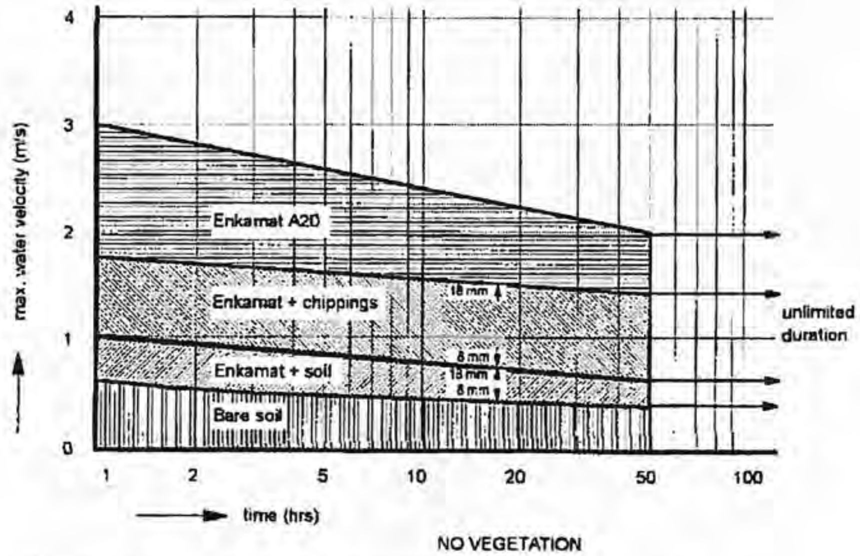


Figure 5.3 Enkamat type related to acting flow and no vegetation.

If the final solution for Section 5 is to have no berm, but the lower slopes protected with Enkamat A20, then this will provide sufficient protection against the currents that occur over the tidal cycle.

9. EFFECT OF SEA LEVEL RISE

If 1m of sea level rise is considered, this results in increased wave heights acting on the upper slopes as the waves are less depth limited. The time that the upper slopes are subject to wave attack also increases, as the water level will be above the berm level for a longer period of time.

Table 9.1 shows the wave heights that can reach the upper slopes and the time of exposure at section 1, including for the effect of 1m of sea level rise. The table columns are as described in Section 4.2. This table shows that at Section 1, waves with a significant wave height of around 0.9m can reach the upper slopes for up to four hours at a time.

It is assumed that over time vegetation will be established on the upper slopes, providing protection as described in Section 3.2. Proving the vegetation is maintained, and it can be described as 'good turf', then it will be able to sustain attacks of 0.9m waves for a period of 4 hours without any significant damage. Therefore no additional protection measures need to be included to take into account the effect of sea level rise.

Table 9.1 Wave heights reaching upper slope of Section 1 including for 1m of sea level rise

[1] exceedance prob	[2] Return Period	[3] Water level (mAOD)	[4] Hs (m)	[5] T_m (sec)	[6] water depth over berm	[7] max wave height Hs (m)	[8] time of exposure (hrs)
5%	20	3	0.96	3.43	-	-	-
5%	20	4.5	0.94	3.39	0.5	0.40	-
5%	20	4.86	0.9	3.32	0.86	0.69	-
5%	20	5	0.88	3.28	1	0.80	0
5%	20	5.23	0.8	3.13	1.23	0.80	3.83
5%	20	5.4	0.7	2.93	1.4	0.70	3.83
5%	20	5.41	0.7	2.93	1.41	0.70	3.83
5%	20	5.59	0.6	2.71	1.59	0.60	4.17
5%	20	5.75	0.4	2.21	1.75	0.40	4.17
5%	20	5.8	0.22	1.64	1.8	0.22	4.33
5%	20	5.81	0	0	1.81	0.00	4.33
2%	50	3	1.01	3.52	-	-	-
2%	50	4.17	1	3.5	0.17	0.14	-
2%	50	4.5	0.98	3.46	0.5	0.40	-
2%	50	5	0.94	3.39	1	0.80	3.50
2%	50	5.14	0.9	3.32	1.14	0.90	3.50
2%	50	5.4	0.81	3.15	1.4	0.81	3.83
2%	50	5.41	0.8	3.13	1.41	0.80	3.83
2%	50	5.62	0.7	2.93	1.62	0.70	4.17
2%	50	5.78	0.6	2.71	1.78	0.60	4.33
2%	50	5.8	0.58	2.67	1.8	0.58	4.33
2%	50	5.9	0.4	2.21	1.9	0.40	4.50
2%	50	5.92	0	0	1.92	0.00	4.50
1%	100	3	1.04	3.57	-	-	-
1%	100	4.5	1.03	3.55	0.5	0.40	-
1%	100	4.79	1	3.5	0.79	0.63	-
1%	100	5	0.98	3.46	1	0.80	0.00
1%	100	5.38	0.9	3.2	1.38	0.90	3.83
1%	100	5.4	0.88	3.28	1.4	0.88	3.83
1%	100	5.54	0.8	3.13	1.54	0.80	4.17
1%	100	5.8	0.7	2.93	1.8	0.70	4.33
1%	100	5.81	0.7	2.93	1.81	0.70	4.33
1%	100	5.91	0.6	2.71	1.91	0.60	4.50
1%	100	5.98	0.4	2.21	1.98	0.40	4.50
1%	100	6.01	0	0	2.01	0.00	4.50
0.50%	200	3	1.09	3.65	-	-	-
0.50%	200	4.5	1.07	3.62	0.5	0.40	-
0.50%	200	5	1.03	3.55	1	0.80	3.50
0.50%	200	5.14	1	3.5	1.14	0.91	3.50
0.50%	200	5.4	0.93	3.38	1.4	0.93	3.83
0.50%	200	5.51	0.9	3.32	1.51	0.90	4.17
0.50%	200	5.74	0.8	3.13	1.74	0.80	4.17
0.50%	200	5.8	0.79	3.11	1.8	0.79	4.33
0.50%	200	5.96	0.7	2.93	1.96	0.70	4.50
0.50%	200	5.99	0.6	2.71	1.99	0.60	4.50
0.50%	200	6.05	0.4	2.21	2.05	0.40	4.50

