Les côtes atlantiques d'Europe, évolution, aménagement, protection-Brest, France, 15-16 mai 1979
Publications du CNEXO : Actes de Colloques n° 9, pages 35 à 44

SOME ASPECTS OF BEACH RIDGE DEVELOPMENT ON A FRINGING GRAVEL BEACH, DYFED, WEST WALES

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ABSTRACT

—Fringing gravel beaches are an important element of North West European littoral sedimentation, yet few investigations have been made concerning their development or stability. Often the only sign of accumulation on fringing gravel beaches is in the form of ridge building.—Ridge development is controlled by : sediment source, the distribution of littoral power for longshore sediment supply and a mechanism by which beach sediment is transferred to the beach ridge.

This paper examines gravel ridge accretion on a unit of West Wales crenulate coastline. The nature of sediment supply and littoral power distribution is examined along one crenulate beach. Spatial variations in beach ridge height related to swash overtopping during two known storm events are considered. Variation is related to incident wave direction and refraction, angle of wave approach, breaker height and type, beach slope and sediment roughness.—

RESUME

— Les grèves frangeantes de galets occupent une place privilégiée dans le domaine de la sédimentation littorale du Nord-Ouest de l'Europe. Cependant, leur développement et leur stabilité ont encore été peu étudiés. Fréquemment, le seul signe d'accumulation sur ces grèves réside dans la construction de cordons.—Les facteurs influant sur le développement d'un cordon sont : la source de sédiments, la répartition des agents littoraux responsables de l'approvisionnement et du déplacement latéral des galets, et un mécanisme de transfert de ces galets de la partie basse de la grève au cordon.

On examine l'accrétion caractérisant une levée de galets sur un secteur littoral crénelé de l'Ouest du Pays de Galles. Sont notées les variations spatiales de l'élévation du cordon en fonction du swash qui le recouvre, lors de deux tempêtes. Ces variations sont reliées à la direction incidente des houles et à leur réfraction, à l'angle d'approche des vagues, à la hauteur et à la catégorie des vagues déferlantes, à la pente de la grève ainsi qu'à la granulométrie et la rugosité des sédiments.

KEY WORDS :-gravel beaches, crenulate bays, ridge building, overtopping, extreme events.—

MOTS-CLES : grève de galets, baies crénelées, construction de cordons, recouvrement par le jet de rive, événements extrêmes.

INTRODUCTION

Any consideration of shoreline changes along the Atlantic coasts of North West Europe would be incomplete if recognition of the dynamics of gravel beach sedimentation were absent. To avoid unwarranted genetic connotations, the term 'gravel' rather than 'shingle' is preferred in reference to conglomeratic based beach sedimentation. Gravel is used to identify beaches where the predominant particle B axis is >-2.0 phi (4mm), though few, if any, gravel beaches are completely free of a fine clastic element.

The littoral importance of gravel beaches can be gauged by Randall's (1977) 900km estimate of their spatial extent along the English and Welsh coastline, while their presence is equally marked along the North West European coastline. It is pertinent to note that the presence of gravel beaches is primarily a reflection of a Pleistocene inheritance of glacially and periglacially derived, heterogeneous, non-indurate deposits across North West Europe. Gravel beach accumulations have evolved from either a substantial longshore supply of such sediments by continuing shoreline erosion, or represent the remnants of material swept-up off the continental shelf areas and rolled onshore by a rising post-glacial sea level (Hardy 1964). The world wide gravel distribution on continental shelf areas indicates that approximately 68% of all shelf gravel is located between latitudes 45° and 90° (Hayes 1967), a zonation which correlates with the presence of modern gravel beaches.

