MORPHOLOGY AND MORPHODYNAMICS OF GRAVEL BEACHES

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Summary

Gravelly beaches are at least partly composed of coarse grained material. They have steep and typically concave profiles with slope increasing up the beach face. Gravelly beaches often contain multiple steps or berms and are invariably associated with a beach step, at or about, low tide mark. Beach cusps are a characteristic feature and are associated with the berms. Beach width is narrow, ranging from less than 20 m on some gravel barriers to about 200 m on some mixed sand and gravel beaches. Slopes are inversely related to beach width. Gravelly beaches always extend above mean sea-level (MSL) with storm berms preserved up to at least 12 m above Spring High Tides on high energy coasts. By contrast, the gravelly portion of the shoreface rarely extends more

than a few decimeters below low tide mark. The gravel terminates either at the beach step, as is common on sand and gravel beaches, or as an apron of rounded clasts extending a few metres beyond the beach step.

Gravel beaches occur in erosional coastal settings. They retreat shoreward as their coarse sediment supply is abraded and moved off shore as fines. Under rising sea-levels enhanced coastal retreat will occur, if the beach system is in sediment deficit. Alternatively the barrier height will increase, if local sediment supply keeps pace with sea-level rise. This latter style of response causes an increased hazard of freshwater flooding on the lower reaches of rivers behind the coast.

Note on terminology

There are two groups of beaches that contain gravel. These are i) pure gravel beaches and ii) mixed sand and gravel beaches. The two are similar enough to treat as a group but they do have distinctive characteristics. Henceforth, the terms ‘gravel beach’ and ‘mixed sand and gravel beach’ (MSG) will be used when the specific form is referred to, while the term ‘gravelly beach’ will be used to describe all beaches containing gravel, irrespective of type.

1. Introduction

Gravel beaches are poorly documented coastal phenomena. As their name implies, they are at least partially composed of sediment coarser than sand (>1mm) and they are associated with coarse sediment supply to the coastal zone. They are fairly common at mid- to high latitudes, where glacial and braided alluvial sedimentary systems act as the primary sediment source. The largest gravel beach systems are associated with eroding alluvial fan complexes (e.g. Canterbury Bight in New Zealand) while the intensively studied occur in formerly glaciated areas (e.g. in Nova Scotia, Canada and in the British Isles). Except in very unusual circumstances, they are associated with eroding coastlines.

Gravel beaches are important because;

1) They are a naturally stable form of shore defense
2) Their response to sea-level forcing is distinctive and can be preserved in the fossil record.
3) Ancient gravel barrier and lagoon complexes act as potential hydrocarbon traps and sources respectively.

2. Gravelly beach morphology

2.1. Gravelly beach profiles

All gravelly beaches have steep slopes, with overall beach slopes (β) typically in excess of 5° and often as high as 15 to 20°. The steepness of an individual profile relates to the local wave climate, and to the size of clasts in the beach. These factors are interrelated—coarser sediments and steeper waves produce steeper profiles, and steep profiles encourage steeper wave types. At one end of the spectrum gravel barrier beaches have concave profiles; while at the other, MSG beaches have a convex overall shape (see Figure 1). In both instances, the profiles can be described as a series of near linear elements separated by berms. Typically, the steepest slopes are located at the storm berm and at the beach step.

Recent work has suggested that profile responses on gravel beaches are cyclic and are related to wave energy. The overall profile is reduced during storm events and builds back up under lower energy waves. This might initially suggest that a morphodynamic model for gravelly beaches, similar to the model for sand, may be possible, but volume changes are small and we will present evidence that these cycles reflect no more than surface reworking of the beach.