10. SUMMARY

- Once vegetation is established, this provides sufficient protection to the embankment against wave attack, even accounting for 1m of sea level rise.

- Vegetation could be difficult to cultivate in the intertidal zone, although if the saltmarsh establishes this will provide support to the lower slopes of the embankment (this will occur over a longer time frame)

- In the short term prior to the establishment of vegetation, additional protection is needed in some areas to reduce the risk of damage to the embankment

- A 15m berm at a level of 4mAOD should be constructed along the whole length of the embankment to reduce the risk of damage by undercutting the upper slopes (which are the most critical in terms of failure of the embankment by breaching), although the width of this could be reduced along Sections 4&5 where wave action is less than at Sections 1 to 3 if there wasn't sufficient material available.

- Sections 1 and 2 can be exposed to waves of up to 1.1m for periods of up to eight hours. It is not considered that an unprotected berm provides adequate protection against these conditions. Armorflex 180 should be placed on the lower slopes of Sections 1 & 2 to protect against wave attack, which can withstand wave heights (H_s) of 1.3m on a slope with a gradient of 1 in 3.

- For Sections 3 to 5 wave heights attacking the lower slopes are significantly lower than for sections 1 and 2 (up to 0.55m maximum significant wave height). An unprotected berm will provide adequate protection against undercutting of the embankment along these sections, and therefore no further protection is required.

- The upper slopes and berm of all sections, should be protected using Enkamat A20, which can withstand regular waves (H_s) of up to 0.3m Hs, and short durations of larger waves in an unvegetated state. The Enkamat provides protection to the toe of the upper slope for small waves in the short term, and helps to encourage vegetation growth, by preventing seed loss.

- There is a small risk of damage occurring to the upper slopes of Sections 1 and 2 if storm events occur immediately following the breach, as waves up to 0.7m could attack the upper slope in a 1 in 200 year storm. The risk of failure of the embankment is considered to be low however due to the low probability of occurrence, and the short duration of any event that does occur. The risk should be mitigated through the design of the profile of the upper slopes (flat slopes and wider crest), to ensure that any damage that does occur does not result in failure of the crest.

- If no berm is to be created, Sections 1&2 should be protected using Armorflex 180, up to the 1in200yr water line, with section 3 being protected using Armorflex 14. Enkamat A20 would be sufficient to provide protection for sections 4&5 with no berm in place.

- Currents of up to 1.4m/s can occur over a 700m length of embankment on high spring tides, affecting parts of Sections 1, 2 & 5. Armourflex and Enkamat (open or filled) are sufficient to provide resistance against this level of current, but an unprotected slope may be subject to erosion. If an unprotected berm is to be used for section 5, the risk of this being undermined due to current action acting over a short period of time on each tide should be considered. As the current will only act for a limited time only on each tidal cycle, it may be considered that some erosion of the berm is acceptable. Any substantial damage could then be repaired before it became too critical. If the risk is considered too high, or repairs too costly the lower slopes should be protected using Open Enkamat 7220 over the length where high currents can act.

11. SUMMARY TABLES OF REQUIRED PROTECTION

Table 11.1 Summary of protection measures required if a berm is constructed

Section	Lower slope	Upper slope & berm
Section 1	Armorflex 180	Enkamat A20
Section 2	Armorflex 180	Enkamat A20
Section 3	Unprotected	Enkamat A20
Section 4	Unprotected	Enkamat A20
Section 5 - areas of low current	Unprotected	Enkamat A20
Section 5 - areas of high current*	Enkamat 7220 + chippings*	Enkamat A20

* This solution should be considered if the risk of an unprotected berm being eroded due to current action is deemed to be too high.

