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FUNDAMENTALS OF COASTLINE PROTECTION AND THE ROLE OF GEOSYNTHETICS

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ABSTRACT

Many coastlines have beaches composed of loose sediments such as gravel, sand, or mud that are constantly acted upon by waves, currents and winds. Waves, tides, ocean flow and wind are the major external energy sources for the coastline equilibrium system. However, waves are the most important energy source among of them for coastal erosion. Hard armor and soft protection technologies are commonly used to protect coastline resources and properties. Typical protection strategies include: retreatment, accommodation and protection. The typical armor protection methods included seawalls, revetments, groins, offshore or detached breakwaters, submerged breakwaters, and artificial reef works. The typical soft protection schemes consist of beach nourishment, sand dunes, headland defense works, controlled beach water level and ecological treatments. The cost of installing hard structures for coastal protection is very high. Strong negative public reactions to rock emplacements along the coast are common. The combination of hard and soft options has recently become more popular for optimum results. Geotextiles have been widely placed under seawalls, dikes and river bank protection works as filters or separators in hydraulic applications. The use of geotextiles as flexible forms in the context of bags, containers, mattresses and tubes is growing at an incredible rate. The primary applications are erosion control and dewatering. Many Geosynthetic coastline protection application cases are discussed in this paper. Coastline classification, problems and seawall, groin, offshore breakwaters and geosynthetic applications for coastline protections are also discussed.

1. INTRODUCTION

The coastline is the boundary dividing land from sea. Coastlines are not lines, but are generally geological environments unique in their composition and the physical processes that affect them. The boundaries are difficult to identify. The shoreline is the boundary dividing the land from the seawater. Shorelines vary with the tide, wind direction, wind flow, wave height and the variations in coast slope. The shore generally includes the strip region from the average low tidal line to the farther end at which sand can be transferred by wave energy. Since the tidal height continuously varies, the highest tidal line or the average tidal line is not a constant value. The shore is the general location at some specific period. Therefore, coastline and shoreline are a commonly used terms for each other (Kao, 1988).

Many of these coastlines have beaches composed of loose sediments such as gravel, sand or mud that are constantly acted upon by waves, currents and winds. Shoreline changes induced by erosion and accretion are natural processes. These activities also induce coastline associated problems such as ground settlement, coastline erosion, coast pollution, environmental protection, land use concurrence and disaster prevention. For the protection of coastline resources and properties, hard armor and soft protection schemes are commonly used. The geotextile is one of the geosynthetic family members. Geotextiles have been widely placed under seawalls, dikes and river bank protection works as filters or separators in coastline protection applications. Geobag, geotube and geo-container applications for coastline management projects have recently become very popular.

2. COASTLINES CLASSIFICATION AND CAUSES OF EROSION

Coastlines can be classified as primary coast and secondary coast. (Kao, 1988) Primary coasts are land activities that influence local areas, while secondary coasts are coast activities that influence entire regions. Based upon geological formations, a coastline could include hard rock or soft deposits. These materials also can present different Physical and Chemical reactions. A typical coastline can be divided into rock coastline, sedimentary coastline and river delta coastline (Kao, 1988).Many of these coastlines have beaches composed of loose sediments such as gravel, sand or mud that are constantly acted upon by waves, currents and winds, continuously reshaping them. Despite the different wave climates, the nature and behavior of beaches are often very similar (Dean and Dalrymple, 2002).

Beaches around the world are quite similar in composition and shape. The beach profile is generally composed of four sections: the offshore, the near-shore, the beach and the coast, as shown in Figure 1. The sand making this profile is shaped by waves coming in from offshore and breaking in the near-shore zone, where sand bars may exist (Dean and Dalrymple, 2002).

In an aerial view, the coast can be fronted by a barrier island with tidal inlets transecting it at various locations as shown in Figure 2. This situation occurs in numerous locations around the world, with a large concentration of barrier islands found in North America (Dean and Dalrymple, 2002).

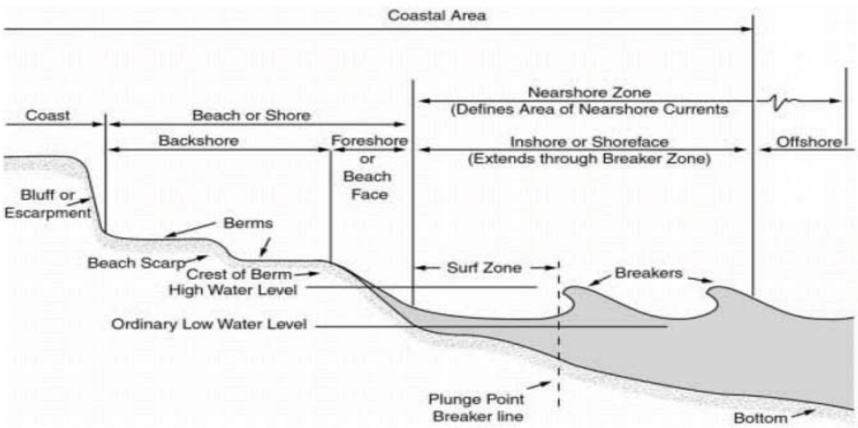

Fig. 1: beach profile terminology (U.S. Army Corps Eng., Shore Protection Manual, 1984)

Tidal inlets play a major role in the sand balance of many shorelines. The size and shape of inlets are the result of the balance between the sand that is carried into them by the waves and the scouring ability of tidal flows that course through daily. Some of their common features are shown in Figure 3. The two most important features of a tidal inlet are the ebb and flood tidal shoals (Dean and Dalrymple, 2002).