The likelihood of gravel beach progradation is clearly related, through the morphological type of accumulation, to sediment supply (source), the distribution of littoral power available for longshore transport by beach drifting (transport conduit) and the mechanism by which the sediment is removed from the littoral drift and immobilised in the accumulation form (sediment sink). This latter point in gravel sedimentation is dominated by the propensity for beach ridge building as a means by which sediment is removed from the transport conduit. As the accumulation form is dependent on these three factors, it also serves as an index of the overall beach economy. Deposits which show active progradation are typical of economies of abundance, while economies of scarcity denote a lack of progradation. Tanner and Stapor (1972) note that on a world basis, few beach deposits can be seen as denoting economies of abundance and over time this number will eventually decline as the sedimentation response lag to process variation caused by post-glacial sea level changes, works through.

Randall (1977) advocates five types of beach gravel accumulations; spits, bay-mouth barriers, foreland accretions, offshore barrier islands and fringing beaches. The last type refers to linear, usually single ridge forms which parallel the grain of the coast. It is unfortunate that in gravel beach research, stress has been laid onto the striking but rare structures of barriers, spits and forelands (eg Chesil Bank: Carr and Blackley 1974, Orfordness: Steers 1926, Dungeness: Lewis 1932) to the detriment of fringing beaches. The majority of non-fringing accumulations are typified by economies of abundance, even though some major English examples now show a movement towards economies of scarcity. However, the minority lateral extent of such forms when compared with the extent of fringing gravel beaches only reinforces the need to investigate the fringing forms as a basic model of littoral sedimentation along the Atlantic coastlines of North West Europe. This paper therefore examines several aspects of gravel beach ridge building on a fringing beach located within a Welsh unit of semi-crenulate coastline adjacent to Cardigan Bay (fig.1a). The use of crenulate refers to a skewed arrangement of headlands and down drift bays and follows Silvester's (1970) terminology.

1. CRENULATE COASTLINE OF NORTH DYFED (CARDIGAN)

From New Quay to Aberystwyth (fig.1a), the mid-Welsh Coastal Plateau has a series of coastal embayments which are floored with periglacially derived heterogeneous sized, local mudstones and greywacke based deposits. Lithologies are all locally derived from the Aberystwyth Grits. Breaking through the present coastline are remnants of past sea levels, notably fossil cliffs and wave cut platforms formed in *in situ* Aberystwyth Grits. The north-east to south-west grain of the present coast transects the sinuous nature of the old coastline and the resultant resistant headlands (10-100m high) act as pivoting points for the generation of a series of elongated crenulate or zeta-shaped bays, the most striking of which are represented by New Quay Bay and Llanrhystyd Bay (fig.1b). Due to the contrast between swell waves from the south-west and the dominant storm waves from the north-west, the bays are often immature and rarely show the full equilibrium form noted by Silvester (1970).

2. LLANRHYSTYD GRAVEL BEACH

2.1. Description of study beach

Llanrhystyd gravel beach (U.K. Grid Ref.SN524692) is designated as a semi-diurnal, macro-tidal (mean spring range: 4.2m, mean neap range: 1.9m) beach in a storm wave environment. The crenulate nature of the bay is based on a southern resistant headland composed of <20m of periglacial drift, masking an old inter-glacial wave-cut platform. A lateral extension of the headland is observed in Cadwgan Reef, which dominates the southern approaches to the bay (fig.2). A modern wave-cut platform at Llanrhystyd has a subdued relief related to the broad swell and swale of the landward drift surface behind a modern gravel ridge (fig.4). The platform relief has lateral antecedents with the offshore zone and reflects a similar beach plan geometry at earlier stages of Llanrhystyd's development.

The gravel ridge extends 3km south from the River Wyre. Refracted waves can impinge obliquely on to the beach within a 235°-010°N vector range. The north and south ends of the ridge merge with the backing drift and show no landward ridge slope. At the centre beach (P7 and P8, profiles marked on fig.1b), the drift surface falls to 4m below the ridge crest. The drift surface at the Wyre is <0.5m above the ridge, while in the south, the drift surface reaches 10m above the crest of the ridge (near the Old Limekilns). The ridge is asymmetrical in cross-section (fig.3) and its height varies longshore between 2.5m in the south and 7.5m in the centre. Figure 4 indicates how the ridge crest has varied during 1971-76 along the free standing section.

