Coastal Engineering 95 (2015) 147–159

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Performance of submerged nearshore sand-filled geosystems for coastal protection

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ARTICLE INFO

Article history:
Received 7 May 2014
Received in revised form 17 October 2014
Accepted 20 October 2014
Available online 10 November 2014

Keywords:
Erosion
Scour
Beach lowering
Geosystems
Movable-bed models
Shoreline protection

ABSTRACT

Nearshore submerged structures made of sand-filled geosystems are an interesting use for this type of coastal protection technology. These systems have an advantage over more traditional materials such as concrete units or rock, which is the limited and non-permanent impact on natural coastal processes. On top of that are also some important research achievements and improvements at the level of the materials. However, at more exposed hydraulic conditions under high wave energy its application is still hampered by the lack of knowledge about their performance. This paper describes research results based on a series of laboratory measurements of the hydrodynamic and morphodynamic change produced in the vicinity of submerged nearshore structures. An analysis of the different model outputs produced, with respect to sediment transport, wave reflection and wave-induced pressures, has been made and is discussed throughout the paper. Such a comparative analysis provides insights into the efficiency of each defence scheme in maintaining a beach and in protecting the shoreline. The sand-filled geosystems as nearshore submerged structures proved to be efficient in retarding the offshore movement of sediments and in maintaining the shoreline, even if instabilities due to elements' displacement and local scour have been observed.

1. Wave–geosystems interaction

The growing importance of delivering more sustainable coastal erosion techniques, which make use of readily available materials and have lower permanent impact on natural coastal processes, is becoming more and more present in design and in decision-making. Examples of such techniques are, for instance, the artificial infill of a beach with sand, concentrated sand nourishments (De Vriend and Van Koningsveld, 2012), the construction of wave farms (Abanades et al., 2014a, 2014b), and also coastal structures incorporating sand-filled geosystems. Within this context the use of sand-filled geosystems in coastal engineering is of growing interest and is a solution in full development as far as materials, applications and design tools are concerned. A geosystem for erosion control can be defined as a flexible structure constructed with readily available soil-fill wrapped in a synthetic fabric that withstands the erosive power of water. The possible applications of sand-filled elements are typically categorised into closed systems (such as bags, tubes or containers) and open systems (retention of soil by an anchored fabric). The concept has been used successfully in low energy coasts with low tidal range and as temporary structures. However, there are many advantages to these systems of which the cost-effectiveness and the environmental-friendliness are possibly the most relevant ones working in support of the growing of interest and acceptance of the use of sand-filled geosystems for coastal protection also in higher wave energy coasts and as permanent structures. The research carried out at the Leichtweiβ Institute in Germany (see, e.g., Oumeraci and Recio, 2009; Recio, 2007; Recio and Oumeraci, 2007a, 2007b, 2007c; Oumeraci et al., 2002; Dassanayake, 2013) and at DELTARES in The Netherlands (see, e.g., van Steeg and Vastenburg, 2010; van Steeg and Breteler, 2008) has provided valuable improvements to the knowledge available on the stability of geotextile encapsulated-sand systems under wave loading. A recent research by das Neves (2011) gives further contribution to that knowledge, with emphasis on scour development and more widespread beach lowering. Notwithstanding, valid design guidelines are yet to be available and a significant part of the knowledge still stems from the practical experience worldwide, constituting an obstacle to a wider application. The intrinsic limitations of the geotextile materials and some constructability issues are also a point of concern. The influence of the mechanical properties of geotextile materials on the stability of encapsulated-sand systems has been extensively investigated, being found that characteristics such as tensile strength, interface shear strength and permeability of a sand container are greater than that of the container material itself (see, e.g., Matsuoka et al., 2001, cited in Recio, 2007). The permeability of a geosystem, which significantly influences its hydraulic stability, is governed by the gaps between elements rather than the permeability of the geotextile material itself (e.g., Bourzaev, 2003—cited in Recio, 2007).

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http://dx.doi.org/10.1016/j.coastaleng.2014.10.005

The effect of a submerged structure is higher when placed in the nearshore zone, because the influence on wave transformation processes is higher making the influence on sediment transport mechanisms higher as well. For design purposes, it is assumed that incident wave energy can be partly dissipated by wave breaking, surface roughness and porous flow; partly transmitted leeward due to wave overtopping and penetration (if the structure is permeable); and partly reflected seaward (USACE, 2008). The main parameters influencing wave transformation over a submerged structure are: relative crest freeboard or submergence (Rc), crest width (B), seaward slope (tanβ), water depth at the structure (h), incident wave height (H_i), peak wave period (T_p), and breaker parameter ($\xi = \tan\beta \, / \, (H_0 \, / \, L_0)^{0.5}$, with H_0 and L_0 being the deep water wave characteristics) (see, e.g., Van der Meer et al, 2005; Pilarczyk, 2003).

Considerable research has been carried out on the hydrodynamics around conventional structures (see, e.g., Castro et al., 2011; Taveira-Pinto, 2001; Van der Meer and Deamen, 1994; Van der Meer et al., 2005); however, little information on this topic is available for geotextile encapsulated-sand systems. Pilarczyk (2000) includes some references on the wave transmission over geosystems and submerged reefs referring to the experiments carried out by DHI (1970), Ahrends (1985) - cited in Pilarczyk (2000) and Goda (1996). Reflection coefficients for non-woven geocontainers were obtained from small and large scale model tests performed by Oumeraci et al. (2002). The increase of the transmission coefficient with the relative crest submergence and the increase of the reflection coefficient with the breaker parameter were stated in research published for both types of structures, i.e., conventional structures and geosystems.

