Form and Function of Natural and Engineered Perched Beaches

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Abstract
With predicted sea level rise and possible changes in storminess associated with climate change, it is not known how *perched beaches,* whether natural or engineered, will respond. Perched beach types range from beaches fronted by wall-like structures in the nearshore that may be connected to the dry beachface, to having underlying and outcropping geological formations. They may also be backed landward by hard structures such as cliffs or infrastructure instead of dunes. In this study, the global distribution of natural perched beaches from existing literature was mapped. 'Hot spots' include the West Indies, Central and South America, Pacific Island Atolls, Indian Ocean islands, the Red Sea and the Mediterranean region. Many of these areas are in the tropics and subtropics and hence are associated with beachrock with is common in areas with coral reefs. Mechanisms of beach control by coastal structures are still poorly quantified. Suggested mechanisms include: limited free-profile fluctuation, decreased sediment availability and increased erosion rates due to less water infiltration and raised beach groundwater tables. Field research in southwest Western Australia indicated that perched beach profiles may recover more slowly from the daily summer sea breeze erosion than exposed profiles. During a storm, perched profiles had less erosion, occurring lower on the beachface than exposed profiles. Perched profiles however did not recover as easily by accretion during low sea level phases of storm activity. Lower rates of recovery for perched profiles could be due to a scour step forming seaward of the rock formations inhibiting cross-shore sediment transport. Results indicate that natural perched beach behaviour has extreme spatial variation. Beach response to changing hydrodynamics is strongly dependent on the configuration and geometry of local coastal structures, whether natural and anthropogenic.

Keywords: geologic framework, rock platform, reef, coastal structure, geological control

1. Introduction

Globally, up to 75 % of the world's coasts are rocky [1]. Of Australia's 10,685 beach systems, 779 are classified as rocky and 254 as having coral reefs [16]. These coral and rocky beaches are classified as reflective according to [21]. The term *perched beach* is used loosely in engineering literature. According to [19], a perched beach is 'a beach or fillet of sand retained above the otherwise normal profile level by a submerged dike'. Another engineering term used for perched beaches is a *hard bottom* beach. A hard-bottom was defined by [12] as 'a non-erodible feature that may be located anywhere on the subaerial and subaqueous beach'. They noted that hard bottom may consist of natural materials including worm-rock, limestone, coquina, coral and sedimentary rocks; or engineered structures such as concrete. Combining these definitions, here we define a perched beach as '*a beach underlain and/ or fronted seaward by shallowly-buried or outcropping natural or engineered hard structures'*.

With forecasted sea level rise and possible associated changes in wave climate and storminess, it is not known how perched beaches will respond. The general consensus is that perched beaches do not behave in the same manner as sandy beaches that are not associated with coastal structures. To predict how perched beaches will behave, first the mechanisms of beach control by coastal structures need to be identified and quantified. There is still much debate over how structures engineered for coastal protection, including seawalls and breakwaters affect beach behaviour [4; 13], let alone naturally-occurring coastal structures.

The overall aim of this research was to consolidate existing information on the global natural perched beach distribution, types and behaviour. This aim was divided into three sub-objectives which were:

(1) develop a simple geomorphic-classification of natural and engineered perched beaches;

(2) map the global distribution of different types of natural perched beaches; and

(3) develop a conceptual model of perched beach behavioural mechanisms, focusing on Yanchep Beach and Lagoon in southwest Western Australia (WA) (Figure 1) as a case study.

2. Methodology

Existing literature was used to develop a global distribution of different types of natural perched beaches and a simple classification, building on the work of [6]. This distribution is not exhaustive as there are still many perched beaches around the world that have not been mentioned in the literature, especially in developing countries. The distribution does not include bare rocky coasts with no beaches, nor perched beaches formed purely due to coral reefs. Essentially all beaches fronted by nearshore coral reefs can be considered as perched, and the world-wide distribution of coral is already well established (e. g. [17]). The geomorphic type of perched beach included in the distribution map, consisted of first establishing a classification scheme of types of natural perched beaches. A conceptual model was developed of mechanisms by which coastal structures at a perched beach control the beach behaviour. This model used both existing literature and findings from field work undertaken at Yanchep Lagoon in Western Australia (Figure 1) as a case study.