Table 11.2 Summary of protection measures required if no berm is constructed*

Section	Protection
Section 1	Armorflex 180
Section 2	Armorflex 180
Section 3	Armorflex 140
Section 4	Enkamat A20
Section 5	Enkamat A20

12. SUPPORTING DOCUMENTS

- Extracts from Enkamat Design Manual
- Enkamat A20 technical data sheet
- Enkamat 7220 technical data sheet
- Armorflex data

CHAPTER 2

ENKAMAT

2.1 What is Enkamat

A plain vegetation is a very good way to protect soil from erosion by water and wind. Sometimes however vegetation is absent, for instance just after construction works, or difficult to establish, for instance on steep slopes. Also the loadings may be too high for plain vegetation to withstand.
Often a temporary protection of the soil to enable the development of vegetation or to give extra strength to the vegetation is desired.

Enkamat is an open three dimensional synthetic mat consisting of randomly placed filaments of polyamide (nylon).
The objective of Enkamat is twofold:

- the first objective is to provide temporary protection to the bare soil to encourage the development of vegetation under circumstances where this is normally difficult or impossible;
- the second objective of Enkamat is to permanently reinforce vegetation. It gives extra strength to the vegetation so that higher loadings can be withstood than with a plain vegetation

Due to the fact that Enkamat is made of an inert material the durability is very high and its protective function is maintained for a long period.

Natural vegetation reinforcement materials, such as jute, coir, flax, wood wool or strawmats, only last for a short period of time and are only meant to provide temporary protection up to the point that the vegetation can take over this task. Enkamat, however, also provides extra strength to the vegetation after it is fully grown.
Also the quality of these natural materials is not constant. Enkamat is manufactured under controlled conditions. This ensures a high quality of the material according to ISO 9001 standards.

In fact Enkamat fills the gap between a protection with a plain vegetation and a more radical protection with materials such as rock, concrete or asphaltic mixtures.
The advantage is:

- protection of a ground surface by vegetation is to be preferred from an environmental point of view. Aesthetically, reinforced grass is indistinguishable from a plain vegetation cover so it blends in with the landscape. Also, the use of vegetation encourages the development of flora and fauna;
- generally, vegetation reinforcement is cheaper than the more traditional constructions using hard materials;
- under normal circumstances, vegetation reinforcement is easier to place than more traditional methods.

2.2 How does Enkamat function

A vegetation cover provides protection to the subsoil against erosion in several ways:

- a composite soil/root mat is formed at the surface with a higher erosion resistance than soil alone. This mat is anchored to the subsoil by the roots;
- the vegetation provides ground cover and reduces erosive velocities.

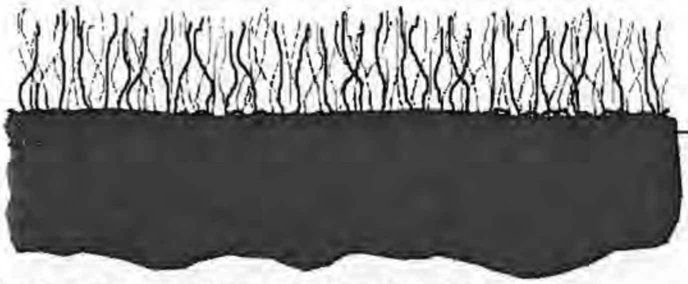


Figure 2.1 Soil, roots and fibers working together.

With Enkamat the vegetation roots bind around the filaments thus forming a dense and continuous system of filaments, soil and roots (Figure 2.1). This implies that (Hewlett, 1987):

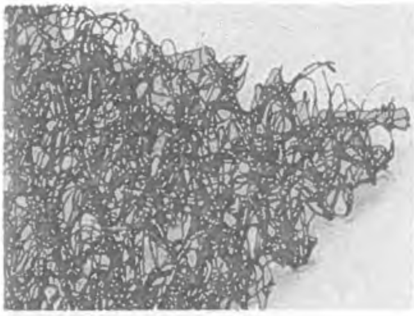
- the soil itself is given extra strength to withstand loadings. The formation of local weak spots is retarded. This certainly is an advantage in situations where the vegetation cover has not fully been developed yet and when bare spots are present;
- the root structure is given assistance in restraining soil particles from washing out;
- lateral continuity of plants is improved which results in a reduction in the risk of localised failure which in its turn may initiate more severe damage.

