Journal of Coastal Conservation
https://doi.org/10.1007/s11852-018-0653-6

Coastal dunes with resistant cores

Karl F. Nordstrom [1]

Received: 14 June 2018 / Revised: 18 August 2018 / Accepted: 23 August 2018

Abstract
Hybrid shore protection projects combine hard structures with beaches, sand dunes and vegetation, mimicking the appearance and function of natural landforms. These advantages can also accrue to structures built as primary protection that eventually become covered by sand following natural accretion, artificial nourishment or burial by earth-moving equipment. This study reviews the advantages and disadvantages of dunes designed and built as hybrid structures using geotextiles, gabions and clay as core elements and dunes that eventually form over traditional beach protection structures that are built independently of a sand cover. Dunes constructed with hard cores can be considered soft solutions that overcome restrictions by regulatory agencies against hard shoreline armoring, but most hybrid designs are low-cost temporary solutions. Protection plans should also include subsequent protection actions that address long-term needs. Hard cores should be placed close to the human facilities to be protected to increase space for naturally functioning landforms and habitats seaward. Mechanical reburial of exhumed cores should occur as soon as possible to help prevent damage to them, reestablish habitat and aesthetic value, reestablish safe access between beach and upland for native fauna and beach users, and keep nature and the need for restoration in the minds of beach users. Keeping the fronting beach wider by artificially nourishing it can protect the structure from exhumation, provide a larger sand surface for dune buildup by aeolian processes and provide space for a more natural environmental gradient across the shore.

Keywords Beach erosion · Coastal hazards · Dune restoration · Geotextiles · Protection structures

Introduction

Development of coastal zones has increased through time, placing ever more human infrastructure at risk from flooding and erosion (National Research Council 2014). Adaptation to coastal hazards by relocating human development away from the shore is often advocated but is usually resisted by the public and rarely implemented (Abel et al. 2011; Roca and Villares 2012; Niven and Bardsley 2013), leading to demands for protecting buildings and infrastructure in place through shore protection programs. The emphasis on these programs in many countries shifted through much of the twentieth century from primary dependence on hard structures to soft solutions, including beach and dune nourishment (Paskoff and Kelletat 1991; Hillyer et al. 1997; Manno et al. 2016) and vegetation plantings in low-energy environments (O'Donnell 2017). Despite this interest in environmentally compatible options, static structures are often still needed. Ongoing erosion is decreasing available beach space while economic and environmental constraints and exhaustion of local sediment sources constrain beach nourishment as an easy solution. Hard structures are now often used as a complement to soft solutions. Complementary structures include breakwaters, sills or groins built to hold beach fill in place (Luo et al. 2016) or facilitate growth of vegetation (Gittman et al. 2014; Kochnower et al. 2015), breakwaters to allow natural environments to form landward (Hardaway and Gunn 2010), or resistant cores embedded within beaches and dunes to restrict their erosion during storms and provide temporary protection until larger or costlier protection projects are initiated (d'Angremond et al. 1992; Dette and Raudkivi 1994; Feagin 2005, 2013; Antunes do Carmo et al. 2010).

Shore protection structures are designed to alter the impact of waves, current flows and sediment transport relative to natural processes, and they introduce exotic hard habitat to sandy environments and create barriers to movement of fauna. Previous reviews address the effects of shore protection structures on beach change, sediment budgets, and the biodiversity, productivity, structure and function of coastal ecosystems, as

✉ Karl F. Nordstrom
nordstro@marine.rutgers.edu

1 Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA

Published online: 30 August 2018

well as the ways the structures can be made less environmentally damaging or their effects mitigated (Kraus 1988; Kraus and McDougal 1996; Bulleri and Chapman 2010; Dugan et al. 2011; Nordstrom 2014). Greater attention is now being placed on designing structures that replicate or enhance natural landforms and habitats to the extent possible (Brunsden and Moore 1999; Chapman and Underwood 2011; Nordstrom 2014).

A case can be made for the need to provide multiple levels of protection in erosion control projects to make coastal communities more resilient (Smallegan et al. 2017). Hybrid shore protection projects combine structures with natural components, including beaches, sand dunes and vegetation. These projects can take advantage of the best characteristics of built and natural elements, allow for innovation in designs, provide benefits besides coastal protection, provide a greater level of confidence than natural approaches alone, and can be used where there is little space for a purely natural approach (Sutton-Grier et al. 2015). Exposed shore protection structures can have a negative effect on environmental quality by severing the connection between beach and upland and human welfare (as a result of decreased safety and aesthetic quality), whereas beach and dune nourishment and dune building have a positive effect (Semeoshenkova and Newton 2015). Burial of hard shore protection structures can re-establish the connection between the beach and landward habitats and restore some of the natural process-response relationships between waves and currents and faunal interactions.

The coastal zone is aesthetically desirable and economically important, although risk is highly correlated with amenities (Bin et al. 2008). Accordingly, aesthetics is now becoming part of the rationale provided for developing new shore protection designs and converting older emerged structures to submerged structures (Lamberti et al. 2005; Pranzini et al. 2018). Stakeholders can prefer natural infrastructure for aesthetics as well as for ecosystem benefits and recreation, but they may also believe that engineered infrastructure is more effective in coastal hazard mitigation (Roca and Villares 2012; Ewalt Gray et al. 2017).

This study reviews the ways hard structures are incorporated as cores within dunes resulting in surficial landforms that at least partially mimic the appearance and function of natural dunes, with an assessment of the advantages and disadvantages of these hybrid structures. Examples of hard cores in dunes include (1) resistant cores designed as components of dune-building projects using geotextiles (Gibeaut et al. 2003; Feagin 2005, 2013; Antunes do Carmo et al. 2010) (Fig. 1), gabions (d'Angremond et al. 1992), clay (Wamsley et al. 2011) and rock or concrete units (Basco 1998); (2) structures built independently of a sand cover but intended to be followed by beach or dune-nourishment projects, such as emergency sheet pile bulkheads built right after storms (Young et al. 2016; Nordstrom and Jackson 2018) (Fig. 2); and (3) rock revetments and seawalls designed as primary protection that become covered by beach accretion or aeolian transport later, when the local sediment budget is enhanced (Irish et al. 2013; Smallegan et al. 2016) (Fig. 3). Sand fences, hastily emplaced riprap, buildings partially destroyed by wave action, and intact cultural features that are perceived to interfere with aesthetics or recreational uses can also become hard elements in dunes through burial by natural or human processes. These elements are not designed as resistant layers nor do they provide sufficient protection against attack by waves and swash and inundation landward. This discussion is confined to cores that incorporate protection structures normally considered appropriate to the energy level of the waves where they are deployed.