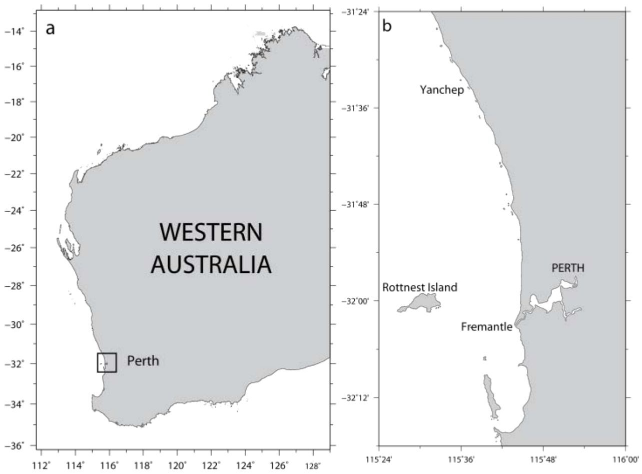

Figure 1 (a) Location of Yanchep in Western Australia and (b) the Perth region.

3. Engineered Perched Beach Classification

Many beaches with coastal structures built for beach protection, as was outlined in [10], can be classified as perched beaches. Structures built for coastal protection resulting in perched beaches include seawalls and shore-parallel breakwaters and multipurpose reefs, which are often used in combination with beach nourishment (Figure 2).

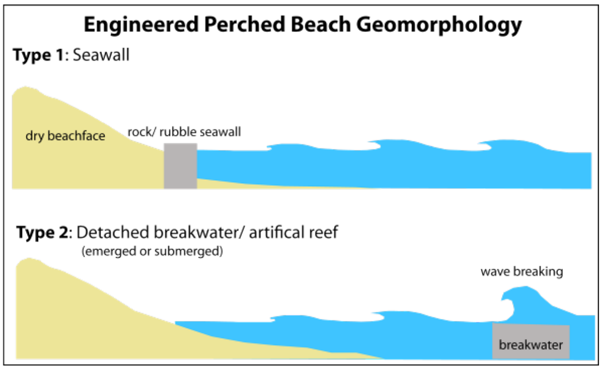

Figure 2. Classification of Engineered perched beaches.

4. Natural Perched Beach Classification

Natural perched beaches are formed in association with a variety of natural coastal structures. The most common formations associated with perched beaches include coral reefs (live or fossilised), beachrock and aeolianite (dune rock). Beachrock is most common in tropical and subtropical seas, and rare in temperate seas. Aeolianite is a term used to describe consolidated sedimentary rock deposited by wind [14] where sediment has been lithified.

Figure 3 Examples of natural perched beaches: (a) Cuba (source: M. Vousdoukas); (b) south of Yanchep in Western Australia (source: S.L. Gallop); and (c) near Colombo in Sri Lanka (source: A. de Vos).

Whilst there are several theories of beachrock formation [20], the term 'beachrock' is used to describe a consolidated deposit due to lithification by calcium carbonate of sediment in the intertidal and spray zones [15]. The most widely proposed mechanisms of beachrock formation are due to direct cement precipitation from marine or freshwater, followed by lithification due to biological processes then cement precipitation from mixed marine and meteoric waters [20]. In this paper we have taken a purely geomorphic focus on perched beach classification, classifying beach types by the geometric form of the coastal structure rather than the material the structure is made of.

The three main geomorphic types of natural perched beaches mentioned in existing literature are: (i) intertidal platform of relatively continuous rock; (ii) patchy beachrock in the intertidal zone and/ or on the beachface; and (iii) a rock or coral reef attenuating wave energy which may be in combination with an intertidal platform and/ or rock patches in the intertidal zone or on the beachface (Figures 3 and 4).