Shoreline changes induced by erosion and accretion are natural processes that take place over a range of time scales. They may occur in response to smaller-scale (short-term) events, such as storms, regular wave action, tides and winds or in response to large-scale (long-term) events such as glaciations or orogenic cycles that may significantly alter sea levels (rise/fall) and tectonic activities that cause coastal land subsidence or emergence. Hence, most coastlines are naturally dynamic with cycles of erosion often

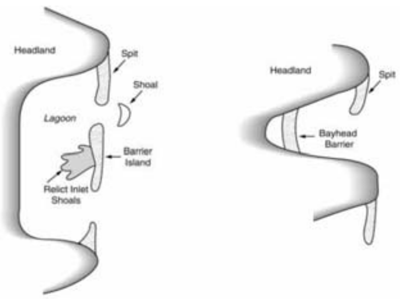

Fig. 2: Shoreline plan form terminologies (Dean and Dalrymple, 2002)

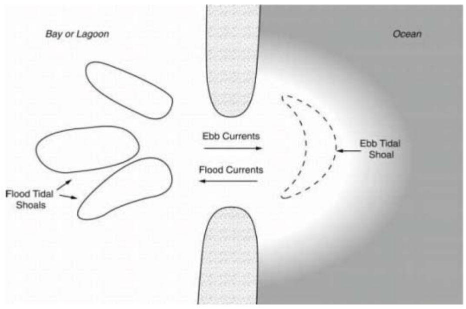

Fig. 3: Tidal inlet terminologies (Dean and Dalrymple, 2002)

an important feature of their ecological character. Wind, waves and currents are natural forces that easily move the unconsolidated sand and soils in the coastal area, resulting in rapid changes in the shoreline position (Prasetya, 2006).

Coastline region activities have increased significantly due to human and industrial activities. These activities also induce coastline associated problems such as ground settlement, coastline erosion, coast pollution, environmental protection, land use concurrence and disaster prevention. These problems are very complex and require coastline management to resolve them. (Kao, 1988) The erosion problem becomes worse whenever countermeasures (i.e. hard or soft structural options) are applied inappropriately, improperly designed, built, or maintained and if the effects on adjacent shores are not carefully evaluated. Figure 4 lists the coastal erosion and accretion processes, as well as natural factors and human activities (Prasetya, 2006).

The cost of installing hard structures for coastal protection is very high.Strong negative public reaction to rock emplacements along the coast is common. This has led to uncertainty among owners and local authorities on how to treat shoreline erosion. It has become an issue for serious debate in areas of intensive use and rapidly rising coastal land value. Many of these owners are resorting to planned retreat where houses or hotels are simply removed and the coast is left to erode.

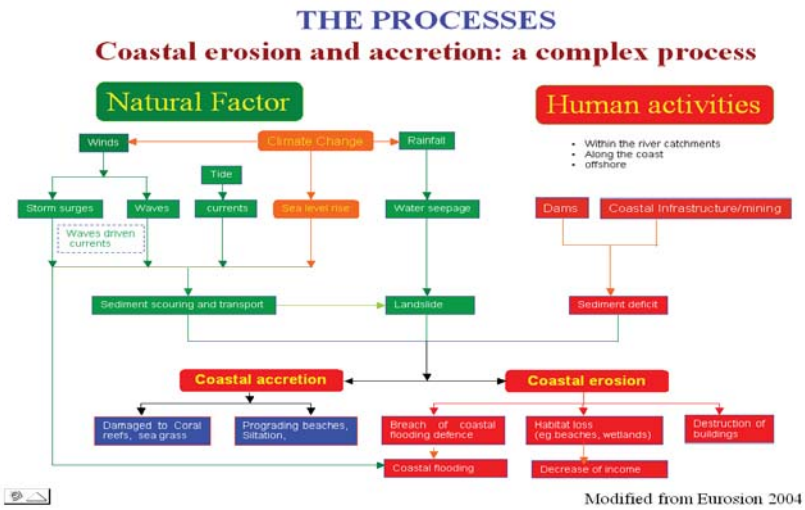

Fig. 4: The complex coastal erosion and accretion processes (Prasetya, 2006).

Increased interest in soft structures for coastal protection using a combination of hard and soft structures is predominating and consonant with advanced knowledge of coastal processes and natural protective functions.

3. WAVES

Geometry, ocean weather condition, and meteorology are the most important factors for coastline management. Wave, tide, ocean flow and wind are the major external energy sources for coastline equilibrium system. However, waves are the most important energy source among of them. Surface tension wave, ripple, gravity wave, wind wave, long wave, storm wave, and tidal wave are general ocean weaves with different frequency. Ocean weaves are normally different in height and shape, direct and commonly move over the top of each other, and therefore are also named irregular waves. However, regular waves with the same height, same frequency and same direction are normally used in classical wave theoretical analysis. Along the coast region, ocean and tidal currents have the same wave celerity and flow direction caused by steady wind or constant density difference, and nears ho re currents induced by surf waves. Considering the duration and space, ocean currents consist of higher magnitudes than tidal and near shore currents. Near-shore currents are more complex and have a greater influence on coastline geometry and coastline littoral (Kao, 1988).

4. COAST &BEACH GEOMETRY

In general, the existing coast geometry is the result oflong-term interaction between the ocean and land. Typical coast geometry include rock coastline, sedimentary coastline and river delta coastline. Marine erosion is the result of continuous coastline attack by ocean impact factors. Wave erosion is the major item among marine erosion phenomena.

A rock coastline results from mountains or rock terrain existing beside the ocean. Typical rock coastlines exist at the northeastern corner of Taiwan. Sedimentary coastline is the secondary coastline and is greatly influenced by ocean waves. The sediment carried from up-stream rivers is deposited at the delta area near the ocean due to low river flow velocity (Kao, 1988).

Beach and near shore regions are the typical wave energy dissipation areas. Wave energy transfers energy to the near-shore current and disturbs the sand in the ocean bed during the wave breaking process which has great influence on ocean bed formation. The major influence factor for ocean formation includes beach sand granular size, beach slope, wave travel direction, tidal height, source of liftoff, near shore geometry and other human factors. Coastline geometry typically changes as the wave magnitude varies. Some littorals and will be transported by near-shore currents. This is a dynamic process. Erosion and the deposit of littorals and along a coastline is based upon the amount of sediment supplemented or transported from up-stream (Kao, 1988)

4.1 Sea Level Variation

The sea level is the baseline for ground elevation and also is a very important factor related to the variation in coastline geometry. Crustal movement, the interaction between earth plates, eustatic movement, the variation in sea level and both movements will change the land elevation to sea-level. The global warming effect has induced global temperature increase and sea level rise. Based upon the IPCC report, the sea level is expected to rise from rise 48cm to 87 cm from 1990 to 2100 (IPCC, 2001). Sea level rise would induce river delta flooding and create impacts on coastline groundwater, coastline geometry, natural ecology systems, human living environment, harbors and coastline disaster prevention programs and infrastructure. Therefore, the variation in sea level has a great impact on coastline stability and protection (Kao, 1988).