Methods

Most projects involving use of new hard cores are small scale and implemented by private organizations or municipalities, so information is difficult to obtain outside of newspaper articles and websites. The scholarly literature is used to address the few examples of hard core dunes subject to scientific and engineering evaluations and make a case for the significance of results from reports in the gray literature. Many of the sites used as examples in this paper are in the state of New Jersey, USA (Fig. 4), where shore protection structures are numerous and where recent beach and dune nourishment projects have resulted in intentional and unintentional burial. Storm waves from Hurricane Sandy, which caused extensive damage in the state in October 2012, exhumed several buried structures and provided the impetus for construction of several new projects using buried cores (Irish et al. 2013; Plumlee et al. 2016; Nordstrom and Jackson 2018). Dimensions of some projects were determined from design specifications identified in Corps of Engineer projects (U.S. Army Corps of Engineers Philadelphia District 2016). Dimensions of structures, where not provided in publications or government documents, were obtained from Google Earth images at scales of 1:1000. Evaluation is separated into the type of core material used (geotextiles, gabions, clay, hard structures), the significance of the surface placed over the core, the need for reburial of the core when exposed, and the spatial constraints of constructing hybrid dunes on narrow eroding beaches. The discussion of use of geotextile cores is more extensive than discussion of cores designed using other materials because projects using geotextiles are better documented. Many of the concepts applicable to geotextiles apply to other core materials.

Core materials

Geotextiles

Geotextiles made of natural fibers have been in use for engineering purposes for thousands of years (Ashis 2015), but the

Fig. 1 Geotube being repaired at Atlantic City, New Jersey in March 1996. The dunes to either side of the installation site are similar geotubes covered by bulldozed sand

growth of geotextile container technology has been especially rapid in recent years (Saathoff et al. 2007), with increased use as shore protection systems (Hornsey et al. 2011). Geotextile containers can be used in lieu of more traditional materials in breakwaters, groins, revetments, and offshore breakwaters (Saathoff et al. 2007; Balouin et al. 2016) as well as in mid-beach use to create perched beaches (Gutman 1979; Alvarez et al. 2007). Geotextiles can be used in closed forms as bags or tubes or open as sheets and wraps. Geotextiles may be selected over more durable alternatives because of cost effectiveness, ease of construction, local shortage of other construction materials or reduced effect on the environment relative to larger-scale hard structures (Pilarczyk 1996; Schreck Reis et al. 2008). The consideration that geotextiles are more environmentally and user friendly than rock or concrete and more temporary, make them preferable to users and environmental regulatory agencies (Saathoff et al. 2007; Hornsey et al. 2011; Corbella and Stretch 2012).

Geotextiles are most appropriate in locations where the infrastructure at risk is not critical (das Neves et al. 2009),

Fig. 2 The exposed portion of the 5.6 km-long steel bulkhead built at Mantoloking, New Jersey in October 2016. The bulkhead was built after erosion caused by Hurricane Sandy in October 2012. The sand cover initially placed over the structure has eroded. Fence placement well landward of the structure reduces the risk of accidental fall. A beach nourishment operation conducted in the winter of 2017–2018 subsequently restored the beach and allowed aeolian accretion to occur

Fig. 3 Accretion of beach and dune at Sandy Hook, New Jersey following a large scale beach nourishment project. The seawall was initially built in the early twentieth century (Dallas et al. 2013). Accretion over the seawall in the distance was aided by a landward re-curve in the seawall that provided a wide beach that facilitated aeolian transport

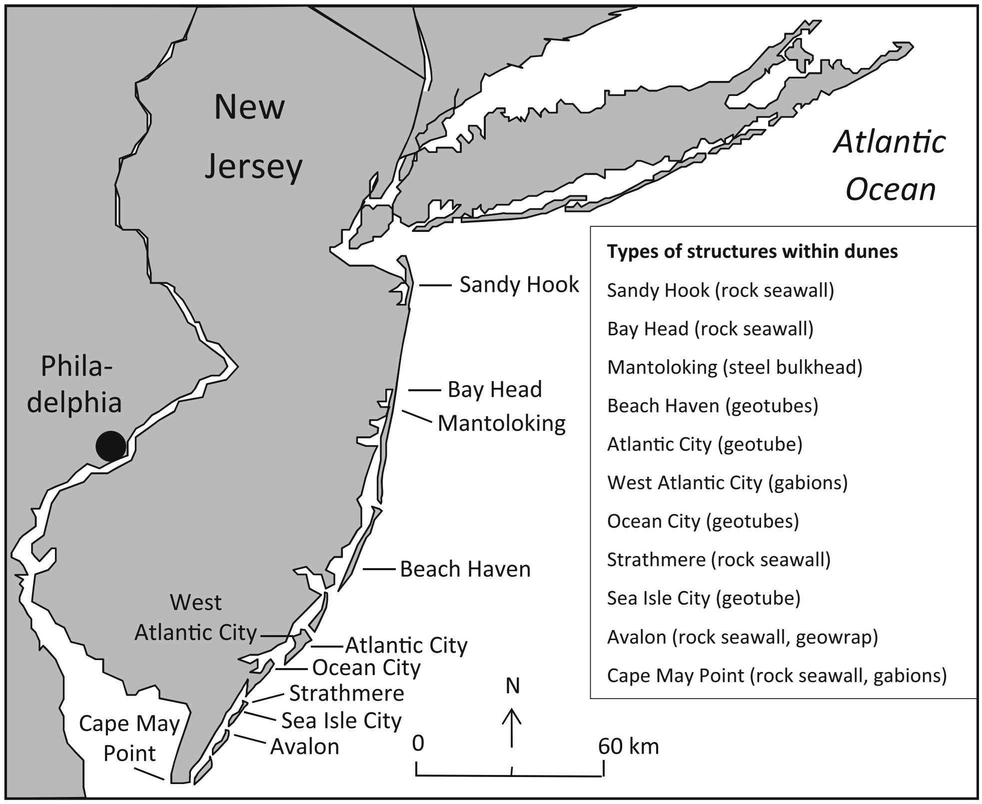

Fig. 4 Locations of sites where dunes cover hard cores in New Jersey, USA

but sizeable structures have been employed as dune cores in locations of moderate development (Feagin 2005) and intensive development, where fronting beaches are of adequate width to dissipate wave energies during moderate-intensity storms (Fig. 1). Geotextiles continually exposed to the elements can suffer damage and degradation from UV radiation, abrasion by coarse sediment and driftwood moved by waves and currents, vandalism, shifting of sand or escape of sand from the containers (Saathoff et al. 2007; Antunes do Carmo et al. 2010; Corbella and Stretch 2012), so they must be buried to retain their integrity. The need to cover geotextiles is not limited to dune projects. Burial is suggested for geotextile seawalls fronting bluffs as well (Corbella and Stretch 2012).