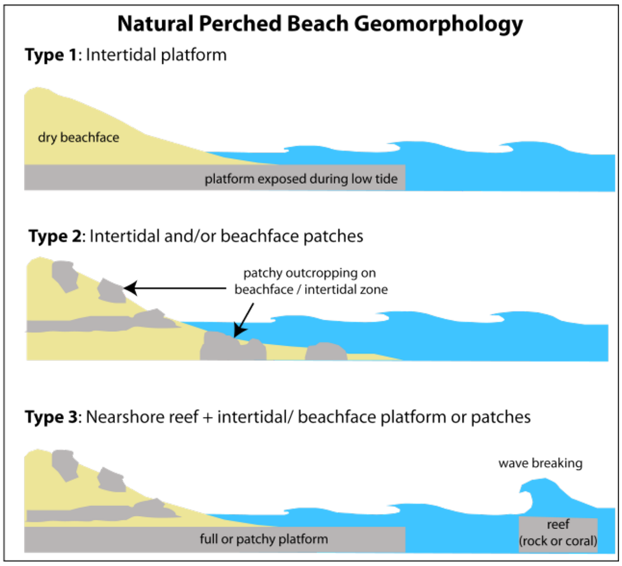

Figure 4 Classification of natural perched beaches using a geomorphic approach.

Seasonal or shorter-term changes such as those experienced during a large storm event, may expose and then re-cover rock outcrops at a perched beach with sediment. For example at Cottesloe Beach in southwest Western Australia, seasonal patterns of erosion and accretion were identified, exposing then re-covering the rock platform on the beachface [2]. For a beach to be classified as perched, the underlying rock must be shallow enough so that it has an effect on the beach sediment transport and beach morphology. Similarly, if the perched beach is associated with a nearshore reef or similar structure, the structure must be close enough so that it can influence sediment transport. The structure therefore must be landward of the *closure depth* – a measure of the maximum water depth for intense re-suspension of sediment by shoaling waves of a given height and period [9]. Beyond the closure depth, no significant longshore or cross-shore sediment transport occurs due to littoral processes i.e. it is the seaward boundary of the littoral zone.

5. Natural Perched Beach Distribution

Analysis of perched beaches mentioned in literature revealed that natural perched beaches occur globally. 'Hot spots' include the West Indies, Central and South America, Pacific Island Atolls, Indian Ocean islands, the Red Sea and the Mediterranean region (Figure 5). Most of these hot spots are in the tropics and subtropics and are associated with beachrock [20] which is especially common on island beaches that are fronted by coral reefs [3; 8]. Beachrock however does not occur exclusively where there are coral reefs. While in some areas they are found only on coasts with carbonate rocks such as limestone and marble, they are also found in arid areas and on coasts with islands that are too small to have permanent fresh watertables [20].

