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Dynamics of rip currents associated with groynes — field measurements, modelling and implications for beach safety

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ABSTRACT

Rip currents can occur around groynes and other coastal structures (e.g. breakwaters and geological headlands), which provide a boundary to the wave-induced flow field and present a hazard to water users worldwide. Shore-normal groynes are common along drift-aligned coasts. In northern Europe these are often low-energy, fetch-limited environments that are dominated by locally generated wind waves. The presence of boundary-controlled rip currents due to groynes is supported anecdotally in literature, but few field measurements of their presence and dynamics exist. This study provides new quantitative scientific understanding of the dynamics of boundary-controlled rip currents within this setting. A 10-day field experiment at Boscombe beach on the south coast of England measured rip currents and nearshore hydrodynamics around an impermeable groyne field. Observations from both fixed instruments (wave, tide and current metres) and GPS-drifters confirmed the presence and characteristics of hazardous topographic rip currents around a groyne structure during a number of oblique wave events and drift reversals. The strongest offshore-directed rip velocities of up to 1 m s^{-1} (10-min average) and 2 m s^{-1} (instantaneous) were measured on the updrift side of the groyne where the longshore current generated within the embayment was deflected offshore. These strong rip flows were measured under relatively small wave heights (H_s < 1 m) and presented a significant bathing hazard. A calibrated and validated numerical model (XBeach) was used, in support of measured data, to explore the key environmental controls on rip behaviour across a range of groyne configurations and wave conditions not observed in the field. Key outcomes were that: 1) upstream deflected rip flows were found to be strongly correlated to the alongshore thrust due to wave forcing; 2) the groyne length relative to surf zone width strongly controlled the offshore extent of rip flows, with a significant increase in surf zone exits above a relative groyne length (length/surf width) of 1.25; and 3) rip flows increase up to a relative groyne spacing (spacing/length) of around 4–6, above which alongshore currents are fully developed. These findings have been distilled into some key principals that are relevant to the assessment of boundary-controlled rip hazard on beaches.

1. Introduction

Rip currents can occur around groynes and other coastal structures (e.g. breakwaters and geological headlands) which provide a boundary to the wave-induced flow field. The occurrence of boundary-controlled controlled rips and the strength of the associated flows depend primarily on a combination of the dynamic forcing factors (primarily wave characteristics) and the static controlling factors (location, dimensions and characteristics of the topographic feature, e.g., length of groyne, shape of the headland). The generation of boundary-controlled rips is conceptually explained by the seaward deflection of a strong longshore current upstream of the structure (Castelle and Coco, 2013). Such longshore currents are most commonly associated with obliquely-incident wave approach, but can also be generated by an alongshore gradient in the wave energy level (driving an alongshore pressure gradient due to wave set-up).

The research presented here focuses on rip currents around a groyne field, which are commonly located on drift-aligned coasts susceptible to coastal erosion (e.g., van Rijn, 2011), but the findings relate to any obstruction in the surf zone of similar permeability and scale. While the presence of rip currents both on the upstream and downstream flanks of groynes is regularly supported anecdotally in literature (e.g., Kraus et al., 1994; Short, 1992), very few field measurements (with the exception of Pattiaratchi et al., 2009) exist in literature of their presence and dynamics. In the case of groynes in fetch-limited environments there are no published field measurements to our knowledge.

Most laboratory and field studies into rip current generation around groynes focus on the presence of a pressure gradient driven cell circulation forming on the downstream side of the groyne due to alongshore gradients in wave height, and hence wave setup, due to diffraction

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and wave shadowing (Bowen and Inman, 1969; Gourlay, 1974). In contrast, modelling work around groyne fields in fetch-limited seas using Delft3D (van Rijn, 2011) suggests that the dominant offshore-directed current occurs through the deflection of the longshore current on the upstream side of the groyne. These modelling results further show that under oblique wind wave conditions ($H_s = 1$ m; $T_p = 5$ s; $\alpha = 15^o$), a key geometric control on circulation is the ratio of groyne spacing to groyne length (L_s/L_g). In particular, decreasing L_s/L_g reduces circulation velocities within the cells, while increasing L_s/L_g results in the reestablishment of longshore currents within the cells and an increase in offshore-directed currents. van Rijn (2011) also recognise the significance of the ratio of groyne length to surf zone width (L_g/X_b) as a control on sediment bypassing, but little is known about the impact of L_g/X_b on rip flows.

Recent modelling studies by Castelle and Coco (2013) of boundary-controlled rip currents associated with rocky headlands and embayed beaches (where $L_g/X_b \approx 2$) are also of relevance to the present investigation. They provide a "scaled up" version of a similar problem on high-energy fetch-unlimited coasts. Their modelling results indicated that under oblique swell-wave conditions, the upstream (upwave) rip currents generated are the main mechanism for the exchange of floating material offshore, while the downstream (downwave) rip recirculates within the surf zone, similar to observations by Pattiaratchi et al. (2009). This held true as long as L_s offered a sufficient distance for a longshore current to develop. In narrow embayed beaches the upstream rip became the dominant feature and the most significant offshore exchange mechanism.

Flow characteristics around groynes are of obvious and significant interest to coastal engineers, because the ability of groyne fields to retain sediment is directly linked to the degree of hydrodynamic communication between the groyne embayments: if there are no (strong) flows around groynes it is likely that sediment will (not) be retained. Strong offshore rip flows acting near groynes may also be a significant conduit for transporting sediment offshore. The length, spacing and permeability of the structures are important considerations in the design of groynes and groyne fields and these factors all have a bearing on the development of topographic rip currents, as demonstrated by the modelling of van Rijn (2011).

