

The Influence of Fish-Tail Groynes (or Breakwaters) on the Characteristics of the Adjacent Beach at Llandudno, North Wales

Christopher F.J. Bull†, Angela M. Davis† and Rodney Jones‡

†School of Ocean Sciences
University of Wales Bangor
Menai Bridge
Gwynedd LL59 5EY, U.K.

‡Countryside Council for
Wales
Plas Penrhos
Ffordd Penrhos
Bangor
Gwynedd LL57 2LQ, U.K.

ABSTRACT

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Three Fish-tail groynes or breakwaters of rock rubble construction were installed during 1991 on the West Shore at Llandudno, North Wales as part of a coastal protection programme. This study considered the effect of the northern (Gogarth) breakwater on the adjacent beach. It was found that while the breakwater appears to be effective in protecting the sea wall forming the coastline behind, it has not been successful in increasing beach levels, as proposed, and has also resulted in the accumulation of a large amount of fine material in its lee which reduces its appeal to recreational users. From this study it is believed that beach levels at the site are controlled by the tidal flows across the beach, particularly by the scouring effect within the adjacent North Channel, which prevents the normal beach profile being attained. The build up of fine material is due to the quiescent conditions behind the breakwater, however, it appears that the conditions created are far calmer than anticipated at the design stage.

ADDITIONAL INDEX WORDS: *Beach, macro-tidal, groynes, breakwaters, rubble around, above seasons.*



INTRODUCTION

The installation of 'fish-tail' groynes or breakwaters as a method of coastal protection appears to be gaining favour, with a number of these structures having been installed at various sites around the coast of Wales. The dual description of groyne/breakwater describes the dual function which the structures may perform, in that they may act as a groyne to prevent littoral drift and also as a wave screen and thus performing the function of a breakwater. We do not wish to debate what the structures should be called, although within this report we have called them breakwaters in line with the designers, British Maritime Technology and later Shoreline Management Partnership. The term groyne could as easily have been used and the dual function/purpose of the structures should be borne in mind. There is however, some concern about the environmental impact which these breakwaters have on the adjacent beach and whether they actually perform fully, the task for which they were designed. This study considers the effect that these structures have had at one such site, the West Shore at Llandudno, North Wales, (Figure 1).

Llandudno is situated on the North Wales coast and has been a seaside resort since Victorian times. The town sits on a low lying isthmus only a few metres above mean sea level and is protected by a sea wall. Like many seaside resorts the

beach is obviously one of the assets which draws holiday-makers to the area and a clean beach is therefore important, with resorts trying hard to obtain awards for the cleanliness of their beaches.

During a structural investigation of the sea wall at the West Shore, it was found that the integrity of the wall was degrading, to the point that if storm surge conditions from the northwest coincided with a spring tide, there would be a risk of the sea wall failing and the town being inundated. To replace the sea wall would have been prohibitively expensive for the local authority and therefore alternative methods of protecting the wall were considered. Aberconwy Borough Council commissioned a series of studies on coastal protection schemes for the whole of the Llandudno area by British Maritime Technology and later by Shoreline Management Partnership. The recommendation for the West Shore was the installation of three fish-tail groynes or breakwaters of rock rubble/boulder construction. The purpose of the breakwaters would be fourfold: (1) to act as a wave screen; (2) to act as a barrier to littoral drift (and thus promote development of a beach); (3) to modify the angle of wave approach to create an environment capable of holding a beach; and (4) to move the tidal currents offshore preventing erosion of unprotected coast. In addition, it was stated that the design of the breakwaters would compliment the area as a recreational amenity and that this popular tourist beach would gain in popularity pursuant to the scheme. Figure 2 shows the layout of the study site with the northern two breakwaters.

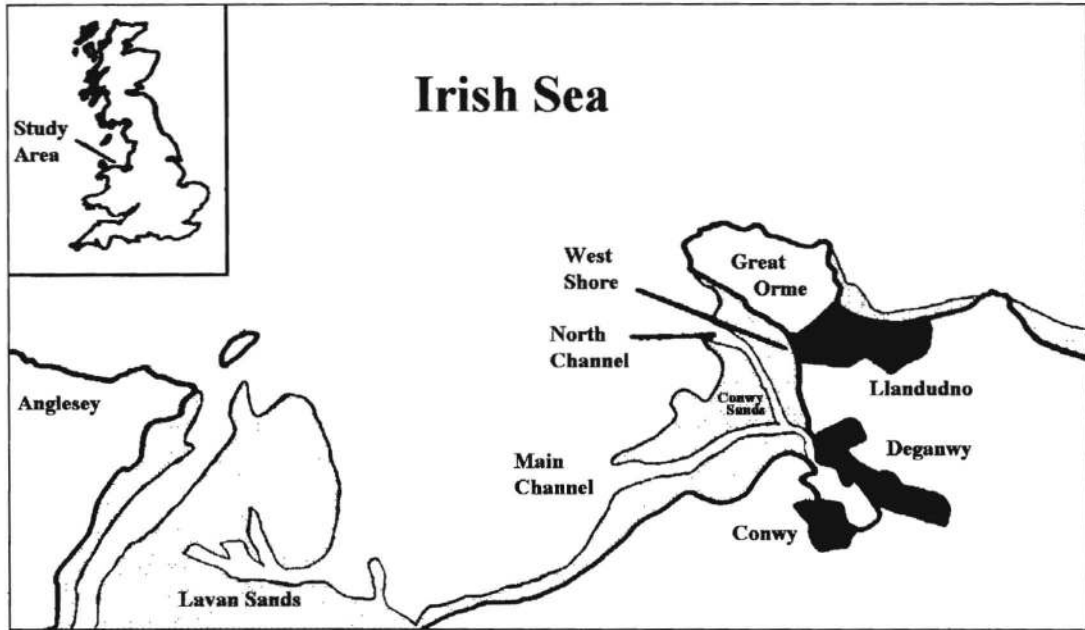


Figure 1. Location map of the study site, showing the coast (point of MHWST) in bold line and the point of LWLT in feint line.