2.3 Enkamat types

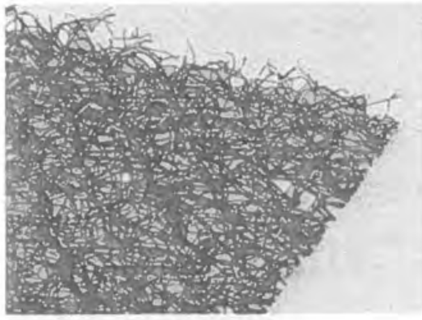
Depending on the purpose for which Enkamat is to be used several mat types are available.
These types are (Figure 2.2):

- *Open Enkamat:*

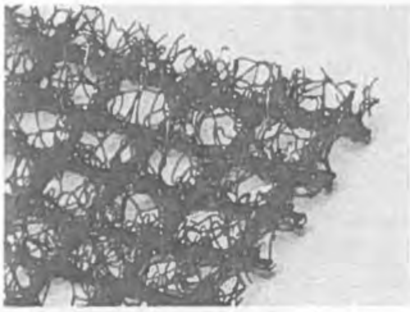
  Plain Enkamat consisting of an entirely open structure of polyamide monofilaments. It is available in thicknesses of 9, 10, 18 and 20 mm. The volume of open space is over 95%.
  When higher loads are present the thicker mat type is to be used, under low loading conditions the thinner mat.
  This type of mat is used in situations where protection is needed of the vegetation against erosion and a proper vegetation can establish by itself in time. Examples of applications are the protection of newly built slopes and embankments.



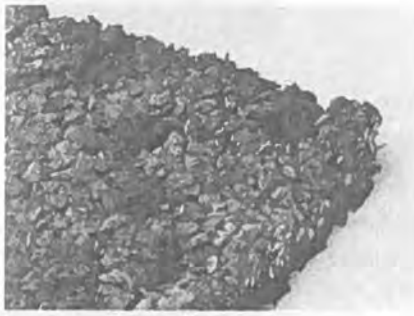
Open Enkamat
(Enkamat 7010/7020)



Flat-back Enkamat
(Enkamat 7210/7220)



Reinforced Enkamat
(Enkamat S)



Pre-filled Enkamat
(Enkamat A20)

Pre-grown Enkamat
(Enkazon)

Figure 2.2 Enkamat types.

- *Flat-back Enkamat*

  This mat type is identical to the Open Enkamat with the exception that the underside of the mat is provided with a flat-back made of a two dimensional layer of filaments. This does not affect the water-permeability.

  The flattened underside allows the mat to be filled with mineral chippings. Filling increases the resistance against erosion, convenient in situations in which vegetation is not allowed to develop fully, for instance when the mat is to be placed (partially) under water.
  On embankments it is therefore possible to achieve a continuous protection of the entire slope above as well as below water using the same construction by simply filling the Enkamat with gravel chippings on those locations where vegetative growth is difficult or impossible.

  The mat is available in two thicknesses: 9 and 18 mm; the choice depends on the loading conditions.

- *Pre-filled Enkamat*

  A mat factory filled with bitumen bound mineral chipping in such a way that the mat remains permeable. Its weight is approximately 20 kg/m^2.
  The permeability and the capacity for vegetative growth are preserved. This mat is much heavier than the other types and can withstand high hydraulic loadings under water where a vegetative cover is not present.
  The thickness of the mat is 20 mm.

- *Reinforced Enkamat*

  This mat is reinforced and can withstand high tensile forces. It is installed on very steep slopes and on smooth sublayers or liners where development of vegetation is desired. Examples are steep rocky slopes and the covering of geomembranes used in pond lining.
  The reinforcement of the mat is achieved in three ways:
  - a polyester grid is intertwisted in an Open Enkamat;
  - a woven geotextile is stitched to an Open Enkamat;
  - reinforcing threads are integrated in the length direction of an Open Enkamat.

  Depending on the construction tensile strengths may vary from 8 kN/m up to 300 kN/m, the thickness from 8 to 23 mm.

- *Pre-grown Enkamat*

  When immediate protection by grass is required or when the time available to achieve a dense vegetative cover is insufficient a Pre-grown Enkamat can be applied. This is an Open Enkamat, 10 mm thick, in which a turf is pre-grown under optimum conditions. It is grown on a perforated polyethylene film and harvested without disturbing the roots, ensuring rapid adherance to the surface.

CHAPTER 5

SIMPLIFIED DESIGN

5.1 General

The simplified design method is carried out step by step for specific applications.

Wet (hydraulic) applications are the protection banks of rivers, canals, ditches, brooks, etc.
Dry applications are the protection of slopes and embankments against rain run-off or wind.

5.2 Wet applications

5.2.1 Step 1: is there a need for erosion protection

The toplayer of soil on the slope determines if erosion is to be expected. Coarse materials do not erode at low water velocities, sandy and silty materials erode at very low water velocities in the water course.
Use Figure 5.1 to determine if there is a need for erosion protection materials.