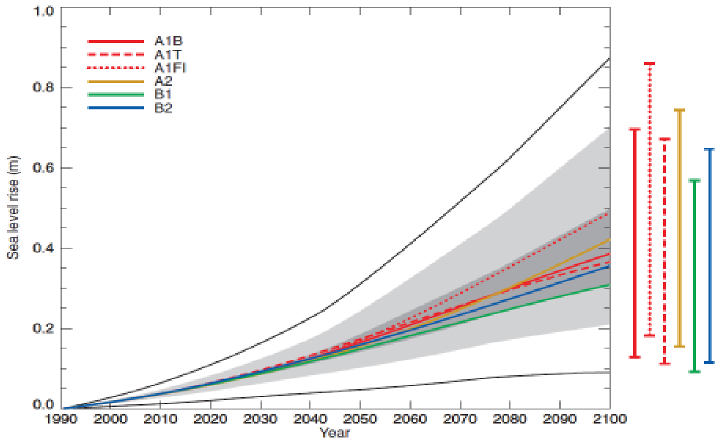

Fig. 5: Century estimated average sea level rising chart (IPCC, 2001).

4.2 Tides and Storm Surges

The coastline responds to various forcing mechanisms that provide the energy and momentum to drive the littoral processes. In addition to the long-term mechanisms, the short-term forces, including storms, waves, current and wind effects. These forces act over periods of seconds, hours and days rather than years and centuries. Long-term sea level rise occurs at rates measured in millimeters per year. More rapidly changing sea levels are caused by astronomical tides, storm surges and waves. Waves are the prime movers for the littoral processes at the shoreline. For the most part, they are generated by the action of the wind over water, but also by moving objects such as passing boats and ships (Dean and Dalrymple, 2002).

5. LITTORAL TRANSPORTATION PROCESSES

The sediment carried by the waves and currents is referred to as the littoral drift. The amount of sediment moved along the coast is the littoral transport, or long shore sediment transport, which is usually measured in units such as cubic meters per year or cubic yards per year. As the wave environment changes during the year, the transport can change. However, at most coastlines there is a dominant sediment transport direction. Down drift refers to a direction coincident with this dominant transport direction, whereas updrift is the opposite direction (Dean and Dalrymple, 2002).

Littoral transport can be parallel along the coastline. In addition, cross shore sedimentcan be transported perpendicular to the coastline. The cross-shore transport, which is caused by wave- or wind-induced mean cross-shore flows, is largely responsible for the existence of sandbars and other beach profile changes. These changes can be slow, on the order of years in duration, or they can occur rapidly during storms with time scales on the order of hours (Dean and Dalrymple, 2002).

6. MANAGING COASTAL EROSION PROBLEMS

Assessing coastal erosion can be done using visual observation and through discussions with inhabitants to ascertain its degree and when it started. Common visual indications to identify erosion problems are summarized in Table 1 (Prasetya, 2006). However, determining the causes of coastal erosion and which coastal protection options should be used requires a comprehensive investigation of coastal processes that study every season on a regional scale. Typical options for combating coastal erosion are traditionally two types, namely hard structural/engineering methods and soft structural/engineering techniques. These solutions have at least two hydraulic functions to control waves and littoral sediment transport. The combination of hard and soft options has recently become more popular for optimum results. Some failure cases have resulted in environmental and socio-economic problems owing to improper design, construction and maintenance. Case studies will be discussed in the following sections (Prasetya, 2006).

Table 1: Common visual indicators for identifying erosion problems (Prasetya, 2006)

All coastlines	Cliff and platform (hard coast)	Clayey banks and muddy coast (semi-hard coast)	Sandy coast (soft coast)
Object (e.g. fence, shed or tree) which falls into the sea	Very steep cliff faces	Tree angle	Stable back dune vegetation in the active zone
Presence of existing coastal erosion management works (particularly poor condition of structures)	Shore platforms	Non-vegetated clayey banks	Damaged vegetation in the active zone (exposed roots)
	Sea caves, notches, stacks	Slumping slopes	Erosion scarps
	Debris at toe of cliff	Dislodged vegetation in the coastal area	Discontinuous vegetation cover on foredunes
	Tree angle at the top of the cliff	Erosion scarps	Irregular foredune crest, blow outs
			Very steep dune formation

7. COASTLINE PROTECTION TECHNIQUES

At eroding shorelines, one sure means of preventing land loss is by coastal armoring, usually with seawalls or revetments. The effects of armoring on the adjacent beaches and the offshore profile are not well understood and the concern over future sea level rise and the consequence of shoreline erosion has mobilized groups favoring letting natural processes occur in general and opposing armoring in particular. Claims have been made that armoring causes the offshore profile to steepen and the adjacent beaches to erode. Many times a coastal engineer must attempt, in a diagnostic mode, to unravel shoreline changes to separate the natural behavior from the impact of armoring or other human interventions. In cases where armoring would be acted upon by the waves daily and the littoral transport rates are low, armoring definitely impacts the adjacent (predominantly downdrift) beaches. However, in cases where the armoring would be required to provide protection only rarely, it may be regarded as an insurance policy. If the cost of armoring, including consideration of the impacts on adjacent beaches, is lower than the benefits to be accrued, then armoring or other shoreline protection schemes are appropriate (Dean and Dalrymple, 2002).

Long term earth plate contact variations, ocean surface raising, ground settlement, littoral reduction and increasing frequency of storms would induce coastline erosion. In addition, human coastline investment activities, such as harbor wave protection levees, coastline reclamation, coastline structures, and littoral mininghas increased in last several decades. These activities induce increasing coastline erosion. For the protection of coastline resources and properties, hard armor and soft protection technologies are commonly used in coastline protection applications. Typical protection strategies include: retreatment, accommodation and protection. The retreatment strategy is related to nointention or proceeding of any protection activity. The accommodation strategy would allow the necessary development with some limitations. For some high populated areas, heavy economic zones, or natural resource enriched areas, protection techniques would be constructed to protect erosion potential are as (Kao, 2004).