As far as local hydrodynamics around a submerged structure is concerned, a description of the generated vortices and their effects on the hydraulic performance can be found in Bleck and Oumeraci (2002). For a better understanding of wave transmission and reflection over a submerged structure the analysis of the wave spectra is often performed. According to USACE (2008) transmitted wave-periods are about half that of the incident waves. A simple and basic model to predict the transmitted spectra for rubble mound and smooth structures was developed by Van der Meer et al. (2000).

Movable-bed models are commonly used to study sediment transport, beach evolution and coastal problems. The coastal sediment transport can be read as two separate components: longshore component (or littoral drift current) and cross-shore component. Yet, it is the cross-shore component of sediment transport that is most interesting in the assessment of the dune–beach evolution under wave-loading, the main scope of the present work. From the available knowledge, it appears that the cross-shore transport processes mainly depend on the sediment properties (e.g., grain size, density, and fall speed) and hydrodynamic conditions (e.g. wave characteristics, and local water depth), and the interplay between both. The complex and stochastic nature of incipient motion led researchers to investigate the influence of other features such as turbulence (Zanke, 2003); density (Nielsen, 2009), sorting (Mitchener and Torfs, 1996), and packing (Komar, 1998); bed slope angle (Dey, 2003); and wave shape (Terrile et al., 2006).

A coastal stretch exposed to changing hydrodynamic conditions reacts with readjustments in the beach- and nearshore profiles. In deep waters most of the sediments are transported due to tidal or ocean currents, by bed-load transport, whilst in the nearshore zone suspended-load transport is relevant. Dean (1977) — cited in e.g., USACE (2008) proposed an equilibrium condition for beach profiles useful for practical approximations although it does not represent bars, that reads:

$$d(x) = Ax^{2/3} \tag{1}$$

in which d is the profile water depth to Mean Sea Level (MSL) at a distance x from the MSL shoreline and A represents a sediment scale parameter depending on the grain size D.

Other authors proposed additional equilibrium profile shapes to overcome the mentioned shortcoming (see, e.g., Inman et al., 1993; Wang and Davis, 1998).

The presence of a structure induces changes on the hydro- and morphodynamic processes, often linked to scour development and consequent geotechnical structure's instability. Sumer and FredsØe (2002) and Whitehouse (1998) cover many of the background information on the process of scour and the prediction methods currently in use. Several field, experimental and numerical studies have developed non-dimensional relationships for predicting the maximum scour depth, S_{max} (see, e.g., the formulations by Xie, 1981; Sumer and FredsØe, 2000; Hughes and Fowler, 1991; Fowler, 1992; Sutherland et al., 2008). A significant part of these studies were performed for regular standing waves, with no-suspension sand transport mode and plane beaches (several with flat beaches), which represent important shortcomings. According to Oumeraci (1993), the most dramatic failures due to bottom scour in the field occurred for wave breaking just in front of the structure. The investigation of the scour process on a developed profile would be important, as the natural occurring morphologic perturbations exert strong control over shallow-water wave transformation, and vice-versa. The scour dependency on the reflection coefficient was also addressed by many authors (Sumer and FredsØe, 2000; Xie, 1981) — higher reflection coefficients are linked to greater scour. A conservative scour estimate is then provided by vertical-wall scour prediction equations.

From the knowledge available it can be concluded that further research on the wave–geosystem interaction is needed. A deeper insight on such topics could enable a feasible prediction of the wave climate acting on a sheltered beach and bring in improvements to the existing stability formulae and practical guidelines for the design of geosystems for coastal erosion protection.

An assessment of the performance of sand-filled geosystems in protecting a beach and shoreline is briefly discussed throughout the paper, with focus on the hydrodynamic processes around nearshore structures and on the processes of cross-shore sediment transport and scour development. The discussion is based on experimental results of the evolution of a dune–beach system protected with different geosystems under more exposed hydraulic conditions. The experiments were carried out in the wave basin of the Hydraulics Laboratory (LH) of the Hydraulics, Water Resources, and Environment Division (SHRHA) of the Faculty of Engineering of the University of Porto (FEUP). An intercomparison of the outputs produced by the various coastal defence schemes with focus on wave-reflection, wave induced pore-pressures and response of the bottom profile is described, providing insights into the efficiency of different geotextile encapsulated-sand systems in stabilizing a beach and the shoreline. Because of the efficiency of the nearshore submerged structures in retarding offshore sediment transport observed in the model, these results will be discussed in further detail.

2. Experimental work

The experiments were conducted in the wave basin of LH-SHRHA-FEUP which is 28 m long, 12 m wide, and 1.2 m deep but was partitioned to a wave channel of 2.25 m wide, comprising 3 wave-paddles of the wave generation system available (HR Wallingford, 2007) (Fig. 1). The nearshore hydro- and morphodynamics of a dune–beach system in the presence of different types of defence schemes was studied with the construction of a 2D movable-bed model, scaled to Froude similarity with length scale of 12. A plane beach (slope: 3:20) started 9.7 m from the wave paddles followed by a dune (or erosion control system).

Five models were taken for the investigation — three passive erosion control systems (model B: several individual geotextile sand-filled containers; model C: wrapped-around system; and model D: geotextile tubes), one nearshore detached submerged breakwater (models E1 to E4: geotextile tubes with varying distance to the shoreline, diameter