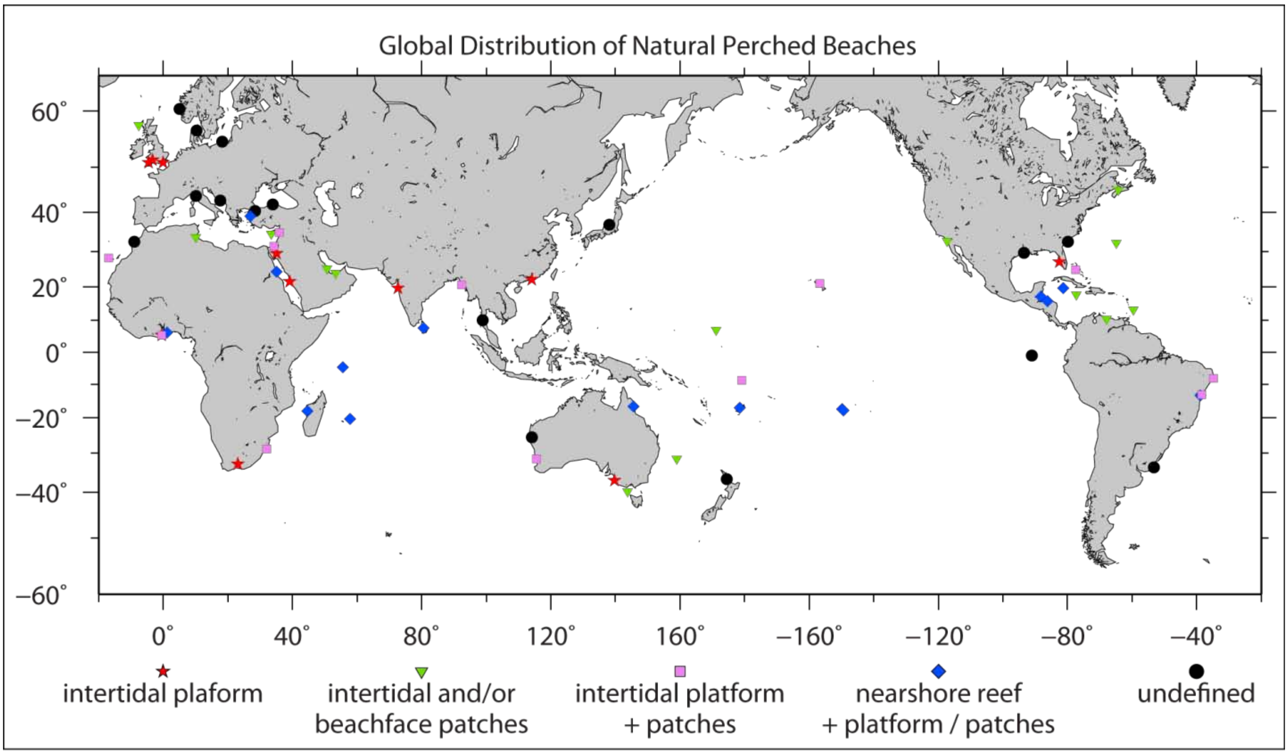

Figure 5 The global distribution of natural perched beaches from existing literature.

The different geomorphic forms of perched beaches (Figure 4) are relatively equally represented over the globe (Table 1). Intertidal platform beaches are scattered spatially. Intertidal and/ or beachface patch perched beaches are mostly found in temperate regions and intertidal platform plus patches mostly in the subtropics. Perched beaches associated with nearshore reefs and platform/ patches are most common in the tropics and subtropics.

Coastal states with the most reported occurrences of beachrock are Australia, Greece and Brazil [20]. Similarly, coral reef hot spots include South East Asia, the Indian Ocean, The Pacific Islands, the Caribbean Sea and the Mediterranean [17]. Perched beaches in more temperate climates such as North America and Northern Europe tend to be associated with other rock types such as aeolianite.

Table 1 Occurrence counts of perched beach types from literature.

Type	Count
Intertidal platform	16
Intertidal and/or beachface patches	11
Intertidal platform + patches	15
Nearshore reef + platform/ patches	14
undefined	12

6. Conceptual Model: Case Study at Yanchep Lagoon

Mechanisms through which coastal structures affect beach behaviour operate on a variety of temporal and spatial scales, from micro- to megascale [11]. Here we focus on changes in the (i) macroscale over months–years over km–10's of km; and (ii) mesoscale over hours – days over m – km. The conceptual model presented here used results from field studies at Yanchep Lagoon [5; 6; 7]. Yanchep Lagoon is perched on Quaternary Limestone formations. The beach consists of medium sand with d_{50} of 0.4 mm. Whilst the local coastal structure geometry varies along the 2 km-long beach, most of the beach is Type 4 – fronted by a limestone reef partially closing a lagoon and underlain by limestone (Figure 6).

In the macroscale, the beach appears to have a seasonal cycle of erosion and accretion. Beaches in general tend to accrete during summer and erode during winter due to storms. This happens at the southern section (Figure 6) that builds up during the summer sea breeze season when the hydrodynamics are wind dominated. However, during summer the northern section erodes due to the sand build up on the southern section blocking sediment supply through the lagoon. During winter when the hydrodynamics are swell-dominated, the southern section erodes and the lagoon extends southwards. This leads to accretion in the northern section as sediment is transported alongshore in the lagoon to the north. There is much greater seasonal beach width variation at the southern section compared to the northern section due to changes in the longshore sediment supply.

Figure 6 Yanchep Lagoon.

In the mesoscale, field data during the strong summer sea breeze [5; 6] and also a winter storm event [7] has revealed processes by which the coastal structures affect the beach behaviour. During a winter storm, beach profiles fronted seaward by limestone suffered less erosion but also recovered less (Figure 7). During the summer sea breeze, the beach section fronted seaward by submerged limestone near the lagoon exit suffered more erosion but had less overnight recovery (Figure 7). The coastal structures at Yanchep strongly influence the hydrodynamics, which in turn affects the beach behaviour.