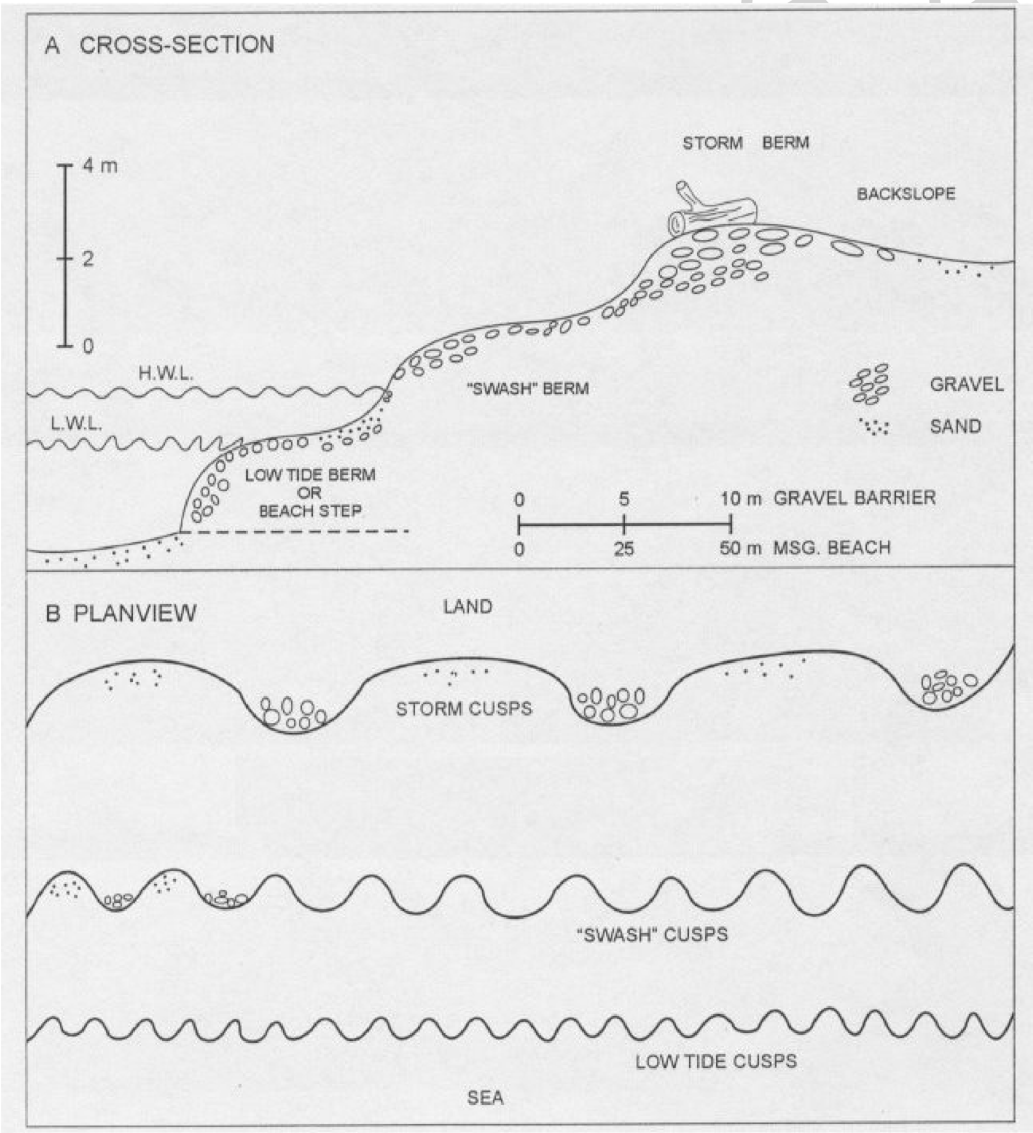

Figure 1. Labeled morphological profiles for a gravelly beach
a) in cross-section and b) in planform

2.2. Berms and the beach step

Most gravel beaches have at least three distinct berms. These are, i) a low-tide berm also known as the beach step, ii) a high-tide or swash berm (informal terminology), and iii) a storm berm at the top of the beach. Each berm is characterised by a very steep foreslope (>10°) and gentle top slope. They contain the coarsest material preserved in that portion of the profile. These sediments form a veneer of less than a metre on the profile. Openwork sediments are common in the sub-aerial berms.