Offshore levees and artificial headlands are commonly used to control modify wave and tide direction in order to change the beach sand response. However, these techniques will not change the amount of littoral activity. Therefore, the most important tasks for coastline erosion prevention are to maintain the river and ocean littoral equilibrium. The most important investigation items in the coastline erosion protection structures design stage include (Kao, 2004):

Maximum tidal elevation, maximum wave and related direction, sea depth map and beach sand particle distribution, nearshore littoral direction, variation inseasonal sediment amount, cross shore sediment limits and seasonal variation, offshore and near beach sediment variation, theaverage shoreline backward speed, the amount and resource and settle locations of sediment, possible sediment circulation system, the needs and priority of various protection schemes, future possible additional influence factors, and future recreation and landscape, and eco-environment needs.

7.1 Typical Armor and Soft Protection Methods Included

The typical armor protection methods included seawalls, revetments, groins, offshore or detached breakwaters, submerged breakwaters and artificial reef work. The typical soft protection schemes consist of beach nourishment, sand dunes, headland defense work, control beach water level and ecology treatments.

In some cases several methods are required to control waves, currentsor littoral transportation. The advantages and disadvantages of these engineering protection methods can be evaluated based upon their function, safety, durability, economy, constructability, environment impacts, landscape condition, recreation function and ecological impact. Each method has its typical function. The owners or the engineers can choose the necessary protection method based on their needs. The planning and design of various methods will be discussed in the following sections.

7.1.1 *Seawalls and Revetments*

Seawalls and revetments are normally constructed parallel to the coastline and at the boundary between the ocean and land to limit landward erosion. A sloping revetment is only slightly higher than the adjacent land. Stone, asphalt or concrete block structures are placed on a slope at the foot of bluffs, dunes or along the beach face. The structure design is intended to create wave breaking and loss of energy during the run-up process, limiting the reflection of wave energy from the beach. The stone revetment design may consist of two or more layers of stone with the upper, larger stones providing stability against wave attack. Figure 6 shows a typical revetment made of stone (Dean and Dalrymple, 2002).

Fig. 6: Example of a revetment.

Seawalls are most often vertical walls fronting a highland with the beach or water on the opposite side. The most common structural materials are timber, concrete or steel sheet pilings. Other seawall designs, usually constructed of concrete, have curved shapes to deflect the incident waves, reducing scour at the toe of the wall, or to reflect the waves. The interaction of seawalls with the beach system is similar in many respects to that of revetments(Dean and Dalrymple, 2002).

7.1.2 *Groins*

Groins are a protective vertical barrier extending directly offshore to cutoff littoral sand and protect beach structures. Groins have served traditionally to prevent shoreline erosion on shorelines with significant alongshore transport. A series of groins are commonly used to prevent the littoral transportation along coastline, impounding a fillet of sand on the updrift sides, resulting in erosion on the downdrift sides. In addition, these structures could increase the beach area for recreation and other applications.

7.1.3 *Offshore Breakwaters*

Offshore breakwaters are a line of artificial seaward constructions in series a distance away from and parallel to the shoreline. The back side of offshore breakwaters general presents sheltering zones due to the wave diffraction effect. This effect can reduce the wave energy impact on the shoreline and cause littoral sand to be deposited near the coastline to create an offshore salient geometry. The length and height of offshore breakwaters are dependent on the local geometry and the littoral sediment requirement. A submerged breakwater was recently introduced to meet the requirement for shoreline landscape design (Kao, 2004).

7.1.4 *Artificial Headland*

Artificial headlands are breakwaters built along the shoreline designed in plan form to producecrenulate bays. These structures have been used effectively in Australia and Singapore. The simplest form of headland control is a series of shore-parallel structures that can be viewed basically as sections of seawalls or shore-attached multiple breakwaters, as shown in Figure 7. Erosion between the structures leads to the equilibrium plan form often referred to as a spiral bay. The spiral shoreline tends to orient itself parallel to the local wave crests (Dean and Dalrymple, 2002).

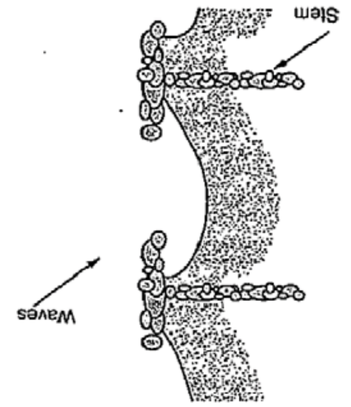

Fig. 7: the use of stems to ensure the integrity of artificial headlands (Dean and Dalrymple, 2002).

7.2 Soft Protection Methods

Soft structural/engineering protection options aim to dissipate wave energy by mirroring natural forces and maintaining the natural topography of the coast. These options include beach nourishment/feeding, dune building, re-vegetation and other non-structural management options.

7.2.1 *Artificial Beach Nourishment*

Beach nourishment is an effective coastline protection method to reduce wave energy and without destroy ocean environments. Beach erosion usually is related to the shortage of sand supply. Therefore, beach nourishment can reduce beach erosion, also stabilize and protect the shoreline. Beach nourishment, or beach fill, is the placement of large quantities of sand on an eroding beach to advance the shoreline seaward from its present location. Beach nourishment is one the most common methods for erosion mitigation because this approach usually does not involve the construction of permanent structures. This erosion control technique is a way of setting the beach system back in time to when the shoreline was more advanced seaward (Dean and Dalrymple, 2002).

Generally, the material for beach nourishment projects is obtained by dredging from an offshore borrows area, although land sources are also used. The material obtained is frequently finer and more poorly sorted than that naturally present on the beach, which may reduce the effectiveness of the project. If sand finer than the native is used, a much greater volume of fill may be required to yield a desired beach width. Also, the longevity of the project will be shown to depend critically on the project length. Doubling the project length quadruples the project life. The wave height is an even more significant determinant. The life of the project constructed in areas experienced the wave heights by a factor of two could be only 20% of that in which the lower waves prevail (Dean and Dalrymple, 2002).

7.2.2 *Dune Buildings / Reconstruction*

Sand dunes are unique among other coastal landforms as they are formed by wind rather than moving waters. They provide an ideal coastal defense system; vegetation is vital for the survival of dunes because their root systems bind sediment and facilitate the build-up of dune sediment via wind baffle. During a storm, waves can reach the dune front and draw the sand onto the beach to form a storm beach profile. In normal seasons the wind blows the sand back to the dunes. In dune building or reconstruction, sand fences and mesh matting in combination with vegetation planting have successfully regenerated dunes via sediment entrapment and vegetation colonization. The vegetation used should be governed by species already present (Prasetya, 2006).