Geotubes were placed in New Jersey at Beach Haven, Atlantic City, Ocean City and Sea Isle City (Fig. 4). Geotubes used as dune cores are usually installed by first cutting a trench where placement will occur, stockpiling the excavated material on the seaward side to provide temporary protection against wave runup; placing a horizontal geotextile scour apron anchored by anchor tubes; emplacing the bags and filling them with a sand and water slurry, allowing the water to exit the containers; then placing the stockpiled sand on the tubes, shaping the dune to desired characteristics and planting the surface. The geotube, scour apron and anchor tubes are most often placed in a horizontal configuration (Fig. 5a), but geotextile (and gabion) containers can be sloped or stepped to help dissipate wave energy when uncovered and in direct interaction with the waves (Kessler 2008).

Settlement of geotubes is a common problem, and seam failure can result from abrasion and water motion (Alvarez et al. 2007). The seaward anchor tube and apron may settle because of wave scour, but the settling will place the apron in a configuration that will provide a wall-like barrier (Fig. 5b) that can protect against further scour (Anon 2014). An anchor tube and scour apron need not be adjusted vertically following storms, but portions of the structure exposed by erosion should be mechanically buried to prevent damage to the cover and reestablish the desired elevation of the overlying dune. Guidelines and instructions for applications for permits, installation, operation, maintenance, repair, replacement and rehabilitation of damaged geotube cores are provided in reports of projects at the Pineda Ocean Club in Satellite Beach, Florida (Kessler 2008) and the Grand Isle, Louisiana Beach Erosion and Hurricane Protection Project (Anon. 2014).

Geotextiles used as wraps (also called geomembranes) may be easier to install than tubes. The geotextile can be placed flat; covered with sand on the landward side; wrapped over the emplaced sand with the closed end facing seaward and then covered with another layer of sand. Wave erosion exposes the closed face of the wrap that stays anchored by the weight of the sand remaining on top of it. One of these wraps was installed in a portion of the dune in Avalon (Fig. 1) in 1993. Geotubes and wraps may be stacked to achieve greater height

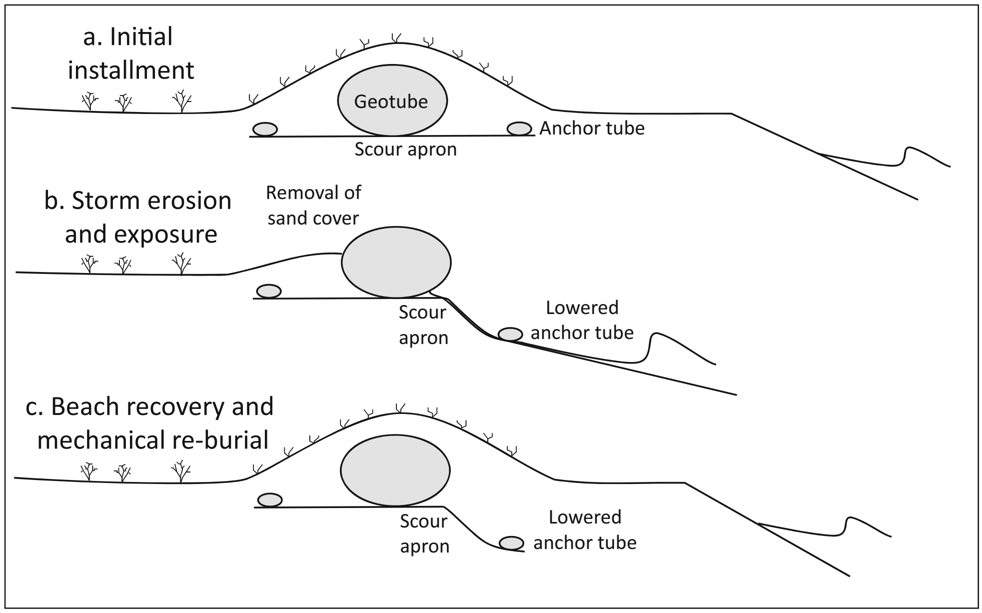

Fig. 5 Profile view of a single geotube emplaced as hard core covered with sand to represent a dune in general position and function

and depth and stitched together. The dimensions of the resulting dunes can differ substantially. At least seven geotube projects, using 3.7 m diameter tubes extend along 11.7 km of Gulf Coast of Texas (Gibeaut et al. 2003). Pineda Ocean Club has 4 rises and is 7.6 m wide and 1.8 m tall on landward side (Kessler 2008); the geotextile containers at Leirosa, Portugal were stacked 8 m high (Antunes do Carmo et al. 2010). The geotube emplaced at Atlantic City (Fig. 1) was 1.8 m high and 3.7 m wide and 1.92 km-long (McKenna 1997). In contrast, geotubes constructed at Beach Haven, New Jersey just after Hurricane Sandy had a combined length of only 107 m.

Gabions

Gabions are wire mesh baskets or mattresses filled with cobble-sized stone. The meshes are unfolded at the job site and assembled by lacing the edges together with wire and then filled with cobbles, converting the small individual components into a large heavy mass. Gabions have the advantage of being readily constructed without heavy equipment and are flexible and can maintain integrity if the foundation settles (US Army Corps of Engineers 1981). Gabions are only considered suitable for low wave-energy environments (US Army Corps of Engineers 1981), but they have been placed on open ocean environments in Puerto Rico because of low cost and ease of placement (Jackson et al. 2006). Once exposed, gabions are subject to failure by degradation or instantaneous failure during a storm that can result in rock leakage onto the beach and protruding wire that negatively affect recreational use (Jackson et al. 2006).

Gabions in New Jersey have been placed on eroding bay shores landward of Atlantic City, where fetch distance for wave generation is 2–5 km, and at Cape May Point, which is exposed to refracted ocean waves entering Delaware Bay and waves generated locally in the bay across fetch distances of >45 km (Fig. 4). Gabions in these two locations were covered by a layer of sand and planted. A short length of rock seawall that was built at Cape May Point prior to gabion installation was also covered. Gabions in both locations have maintained their sand cover, so the success of the structures as backup protection has not been tested. The Cape May Point site (Fig. 4) will provide a valuable test of the integrity of gabions at a relatively high energy estuarine beach if they are exposed.