Boundary-controlled rip currents are also important because they present a hazard to water users worldwide and are demonstrably a key environmental cause of incident on beaches in the UK patrolled by the Royal National Lifeboat Institution (RNLI). According to the RNLI (Scott et al., 2014), over the period 2006–2011, 66% of all water-based incidents on RNLI patrolled beaches were due to rip currents (12,521 incidents) with 21% of all rip incidents involving boundary-controlled rips (2629 incidents). Of all recorded rip incidents over this period, 561 were recorded as lives saved (i.e., without assistance the surf zone user would have drowned) and lives saved associated with boundary-controlled rips (geology and man-made structures) made up 26% of all rip-related lives saved recorded (143). This proportion of lives saved is more than for all other rip incidents, suggesting that boundary-controlled rip incidents were more severe (32% greater potential for lives lost) than those associated with other recorded rip incidents.

Boundary-controlled rip currents are very common in the UK, and indeed along many of the world's coastlines. For example, 74% of all beaches in the UK are classified as being modified by coastal structures; 33% have groynes; 21% have breakwaters; 62% have natural geological outcrops; and 56% have headlands (Scott et al., 2009) — these are all features that have the potential to create boundary-controlled rip currents. If the RNLI incident statistics from patrolled beaches are therefore extrapolated to non-patrolled beaches, it is evidently clear that rips associated with physical hazards are likely to be a major factor in coastal drowning.

The aim of this research is to gain new scientific insight and practical beach safety understanding of boundary-controlled rip currents that occur around coastal structures (e.g., groynes, breakwaters), specifically those located in fetch-limited seas. The principal research aims are: (1) to quantify measured and simulated rip current behaviour (rip flow speed and spatial extent) around a groyne field throughout a range of environmental forcing conditions; and (2) to further explore the impact groyne field geometries have on rip current dynamics throughout a broad parameter space for two important non-dimensional variables L_g/X_b and L_s/L_g.

2. Field site

Rip currents and nearshore hydrodynamics around a groyne field were measured over a 10-day field experiment at Boscombe beach, located in Poole Bay on the south coast of England (Fig. 2). Boscombe is a linear subtidal barred beach (Scott et al., 2011) with a median sediment size (D_{50}) of 0.28 mm. The beach at Boscombe has a relatively steep reflective upper beach (tan$\beta = 0.06$) and flatter more dissipative intertidal low-tide terrace (tan$\beta = 0.03$). The subtidal beach is characterised by a linear subtidal bar (Fig. 3) over which wave breaking occurs at low water under medium-high energy waves (typically when $H_s > 1$ m). Boscombe beach is part of a longer section of a continuous south-facing beach stretching from Poole to Southbourne (15 km). This coastline is characterised by extensive groyne fields that are typical of those found throughout the drift-aligned coasts of the UK. The groyne system at the Boscombe field site has an average longshore groyne spacing (L_s) of 200 m with a design length of 70 m from groyne tip to the promenade, but a typical active groyne length (L_g) from shoreline to groyne tip of 50 m giving a groyne spacing to length ratio L_s/L_g of 4. The beach at Boscombe is known to have intermittent boundary-controlled rip current generation around the groyne systems. RNLI lifeguard incident records for the period 2006–2011 show that 496 individuals have been involved in rip current incidents in Poole Bay.

The wave climate at Boscombe is dominated by locally-generated wind waves with a small amount of Atlantic swell wave energy penetrating up the English Channel from the west. It is a low-energy wave environment that experiences intermittent medium-high energy wind waves from a variety of directions (SE — SW). Wave statistics from data collected by a Datawell directional wave-rider buoy at Boscombe, moored in 10 m water depth (refer to Fig. 2), for the period 2003–2012 are shown in Table 1. The annual mean significant wave height (H_s) is 0.53 m with a peak (T_p) wave period of 7.1 s. While monthly mean values of peak wave direction (D_p) are typically close to shore normal (180°), the mean standard deviation (σ) is 21.3°. On average, the wave angle from shore normal (α) is greater than 10° for 66% of the time. Boscombe is classified as microtidal, and has a mean spring tide range of 1.5 m, with mean low and high water spring tide levels of −0.9 and 0.6 m ODN (Ordnance Datum Newlyn), respectively. The tidal range is small in the context of the UK environment.

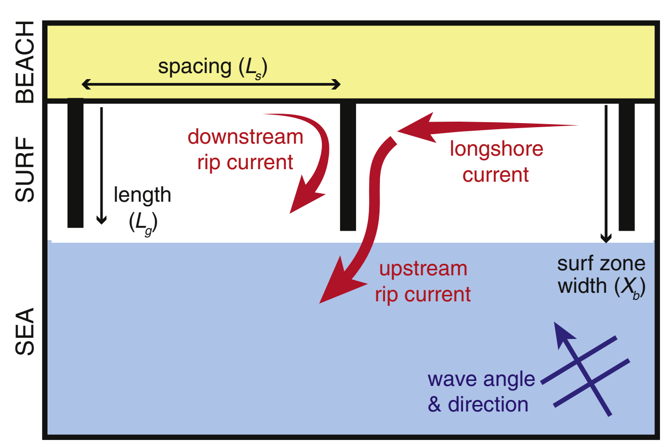

Fig. 1. Schematic of principal topographic rip circulations and parameters governing the geometry of the topographic obstruction.