7.2.3 *Coastal Re-vegetation*

Based upon scientific study results, the presence of vegetation in coastal areas improves slope stability, consolidates sediment and reduces wave energy moving onshore; therefore, it protects the shoreline from erosion. However, its site-specificity means that it may be successful in estuarine conditions. In most cases, re-vegetation fails because environmental conditions do not favor the growth of species at the particular site or there is ignorance as to how to properly plant given the same conditions. The most obvious indicator of site suitability is the presence of vegetation already growing. The can be extended by other factors such as the slope, elevation, tidal range, salinity, substrate and hydrology (Clark 1995 and French 2001).

7.3 Comparison of Various Protection Schemes

Seawalls are the most commonly coastline protection method. Seawalls can protect coastline from waves and tides and shorten the beach distance. However, non-effective seawall design or inappropriate seawall wave incident angle could induce reflection waves and increase the coastline erosion. If a groins design is too long or inappropriate for the wave incident angle, it would also block the littoral transportation or induce more coastline erosion. The current speed near the opening of offshore breakwaters would induce the scouring effect near the foundation of breakwaters. The advantage and disadvantage of several typical used hard armoring and soft coastline protection schemes are summarized in the following Table 2.

Table 2: Comparison between various coastline protection methods (Kao, 2004)

Method	Advantage	Disadvantage
Seawalls	Easy for construction, waves and tides protect functions	Beach erosion occurred for the condition with wall front reflection waves
Groins	Intercept nearshore littoral	Induce downstream beach erosion
Offshore breakwaters	Induce salient terrain behind breakwaters	Induce breakwater foundation scour and difficult for maintenance
Offshore reefs	Reduce wave energy near reefs	Cause sailing difficulty
Artificial headland	Maintain bay area equilibrium	Induce coastline erosion from storm wave
Artificial reef	Low maintenance, would reduce wave energy from wave-reef interaction and reduce littoral	Few applications only
Artificial nourishment	Create natural beach and low environment impacts	Limit on sand resources and high cost

8. GEOSYNTHETICS RELATED COASTLINE PROTECTION METHODS

The geotextile is one of several geosynthetic members. Geotextiles possess good tensile strength, flexibility and permeability. Geotextiles havebeen widely used for civil, geotechnical, water resource, transportation and environmental engineering projects. Geotextiles have been widely placed under seawalls, dikes and river bank protection works as the filters or separators in hydraulic applications.

Seawalls, groins, and offshore breakwater made of concrete are the conventional coastline protection methods.These schemes in some cases are not environmentally friendly methods. Geotextiles used as flexible forms in the context of bags, containers, mattresses, and tubes is growing at an incredible rate. The primary applications are erosion control and dewatering. The fill in erosion control applications is usually cohesionless sand or gravel, while dewatering applications focus on fine-grained dredge spoils or industrial waste sludges, not the least of which is agricultural waste.

Geo-mattresses, geo-bags, geo-tubes and geo-containers made of geotextiles are widely used as the replacement technique for coastline protection works. Geotextile bags manufactured with UV-stabilized antioxidants are being successfully used for erosion control in numerous situations. The application of geotextile bag to protect a Historic Farm Building along North Sea, Germany is shown in Figure 8 (Koerner, 2012).

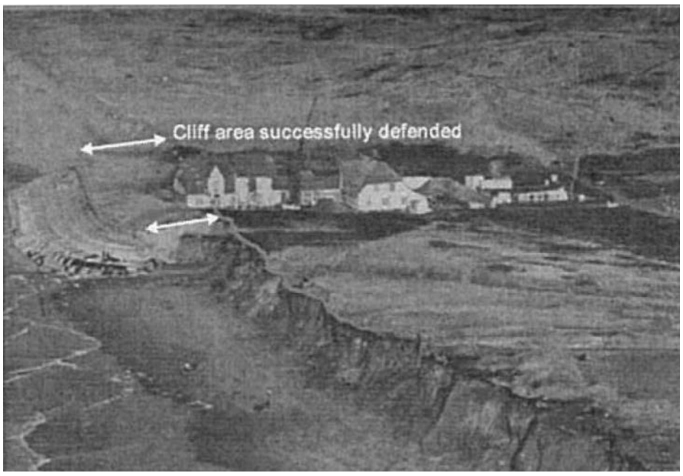

Fig. 8: Geotextile bag protecting the North Sea shoreline, Germany (Koerner, 2012).

Geotextile containers represent an extension of the previous geobags, but the application differs, often involving the removal of river and harbor bottom sediments from shipping channels and navigable water ways. The technique generally utilizes high-strength woven geotextile (50 kN/m) and bottom dump barges. The geotextiles are placed in the empty barge and then filled with the bottom sediments. When full, the geotextile ends are folded over the top and sewn together, thereby completing the enclosure. The barge is towed to the disposal area and, when properly positioned, the split hull of the barge is opened and the sediment-filled container drops to the bottom. Subsurface embankments or breakwaters are being formed using this technique, which has the significant advantage that the sediments never leave the estuary or harbor (Koerner, 2012).

Geotextile tubes form the logical extension to bags and containers and have been increasing in size and length since their inception. Efforts to form flexible sand-filled tubes were made as early as 1957. This technology has rapidly grown since 1967. Geotextile tubes can be as large as 20 m in circumference and an unlimited strength. Figure 9 shows large geotextile tubes filled with dredged sand acting as a beach erosion control system. Tube anchoring, tube connection details, tube rolling during storms, fabrics opening size, strength of fabrics and seams, tube final dimensions are the important design issues need to be addressed. Typical design monograph is shown in Figure 10 (Koerner, 2012).

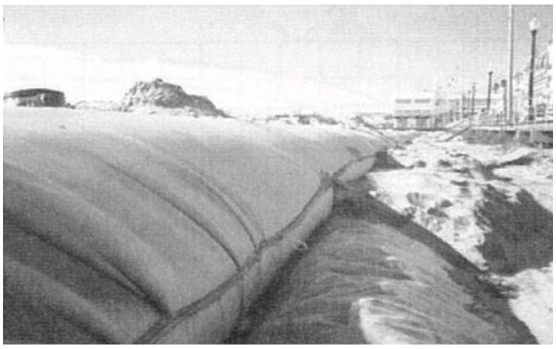

Fig. 9: Sand filled geotextile tubes for beach erosion protection (Koerner, 2012).