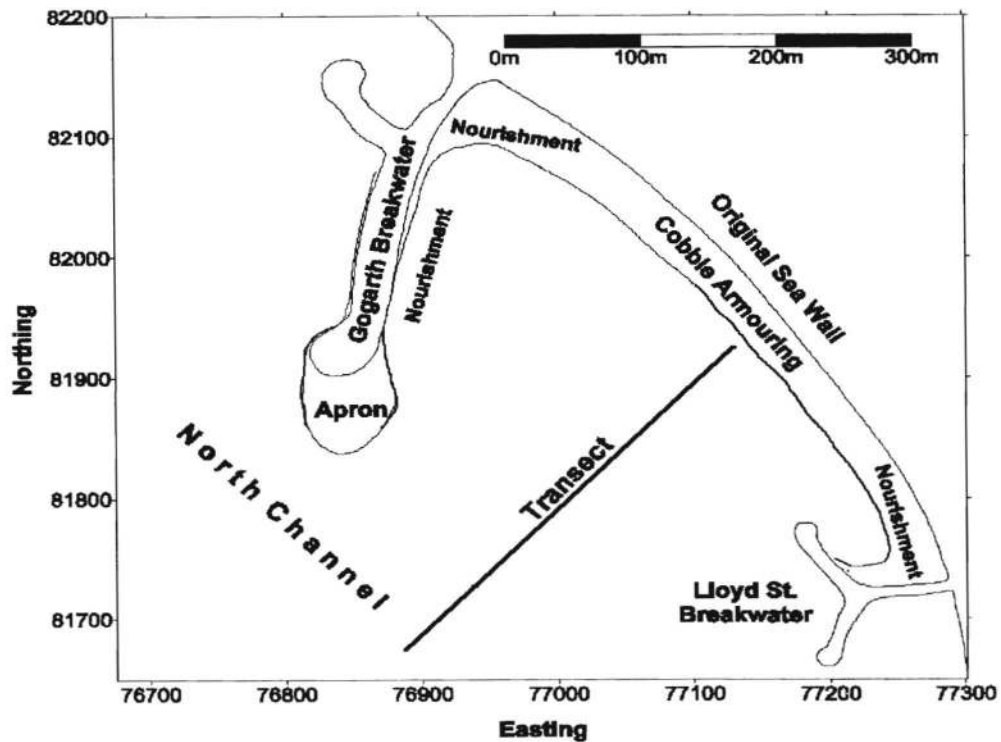


Figure 2. Plan of the study area.

The breakwaters which were installed to the consultant's (Shoreline Management Partnership) design at Llandudno's West Shore, can in broad terms be considered successful in that they act as a wave screen and thus reduce the amount of wave energy impinging on the sea wall. In addition, they also appear to be effective in moving the tidal currents further offshore, and to a lesser degree in modifying the angle of wave approach. However, even on taking a cursory look there appears to be some detrimental effect on the adjacent beach which now accumulates a large amount of fine material in an area behind the northern (Gogarth) breakwater. This has a high organic content, which along with the variety of sanitary products found within it, probably indicates that sewage from the offshore outfall or from the discharge into the Conwy river/estuary, is finding its way onto the beach. Further, there is little evidence for beach development as predicted in the consultant's report (BMT, 1987) (excluding the artificial nourishment), and in addition the proposed higher beach levels which were to provide significant dry areas over calm high waters appear to be largely absent. In addition, the structures are large, upto 300 m in length and over 3 m high, and most local residents do not feel that they compliment the area but are more an eyesore. With regard to the beach gaining in popularity, this does not seem to be the case as most holidaymakers complained about the accumulation of fine sediment and the resulting smell. The aim of the study reported here was to quantify the effect of the Gogarth breakwater on the adjacent beach in terms of temporal and spatial variability in sediment accumulation with respect to grain size distribution and beach elevation, and relating this to the modified hydrodynamic regime.

Environmental Setting

To the north of Llandudno is the large Carboniferous outcrop and headland of the Great Orme, while to the south there are lower lying areas of Silurian Rocks, both of which may be considered unerodable in terms of the coastal protection programme. The low lying isthmus on which Llandudno itself is sited, is comprised of blown sand and alluvium and thus the sea wall is important for protection of this area.

The West Shore beach experiences macro-tidal conditions with a mean spring tidal range of 6.9 m and a mean neap tidal range of 3.5 m (HYDROGRAPHIC OFFICE, Admiralty Tide Tables, 1993). Tidal flows across the study area prior to installation of the breakwaters were parallel to the coastline of the West Shore, with typical velocities of 0.1 msec^{-1} for the flood and 0.2 msec^{-1} for the ebb (BRITISH MARITIME TECHNOLOGY, 1987). The configuration of the coastline means that West Shore is only exposed to significant wave energy for waves approaching from the WSW through to N. Waves from the WSW are however fetch limited by the position of Anglesey as well as the shoaling effects of having to travel across the Lavan and Conwy Sands. BRITISH MARITIME TECHNOLOGY (1987) in their study for Aberconwy Borough Council, calculated the maximum 1 in 50 year significant wave height (H_s) and peak wave period (T_p), for a position offshore, for each cardinal sector. The largest significant wave heights calculated turned out to be from the north with an offshore

height of 7.7 m and a period of 10 seconds. The most frequently occurring waves had a height of 0.9–1.5 m and a period of 6 seconds.

TOPOGRAPHIC SURVEY

Two detailed topographic surveys of the west shore beach comprising a total of 176 levelling points/stations were carried out as part of this study. In addition, biannual survey data going back to 1980 were made available by Aberconwy Borough Council thereby allowing us to compare pre and post-installation data and to establish if the installation of the Gogarth and Lloyd St. breakwaters had resulted in a morphological change of the intervening beach, as outlined in the design proposal. The surveys conducted as part of the study were carried out on the 19 August 1993 and the 6 December 1993.

Interpretation

Contour maps of the beach were produced from the survey data to examine the spatial variation in elevation following the installation of the breakwaters, while individual transects were compared to examine the temporal variation in elevation. The survey carried out on the 19 August 1993 showed that the area to the north of the Gogarth breakwater had not changed significantly in elevation in comparison to the pre-installation elevations as was expected, because the breakwaters were not designed to influence this part of the beach. The changes that did take place were slight increases very close to the structure. To the south of the Gogarth breakwater there appears to have been very little change in elevation over most of the beach either between the pre-installation surveys or those carried out in this study. Many areas remained within the same 20 cm contour as on previous surveys, while those that changed only moved one contour interval indicating a maximum change of 40 cm. However, in interpreting the data, the effects of the beach nourishment programme had to be taken into account, which particularly affected the area adjacent to the south side of the Gogarth breakwater and which also showed the greatest changes. As such, the areas of greatest accumulation are not due to the influence of the breakwaters but due to the beach nourishment programme. In other areas it appears the changes in elevation are due to a morphological change in beach profile rather than a nett accumulation or loss of sediment.

This can be clearly seen in Figure 3 which shows a beach profile transect from close to the central section of the beach with data plotted for 1980, 1985 and the present study. This profile was also levelled again in May 1996 and showed no significant changes from the levels recorded during the main part of the study. The data for 1980 show a concave profile with the lowest overall levels. The data for 1985 have similar profiles although the levels are up to ≈ 30 cm higher at their maximum. Both of the profiles levelled during this study show that the profile appears to have changed with levels decreasing proceeding seawards along the transect until approximately the 50 m point where the profiles rise to a maximum at the 75 m point. From here seaward, levels decrease more quickly than in earlier profiles with both producing low-