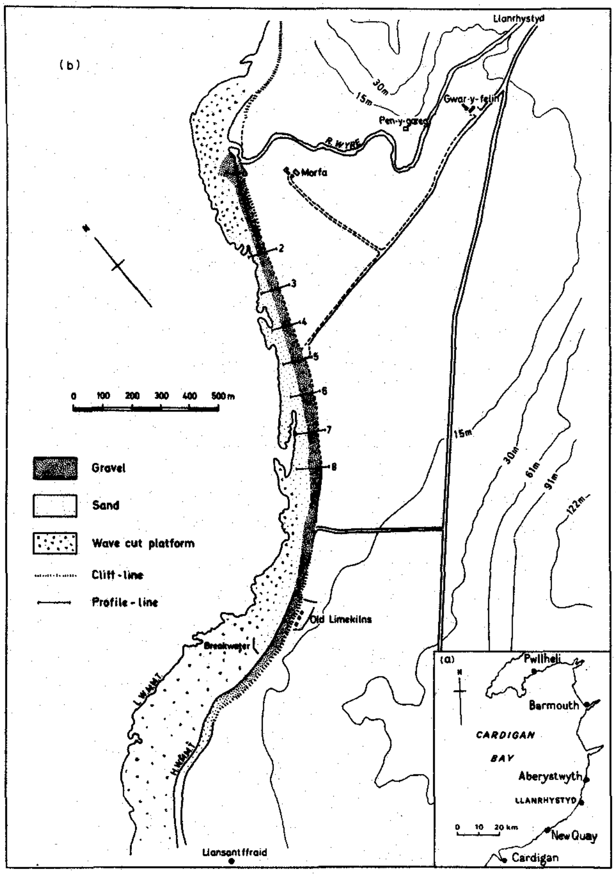

Figure 1. Location map and plan of Llanrhystyd Beach.

The relative width and height of the exposed gravels on the ridge's seaward face (measured section only) depend on wave conditions on the beach face. Exposed gravel height varies between 5m and 8.5m due to inter-tidal sand burying the seaward gravel edge. Maximum burial occurs around P7 and P8. The width of exposed gravels seaward of the crest varies from 15m at P7 and P8, to a maximum of 40m at P4 and P5. Gravel particles range from 4mm to 120mm, with a 70mm-80mm modal class (B axis). Particle sphericity (Sneed and Folk 1958)varies from 0.35-0.85, and shows strong spatial beach face zonation in combination with particle size.

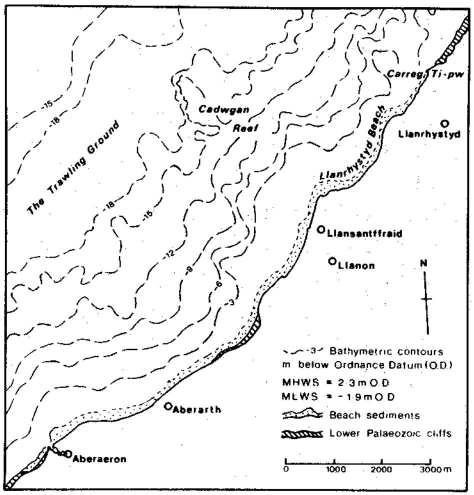

Figure 2. Bathymetry off the Llanrhystyd embayment.

Between the gravel ridge and the wave-cut platform is a zone of inter-tidal sand (Md= +2.75 phi), up to 70m wide at the bay centre measured at low spring water. Areally the zone pinches out to the north and south of the bay. Absolute width of the sand is not as important as the height to which the sand is deposited. In this respect, the sand appears at higher levels in the less exposed southern end of the bay. Sand accretion increases up to the lee of a wooden permeable breakwater(fig.1b). West of this structure, sand diminishes rapidly and the wave cut platform reappears adjacent to a much reduced cliff fringing gravel beach (<3m). West of the breakwater, and without the sand zone, the 4m-5m drift cliffs show the effects of recent marine erosion by their near vertical slopes.