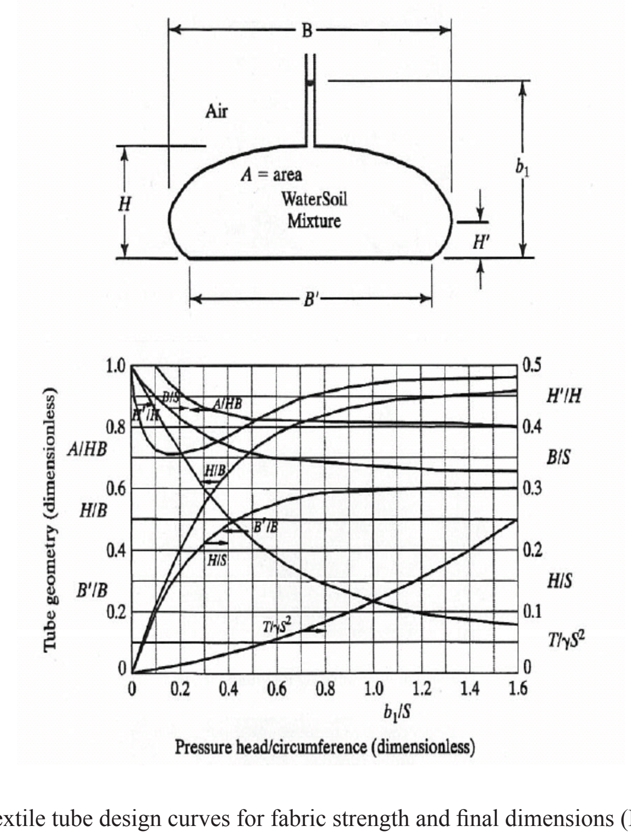

Fig. 10: Geotextile tube design curves for fabric strength and final dimensions (Koerner, 2012).

9. SHORELINE MANAGEMENT

The increased rate of sea level rise and the possibility for increased storminess due to the Greenhouse effect have raised questions about the most appropriate policies for coastal zone management. There are few options that can be considered for shoreline management on eroding coastlines. The first possible scheme is retreat by abandoning shoreline development or moving it landward at the same rate as the shoreline recession. The second approach is nourishing the beach with added sediment to stabilize it. The third program is protecting the beach using hard structures such as groins, seawalls or revetments.

The long-term background erosion rate and its causes are important determinants in identifying appropriate options. Armoring the beach with seawalls or revetments is generally looked on as causing a variety of adverse shoreline impacts. Some of these criticisms are deserved, although the general assessment is probably overly critical. In cases in which the erosion is caused by human activities, such as jetty constructions, matters of equity emerge. (Dean and Dalrymple, 2002)

9.1 Taiwan Coastline Overview and Management Programs

Taiwan is a major island on the west pacific rims. The total area of Taiwan Island is 36,193 km2. Two-thirds of Taiwan Island consists mostly of rugged mountains running in five ranges from the northern to the southern tip of the island. The flat to gently rolling Chianan Plains in the west is home to most of Taiwan's population. Taiwan's highest point is Yu Shan (Jade Mountain) at 3,952 meters. Taiwan is the world's fourth-highest island.

The Taiwan coastline is about 1600 kilometers in length. Taiwan coast topographies can be divided into four major terrains, which include Northern submergence coastlines (85 km), Western gentle deposition coastlines (460 km), Eastern faulty cliff coastlines, and Southern coral reef coastlines as shown in Figure 11. Eastern coastlines have a steep slope and deep ocean beds. However, the west coastlines are flat with wider tidal zones. The north-eastern coastlines consists some special scenery terrains, such as mycoides terrain, honeycomb terrain and candlestick terrain as shown in Figure 12. Typical eastern faulty cliff and southern coral reefs terrains are shown in Figures 13 and 14.

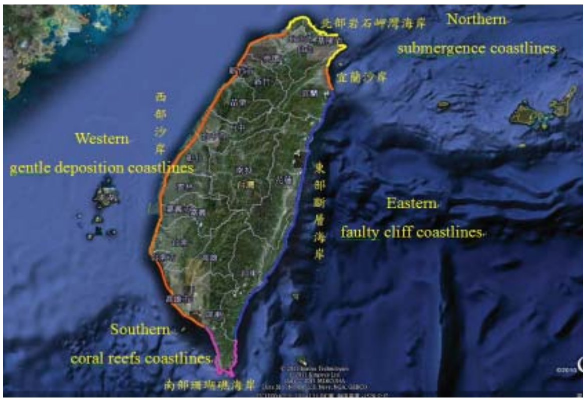

Fig. 11: Taiwan coastline classification map (http://blog.isky.tw/2011/08/blog-post_16.html).

Fig. 12: Typical honeycomb terrain and candlestick terrain in Taiwan North-eastern coastlines (Hsu, 2008).

Fig. 13: Typical Eastern faulty cliff coastlines in Taiwan (Hsu, 2008)

Fig. 14: Typical coral reef coastline in southern Taiwan (Hsu, 2008)

The Taiwan coastline erosion and accretion distribution map is shown in Figure 15. In addition to coastline erosion and accretion situations in Taiwan, sea pollution, groundwater saline intrusion, ecological atrophy and near shore alluvial plain settlement phenomena are severe coastline problems in Taiwan. Typhoon induced sand beach and rocky cliff coastline erosion cases are shown in Figure 16. Figure 17 shows a typical near shore alluvial plain settlement case in southern Taiwan. Five hundred and ten kilometer seawalls were built to protect nearly50,000 hectares of land in Taiwan. Groins and offshore breakwaters were also used for Taiwan coastline protection applications as shown in Figure 18. Some geotube and geobag coastline protection applications have recently been introduced to government agencies. Several projects are under investigation process in Taiwan. Offshore submerged breakwaters with beach nourishment schemes were used to improve beach recreation and tourism applications for Kaohsiung harbor as shown in Figure 19.