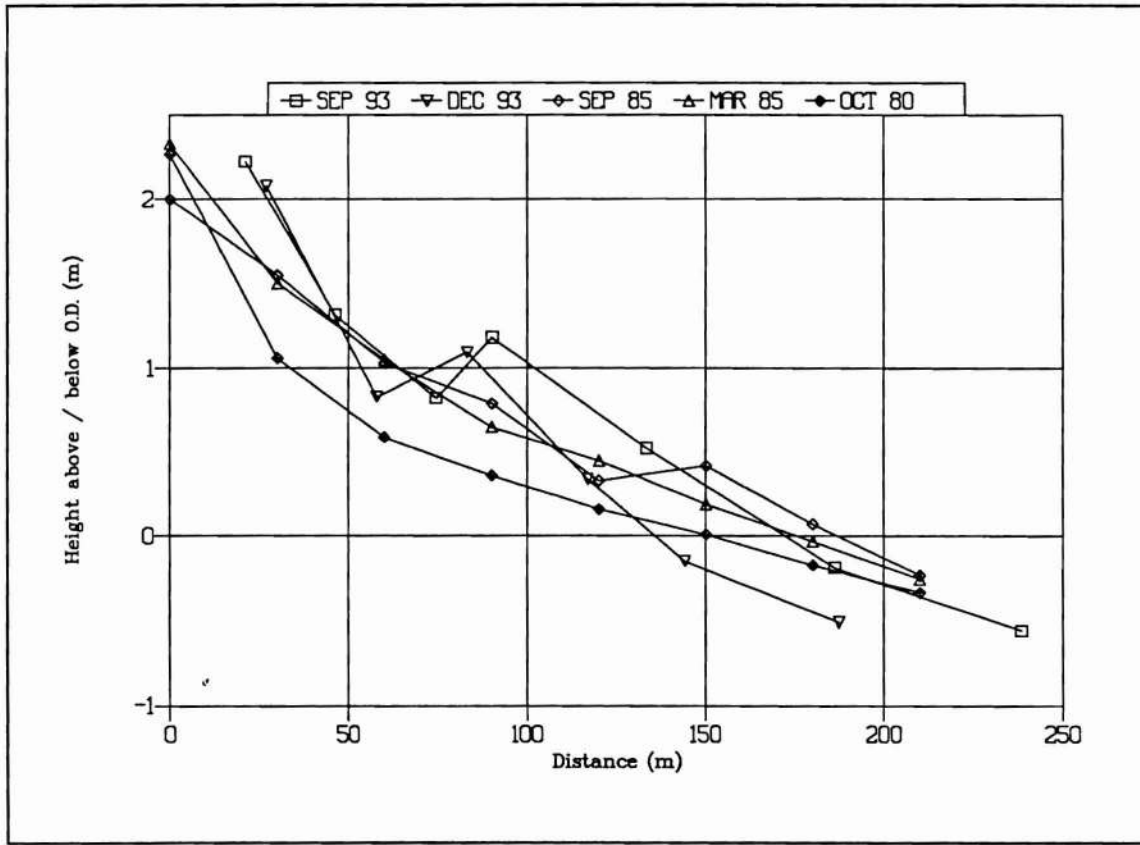


Figure 3. Beach profiles along the transect opposite Gloddaeth Avenue.

er elevations on the distal end of the transect than recorded in any of the previous surveys.

From the survey data there appears to have been no significant change in beach elevation that can be attributed to natural accretion as a result of the modified regime following the installation of the breakwaters. The increase in beach levels recorded that are significant result directly from the beach nourishment programme.

SEDIMENT SAMPLING AND ANALYSIS

Introduction

Two sets of sediment samples were collected at different times. The first set comprising 41 samples was collected on the 20 August 1993 and would provide a baseline data set for which subsequent sample sets could be compared to establish temporal variability, as well as providing information on the longshore variation in the sediments for those areas not apparently influenced directly by the installation of the breakwaters. From this it was hoped that it might be possible to infer the approximate pre-breakwater sediment grain size distribution and variability, and relate this to the present changes in those areas obviously influenced by the breakwaters.

A further set of 26 samples was collected on the 30 Novem-

ber 1993 in the area between the two breakwaters. This set was collected to allow comparison with the baseline data set in order to quantitatively assess the temporal variability. In addition, it was hoped that these samples would allow an assessment as to the extent of the area being influenced by fine sediment accumulation.

Sampling Method

Consideration to the number of samples and the spacing which would be required to reflect changes in the grain size distribution across the survey area, resulted in the choice of a 50 m grid spacing. It was decided to use a sampling grid instead of random sampling procedure as this made it possible to return to the same points and enabled a direct comparison of sediment changes. Samples were collected using a sample ring which was pushed into the sediment until the top was level with the sediment surface and the sediment then removed to a sample bag.

Sediment Sample Analysis

In the laboratory, each sample was washed through a 63 μm sieve using distilled water. The $>63 \mu\text{m}$ fraction was then analysed in accordance with British Standard 1377. For the finer than 63 μm fraction the sample was first washed

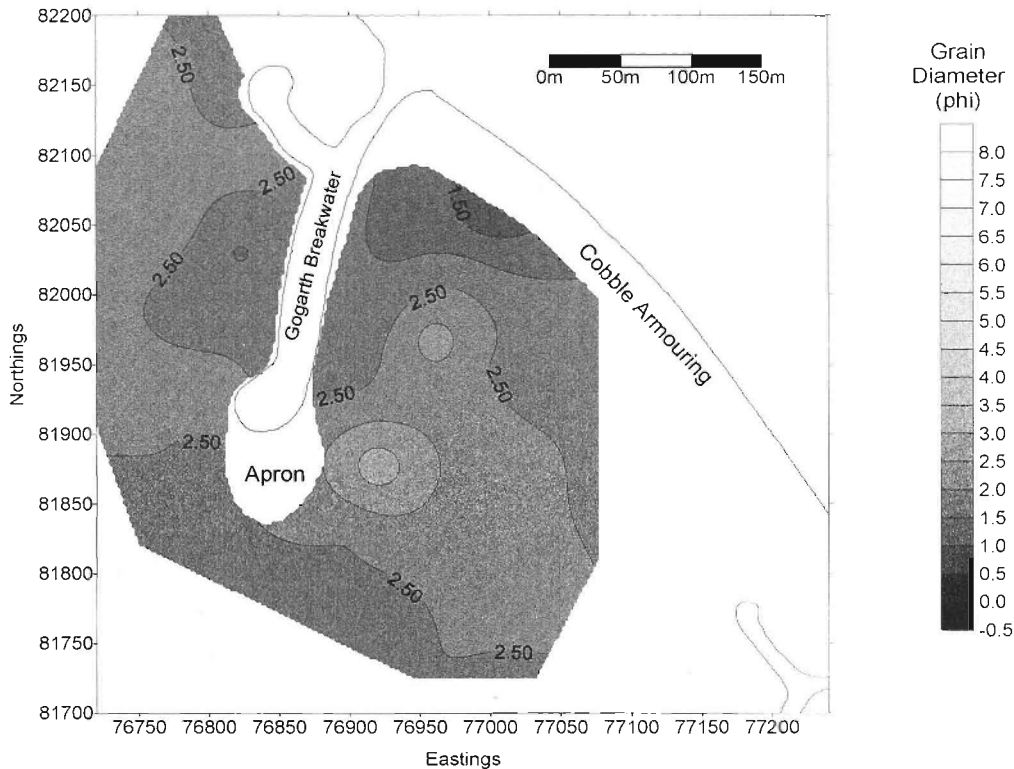


Figure 4. Sediment modal size on 20 August 1993.

to remove the salt from it before being analysed in a Micromeritics Sedigraph to obtain the grain size data. From the sieve data or combined sieve and sedigraph data, the grain size parameters mode, mean, sorting, skewness and kurtosis were calculated in accordance with FOLK and WARD (1957).