The storm berm occurs at the top of the beach. It contains the coarsest clasts found in the beach. Flotsam, in the form of wood and seaweed, commonly caps the berm. The berm sediments may interdigitate with aeolian sands on the landward side. This berm may be indistinct or absent, if the beach is backed by a cliff.

The high-tide or swash berm is the least distinctive of the berms. It is likely to form at the upper limit of mean swash run-up. The swash berm is the most active and is often less well sorted than other berms. Berms are created by deposition of large clasts by swash uprush and by erosion of the active upper foreshore by backwash. The swash berm has been observed migrating upshore during the rising tide under moderate wave energy conditions.

The beach step is a crucial feature of a fair weather gravelly beach and is nearly as coarse as the storm berm. This pronounced berm marks the lower extent of MSG beaches and the active component of gravel beaches. All waves are modified and start breaking when they cross the step. The step is responsible for the plunging breakers typical of gravel beaches and is sometimes referred to as the ‘plunge step’. When set-up is very high, the primary breaking site may transfer up-beach to the swash berm or the storm berm. Direct measurements of both the morphology and dynamics of this part of the profile are rare due to the very high energy conditions encountered.

2.3. Cusps

Beach cusps are crescent shaped, rhythmic embayments and are an important feature of gravel beaches, though they also occur on sand beaches. They are a complex form that may be constructed by erosion or by a mix of erosion and deposition on a beach face. They comprise a central embayment and two confining horns. Typically a suite of cusps forms along a beach at even spacing, and at a constant elevation above MSL. They form perpendicular to the shoreface and are indicative of shore normal processes on a beach. Several sets may be preserved on a beach at different elevations. All aspects of cusp size increase with elevation up the beach face and the increasing size represents a response to a combination of the incident wave height and the swash run-up acting on that cusp set. Within the cusp there are predictable patterns of sediment zonation with coarser and less equant particles preserved on cusp horns and finer, more equant particles in the bays.

The processes of beach cusp formation have become controversial in the recent past. Until the early 1990s it was generally argued that cusps formed in response to swash interactions with edge waves, were trapped in the nearshore and propagated alongshore.

This relationship can be described empirically by the equation;

$$L = g/2(T^2 \sin[(2n + 1) \beta \qquad (1)$$

where L = cusp wavelength, g = acceleration due to gravity, T = the edge wave period, n is the mode number and ß is the beach slope. Harmonic edge waves have a wavelength of L while sub-harmonic edge waves have a wavelength of L/2. Zero mode sub-harmonic edge waves are deemed typical of gravel beaches.

More recently, cusps have been attributed to processes of self–organization. Self-organization involves a pre-existing topography or sediment pattern on the beach that disrupts incident wave patterns. This triggers the establishment of a regular pattern of swash enhancement and suppression along the beach, causing edge waves to form. Recent field studies have examined both processes and have concluded that we cannot resolve between the two models, on current field evidence. More and better designed field experiments are required.

Gravelly beach cusps are a potentially valuable source of localized sea-level information. It has recently been demonstrated empirically that cusp spacing increases systematically with increasing height above sea-level. This opens up the as yet untried possibility of using relict cusps as past sea-level indicators on gravelly coasts. Initial work suggests that comparatively high resolution can be achieved, where boundary conditions for wave climates have not changed.

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Biographical Sketches

James Shulmeister is an Associate Professor in Quaternary Geology at the University of Canterbury, New Zealand. He has widespread interests in aeolian, coastal and glacial geomorphology, sedimentology and stratigraphy with a particular interest in coastal evolution of gravelly coastlines. He has published widely in these fields. He is a recent member of the editorial board of the international journal "Marine Geology".

Richard Jennings works for Scottish Nature. He was a Commonwealth PhD Scholar in gravel beach morpho- and hydro-dynamics at Victoria University in Wellington, New Zealand. He completed an honours degree in Geography at the University of Glasgow.