Evidence of an impeded flow to net longshore sediment movement to the north is shown by the concentration of gravel south of the Carreg Ti-Pw headland (fig.2), with gravel bench levels up to 12m O.D. To judge by the volume of the fringing gravel beach west of the breakwater, there is little material entering the bay from the south at present. Despite the net northerly movement, gross sediment movement north↔ south along the beach dominates the nature of facies variation at the present time.

2.2. Wave climate at Llanrhystyd

The only approach for swell waves into Cardigan Bay is via St George's Channel, from the South Western Approaches of the Atlantic. Refracted long period waves once inside the Irish Sea, continuously feel the bottom with wave orthogonals adjusting to the Welsh coast. By the time wave crests reach Llanrhystyd, orthogonal spacing at the shoreline is significantly more than that found in deep water, leading to less steep constructional wave forms within the bay.

The influence of cyclonic depressions across the U.K. produce west and north-westerly winds capable of generating short period storm waves within the Irish Sea. There is no clear contrast between swell and storm waves as suggested elsewhere for cyclonic disturbances, but beach dynamics at Llanrhystyd reflect the divergent south-westerly swell waves and north/ north-westerly storm waves. Wave data from Draper and Wills (1977) indicate a seasonally varying median H_{max} from 1.2m in the summer, to 2.1m in the winter. Significant wave height varies from 2m in the summer to 3.7m in the winter. Swell waves (>10 sec) are evident in all seasons though principally occurring between July and September, but 55% of all wave trains have a spectral bandwidth between 0.7 and 0.85.

2.3. Llanrhystyd gravel ridge height variation

Figure 3 indicates the overtopping and overwash of the ridge experienced at Llanrhystyd during 1971-1976. Ridge stability in the early 70's, a period of reduced westerly winds, has been affected on two known occasions. A major south-westerly storm and surge accounted for major overwashing of gravels on northern profiles and ridge overtopping on southern profiles in February 1974. Discussion of the process and conditions for this extreme event can be found elsewhere (Orford 1977). A local farmer built up the north crest by replacing overwashed gravels to form a secondary ridge on the existing crest (P3 and P4, fig.3). This element was incorporated into the main beach ridge by accretion and crestline retreat during the second overtopping event that occurred in January 1976. The limited extent of overtopping in that storm is evident on all profiles except for P2 and P5. Profile 2 was overtopped and cleared by the farmer before observations could be made. Profile 5 adjacent to a car park suffered gravel removal by the farmer during 1975 causing the ridge level to drop despite overtopping. This second major event was entirely due to north-westerly impinging storm waves. Figure 4 shows the height changes along the crest and except for the second event at P5, shows a consistent longshore trend in vertical ridge accretion. The rate of accretion is greatest around P6 and P7 (the trend at P3 and P4 being artificially enhanced) with a mean 0.2m/event recorded on the seaward crest limit. The explanation of this crestal spatial variation forms the basis of this paper.