Clay cores

Clay and mixed earth cores are common in dams and are the subject of numerous studies related to maintenance issues. Published studies of clay cores within dunes, in contrast, are lacking (Wamsley et al. 2011). Clay dikes have been commonly used in coastal projects in the past and are now used where more massive solutions are not affordable (Pranzini in press). Clay is more resistant than sand to erosion by waves and wind and to human trampling and compaction by foot and vehicle traffic. As a result, clay has been artificially introduced to coastal landforms to create walkover paths, temporary roads and barriers to wave uprush. The clay used for surface deployment is usually incorporated into aggregates of sand, gravel or shell to improve trafficability.

Clay incorporated within dikes and dunes may be a component of other sizes where the criterion for the core is to provide volume for the dune rather than resistance. Clay was a component of dredged backbay sediment used to make berm-like cores for sand-covered dunes in Mantoloking, New Jersey following Hurricane Sandy

(Plumlee et al. 2016). Clay alone can provide better resistance against wave attack. Clay cores can be deposited as ridges and left uncovered or covered by rock revetments or geotextiles to provide extra resistance (Hartman Engineering Inc. 2007). The clay can also be in-situ natural material covered by sand in nourishment projects (Wamsley et al. 2011). The cost to construct clay-core dunes can be cheaper than sand dunes where clay material is readily available (Wamsley et al. 2011).

Comparison of topographic profiles of a clay core dune and a sand dune without a core before and after Hurricane Ivan on the open Gulf of Mexico coast of Texas revealed that the sand dune lost 50% of the total dune volume and a scarp was created all the way to the height of the crest, whereas the clay core dune lost only 10% of the volume, with only minor scarping at the base of the dune (Wamsley et al. 2011). One advantage of a clay core, is that cultural materials are not left on the beach when the structure erodes, although clay balls may remain until they are eliminated by abrasion. Unlike in situ beach and dune sands, the clay included in sediment from external borrow areas may have contaminants or minerals that enhance corrosion of structures (Plumlee et al. 2016), and some fauna may be vulnerable to clay remaining on otherwise sandy beaches (Marco et al. 2017).

Hard structures designed as "permanent" features

Construction of new seawalls, revetments and bulkheads often occurs soon after intensive storms, such as in New Jersey after the mid latitude storm of March 1962 (Farrell and Sinton 1983) and Hurricane Sandy in 2012 (Nordstrom and Jackson 2018) and after Hurricane Dora in 1964 at Jekyll Island (Yang et al. 2012). Slower processes of erosion, such as downdrift migration of tidal inlet channels, can also threaten infrastructure, leading to construction of bulkheads and seawalls. In both cases, natural processes may restore beach width during the depositional phase of natural cycles, either by onshore migration of swash bars in the weeks or months following storms or by the longer-term onshore migration of inlet shoals aided by cutting of new channels or breaches in barrier islands updrift (FitzGerald et al. 1978). The widened beaches can then provide a greater source width for aeolian transport that can bury the structures. For example, Google Earth images reveal that burial of the seawall just south of Townsend Inlet at Avalon, NJ (Fig. 4) occurred twice between 2002 and 2016. Burial, re-exposure and re-burial occurred at a seawall constructed at the inlet at Strathmere between March 2009 and June 2015. In that case, the seawall was covered in a beach nourishment operation rather than wait for natural accretion associated with inlet cycles. These threatened inlet locations are also sites where smaller backup walls have been deployed, for example geotubes deployed at Ocean City, NJ near the north end of the island, which were also artificially covered.

The likelihood of burial by natural aeolian transport can be enhanced by increasing beach width in nourishment projects, as long as the new beaches are not built too high for wave action to rework surface sediment and eliminate the lag layer that resists aeolian transport (Jackson et al. 2010). Only portions of some seawalls and revetments may be buried (Yang et al. 2012), leaving naturally-functioning segments adjacent to armored shores (Fig. 3). Burial of the seawall in Fig. 3 occurred by aeolian transport following large-scale beach fill operations at and updrift of the site. In contrast, the higher portion of the seawall in the town of Sea Bright just updrift (south) of the portion of the wall in Fig. 3 is not buried, despite the presence of a wide nourished beach first implemented in 1994 and periodically renourished. The width of the beach and dune seaward of the wall is >70 m, but sand fences and vegetation plantings well seaward of the wall prevent sand from reaching the wall. Sea Bright and Ocean City were nourished by US Army Corps of Engineers projects when dunes were not part of design plans and local interests placed sand fences seaward of structures to prevent sand inundation landward of the walls.

Corps of Engineers beach and dune nourishment projects now being conducted in New Jersey include dunes built to heights that exceed the height of most existing protection structures. The Corps design dune for their 2018 nourishment program is 2.1 m higher than the bulkhead at Mantoloking (Fig. 2) and 1.2–1.8 m higher than the crest of the seawall at Bay Head (Fig. 6) (U.S. Army Corps of Engineers Philadelphia District 2016). In both of these cases, the design calls for complete burial of the structures. Designs for several other locations in New Jersey include dunes that are higher than existing shore protection structures but have the landward-sloping toe of the dune contiguous with the seaward

Fig. 6 Buried seawall at Bay Head, New Jersey October 2015, showing condition 3 years after the sediment cover was removed during Hurricane Sandy in October 2012. The height and location of the seawall is revealed in the exposed segment at the municipally-maintained portion in the foreground

face of the structure, not over it. Construction of these dunes will greatly increase the potential for subsequent burial of the structures, providing that local interests will allow sand to blow over the structures.

Direct burial using earth-moving equipment can result in the fastest way to create a sand surface over the highest shore protection structures. Mechanical burial may be required where beaches are not nourished and are too narrow to provide a sufficient source for aeolian transport. Data in Nordstrom et al. (2018) indicate that the seawall in Bay Head (Fig. 6) is 2.9 m above the backshore elevation. The narrow beach and height of the seawall restricted deposition of a sand layer over the structure by natural processes prior to the Corps nourishment project, and bulldozers were used to scrape sand from the beach and place it over the seawall. State and municipal regulations allowed shorefront property owners in Bay Head to remove sand to a depth of 0.3 m above mean high water and place it on the dune, providing that a municipal permit was obtained by the owner. Owners in Bay Head are obligated to install sand fencing or vegetation plantings at their own expense if the dune becomes lower than the elevation approved by the municipal dune consultant, even if the lowering is by natural causes. The Bay Head precedent implies that burial of most structures is possible, given appropriate political will. The new Corps beach nourishment project will now make it easier to retain a sand cover at Bay Head, but the former precedent could be applied to other locations that lack a commitment to nourishment.