5.2.2 Step 2: determine the position and length of the Enkamat on the slope

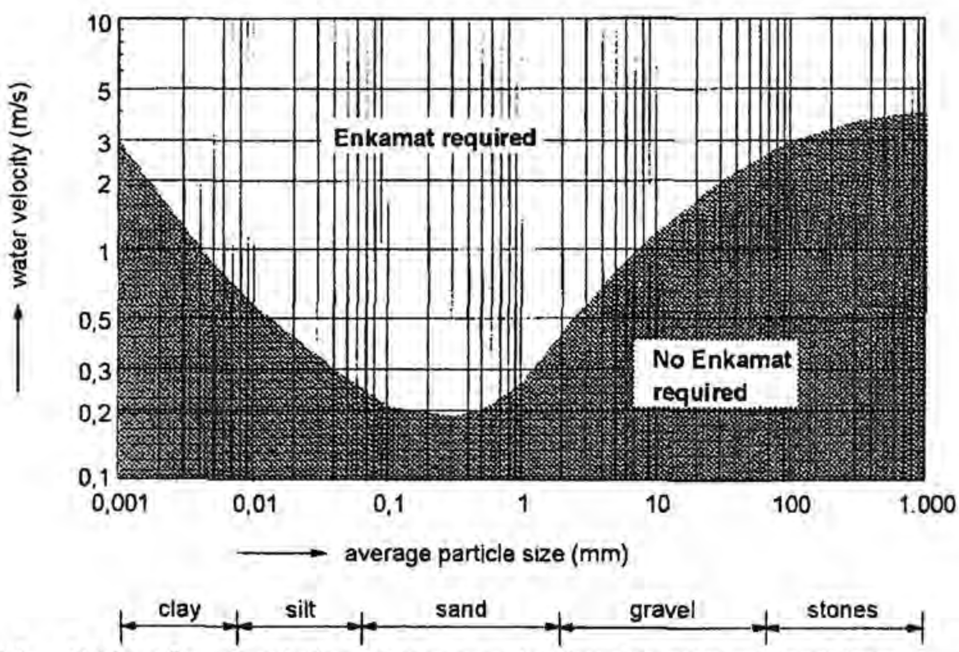


Figure 5.1 Critical flow in relation to mean grain size diameter and soil type.

Establish the high and low water level.
The high water level is estimated as:

- for slightly varying levels (non tidal), the normal high water level;
- for largely varying water levels (non tidal) the level that is exceeded a maximum of three times a year;
- for tidal conditions the mean high water spring level.

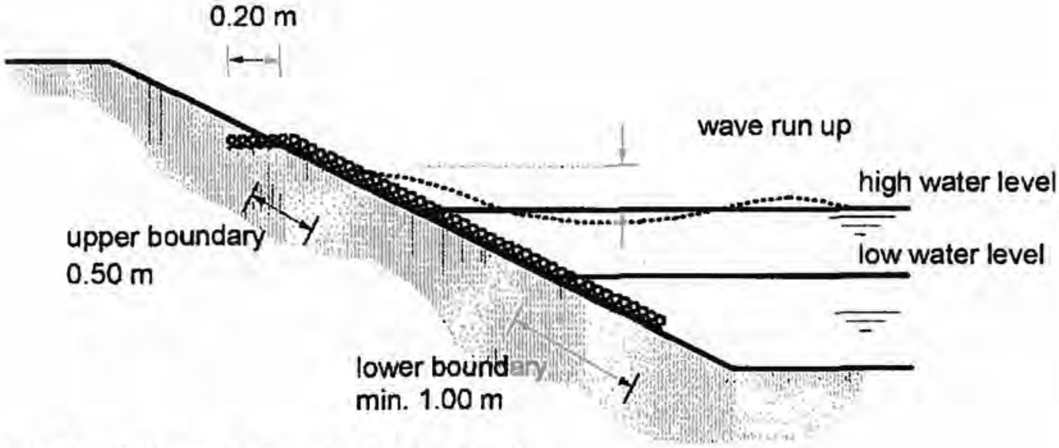


Figure 5.2 Enkamat as protection on banks.

The low water level is:
- for varying levels (non tidal), the normal low water level;
- for tidal conditions, the mean low water spring level.

The upper boundary of the mat is 0.5 m measured along the slope above the high reference level to which the wave run-up is added, when applicable (Figure 5.2).

The wave run-up can be established using Table 5.1.

Table 5.1: Wave run-up (m) depending on the significant wave height (H_s) and the slope angle (measured vertically above the high water level in m).

H_s (m)	Slope		
	26° (1:2)	18° (1:3)	14° (1:4)
0.1	0.40	0.25	0.20
0.2	0.80	0.55	0.40
0.3	1.20	0.80	0.60

The lower boundary of the mat is to be established as (Figure 5.2):
- when the mat is permanently loaded by a shear strength resulting from the water flow, the entire slope or bottom is to be protected;
- when the mat is attacked by wind waves the lower edge is to be calculated as 1.5 to 2 times H_s, measured vertically below the lowest reference water level, with a minimum of 1 m measured along the slope and no navigation activities.