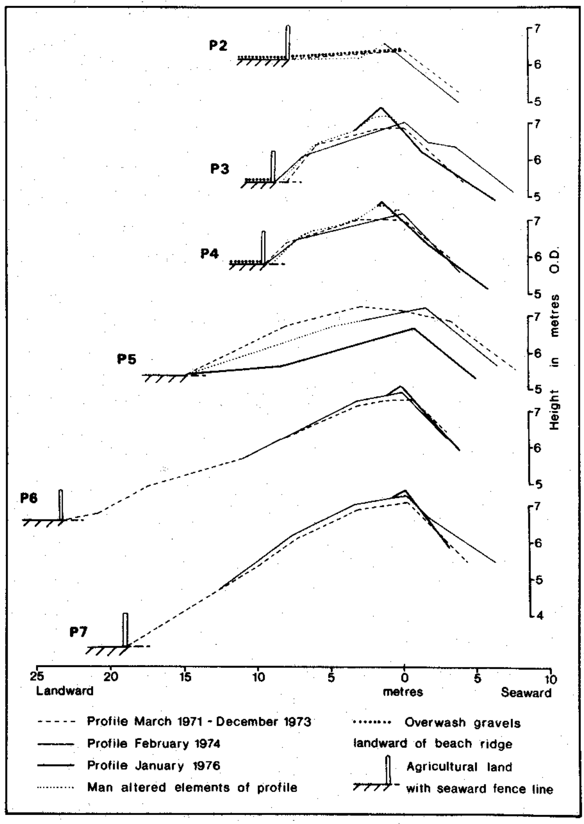

Figure 3. Beach ridge crest profile changes at Llanrhystyd, 1971-76

3. PROCESSES AFFECTING GRAVEL RIDGE DEVELOPMENT ON CRENULATE FRINGING BEACHES

3.1. Sediment supply

Restrictions and fluctuations in sediment supply are considered by Psuty (1964) as the major factors affecting beach ridge growth and progradation. Fringing beaches are affected by supply problems especially when found along crenulate coastlines, as headlands check longshore sediment transport rates to a point of complete transport cessation. The Dyfed crenulate coastline section shows the effects of both an interrupted and declining sediment supply, due to both the non-renewable sources of present littoral gravel and the effects of the crenulate

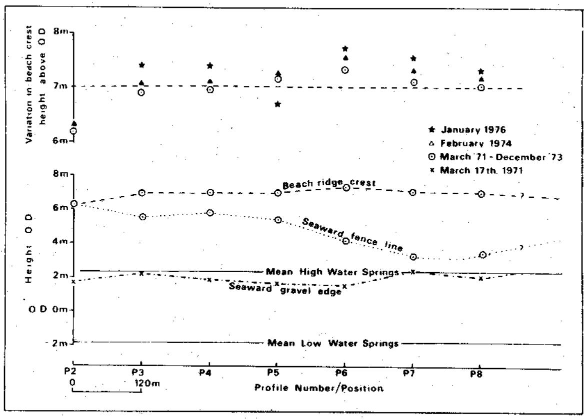

Figure 4. Beach ridge crest elevation changes at Llanrhystyd, 1971-76

topography on transport rates. The original sediment supply (related to the rolling onshore of material with a rising post-glacial sea level) has diminished, while the reduced rate of sea level change experienced in Cardigan Bay over the last 2000 years (Haynes et al, 1977) has restricted any new major onshore supply. Erosion, by present marine action, of local solifluction deposits masking the inter-glacial cliffline is declining in most crenulate cells. This reduction is due to both a decreasing areal availability of periglacial material as exhumation of the in situ Aberystwyth Grits proceeds (Wood 1978), and to the increasing protection within cells of erosion points by available sediment as the crenulate topography attempts to develop towards some quasi-equilibrium (Silvester 1970). Natural and artificial boundaries (groynes) on crenulate cells tend to depress the diminishing littoral drift supply and reinforce the economy of scarcity for this coastal section.

3.2. Distribution of littoral power in crenulate bays

Intermittent sediment supply on a crenulate coast is also a function of the spatial distribution of available littoral transporting power (P_L) due to wave refraction effects imposed by the crenulate offshore bathymetry. The rate of change in the longshore sediment transport rate (Q) as a function of beach drifting of gravel in the swash zone varies with P_L and by definition, $\sin\beta$ (where β = the angle of wave approach at the shoreline). Beach accumulation is usually associated with a longshore rise and then fall in P_L and Q. This type of transportation potential along non-linear coastlines has been identified by May and Tanner (1974) in their 'abc..' model. Nil drift regardless of H_b value occurs when breaking waves parallel the shoreline (β=0), although at the same time variation in breaker height (H_b) due to wave orthogonal convergence/divergence as a response to wave refraction can establish incipient longshore gradients of pressure head variation sufficient to entrain fine sediments. Nil drift positions therefore depend on the approach angle and refraction experienced in the crenulate nearshore wave climate. Given the usual crenulate 'half-moon' shape, nil drift points best develop with short period waves moving obliquely in towards the cell. Nil drift points are spatially extensive when swell waves refract round the cell headland into the bay. Total nil drift is established when the refracted wave breaks at the same time, all round the bay. Despite no longshore beach drifting, non-uniform H_b round the bay is denoted by the breaker type and swash excursion variation, which affects the potential of beach crest sedimentation.