Surface cover

Characteristics of surface cover

Intermittent exposure should be expected of structures designed as backup protection. Although the sand cover may be temporary, it should be designed to maximize its protective, environmental and social value while it exists. The sand layer should be sufficient to add protection against wave runup that exceeds structure height and support vegetation that can stabilize the surface and provide natural habitat. The layer should not be too thin to prevent beach animals from burrowing into the sand (Nourisson et al. 2014) or allow dune vegetation to root into the core and weaken it to the point where its integrity is threatened (Corbella and Stretch 2012). The impact of buried structures on depth of root penetration and water table movement are poorly understood (Nordstrom 2014) but are related to the resistance of the buried core as well as the depth of the sand. Covering geofabrics with a sand and epoxy coating would add to their resistance to root penetration as well as to vandalism and abrasion.

The geotubes at Pineda Ocean Club were covered with 0.9 to 1.5 m of sand (Kessler 2008). The geotube at Pirates Beach, Texas was covered a minimum of 0.5 m; planting included three species, *Panicum amarum*, *Sporobolus virginicus* and *Spartina patens*, placed from seaward to landward respectively (Feagin 2005). A 1-m depth was created prior to planting in the project described by Schreck Reis et al. (2008) and Antunes do Carmo et al. (2010). Planting can occur in shore-parallel zones using vegetation types that reflect the cross-shore zonation of environmental stresses, although the width of the zones is likely to be much narrower than on natural dunes, and the seaward slope is not likely to have the diffusion-like gradient of a gentler and wider slope (Feagin 2005).

Attempts to achieve species diversity in initial planting programs may not be needed where the proximity of the restored dune to the foreshore is expected to result in frequent periodic removal of the sand cover. Gibeaut et al. (2003) found that maintaining even a sparse vegetation cover was impossible on at least half of the project lengths they evaluated. Dominant perennial species, such as *Panicum amarum* and *Ammophila* spp. can grow on all portions of narrow foredunes and can facilitate other species that can grow opportunistically if time permits (Mauriello 1989; De Lillis et al. 2004; Feagin 2005). The dune cover evaluated by Schreck Reis et al. (2008) was planted using only *Ammophila arenaria*, but eleven plant species had already colonized the planted area after 6 months. Where frequent removal of the sand cover prevents vegetation from reaching later evolutionary stages, property owners landward of the hybrid dunes can be encouraged to plant native backdune species that could not survive the environmental stresses close to the active beach, thereby extending the cross-shore environmental gradient.

The need for reburial

Small storms or extended periods of non-storm erosion can expose the structure at the base of the dune but leave the upper portion of the dune perched above the limit of wave attack. Wave uprush from larger storms may remove portions of the surface well landward of the structure even if the structure remains intact (Gibeaut et al. 2003; Feagin 2013; Irish et al. 2013). Exposed hard cores will have different interactions with waves and sediment based on their size, shape, roughness, and durability as well as the extent to which they are exhumed. Structural failure (addressed earlier), visitor use and safety, and interruptions to sediment supply will then be issues.

Removal of the sand cover can interrupt public access (Feagin 2005) either by creating a steep barrier for pedestrians or by necessitating deployment of fences or passage of regulations by public authorities to avoid damage to the hard core or avoid law suits because of injuries to visitors. The bulkhead depicted in Fig. 2 was exposed to a depth of 7.25 m following a series of winter storms (Nordstrom and Jackson 2018). The vertical front of the bulkhead restricts access to the beach, and the drop in elevation is difficult to see when crossing the dune from the landward side, particularly when the bulkhead intersects the seaward slope of the dune. The safety issue is somewhat less problematic at smaller geotextile cores that are more readily traversed.

Shore protection structures that prevent delivery of sediment from the upland to the beach restrict natural long term evolution of the coast (Kraus and McDougal 1996). An increase in erosion at adjacent properties because of reduced longshore transport is a concern where geotubes are employed (Gibeaut et al. 2003; Siasconset Beach Preservation Fund n.d.). Basco et al. (1997) suggest that stakeholders who construct a wall could be required to artificially nourish the beach with a volume of sediment that represents a calculated annual loss from the upland if left unprotected. The Siasconset Beach geotube project has a requirement that sediment from an external source must be delivered to cover the geotubes each time they are exhumed by storms (Siasconset Beach Preservation Fund n.d.). Covering hard cores with sediment can accomplish the goal of maintaining the sediment budget only if done each time the surface cover is removed and the sediment is from a source outside the immediate area. Covering the structure with sediment from the fronting beach does not address the negative effect of the structure on sediment input from the coastal formation landward of it.

Spatial constraints

Covering shore protection structures displaces the dune toe farther seaward than the beach-wall contact, resulting in narrowing of the beach/dune gradient, truncation of backshore habitat, and restriction of recreation space. Gibeaut et al. (2003) found that average beach widths fronting geotubes were 6.4 m, compared to 25.3 m fronting nearby unprotected areas. Data in Nordstrom et al. (2018) indicate that the 1.2–2.0 m-wide sand cover bulldozed on the seaward side of the seawall at Bay Head eliminated 14–17% of the beach space fronting the wall. Space will likely be too limited to cover protection structures and provide the gently sloping seaward dune face that occurs on a beach with adequate sediment supply. Beach plant communities, embryo dunes, shore bird and sea turtle nesting sites are normally concentrated in the landward portion of the backshore (Kelly 2016), and space may not be available for the zonation of plant habitats found in natural areas (Feagin 2005). Ecosystems can play an important role in shore protection and adaptation to coastal change (Spalding et al. 2014), but their value is severely constrained if restricted by available space or by local relief. Hybrid approaches may not provide all of the same benefits of natural infrastructure, although some of the benefits are achievable (Sutton-Grier et al. 2015).

Placing hard cores as close as possible to the infrastructure to be protected can provide space for naturally functioning landforms and habitats seaward and add beach and dune volume as protection against wave erosion. Making the fronting beach wider by artificially nourishing it can protect the structure from exhumation, provide a larger sand surface for dune build-up by aeolian processes and provide space for a more natural environmental gradient across the shore. Care should be taken to ensure that the perception that the hard core provides adequate protection does not prevent the beach from being nourished in a timely manner. Re-nourishment intervals should be selected to maintain natural habitats that have evolved on the previously nourished beach (Nordstrom et al. 2011).

