Marine Geology 249 (2008) 167–183
MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS
www.elsevier.com/locate/margeo

Morphological change and sediment dynamics of the beach step on a macrotidal gravel beach

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Received 8 October 2006; received in revised form 2 November 2007; accepted 26 November 2007

Abstract

The morpho-sedimentary evolution of a pure gravel beach step over a tidal cycle is examined during fairweather conditions using detailed measurements of nearshore hydrodynamics, morphological and sedimentary change, and nearshore sediment transport. The characteristics of the beach step are analysed with specific reference to the concurrent dynamics of the beachface, a departure from previous studies which have treated the step as a feature isolated from the nearshore region as a whole. The step and berm are both accretionary features strongly linked to tidal stage, yet their temporal evolution is independent, the relaxation time of the berm being linked to the spring–neap tidal cycle, and that of the more transient step linked to the semi-diurnal tide. Over this time-scale the beachface is a closed sedimentary unit, although the beach step may be differentiated from the beachface using sedimentary moments. Indeed, despite the location of the step in the region of wave breaking, it has relatively stable sedimentology, remaining characteristically coarser and more leptokurtic than the swash zone. Co-spectral analysis between nearshore bed motion and cross-shore current velocity reveals that significant nearshore sediment transport occurs at sub-incident frequencies in response to wave groups. Motion of the nearshore bed is not a linear function of velocity magnitude or direction, so it is likely that there is a role for the various mechanical properties of the bed. Therefore a better description of nearshore sediment transport in the region of the beach step would require instantaneous sediment size information, allowing the use of a time-variant friction factor.

Keywords: beach step; morphodynamics; gravel beach; sediment transport

1. Introduction

Beach steps are morphological features commonly associated with steep, coarse-grained beaches, particularly those composed of gravel. Typically located around the elevation of the mean water level (MWL), the step evolves according to the tidal stage and forms an acute discontinuity in the beach profile at the transition between the breaker and swash regions (e.g. Miller and Zeigler, 1958; Bauer and Allen, 1995; Ivamy and Kench, 2006), and is illustrated in Fig. 1. The sedimentology of the beach step is usually skewed towards the coarsest fraction found on the beachface, the fines having been selectively removed. The importance of the beach step is two-fold. Firstly, due to the abrupt change in water depth, the beach step forms a steep hydrodynamic gradient close to the breakpoint, thereby exerting a control on wave breaking (Hughes and Cowell, 1987). This region is strongly associated with sediment convergence; non-linear shoaling waves transport sediment onshore (Hoefel and Elgar, 2003), whilst the backwash erodes sediment from the lower swash and transports it seawards (Miller and Zeigler, 1958; Strahler, 1966). It could therefore be argued that the step is the coarse beach analogy to the breakpoint bar (Dhyr-Nielsen and Sorensen, 1970; Roelvink and Stive, 1989). Secondly, the beach step plays an important role in the morphological response of reflective (steep) beaches to storms. Beaches typically respond to energetic waves by becoming more dissipative; offshore sediment transport, conductive to bar formation, prevails, and the beach gradient is reduced. However, beaches that display a significant beach step

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doi:10.1016/j.margeo.2007.11.008