3.3. Gravel beach ridge building

Lewis (1931) is generally credited with the initial recognition of gravel ridge formation by deposition at the swash limit of destructive type waves. Despite the extensive downcombing of the lower beach face by backwash, major ridge accretion with swash limit deposition is associated with swash overtopping the crest during extreme storm and surge conditions. However, any mechanism for the transfer of beach face sediments to the backslope of the ridge by surging swash flow in the form of overwash was not explicitly recognised by Lewis. Hey (1967) commenting on the internal structure of Dungeness gravel foreland, questioned the role of destructive waves in ridge building. The interpretation of structure as units of conformable gravel sedimentation, suggests that deposition was more likely with the superimposition of low amplitude, long period, surging, constructive swell waves on spring tides. Hey did not examine the ridge structure per se, only the foreland upon which the ridges had developed. Dungeness as a form of accumulation, represents ridge building given a positive littoral sediment supply. If the supply is not available, as in most crenulate fringing gravel beaches, then beach ridge sedimentation may show substantial divergence from Hey's model.

Although working on sand beaches, Davies (1957) speculated that interuptions of sediment supply could result in increasing ridge height, as a lowering of the beach level in front of the ridge would allow higher waves to reach closer inshore and generate larger swash run-up, thereby increasing the potential of ridge overtopping.

Previous work at Llanrhystyd (Orford 1977) connected with the first overwash event, indicated that the breaker type is strategic in the process of ridge accretion. A composite type beach profile (step + bar elements on the same profile) is associated with overwash, such that by high water, despite destructive plunging storm waves at the mid-beach level, the breaker structure (following Galvin's 1968 approach to inshore breaker discrimination, fig.5) is associated with the spilling breaker domain. This breaker type is consistent with the hydraulic conditions for beach face sediment transfer over the crest as overwash sediment.

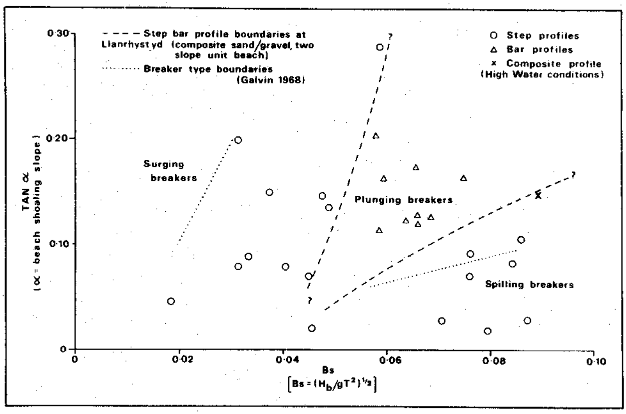

Figure 5. Beach profile discrimination at Llanrhystyd.

The incidence and volume of ridge overtopping is the key to rates of vertical aggradation, so that factors controlling overtopping need elucidation. Overtopping is a function of the swash excursion distance weighted for beach slope. This is reflected in the run-up value as measured by the vertical rise of the swash limit above mean still water level. Run-up depends on the breaker structure (as a function of breaker type, H_b and maximum orbital velocity of the breaker), on β, on beach slope angle and on the bed roughness of the swash zone. Spatial variation of these factors along a crenulate coastline will affect ridge crest height variation.