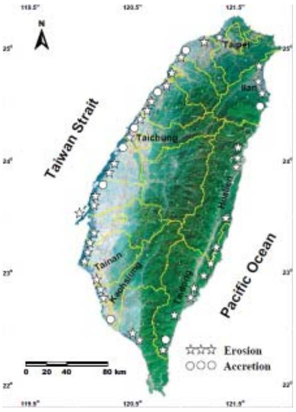

Fig. 15: Taiwan coastline erosion and accretion distribution map (Hsu, 2008).

(a) Beach revetment protected coastline failure after Typhoon attachs

(b) Cliff coastline failure after typhoon attacks

Fig. 16: Typical typhoon induced beach and cliff coastline erosion cases (Hsu, 2008).

Fig. 17: A typical southern Taiwan nearshore alluvial plain settlement case (Hsu, 2008).

Fig. 18: Groins and offshore breakwaters coastline protection cases in Taiwan (Hsu, 2008).

Fig. 19: Offshore submerged breakwaters with nourishment schemes were used for Kaohsiung harbor beach protection project (Kao, 2013).

10. GEOSYNTHETIC APPLICATIONS FOR COASTLINE PROTECTIONS

10.1 Geosynthetics for Sike Protection

Climate change has triggered the need for sea level rise scenarios that show the need for better coastal protection dike structure development. A large-scale research dike has been built in Rostock, Germany, including ten different cross-sections with different slope inclinations, material combinations and geosynthetic solutions. Erosion control mats were used for dike slope surface protection, needle-punched non-woven geo-containers and/or geogrids were used for dike core stabilization. Geogrids were used to increase the dike bearing capacity, as shown in Figure 20 (Saathoff and Cantre, 2014).

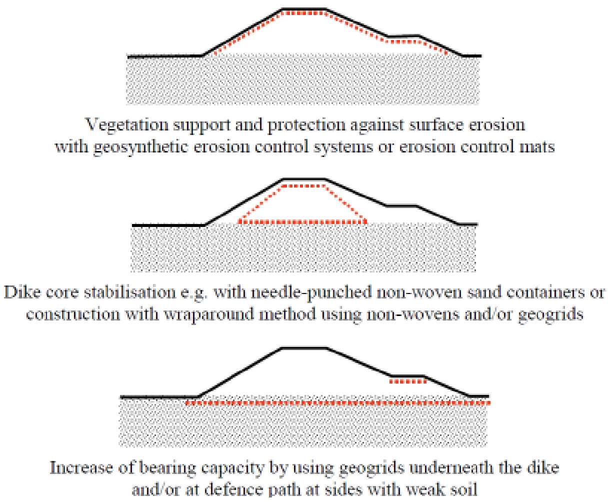

Fig. 20: Geosynthetics application in North Sea dike protection (Saathoff and Cantre, 2014).

10.2 Geotextile Tube for Coastline Protection

A 33.9 km long sea dike links Gunsan to Buan in Korea. More than 26 geotextile tubes were used for polder sea dike construction that serves as a land reclamation dike during the construction period and as a flood protection dike for the long term application. The polder dike consists of a sand filled core with rock revetment for erosion protection on both sides of the dike. A typical polder dike cross section with geotextile tube berm is shown in Figure 21. Two standard tube fabric types were assigned to manufacture the five different tube sizes. The ultimate tensile strength and mean pore size of Type I and type II fabrics are 120 kN/m and 200 kN/m, and 0.3 mm, respectively (Yee et al., 2014).

Sand encapsulated geotextile tube elements were also used at the coast near Lido Sete in the south of France for beach protection. Five meter long geotubes were filled with sand under the waterline at a height of 3 meters. In addition to the coastal protection function, local available sand materials were used to achieve high savings in the carbon footprint calculations (Zengerink, 2015). A schematic view of the geotextile tube sand filling process is shown in Figure 22.

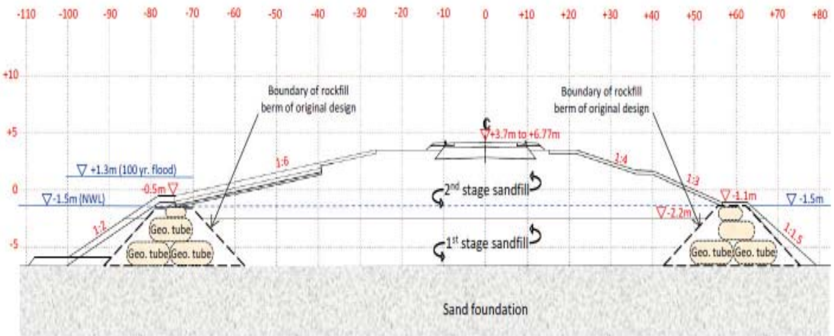

Fig. 21: Typical Polder Dike cross section for alternative design with geotextile tube berm (the original rockfill berm design is indicated) (Yee et al., 2014).

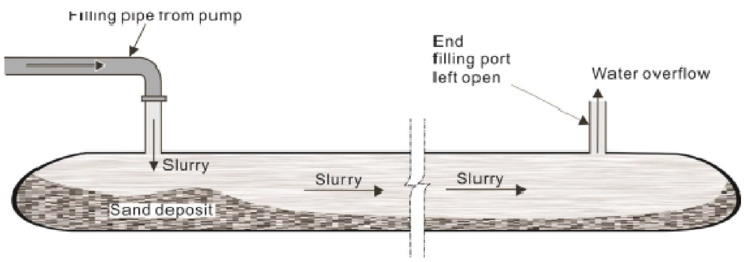

Fig. 22: Schematic view of sand filling process of geotextile tube (Zengerink, 2015).

Geotextile tubes were used for shoreline protection of a coastal town in Mexico. After two beach protection project stages were completed the project area faced strong winds and high waves from Tropical storm Ernesto in July 2012. Only minor scour was observed at the junction between two tubes over more than 2 km of protected shoreline. This is a success case for coastal protection and beach recovery. (Diaz et al., 2013)

From August to November of 2009 the City of Ocean City was subjected to a series of five storms. These storms eroded almost all of the dunes on Waverly Beach as well as approximately a 500 foot long section of beach parking area. A polyester or polypropylene large geotextile containment unit was used in the shoreline protection project as shown in Figure 23. The project was completed in the spring of 2011 almost eighteen months prior to Hurricane Sandy making landfall on October 2012. Hurricane Sandy was equivalent to a fifty year storm for Ocean City. The geotextile tubes were not damaged during the storm event. The city was very happy with the geotextile system performance and would not hesitate to use the system again in the future (Chew, 2015). The use of geotubes for beach restoration projects was also reported by Alvarex et al. (2007) and Chien et al. (2013).