Beach groundwater is also likely to play a key role in perched beach behaviour [12]. There is a need for more research to quantify how beach groundwater is affected by coastal structures as it may lead to higher erosion rates.

7. Discussion and Conclusions

Perched beaches can be formed due to naturally occurring coastal structures, or engineered structures that are generally built for coastal protection. Perched beaches occur globally, and are an important part of the Australian coastline. With increased pressures on the coast from concentrated coastal development and environmental pressures it is not known how perched beaches will behave. This means that it is crucial that baseline data is obtained about the distribution of perched beaches and mechanisms of their behaviour.

In this work the global distribution of different types of natural perched beaches was mapped and a conceptual model of perched beach behaviour was established. While the natural global perched beach distribution is scattered, there are hot spots mostly in the tropics and subtropics, often due to the presence of beachrock and coral reefs.

Mechanisms of perched beach control by coastal structures occur over a range of temporal and spatial scales such as from sea breeze and storm events to seasons. Coastal structures are generally assumed to provide beach protection. At a natural perched beach, in some cases rock structures appear to provide some beach protection from incoming waves. The structure however can also inhibit beach recovery by impeding cross-shore sediment transport from rebuilding the beach.

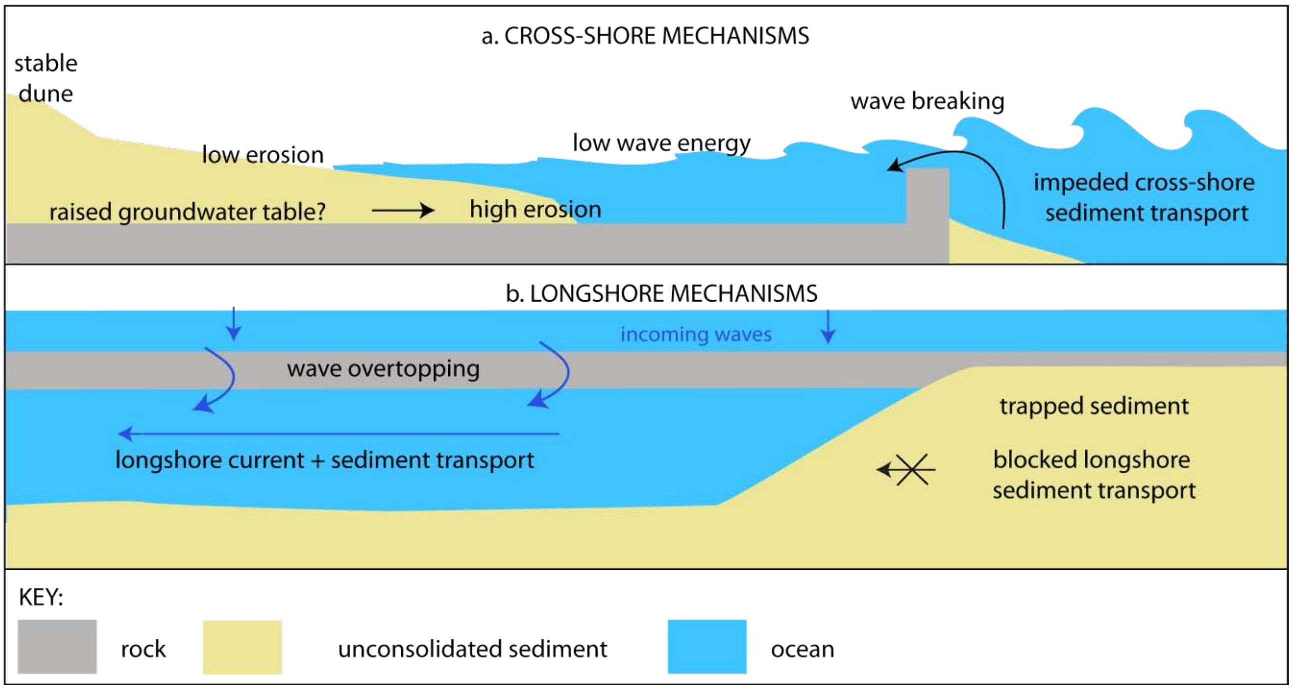

Figure 7 Conceptual model of perched beach behavioural mechanisms in (a) the cross-shore direction and (b) the longshore direction.

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