Organic Carbon Determination

Samples which had the highest proportion of fine material were analysed for organic carbon to assess if the levels of organic material in the sediment were excessively high. A 5 ml sub-sample was taken from the fines fraction and placed in a weighed crucible. This was dried in an oven at 105 °C overnight and then allowed to cool in a desiccator before reweighing to determine the total weight of the sample. The sample was then placed in a muffle furnace at 450 °C for six hours to burn off the organic carbon. The samples were then again placed in a desiccator to cool before reweighing.

Interpretation

For each grain size parameter contour plots were produced to show the spatial variation. Separate plots were made for the samples collected at the beginning of the monitoring period and at the end. In addition, the change in each of the grain size parameters was also calculated and plotted using the same method.

Mean and Mode

The mean and modal grain size distribution at the start of the study period exhibited very similar characteristics to each other. Figure 4 shows the mean size distribution at the start of the study period (first sample set). The area to the north of the Gogarth breakwater showed a fairly uniform mean size distribution, as did the greater part of the area to the south. However, there was an indication of finer material accumulating in the lee of the breakwater and apron on its south side. The coarser material towards the proximal end of the breakwater and along the original sea wall running into the new armouring results from the beach nourishment programme.

At the end of the study period (second sample set, Figure 5), the southern half of the sampled area between the two breakwaters appeared to have remained unaltered, while the area immediately behind the breakwater apron had become much finer grained. In addition, some of the samples from just south of the breakwater were exhibiting bimodal or polymodal characteristics which indicated that there was a new, distinct, finer population being deposited rather than the original population shifting in its distribution.

Sorting

The natural beach area to the north of the Gogarth breakwater was very well sorted as would be expected for a beach

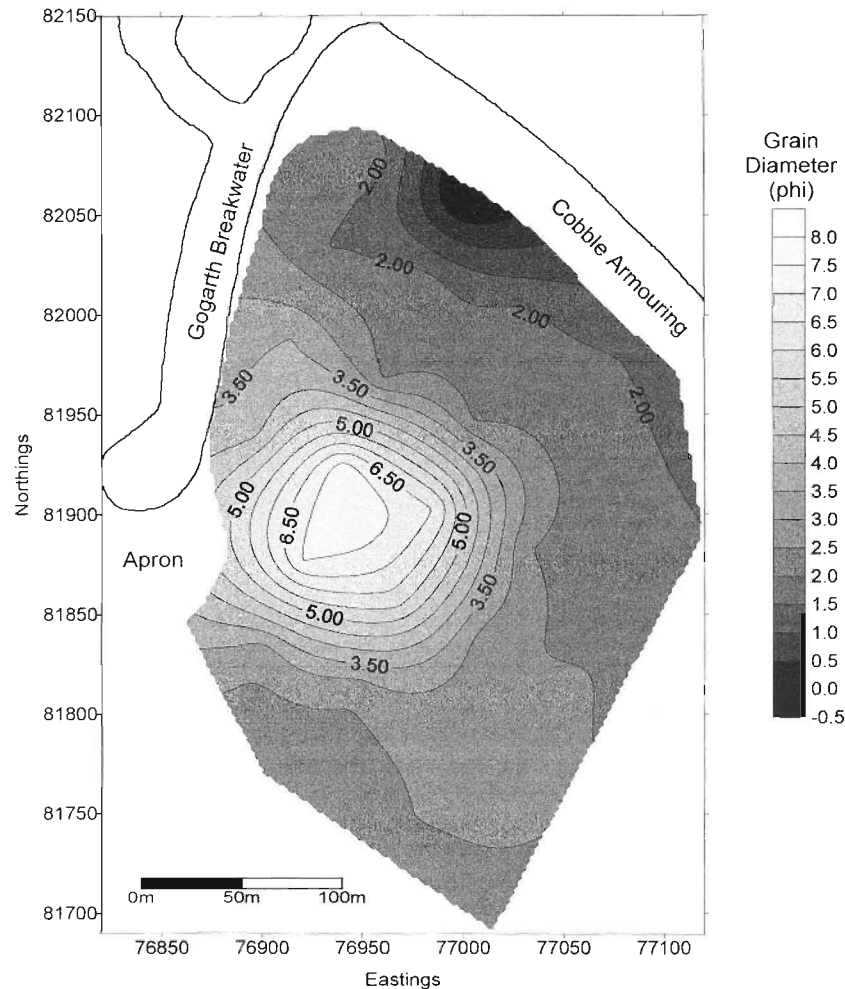


Figure 5. Sediment modal size on 30 November 1993.

exposed to wave and swash action, Figure 6. Similarly, the area to the south of the breakwater appeared very well sorted in the southern half of the section sampled (*i.e.* towards the Lloyd St. Breakwater). By contrast, samples from the northern half of this section up to the breakwater, ranged in sorting from poorly sorted through to moderately well sorted which probably reflected the thin layer of finer sediment which was covering this part of the area at the start of the study period. At the end of the study period (see Figure 7), the southern section was still well sorted and exhibited little or no change; the area in the lee of the apron had become very poorly sorted having a sorting of ≈ 2.5 as would be expected from the change in mean and mode grain size.

Skewness

Most of the beach to the north of the Gogarth breakwater exhibited a slight negative skewness with small patches of slightly positively skewed sediment. The area immediately to the south of the breakwater had a moderate, positive skewness, indicating a moderate fine tail at the beginning of the

study period. However, at the end of the study period this area had become very positively skewed indicating a long fine tail to the distribution. Analysis of the cumulative frequency curves for these samples, shows that this appears to be due to the addition of fine material rather than to a modification of the original sediment distribution, which could still be clearly seen in the curves. By contrast, the area towards the Lloyd St. breakwater and out of the influence of the Gogarth breakwater retained a similar distribution to that found at the beginning of the study, as did the area to the north of the Gogarth breakwater.

Percentage Mud

Although the standard grain size parameters give exact details of the sediment at any particular time and location, they do not necessarily give an easily interpretable, general picture, of the changes that were taking place. By using the Wentworth classification between mud (all material finer than $63 \mu\text{m}$) and sand (in this case all material coarser than $63 \mu\text{m}$) a better impression of the changes taking place can