Discussion

Greater attention is now being placed on soft approaches as the default option for coastal defense (Perkins et al. 2015). Dunes built with hard cores as part of their original designs can be considered soft solutions and overcome restrictions by regulatory agencies against hard shoreline armoring (Saathoff et al. 2007; Feagin 2013), although an extensive permit application process may still be necessary (Kessler 2008). A geotube was allowed at Saco, Maine and buried under a vegetated dune in 2009 (Wurst 2009) despite Maine Coastal Sand Dune Rules that state that no new seawalls can be built (Kelley 2013; Maine Department of Environmental Protection 2017). Definition as a soft solution is not strictly correct when cores are employed to resist erosion (Corbella and Stretch 2012) and when the cores function as hard solutions when the sediment covering them is removed and not replaced. Reburial will be critical where designation as a soft solution was a criterion for project acceptance.

Placing hard cores in dunes and providing only an initial sediment cover is not an ideal solution. The need for hard cores is, in itself, admission that the erosion condition is problematic. The lack of space seaward and landward of the location where protection is most needed necessitates a compromise solution that should be considered temporary. At some point, storm damage can be expected to exceed the design specifications of small scale projects, so plans should include subsequent actions, including options for retreat from the coast as well as providing a greater level of protection in place. Without consideration of short-term advantages and long-term needs, designs cannot be considered resilient. Performance standards and evaluation protocols (including rigorous monitoring) and specific contingencies for future repairs or modifications (adaptive management) should be built into the original project. These kinds of needs take on increased importance for innovative projects with untested outcomes (Nordstrom et al. 2011; Pilkey and Cooper 2012).

Erosion during major storms reveals that small seawalls provide little to no protection (Stauble et al. 1991; Bush and Pilkey 1994). Seawalls designed specifically to protect against the direct attack of storm waves are the only way to achieve adequate levels of protection to landward properties if erosion continues without beach nourishment. Dunes with geotube, gabion or clay cores are reasonable alternatives where large scale beach nourishment projects are imminent. For example, Google Earth images reveal that the geotubes constructed at Beach Haven, New Jersey were fronted by beach widths varying from 0 to 16 m when built in 2012 right after Hurricane Sandy. The combined beach and dune width fronting the location of the structure in October 2017, following a large scale beach fill and dune building project, was 76 m. The beach nourishment projects conducted in 2017 and 2018 fronting the bulkhead in Fig. 2 and seawall in Fig. 6 indicate that nourishment can totally obscure larger structures and provide space for a full environmental gradient to form. The seawall in Fig. 6 did not require the wider beach to provide effective storm protection, but the artificially built dune and aeolian transport off the widened beach will contribute to a longer-lasting dune with greater potential natural value and will eliminate the need for mechanical transfer of sediment from the beach.

Some of the problems encountered with creating dunes with hard cores will be similar to problems in building dunes by more traditional means. Local stakeholders may argue against projects that interfere with views of the sea, reduce ease of access to the beach or extend the dune or vegetation line seaward, thus changing property rights. Problems associated with drought and high temperatures that cause die-out of planted vegetation on hard core dunes (Feagin 2013) also plague attempts to vegetate dunes built without hard cores (Mauriello 1989). Trampling of dune vegetation by visitors is damaging to dunes without hard core dunes as well as to dunes with hard cores. These kinds of problems can be anticipated. They are not exclusive to hard core dunes and are not elaborated here.

Most hybrid shore protection projects have been constructed recently, and data on their effectiveness is limited (Sutton-Grier et al. 2015). The benefits of some hybrid forms are not demonstrated clearly because of the rarity of extreme flood and wave events (Irish et al. 2013). Most reviews of shore management strategies make a plea for more prototype studies, but the need is especially acute for use of geotextiles that are still experimental, low in cost and considered temporary (and thus rarely accompanied by demands for detailed study of effectiveness). Long-term monitoring studies are important in planning the impact of recently-introduced methodologies, such as geotextile cores, especially where erosion and environmental restoration need a long-term vision but projects emphasize immediate socio-economic benefits (Nourisson et al. 2014).

Conclusions

Placing hard cores on the beach for shore protection alters the morphology of the beach and dune and the cross-shore and longshore sediment exchange system. Maintaining a local sand cover over the structures can provide some of the aesthetic and habitat value of natural dunes but not the width, form and full suite of environments found across the beach. Mechanical reburial of exhumed structures as soon as possible will help prevent damage to the structures, reestablish habitat and aesthetic value, reestablish safe access between beach and upland for native fauna and beach users, reestablish the sediment budget, and keep nature and the need for restoration in the minds of beach users. Maintaining the beach seaward of the core structures in ongoing beach nourishment operations can provide an erosional buffer to protect the structures from the full effect of storms, provide the space for wave and wind processes to reinstate natural cross-shore gradients and maintain the regional sediment budget. A long-term vision is required to properly assess the value of these compromise solutions.

Acknowledgements Funding for this review was provided by Rutgers University. I am grateful to Jeffrey Gebert of the US Army Corps of Engineers Philadelphia District and Christopher Constantino of the New Jersey Division of Coastal Engineering for help in identifying characteristics of shore protection projects in New Jersey.

References

Abel N, Gorddard R, Harman B, Leitch A, Langridge J, Ryan A, Heyenga S (2011) Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. Environ Sci Pol 14(3):279–288

Alvarez IE, Rubio R, Ricalde H (2007) Beach restoration with geotextile tubes as submerged breakwaters in Yucatan, Mexico. Geotext Geomembr 25:233–241

Anon (2014) Operation, maintenance, repair, replacement and rehabilitation manual: Grand Isle and Vicinity, Louisiana. U.S Army Corps of Engineers, New Orleans District

Antunes do Carmo J, Schreck Reis C, Freitas H (2010) Working with nature by protecting sand dunes: lessons learned. J Coast Res 26:1068–1078

Ashis M (2015) Application of geotextiles in coastal protection and coastal engineering works: an overview. Int Res J Environ Sci 4:96–103

Balouin Y, Longueville F, Colombet Y (2016) Video assessment of nearshore and beach evolution following the deployment of a submerged geotextile wave breaker. J Coast Res SI 75:616–621

Basco DR (1998) The economic analysis of "soft" versus "hard" solutions for shore protection: an example. Coastal engineering: proceedings of the twenty-sixth coastal engineering conference. American Society of Civil Engineers, New York, pp 1449–1460