4. BEACH SEDIMENT VARIATION AT LLANRHYSTYD AND ITS AFFECT ON RIDGE HEIGHT

4.1. Wave climate and beach facies variation

The crenulate shape of the bay conditions refraction of south-westerly swell waves and thereby influences gravel and sand longshore zonation. Long period waves undergo accelerated refraction due to the shoaling area of Cadwgan Reef. Visual observations show that refraction stemming from this area, produces a discernable non-uniform wave type, H_b and breaking time around the bay. The relief of the modern wave-cut platform also induces minor late refraction of bores at lower tidal levels. Zones of orthogonal convergence occur along the northern beach and round the southern headland. Divergent orthogonals induce low H_b values in the centre and southern lee of the bay. This gradient of H_b is related to a sand build-up at P7 and P8, encroaching upon the gravel beach element and subsequently interdigitating with the large disc/bladed particle zone of the upper beach. Unequal breaking times alongshore indicate sub-parallel breaker crests with the shoreline which are open to the north. This shows that an equilibrium between beach orientation and refracted swell waves is rarely, if ever, achieved. The slightly oblique wave approach at the northern profiles induces a northerly beach drifting of gravel. The coarser the particle the greater the net movement, due to their bridging affect across the gravel frame, into which small particles fall. Tracer movement, of >80mm discs, over 100m in two tides north from P6, has been encountered under extreme south-westerly conditions.

When north/ north-westerly storm waves operate the transport emphasis is placed on a down-beach sediment motion due to profile downcombing. However, due to the obliquely impinging storm waves, a redistribution of gravel to the south occurs. The bed roughness gradient inherited from the south-westerlies is reversed, allowing finer disc and bladed particles to move rapidly down drift to the south, so that the bed roughness of the lower gravel beach zone decreases towards the energy lee. The obliquity of these storm waves means that a nil drift position develops in the proximity of P6 to P8. The combination over time of nil drift under storm waves and northerly beach drifting under swell waves ensures that the bed particle roughness of P2 to P4 is at least one order of magnitude greater than that found around P6 to P8.

4.2. Interpretation of ridge height spatial variation

This interpretation can only be considered as tentative in view of the limited evidence due to the low frequency nature of ridge overtopping. The first event (storm) appears greater in energy magnitude than the second event, on the basis of its greater overwash potential (even given the build-up of the ridge that the second event had to overcome). The first event showed a marked concentration on the northern profiles as witnessed by the zone of major overwashing (up to 15m beyond the fence line shown in fig.3). Despite any beach profile bed roughness variation longshore, it appears that the H_b was greater at the north than south end of the beach. This would be symptomatic of a south-westerly storm with refracting long period waves masked by local shorter period wind waves.

The greatest ridge accretion (as a function of present ridge height) appears in the centre beach (P6-P7). This suggests that the north-westerly storms are either more frequent or lead to greater deposition. Given the propensity of south-westerly overwashing to scour the beach crest, as well as depositing fresh sediment, while the north-westerly waves appear to overtop only the present ridge and add an accretional unit, then the latter point may be valid. Yet given the longer period of build up required for south-westerly storms relative to north-westerly storms (days:hours), then the greater incidence and ridge building potential of the north-westerly storms is feasible.

The ridge build-up at P6 and P7 may, however, indicate the nil drift position and the point where run-up is maximised for north-westerly storms, due to swash excursions occurring normal to the beach crest. North of this position, beach sheltering by the modern wave-cut platform, the concentration of beach gravels ensuring a rougher swash slope than at P6 to P8, and the obliquely impinging storm waves, may all combine to produce a lower run-up potential than exhibited between P6 and P8.

CONCLUSIONS

Gravel beaches should not be ignored in any study of North West European shoreline changes. Most gravel beaches fall into the fringing category which predominantly show economies of scarcity, *ie* declining sediment budgets. Longterm aggradation on such beaches is usually only vertical, and located on the back beach gravel ridge. Ridge building on fringing, crenulate plan view beaches, relates to the incidence and potential of overtopping and in extreme conditions, overwashing by swash excursion. Crenulate beaches show spatial variation in beach ridge height due to the non-uniform distribution of littoral power and sediments around the bay, in response to wave climate variations induced by the non-uniform coastal trend. Ridge building is conditioned by wave direction and angle of breaker approach, breaker type and height, beach slope angle and beach bed roughness.

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