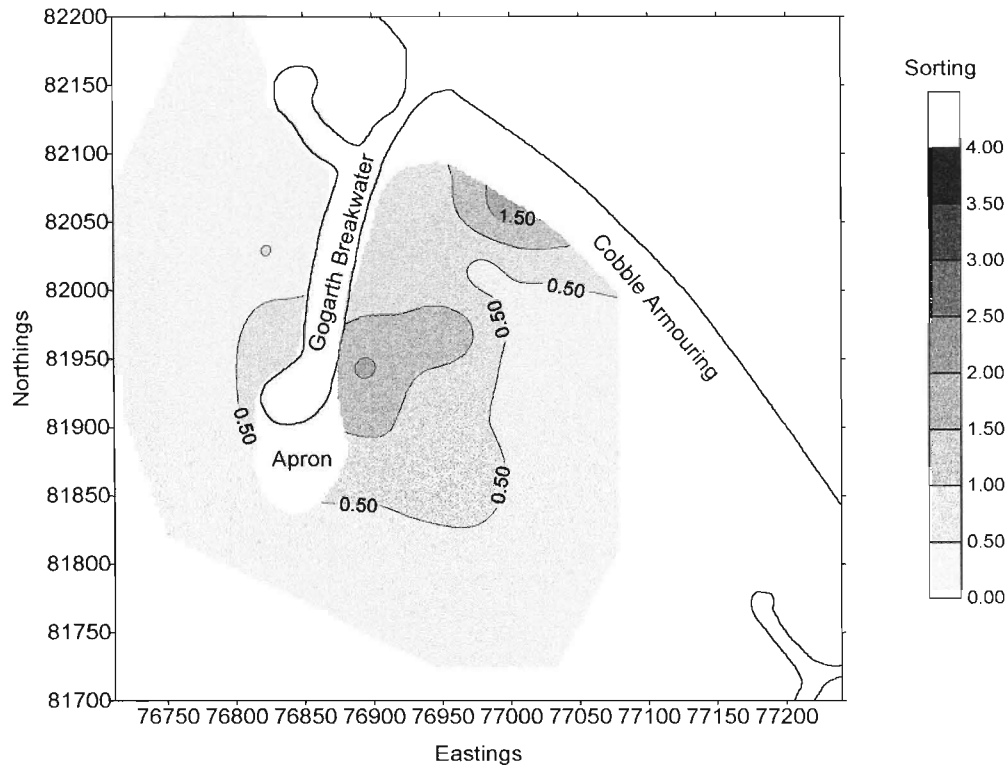


Figure 6. Sediment sorting on 20 August 1993.

be observed. Beach deposits are mainly sands and/or pebbles and sometimes boulders, more rarely mud (WHITTEN and BROOKS, 1972). Examination of the data for those areas outside the apparent influence of the breakwaters, such as the area north of the Gogarth breakwater and towards the very south of the study area, showed that the beach was comprised of less than 1% mud (see Figure 8). From this, it may be inferred that the whole beach should be comprised of sand with negligible amounts of mud present, with any change expected to occur gradually. Figure 8 shows that even on the first survey there was an isolated area of mud starting to accumulate behind the breakwater and the apron which had not been present on the initial visit to the site in preparation for the study. However, by the 30 November 1993 the area close to the breakwater and apron had become very muddy with some samples containing less than 15% sand (see Figure 9). In this area it may be considered that the beach had ceased to exist and that the area had become an inter-tidal mud-flat, while the areas just outside of the lee of the breakwater generally still had less than 1% mud.

Organic Carbon

According to ELTRINGHAM (1971) organic carbon values for a beach sediment should normally be negligible and generally well below 1% (BLACK, 1993, personal communication). The values obtained for the organic carbon from those samples occurring primarily in the area of the greatest amount of fine

material ranged from 4.5% to 9.8% organic carbon by weight, which is extremely high for what was, and is supposed to be, a sandy beach. This would appear to indicate that the breakwater is allowing the trapping and deposition of organic matter, some of which may originate from the offshore sewage outfall or from sewage discharged into the Conwy river/estuary, the effect of which is to produce a pungent smell as well as creating a health risk to children (or adults) playing around this area of the beach.

DISCUSSION

Beach Levels

One of the major aims of the installation of the breakwaters was to modify the angle of wave approach thus creating an environment capable of holding a stable beach. It was also implied by the engineers that beach development would occur following installation of the breakwaters, initially from artificial nourishment but in the longer term by natural processes, and was further implied that the extent of this beach development would lead to "locally higher beach levels which would provide significant dry areas over calm high waters" (BRITISH MARITIME TECHNOLOGY, 1987).

There appears, however, to be little change of beach elevation between the existing survey data (provided by Aberconwy B.C.) and the surveys carried out in August 1993 and December 1993. Those changes that have taken place such as the increase in elevation at the 50–75 m distance along

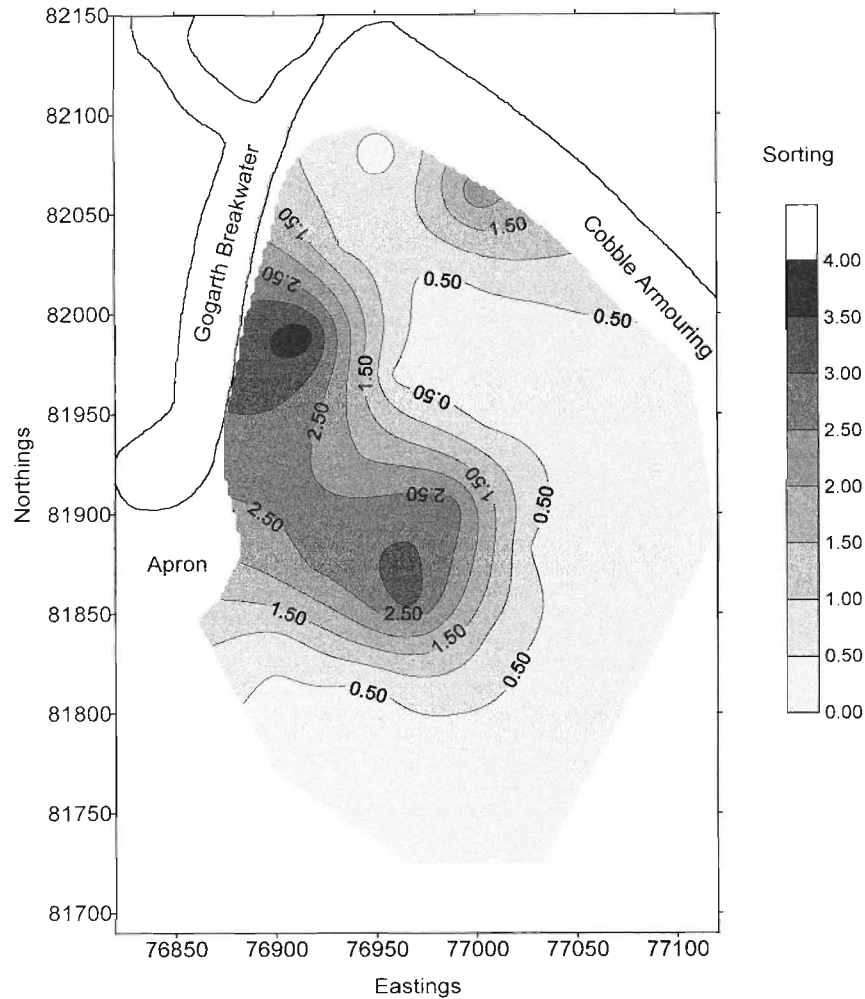


Figure 7. Sediment sorting on 30 November 1993.

the transect are probably a response to the armouring. However, the lower levels towards the seaward end of the transect would appear to result from the removal of sediment by the flows in the North Channel.

More significantly though, comparing both surveys with data supplied by Aberconwy B.C. for August 1990, it can be seen that overall there has been no significant change in beach elevation between the Gogarth and Lloyd St. breakwaters following their installation, with the exception of that change in elevation attributed to anthropogenic beach nourishment. This is further evidenced by a subsequent survey carried out in May 1996, which showed no significant changes from the earlier surveys. To the north of the Gogarth breakwater there was however some evidence of increased beach elevation close to the structure itself. The greatest recorded difference between the two surveys was at the shoreward end of the breakwater, where, just north of the knuckle, there were height differences of approximately 0.5 m (increase). This change in elevation diminished towards the distal end of the breakwater proper, where there appears to be

no noticeable difference between the two surveys. It is thought that the accumulation of sediment to the north of the breakwater was most probably merely due to the restriction on littoral drift imposed by the structure. It is likely that the extension of the original groyne field, as far offshore as the breakwater extends and with sufficient height, would probably have resulted in a similar effect.