Basco DR, Bellomo DA, Hazelton JM, Jones BN (1997) The influence of seawalls on subaerial beach volumes with receding shorelines. Coast Eng 30:203–233

Bin O, Crawford TW, Kruse JB, Landry CE (2008) Viewscapes and flood hazard: coastal housing market response to amenities and risk. Land Econ 84:434–448

Brunsden D, Moore R (1999) Engineering geomorphology on the coast: lessons from West Dorset. Geomorphology 31:391–409

Bulleri F, Chapman MG (2010) The introduction of coastal infrastructure as a driver of change in marine environments. J Appl Ecol 47:26–35

Bush DM, Pilkey OH (1994) Mitigation of hurricane property damage on barrier islands: a geological view. J Coast Res SI 12:311–326

Chapman MG, Underwood AJ (2011) Evaluation of ecological engineering of "armored" shorelines to improve their value as habitat. J Exp Mar Biol Ecol 400:302–313

Corbella S, Stretch DD (2012) Geotextile sand filled containers as coastal defence: south African experience. Geotext Geomembr 35:120–130

Dallas K, Berry M, Ruggiero P (2013) Inventory of coastal engineering projects in Colonial National Historical Park. Natural Resource Technical Report NPS/NRPC/GRD/NRTR-2012/690, National Park Service: Fort Collins CO.

d'Angremond K, van den Berg EJF, de Jager JH (1992) Use and behavior of gabions in coastal protection. Coastal engineering: proceedings of the twenty-third coastal engineering conference. American Society of Civil Engineers, New York, pp 1748–1757

das Neves L, Lopes ML, Veloso-Gomes F, Taveira-Pinto F (2009) Experimental stability analysis of geotextile sand-filled containers for dune erosion control. J Coast Res SI 56:487–490

De Lillis M, Costanto L, Bianco PM, Tinelli A (2004) Sustainability of sand dune restoration along the coast of the Tyrrhenian Sea. J Coast Conserv 10:93–100

Dette H-H, Raudkivi AJ (1994) Beach nourishment and dune protection. Coastal engineering: proceedings of the twenty-fourth coastal engineering conference. American Society of Civil Engineers, New York, pp 1934–1945

Dugan JE, Airoldi L, Chapman MG, Walker SJ, Schlacher T (2011) Estuarine and coastal structures: environmental effects, a focus on shore and nearshore structures. Treatise Estuarine Coast Sci 8:17–41

Ewalt Gray JD, O'Neill K, Qiu Z (2017) Coastal residents' perception of the function of and relationship between engineered and natural infrastructure for coastal hazard mitigation. Ocean Coast Manag 146:144–156

Farrell SC, Sinton JW (1983) Post-storm management and planning in Avalon, New Jersey, coastal zone 83. American Society of Civil Engineers, New York, pp 662–681

Feagin RA (2005) Artificial dunes created to protect property on Galveston Island, Texas: the lessons learned. Ecol Restor 23:89–94

Feagin R (2013) Foredune restoration before and after hurricanes: inevitable destruction, certain reconstruction. In: Martínez ML, Gallego-Fernández JB, Hesp PA (eds) Restoration of coastal dunes. Springer, New York, pp 93–103

FitzGerald DM, Hubbard DK, Nummedal D (1978) Shoreline changes associated with tidal inlets along the South Carolina coast. Coastal zone 78. American Society of Civil Engineers, New York, pp 1973–1994

Gibeaut JC, Hepner TL, Waldinger R, Andrews JR, Smyth RC, Gutierrez R (2003) Geotubes for temporary erosion control and storm surge protection along the Gulf of Mexico shoreline of Texas. Proceedings of the 13th biennial coastal zone conference

Gittman RK, Popowich AM, Bruno JF, Peterson CH (2014) Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a category 1 hurricane. Ocean Coast Manag 102:94–102

Gutman AL (1979) Low-cost shoreline protection in Massachusetts. Coastal structures '79. American Society of Civil Engineers, New York, pp 373–387

Hardaway CS, Gunn JR (2010) Design and performance of headland bays in Chesapeake Bay, USA. Coast Eng 57:203–212

Hartman Engineering Inc 2007. Grand isle barrier shoreline stabilization study: preliminary engineering report. Louisiana Department of Natural Resources. DNR contract no. 2512-05-05

Hillyer TM, Stakhiv EZ, Sudar RA (1997) An evaluation of the economic performance of the U.S. Army Corps of Engineers shore protection program. J Coast Res 13:8–22

Hornsey WP, Carley JT, Coghlan IR, Cox RJ (2011) Geotextile sand container shoreline protection systems: design and application. Geotext Geomembr 29:425–439

Irish J, Lynett PJ, Weiss R, Smallegan SM, Cheng W (2013) Buried relic seawall mitigates hurricane Sandy's impacts. Coast Eng 80:79–82

Jackson CW, Bush DM, Neal WJ (2006) Gabions, a poor design for shore hardening: the Puerto Rico experience. J Coast Res SI 39:852–857

Jackson NL, Nordstrom KF, Saini S, Smith DR (2010) Effects of nourishment on the form and function of an estuarine beach. Ecol Eng 36:1709–1718

Kelley JT (2013) Popham Beach Maine: an example of engineering activity that saved beach property without harming the beach. Geomorphology 199:171–178

Kelly JF (2016) Assessing the spatial compatibility of recreational activities with beach vegetation and wrack in New Jersey: prospects for compromise management. Ocean Coast Manag 123:9–17

Kessler R (2008) Sand dune stabilization at Pineda Ocean Club. Land and Water 52(3):13–22

Kochnower D, Reddy SMW, Flick RE (2015) Factors influencing local decisions to use habitats to protect coastal communities from hazards. Ocean Coast Manag 116:277–290

Kraus NC (1988) The effects of seawalls on the beach: an extended literature review. In Kraus, N.C. And Pilkey, O.H. Editors, effects of seawalls on the beach. J Coast Res Spec Issue 4:1–28

Kraus NC, McDougal WG (1996) The effects of seawalls on the beach: part I: an updated literature review. J Coast Res 12:691–702

Lamberti A, Archetti R, Kramer M, Paphilitis D, Mosso C, Di Risio M (2005) European experience of low crested structures for coastal management. Coast Eng 52:841–866

Luo S, Liu Y, Jin R, Zhang J, Wei W (2016) A guide to coastal management: benefits and lessons learned of beach nourishment practices in China over the past two decades. Ocean Coast Manag 134:207–215