5.2.3 Step 3: choose the correct type

Figure 5.3 gives the boundary conditions for the use of the various types of Enkamat in relation to the leading condition for the unvegetated situation. Figure 5.4 gives the situation for fully vegetated condition. With the help of these graphs the type of Enkamat can be determined which is required to withstand the maximum water velocity and the duration of it. Both cases, no or limited vegetation and fully developed vegetation, must be checked. It is advised to apply a loading factor of 1.2 ... 1.5 to the design times or to the velocities.

The unvegetated Pre-filled Enkamat can withstand continuous wave attack with a maximum height of 0.2 to 0.3 m. Incidental higher waves are allowed. The filter function should be checked. The Open Enkamat, when properly vegetated, can withstand a wave attack of 0.3 m for a period of several days. Waves of 0.50 m can be withstood for a period of 6 hours. Incidental wave attack up to 0.7 m will give no severe erosion.

Situations in which high turbulence occurs, such as around bridge piers, narrowing of the watercourse, irregular bottom, should be dealt with separately.

When placing the mat it is essential to achieve a close contact with the subsoil. This is achieved by ballasting and/or pinning according to the following specifications:

- normal conditions: 1 pin per 3-4 m^2
- severe conditions (high turbulence, etc): 1 pin per m^2
- overlaps: 1 pin/m

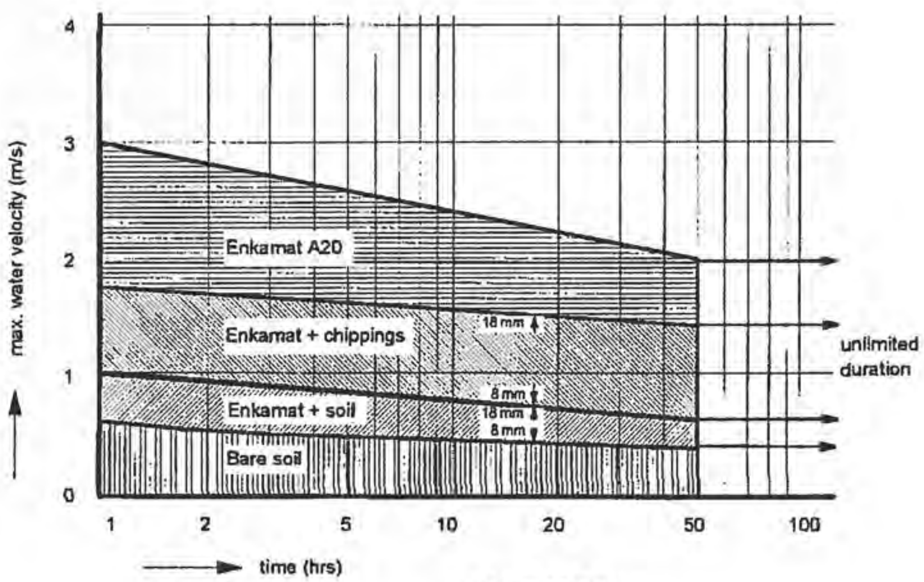


Figure 5.3 Enkamat type related to acting flow and no vegetation.

6.2.2 Waves

Wave attack

Waves are generated by tides, wind or ships. The wave conditions for wind-induced waves can be established using hindcasting methods. In Figure 6.10 the approximate conditions for a wave height H_s = 0.3 m are given. H_s is the significant wave height.

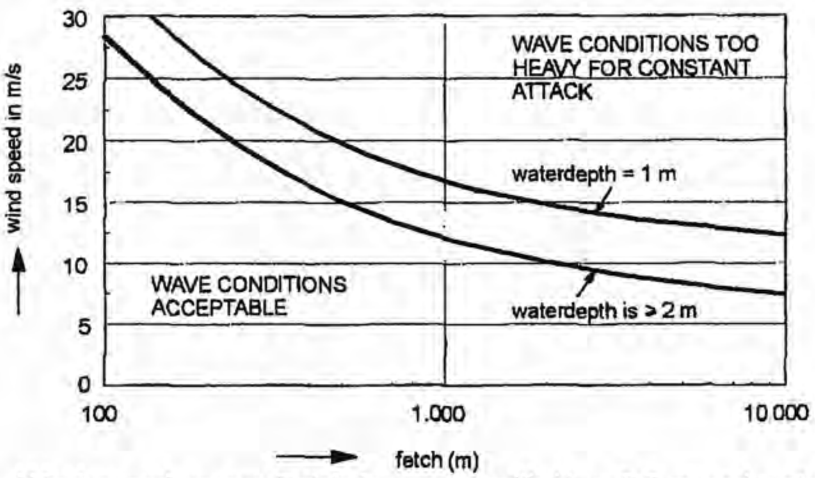


Figure 6.10 Wind speed versus Fetch for waves with H_s = 0.3 m and water depths of 1 m and ≥ 2 m.