The effective absence of any change in beach elevation following the installation of the breakwaters is attributed to the morphodynamics of macro-tidal beaches and the influence of the North Channel running across the beach. From a study of the literature, apart from WRIGHT *et al.* (1982) and JAGO and HARDISTY (1984), there appears to have been little published work carried out on macro-tidal beaches until relatively recently; the most significant recent works include SHORT (1991), MASSELINK and SHORT (1993) and HORN (1993). In trying to compare the West Shore beach at Llandudno with others *e.g.* Pendine Sands as studied by JAGO and HARDISTY (1984), there is one immediate problem to overcome, that of defining the distal end of the beach profile. From a field sur-

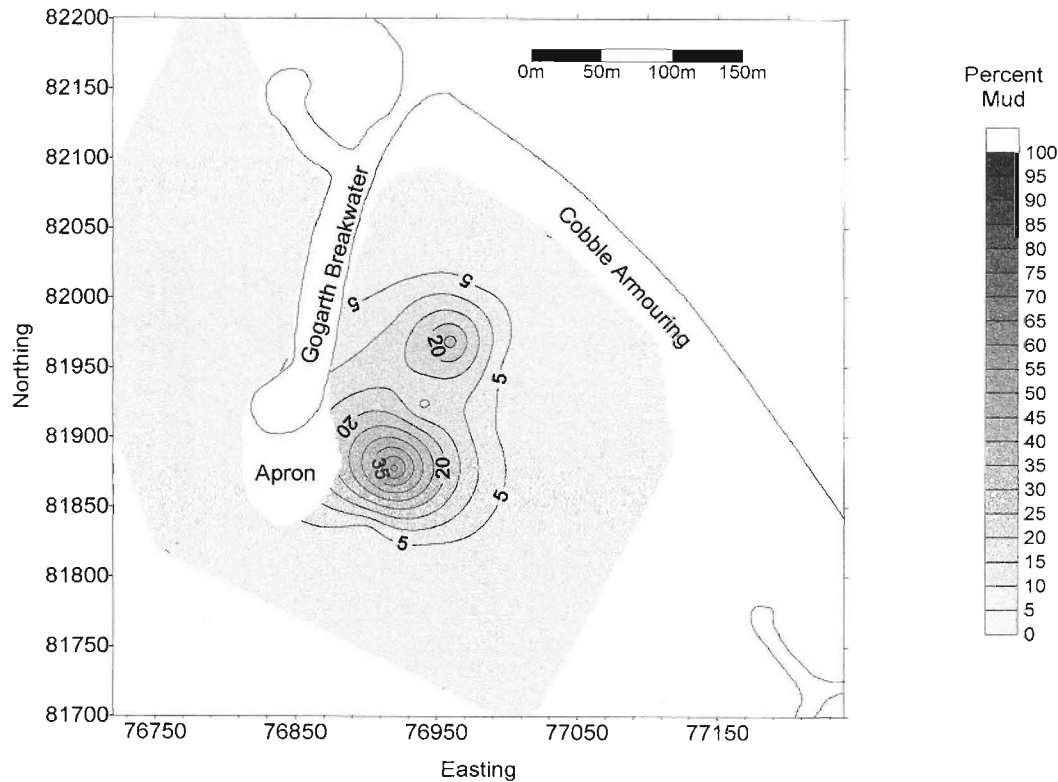


Figure 8. Percentage mud at 20 August 1993.

vey perspective the North Channel appears to present a natural barrier between the study area and the Conwy Sands on the opposite side which were considered to be an inter-tidal sand flat. Even at low water spring tide (LWST) the channel is over 0.5 m deep and obviously much deeper at low water neap tide (LWNT). However, with reference to laboratory data and the work of others, it becomes apparent that this is probably inappropriate and that the more significant point would be the point of low water lowest tide (LWLT). This effectively takes in not only the beach but the whole of the Conwy Sands. If this is done, then by plotting the tidal levels against distance along the transect a general profile of the beach which is comparable with other macro-tidal beach profiles *e.g.* Pendine Sands (JAGO and HARDISTY, 1984) may be produced, Figure 10.

However, in making any comparison it has to be taken into account that the sediment levels on the Conwy Sands side of the channel are above the level of LWNT. Therefore, it is possible to argue that the start of the mid-foreshore is at point D in Figure 10 and not on the shoreward side of the channel, point C. If that were the case and the channel was not present, then it is likely that there would be an increase in sediment accumulation over the area of the channel and the foreshore. However, the amount of accumulation would likely be limited by the morphodynamics of the system and it would probably not be possible to increase the relative levels much above what they are at present.

To test if this tentative assumption is correct, it is necessary to classify the West Shore beach with similar shores studied by other workers; once this is achieved similar models, and therefore processes may be applied to aid interpretation. As it was not possible to directly compare profiles as the levelling survey had only been carried out as far as the North Channel, it was decided to adopt the method of classification proposed by MASSELINK and SHORT (1993) which is based on Dimensionless Fall Velocity, $\Omega = H_b/w_s T$ (GOURLAY, 1968; DEAN, 1973), where H_b is the breaker height (m), w_s is the sediment fall velocity (m/sec) and T is the wave period (sec). A further parameter of significance to the definition is Relative Tidal Range, $RTR = \text{Tidal range}/H_b$. For the West Shore the following values were used to calculate Ω and RTR:

$$H_b = 0.9 \text{ m}, T = 6 \text{ sec}, w_s = 0.017 \text{ msec}^{-1}$$

with w_s interpolated from KOMAR and REIMERS (1978), based on a grain size of 2.5 phi (0.177 mm). This provides a $RTR = 7.7$ and $\Omega = 8.8$ which classifies the West Shore at Llandudno as an ultra-dissipative beach and places it in the same class as Pendine Sands; the extrapolated profile calculated earlier would also appear to fairly closely match that of a beach with a similar tidal range and sediment grain size.