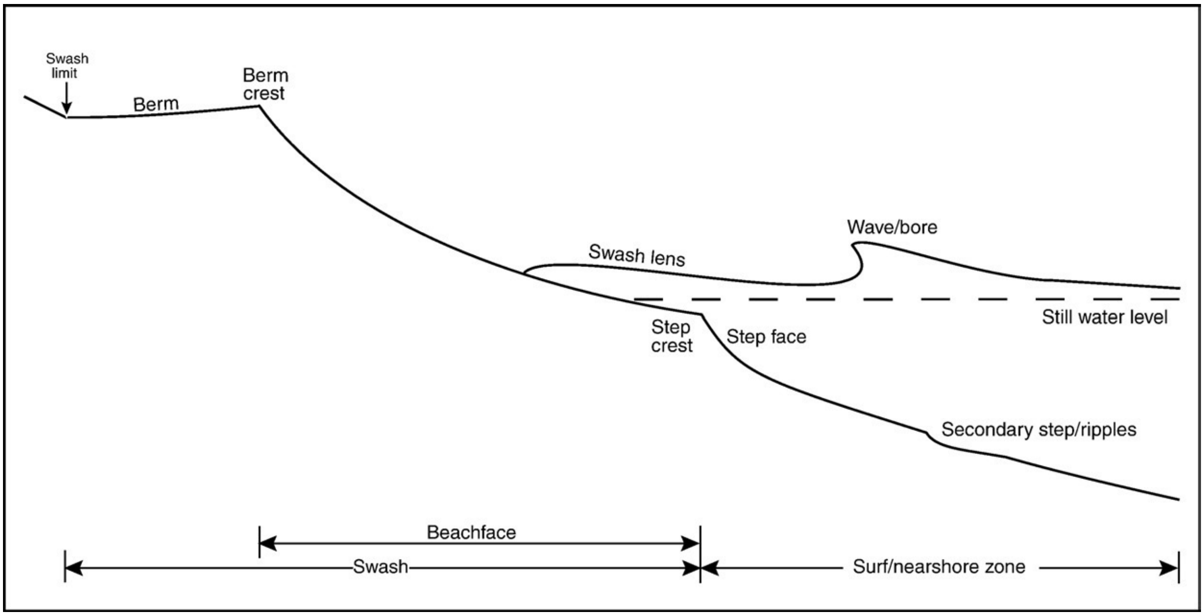

Fig. 1. Generalised schematic diagram of the nearshore profile of a stepped gravel beach indicating the beachface and swash zone morphology, terminology and principal processes found on such a beach.

remain reflective long into storms by increasing the size of the step (Hughes and Cowell, 1987). This forces turbulent wave breaking at the base of the beach and maintains inshore water depth, thereby reducing the sensitivity of the beachface to incident wave energy and preventing the formation of a wide surf zone (Hughes and Cowell, 1987; Austin and Masselink, 2006).

The formation of the beach step has provided an interesting problem for past researchers, and several theories have arisen which attempt to explain its formation; these can be separated into two groups: (1) those associated with sediment convergence and accretionary evolution; and (2) those linked to the formation of a backwash vortex. Miller and Zeigler (1958) and Strahler (1966) argue that the step is an accretionary feature formed by the convergence of sediment at the foreshore base; the incoming wave deposits sediment at the step upon breaking and the backwash draws sediment down-slope from the swash. This also accounts for some of the observed coarsening of the sediments at the step, since wave breaking will remove any fines through suspension processes leaving only the coarse fraction.

The alternative explanation for step formation is the backwash vortex (Matsunaga and Honji, 1980, 1983; Takeda and Sunamura, 1983). Under this hypothesis, flow separation during the backwash creates supercritical flow and vortex formation, whereby landwards flow at the base of the step sustains the step face through avalanching. The flow of water up the step face is thought to maintain fine sediments in suspension, which are subsequently removed by wave induced currents, leaving the coarse fraction at the step. Larson and Sunamura (1993) indicated the importance of phase coupling between incident waves and swash motions to backwash vortex formation thereby suggesting a dependance on wave breaker type (e.g. Kemp, 1975; Bauer and Allen, 1995).

While there have been a number of previous studies that examine the beach step, many of them do so in isolation without consideration of the morphodynamics of the beachface as a whole. For example, the formation and/or migration of a beach step suggests considerable sediment transport—but, a parallel process on most coarse-grained beaches, which also transports a large volume of sediment, is berm formation. Berms principally develop due to asymmetric swash processes stranding sediments around the run-up limit (e.g. Duncan, 1964); however, these sediments must be sourced from lower on the beachface. The step may facilitate berm building by pushing sediments onshore over successive tidal cycles with the result that sediments liberated from depths of several metres must pass through the step region to replenish the beachface. Alternatively, if the volume of sediment landward of the step is plentiful, then the berm may be restructured from these existing materials.

The beach step serves as an ideal setting to examine the relationship between morphological and sedimentological variability, which traditionally receives poor coverage in morphodynamic experiments. The relationship between the spatial variation in sediment size and beach slope is well documented, both in the field (e.g. Krumbein, 1938; Davis, 1985; Inman, 1953) and simulated in the laboratory (e.g., Bagnold, 1940; Kamphuis and Moir, 1977). Sediment size has been invoked to partially explain the development of gravel beach features such as the berm (Masselink and Li, 2001; Austin and Masselink, 2006), and cusps (Sherman et al., 1993). The observed persistence of coarse sediments at the step (Miller and Zeigler, 1958; Bauer and Allen, 1995) would also suggest that sediment size has morphodynamic implications in the region of wave breaking. Indeed, previous studies have suggested that sediment size and morphological change have a co-variability which may reinforce individual distinct morphological features, and sediment transport characteristics through those features, through feedback processes (e.g. Sherman et al., 1993; Tolman, 1994; Rubin and Topping, 2001).