The resistance against waves depends on the slope angle, type of soil and the duration of wave attack. Enkamat can provide extra protection to vegetated slopes against wave attack.
From experience it can be derived that the Pre-filled Enkamat (unvegetated) can withstand regular wave attack with a height of H_s = 0.2 to 0.3 m.
A vegetated grass slope can withstand wave attack as indicated below (Waterloopkundig Laboratorium, 1996).

1. Waves less than 0.4 m.
   - a good turf is not seriously damaged within a period of 1 to 2 days. (The turf itself remains intact).
   - a turf in a bad condition is damaged quickly and holes up to 0.2 m - 0.4 m depth develop within 24 hrs.
   - turf of acceptable quality as a sandy subsoil may be affected severely within 24 hrs. Holes with a depth of 0.3 m may develop.

2. Waves between 0.4 m and 1.0 m.
   - an acceptable or good turf is affected only slightly within a period of 1 day or 2 days. The vegetation itself is damaged within 24 hrs.
   - turf in a bad condition is affected severely. Within 36 hrs. holes with a depth of several decimeters may occur.

3. Waves between 1.0 m and 1.4 m.
   - an acceptable or good turf may yield within 15-20 hrs. under the condition that the subsoil is sufficiently resistant against erosion and no large damages are present.
   - when large damages are present a turf of good or acceptable quality will yield within several hours.
   - when the quality of the turf is bad deep scrusing takes place within several hours.

The rate of erosion is mainly determined by the quality of the turf and less by that of the subsoil.

No information is available on the resistance of grassed slopes in combination with Open Enkamat. Therefore it is assumed that these structures provide similar protection to plain grass. However, the duration before erosion will occur, can be prolonged by several days. Also the quality of the turf will be better.

At Loch Lomond (Scotland) at several locations grass-reinforced structures, including Enkamat, have been tested. In the winter these locations were attacked by storms causing the embankment to be flooded and loaded by waves (Alexander, 1982/1983). The water level at the toe of the embankment was exceeded approximately 5 % per annum, the predicted maximum wave height was 1.0 m.
The slope of the embankment was between 1 : 2 and 1 : 2.5. The subsoil consisted of gravel and sand.

The following types were placed in Spring 1982:
- Pre-filled Enkamat;
- Pre-filled Enkamat with a geotextile attached;
- Flat-back Enkamat (thick 18 mm).

The Flat-back Enkamat was filled with soil and seeded in May. No wash-off was found.

In spring 1983 two more Enkamat test slopes were constructed:
- one with Flat-back Enkamat 18 mm, similar to the previous construction;
- one with Flat-back Enkamat 9 mm thick.

These mats were also filled with soil and seeded. The former sites were reseeded.

In Table 6.4 a summary is given of the findings.
The general conclusion was that the Enkamats performed satisfactorily.

COLBOND

Enkamat®

Permanent erosion prevention system

PRODUCT DATA

			7010	7018	7020	7220
Product details						
Mass per unit area	(EN ISO 9864)	g/m^2	259	287	395	399
Nominal thickness		mm	10	18	20	18
Tensile strength (md/cmd) [1]	(EN ISO 10319)	kN/m	2.0/1.4	2.0/1.2	2.3/1.5	2.0/2.2
Polymer 3-dimensioinal core			PA6			
Color			black			
Polymer density		kg/m^3	1140			
Temperature resistance		°C	-40 to +80			
Inflammability	(DIN 4102)		B2			
Structure type			open	open	open	Open, one side flat back
3 dimensional structure providing free volume		%	> 95			
Soil retention factor		m/m^2	1810	1290	1420	2980
Dimensions						
Length [2] x width of geocomposite		m	1.0 x 150	1.0 x 120	1.0 x 100	1.0 x 60
Length / diameter of roll		m	1.03 / 1.15	1.03 / 1.25	1.03 / 1.2	1.03 / 1.2
Gross weight [3]		kg	39.5	35.5	40.5	24.5

Material properties

Ageing:	Good resistance to weathering and UV radiation.
Chemical resistance:	Resistant to all chemicals in concentrations which are normally contained in the earth and surface water.
Inflammability:	Low flammability and low smoke formation; approved for use in tunnels
Toxicity:	None; approved for use in potable water reservoirs; Enkamat is inert and not harmful to the environment.
Rodent damage:	No nutritive value; the tangled structure of the mat is unpleasant to burrowing animals and rodents.

[1] md = machine direction / cmd = cross machine direction.
[2] Standard width is 1.0 m; widths of 1.95 m and 3.85 m are available on request;
[3] Gross weight = matting + packaging, individual values may vary.