For Pendine Sands, JAGO and HARDISTY (1984) found that over the lower foreshore the shoaling effect on the incoming waves formed spilling breakers which have relatively sym-

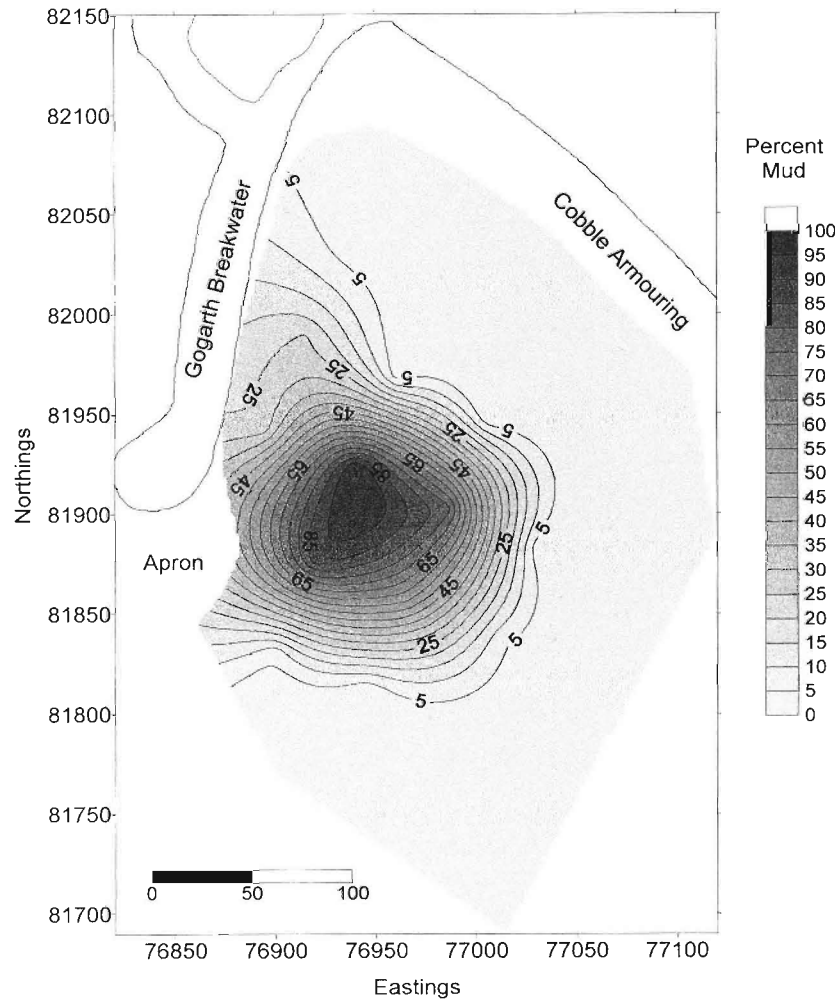


Figure 9. Percentage mud at 30 November 1993.

metrical onshore and offshore flow components. Therefore, to maintain a balance between the onshore and offshore sediment transport only a low beach gradient is required. As the tide rises and the surf zone moves up the beach, there is a gradual change from spilling to plunging breakers creating asymmetric flows over the upper foreshore which results in a steeper gradient. Furthermore, JAGO and HARDISTY (1984) found that the large tidal range creates a variable shoaling modification of unbroken nearshore waves such that the breaker height can change significantly during the tidal cycle, the result being that as the tide ebbs, the breaker height decreases, swash and surf zones widen, the surf zone becomes increasingly dissipative and swash zone velocities diminish.

The slope of the beach at any point therefore represents the equilibrium gradient that is required to maintain a balance between onshore and offshore sediment transport components (JAGO and HARDISTY, 1984). The beach is therefore self stabilising, so that if the beach gradient is too steep and the offshore flow velocity too high, the gradient and flow combine to increase offshore sediment transport which moves

material down the beach thus flattening the profile until the equilibrium gradient is reached. Conversely, if the beach slope is too low and the onshore velocities too high, this combines to increase onshore sediment transport which steepens the profile until equilibrium is established again. Jago (personal communication, 1994) does point out that the model adopted for Pendine was somewhat simplistic and conceptual, in that there are many other processes taking place such as infra-gravity waves and tidal currents sweeping along the beach, which all combine to produce the morphological effect observed.

From initial observation, the West Shore would appear to fit well with the model of Pendine Sands, in that at low tide there is extreme dissipativeness in the surf zone with multiple lines of breakers. Further the intertidal zone is very wide and breaker height increases as the tide moves across the beach. Thus it would appear that the morphodynamic processes taking place at the West Shore are similar to those governing Pendine, including the tidal currents sweeping across the beach, in which case the earlier assumption that

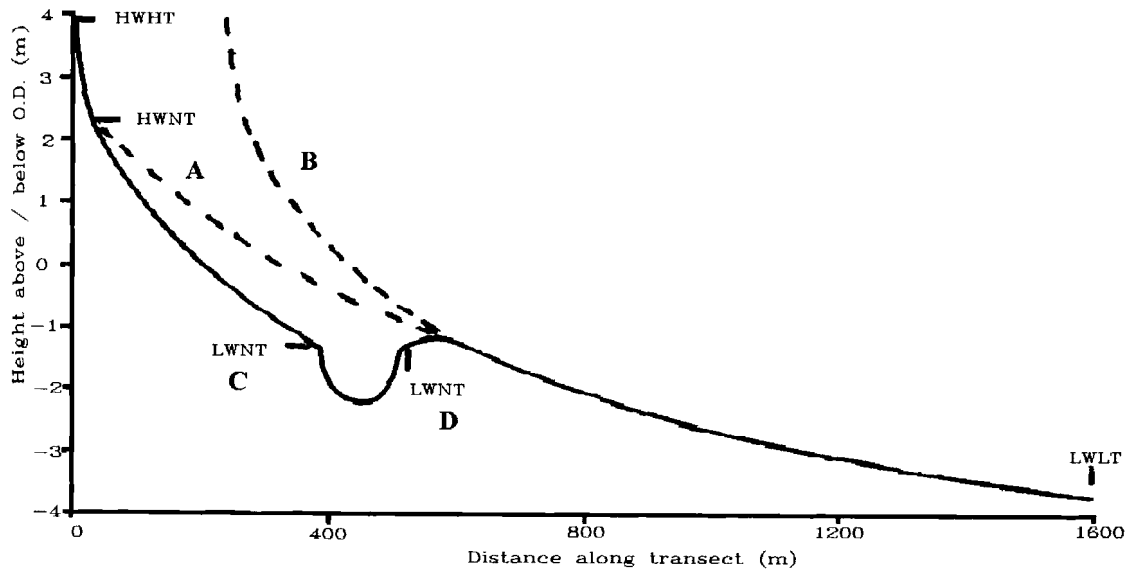


Figure 10. General beach profile from the West Shore and out across the Conwy Sands. The solid line shows the current profile. Dashed lines show the possible new profiles if the North Channel was absent; A) for the point of HWNT staying in the same position so that a more gentle profile is produced and B) if the original profile is retained which would move the points of HWNT and HWST offshore from their present position.

should the North Channel not be present then there would be an accumulation of sediment over the study area, is probably correct.

At the present time there are in effect two points of MLWNT on the West Shore beach profile: one which is located on the seaward side of the North Channel (point D, Figure 10), and one on the shoreward side of the channel (point C, Figure 10). The former has a true beach slope down to the level of LWLT but no actual beach slope from this point shoreward to the point of MHWNT, only an imaginary one; the latter point with MLWNT located on the shoreward side of the North Channel has no true slope to the point of LWLT, only an imaginary one, but does have a true slope to the point of MHWNT, the gradient of which is controlled by the morphodynamics of the system. With regard to the study area, at the present time any material which is added through beach nourishment will automatically be removed seaward as the beach tries to reach an equilibrium profile. As the material reaches the channel it is removed from the system by high velocity tidal currents. Ebb tidal currents on a neap tide have been measured at 0.4 m sec^{-1} but the presence of large mega-ripples within and adjacent to the channel at low water springs, and the grain size of the sand, would indicate velocities in excess of 0.6 m sec^{-1} . This shows that the tidal currents following installation of the breakwaters have a higher velocity than those recorded prior to installation. The breakwaters were designed to move the currents offshore but by doing so they have restricted the cross-sectional flow area resulting in faster current flows. Therefore, at present, the beach is effectively being maintained at a lower level because of both the removal of sediment from this part of the system by the fast tidal currents in the channel and also because the point of MLWNT is maintained more shoreward by the chan-

nel than what may be its natural equilibrium position if the channel was not present.