Maine Department of Environ Prot (2017) Protecting Maine's beaches for the future: 2017 Update Report to the Evnironment and Natural Resources 128th Legislature, Fist Session, Augusta

Manno G, Anfuso G, Messina E, Williams AT, Suffo M, Liguori V (2016) Decadal evolution of coastline armouring along the Mediterranean Andalusia littoral (south of Spain). Ocean Coast Manag 124:84–99

Marco A, Abella-Perez E, Tiwari M (2017) Vulnerability of loggerhead turtle eggs to the presence of clay and silt on nesting beaches. J Exp Mar Biol Ecol 486:195–2013

Mauriello MN (1989) Dune maintenance and enhancement: a New Jersey example. Coastal zone 89. American Society of Civil Engineers, New York, pp 1023–1037

McKenna WT (1997) Effect of shore protection strategies on shoreline change at Atlantic City, New Jersey. Unpublished M.E. Thesis, Stevens Institute of Technology, Hoboken

National Research Council (2014) Reducing coastal risk on the east and gulf coasts, the National Academies Press, Washington, DC

Niven RJ, Bardsley DK (2013) Planned retreat as a management response to coastal risk: a case study from the Fleurieu peninsula, South Australia. Reg Environ Chang 13:193–209

Nordstrom KF (2014) Living with shore protection structures: a review. Estuar Coast Shelf Sci 150:11–23

Nordstrom KF, Jackson NL (2018) Constraints on restoring landforms and habitats on storm-damaged shorefront lots in New Jersey, USA. Ocean Coast Manag 155:15–23

Nordstrom KF, Jackson NL, Kraus NC, Kana TW, Bearce R, Bocamazo LM, Young DR, DeButts HA (2011) Enhancing geomorphic and biologic functions and values on backshores and dunes of developed shores: a review of opportunities and constraints. Environ Conserv 38:288–302

Nordstrom KF, Liang B, Garilao ES, Jackson NL (2018) Topography, vegetation cover and below ground biomass of spatially constrained and unconstrained foredunes in New Jersey, USA. Ocean Coast Manag 156:117–126

Nourisson DH, Bessa F, Scapini F, Marques JC (2014) Macrofaunal community abundance and diversity and talitrid orientation as potential indicators of ecological long-term effects of a sand-dune recovery intervention. Ecol Indic 36:356–366

O'Donnell JED (2017) Living shorelines: a review of literature relevant to New England coasts. J Coast Res 33:435–451

Paskoff R, Kelletat D (1991) Introduction: review of coastal problems. Z Geomorphol Suppl 81:1–13

Perkins MJ, Ng TPT, Dudgeon D, Bonebrake TC, Leung KMY (2015) Conserving intertidal habitats: what is the potential of ecological engineering to mitigate impacts of coastal structures? Estuar Coast Shelf Sci 167:504–515

Pilarczyk KW (1996) Geotextile systems in coastal engineering - an overview. Coastal engineering 1996, American Society of Civil Engineers, New York, pp 2114–2127

Pilkey OH Jr, Cooper JAG (2012) "Alternative" shoreline erosion control devices: a review. In: Cooper JAG, Pilkey OH Jr (eds), Pitfalls of Shoreline Stabilization: Selected Case Studies. Springer Science+ Business Media, Dordrecht pp 187–214

Plumlee GS, Benzel WM, Hoefen TM, Hageman PL, Morman SA, Reilly TJ, Adams M, Berry CJ, Fischer JM, Fisher I (2016) Environmental implications of the use of sulfidic back-bay sediments for dune reconstruction – lessons learned from post hurricane Sandy. Mar Pollut Bull 107:459–471

Pranzini E (in press) Coastal erosion and protection: a brief historical analysis. J Coast Conserv. https://doi.org/10.1007/s11852-017-0521-9

Pranzini E, Rossi L, Lami G, Jackson NL, Nordstrom KF (2018) Reshaping beach morphology by modifying offshore breakwaters. Ocean Coast Manag 154:168–177

Roca E, Villares M (2012) Public perceptions of managed realignment strategies: the case study of the Ebro Delta in the Mediterranean basin. Ocean Coast Manag 60:38–47

Saathoff F, Oumeraci H, Restall S (2007) Australian and German experiences on the use of geotextile containers. Geotext Geomembr 25: 251–263

Schreck Reis C, Antunes do Carmo J, Freitas H (2008) Learning with nature: a sand dune system case study (Portugal). J Coast Res 26: 1506–1515

Semeoshenkova V, Newton A (2015) Overview of erosion and beach quality issues in three southern European countries: Portugal. Spain Italy Ocean Coast Manag 118:12–21

Siasconset Beach Preservation Fund (n.d.) More details on geotubes http://sconsetbeach.org/more-detail-on-geotubes/

Smallegan SM, Irish JL, Van Dongeren AR, Den Bieman JP (2016) Morphological response of a sandy barrier island with a buried seawall during hurricane Sandy. Coast Eng 110:102–110

Smallegan SM, Irish JL, Van Dongeren AR (2017) Developed barrier island adaptation strategies to hurricane forcing under rising sea levels. Clim Chang 143:173–184

Spalding MD, Ruffo S, Lacambra C, Meliane I, Hale LZ, Shepard CC, Beck MW (2014) The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean Coast Manag 90:50–57

Stauble DK, Seabergh WC, Hales LZ (1991) Effects of hurricane Hugo on the South Carolina coast. J Coast Res SI 8:129–162

Sutton-Grier AE, Wowk K, Bamford H (2015) Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ Sci Pol 51:137–148

U.S. Army Corps of Engineers (1981) Low cost shore protection: a guide for engineers and contractors. Office of the Chief of engineers, Washington, DC

U.S. Army Corps of Engineers Philadelphia District (2016) Manasquan Inlet to Barnegat Inlet, Ocean County Beach Fill Initial Construction Cross Sections

Wamsley TV, Waters JP, King DB (2011) Performance of experimental low volume beach fill and clay core dune shore protection project. J Coast Res SI 59:202–210

Wurst L (2009) Dune recovery at Ferry Beach, Saco: a helping hand Main Geological Survey Circular GFL-147

Yang B, Hwang C, Cordell HK (2012) Use of LiDAR shoreline extraction for analyzing revetment rock beach protection: a case study of Jekyll Island State Park, USA. Ocean Coast Manag 69:1–15

Young W, Kesevan S, Chang YW (2016) Post-hurricane Sandy beach erosion protection. Ports 2016: Port Engineering. American Society of Civil Engineers, New York, pp 431–440