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EMT-001-GB-A-05/2009

COLBOND

Enkamat® A20

Permanent erosion prevention system

PRODUCT DATA

Application			
Erosion control			Immediate erosion protection of banks from high velocities and small wave attack
Product details			
Polymer 3-dimensional core			PA
Pre-fill			Bitumen-bound mineral filter of 2-5 mm chippings
Color			Black
Mass per unit area	(EN ISO 9864)	kg/m^2	22
Nominal thickness	(EN ISO 9863-1)	mm	22
Tensile strength core (md)	(EN ISO 10319)	kN/m	2.4
Tensile strength core (cmd)	(EN ISO 10319)	kN/m	2.5
Dimensions			
Length x width of geocomposite		m^2	20 x 4.80
Effective width [1]		m	4.50
Length / diameter of roll		m	5.6 / 0.8
Gross weight [2]		kg	2200
Prescription of installation			
Preparations			Smooth profile
Fixation			1 pen per 1.5 m (top/bottom),1 pen per m (overlap)
Lateral overlap		m	0.30
Anchorage		m	Dig in at the toe and the crest of the slope by means of a trench; 0.30
Filling on site			Not applicable

[1] Rolls shall be unrolled perpendicular to the bank.
[2] Gross weight = matting + steel core, individual values may vary

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EMT-003-GB-A-06/2009

Specifications

Concrete cube strength: 50 N/mm^2 at 28 days
Sulphate resistant to Class DS-2.
Cables: galvanised or polyester.
Mat sizes 6 x 2.4m, 6 x 1.2m, other lengths available.
(see also detailed specification sheet)

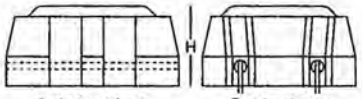
Cellular block mats

Armorflex 140
L x B x H: 340 x 400 x 85mm
Block weight: 17.5kg each
Unit weight: 140kg/m^2
Open area (max.): 35%

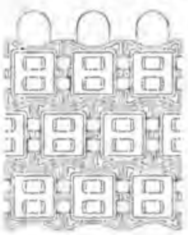
Armorflex 140S
L x B x H: 340 x 400 x 90mm
Block weight: 19kg each
Unit weight: 150kg/m^2
Open area (max.): 35%

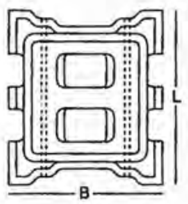
Armorflex 180
L x B x H: 340 x 300 x 120mm
Block weight: 17.3kg each
Unit weight: 180kg/m^2
Open area (max.): 35%

Armorflex 220
L x B x H: 340 x 300 x 150mm
Block weight: 21.9kg each
Unit weight: 225kg/m^2
Open area (max.): 35%



Cellular block   Cable ducts





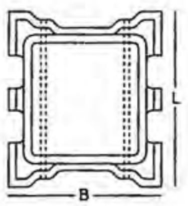
Solid block mats

Armorflex 165
L x B x H: 340 x 400 x 85mm
Block weight: 20kg each
Unit weight: 160kg/m^2
Open area (min.): 6%

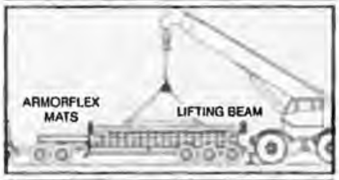
Armorflex 215
L x B x H: 340 x 300 x 120mm
Block weight: 21kg each
Unit weight: 220kg/m^2
Open area (min.): 6%

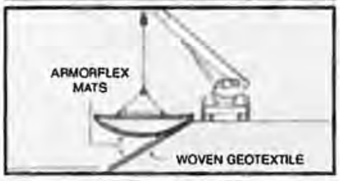
Armorflex 305
L x B x H: 340 x 300 x 150mm
Block weight: 26.7kg each
Unit weight: 285kg/m^2
Open area (min.): 6%

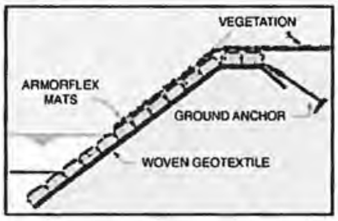
Armorflex 435
L x B x H: 340 x 300 x 225mm
Block weight: 41kg each
Unit weight: 435kg/m^2
Open area (min.): 6%



Also refer to:- Revetment Systems against wave attack – a design manual. Hydraulics Research, Wallingford.







Wave attack data

The following table is based on Delft Hydraulics Laboratory Report M 1910 and is intended to offer a guide to designers. Designs for specific projects can be prepared using the report itself.
The table assumes the following data:

a) Revetment slope 1 in 3.
b) No reinforcement effect from cables (assumed corroded).
c) Revetment blinded with sand/gravel mixture after installation.
d) Irregular wave pattern Tp = 3.75 secs (most damaging period found in tests).

Armorflex type	Significant Wave Height Hs	Maximum Wave Height H max
140 Cellular	1.0m	1.2m
180 Cellular	1.3m	1.5m
220 Cellular	1.6m	1.8m

NB. Run-up Cellular blocks mats can reduce wave run-up by 30% as compared with smooth revetment. This may enable a reduction in the height required for the protected area.

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06/06