If the channel was absent, and there was only one point of MLWNT which was on the seaward side of the channel as one of the points is already (point D, Figure 10), then the system would in-fill in the area over and above the channel height and create an equilibrium beach gradient towards the point of MHWNT, Figure 10. If this gradient was the same as the present beach gradient, then it is probable that the point of MHWNT would move seaward as sediment accumulates within the system until equilibrium is reached. However, if the point of MHWNT stayed in the same position, then a lower gradient slope would be produced but there would still be sediment accumulation which would increase the beach level. In either case there would be an increase in the amount of wave energy dissipated by the system due to the increase in beach levels, which although superficially small, with a maximum of $\approx 1.5 \text{ m}$ at the point of greatest difference, would be acting over a considerable distance of approximately 600 m.

To summarise, on the basis of this study, it is considered that the breakwaters are proving ineffectual in increasing beach levels as originally proposed, because although they are causing a certain amount of wave diffraction and thus making wave approach more shore normal, the beach processes required to provide a natural accumulation of sediment are acting secondary to the tidal effect of the North Channel which is effectively removing sediment from the system as a result of the faster tidal flows.

Accumulation of Fine Grained Sediment

The installation of the Gogarth breakwater has created an area of exceptionally quiescent conditions immediately to the

south of the structure, which is clearly allowing fine material to accumulate. One of the main purposes of the breakwater was to cast a wave shadow in this area; in addition the breakwater was designed with a round head at its terminus so as to draw by diffraction the waves round into the lee and encourage the build up of a new beach in this area. However, qualitative observations at the site show an apparent absence of this diffraction at lower tidal elevations during the period that this area is covered by the tide. In addition, it was observed that the apron at the end of the breakwater was absorbing a large amount of wave energy during the early stages of coverage by the tide as the waves passed over it. Therefore, the wave energy is reduced at the round head by the apron, which limits the effectiveness of the structure in diffracting waves around it, as well as reducing the actual height of the waves that are propagating over this area. The absorption of energy from the waves by the apron relates to the size of the rock material making up the breakwater apron which is in excess of -6.25ϕ (75 mm) and thus has a very large roughness length.

As the tide rises over the apron, the incoming waves increase in amplitude as they pass the step onto the apron until they become limited by the actual depth of water over the apron itself which will cause breaking. As the waves travel across the apron, the amplitude becomes reduced due to friction as a result of the large roughness length of the apron, until the modified waves move across the step and over the beach, on the shoreward side where a further amplitude reduction occurs. As the tide rises and depths increase, the wave amplitude undergoes less modification due to the greater depth having a less limiting effect on the increase in wave amplitude as it passes onto the apron. In addition, the difference in wave speed becomes less as the depths increase, the wavelength is therefore not reduced by as much, so that the loss of amplitude due to the roughness of the bed and associated friction becomes less. Thus, while the water depths are low, there is little wave breaking or surf zone swash and backwash taking place immediately shoreward of the apron, because, as the waves are now travelling in relatively deeper water they have become stable. Therefore, the waves do not break and so are not having a stirring effect on the bed leading to re-suspension of the fine material.

It is probable that there is little deposition of fine material during the flood and early part of the ebb as the wave action would be sufficient to keep most suspended sediment in suspension. However, as the tide continues to ebb it is likely that fine grained material will be brought down the North Channel from the Conwy estuary. At this time, the net ebb flow is SE to NW across the beach with the Gogarth breakwater restricting the divergent flow. Suspended sediment being brought down from the Conwy would still be undergoing flocculation compared with material already in suspension in the open sea water. Thus, there is a likelihood of increased settling out of sediment due to flocculation and decreasing velocities in those areas out of the main fast flow of the North Channel, such as in behind the Gogarth breakwater and apron. In addition, JAGO and HARDISTY (1984) found that at Pendine breaker height decreased during the ebb so conditions would become more quiescent, which would obviously

aid settling out. Suspended sediment would also be subject to stranding by the limited swash, which although increasing in width during the ebb, has decreasing velocity. It is therefore most likely that deposition of the fine sediment takes place during the ebb phase which allows increased cohesion to take place during exposure at low tide. Thus, by the time the flood tide has covered the sediment once again, there is sufficient cohesion between the particles to prevent re-suspension in the absence of high wave energies. Because of this, there is some seasonality to the accumulation of the fine sediment, with accumulation appearing to occur during the summer months, and erosion and re-suspension during the winter when the occurrence of strong westerly winds is higher, allowing waves to come in behind the breakwater and on to the beach. This seasonality was apparent following several visits to the study site after the main monitoring period when it was found that most of the surficial fine sediment was absent with most of the area appearing to be sandy once again. However, closer examination of the sediment profile shows that the sand visible at the surface was not homogenous through the profile and that the mud or sandy mud observed during the monitoring period was present in layers below the superficial surface. This is due to the beach undergoing "armouring", whereby the surface fines are removed by erosion and re-suspension during periods of high wave energy, leaving behind a layer of sand which is uneroded by the increased wave action. This acts to protect the fines further down within the sediment column, preventing re-suspension. Thus, winter storm conditions will go some way to removing the fines from the beach, but it is unlikely that all of the fine material will be eroded out unless the beach is stripped of sediment to some considerable depth.

CONCLUSIONS

From a coastal engineering or protection aspect, the installation of the Gogarth breakwater may be considered successful in its prime objective of protecting the sea wall behind it. However, from an environmental perspective, it has not increased beach levels as proposed and the installation of the breakwaters has had an extremely detrimental affect on the natural beach environment which has certainly not enhanced the Llandudno, West Shore as a recreational amenity.

The reasons that the breakwater have not increased beach levels as proposed at the design stage are believed to be due to the morphodynamics of the macro-tidal beach which give it a long, gently sloping, concave up profile, and because of the tidal currents flowing through the North Channel. These currents are presently controlling the position of the MLWNT level of the beach profile by the removal of sediment from the system. In addition fine sediment is collecting in the lee of the breakwater because, not only does the breakwater act as a wave screen, but the large apron at the end of the breakwater has the same effect by damping out wave energy at lower tidal levels. This creates extremely quiescent conditions during the ebb phase when breaker height decreases allowing settling out and stranding of the suspended sediment. This is aided by continuing flocculation of fine material brought down from the Conwy estuary and decreasing flow

velocities. Cohesion of the particles during exposure at low water reduces the likelihood of re-suspension during the next flood tide, except under high wave energy conditions from the west.

A further detriment to the area is that the fine material accumulating behind the breakwater and apron has a high organic carbon content, probably resulting from the trapping and deposition of sewage, either from the offshore outfall or that being brought down the Conwy estuary, a factor which appears to have been completely overlooked at the design stage.

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