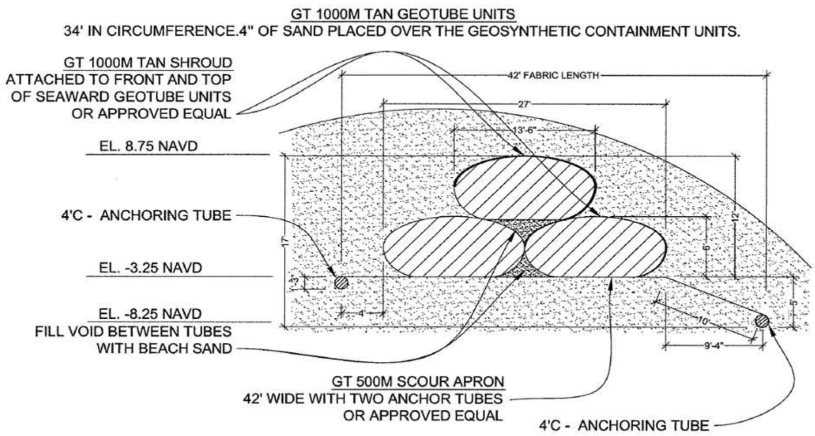

Fig. 23: Geotextile Structure Cross Section (Chew, 2015).

10.3 Geotextile Tube Failures

Geotextile tubes are generally subjected to multiple fills during construction. Each filling subjects the tube to circumferential and axial stresses which cause yarn elongation. Repeated cycles can cause fatigue resulting in rupture. The controlled failure of a geotextile tube is shown in Figure 24. Various mechanisms are responsible for geotextile tube failure during filling. Gaffney (2013) investigated six geotextile tube fabrics using a modified ASTM D4595 test method. The test fabrics were subjected three-cycle tension loads. The specimen was pulled to failure during the third cycle. The engineering design should consider stacking geotextile tubes in layers. The specified fill height should account for the possibility of a gap under the tube. The test results showed a loss of tensile strength due to cyclical stress. Large dewatering geotextile tube design, especially stacked tubes, should address the potential for this type condition.

Fig. 24: Controlled failure of geotextile tube (Gaffney, 2013).

10.4 Geosynthetic Mattresses for Revetment Protection

Stone-filled geosynthetic mattresses, also known as marine mattresses, have been in use since the mid-1990's. To improve performance the mattress geogrid is now a HDPE and PP copolymer. The mattresses are fabricated into a variety of shapes that are generally rectangular (5 or 6.5 feet wide and 10 to 45 feet long) with thicknesses ranging from 6 to 24 inches. The mattresses have interior baffles to keep the stone at the specified density within each compartment as shown in Figure 25. The marine mattresses are subject to direct wave forces and high shear stresses. Generally, the marine mattresses provides scour and erosion protection. The mattresses also serve as a filter layer by separating the upper layer of stone from the foundation material. The mattress performance from the three earliest marine projects, more than 20 years old, in Boston, Atlanta Georgia and Puerto Rico were assessed. The assessment results indicated that the UV degradation and engineering performance of the HDPE geogrids met the design team expectations (Fiske, 2015).

Fig. 25: Marine Mattress being hoisted from the filling frame (Fiske, 2015)

10.5 Earthen Levee Strengthening with High Performance Turf Reinforcement Mat (HPTRM)

Hurricane Katrina caused catastrophic overtopping and extensive damage to the levee system that surrounds New Orleans. Post-Katrina investigation revealed that most earthen levee damage occurred on the levee crest and landward-side slope resulting from wave overtopping, storm surge overflow or a combination of both (ASCE, 2007). High performance turf reinforcement mat (HPTRM) was used as one of the strengthening systems that can be used on the crest and landward-side of an earthen levee. This system was evaluated in a series of full-scale flume tests. A profile view of the large wave flume and levee embankment location is shown in Figure 26. Overtopping conditions were included in the tests simulating waves or combined wave and storm surge. As the grass roots grow through the open HPTRM spaces, roots become entwined within the turf reinforced mat. The interlocking between the roots and HPTRM can enhance the resistance against hydraulic and shear forces created by high water flow hydraulic conditions. Based upon the flume test results a design guideline and equation were developed for wave and surge overtopping conditions for levee systems. (Li et al., 2013)

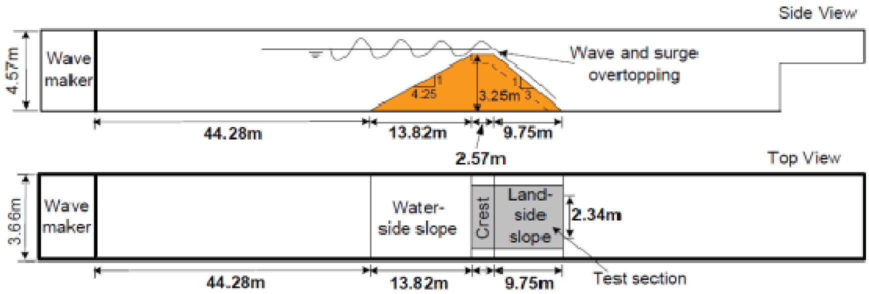

Fig. 26: Profile view of the large wave flume and location of levee embankment (Li, 2013).

10.6 Geotextile Filter for Revetment

Geotextile filters have proven an important element between the subsoil and erosion-proof armor layer. A revetment was built underwater, showing that a geotextile is not only subject to predicted loads during installation, but also exposed to unforeseen loads. The robustness of the geotextiles and quality assurance during installation both play important roles in this application. (Kunz et al., 2014)

On June 27 2004, Tropical Storm Tingting hit the island of Guan, dumping up to 555 mm of rain in 24 hours. This rain was preceded by a two-week period that had produced an additional 360 mm of rain on Guam. The saturated soil conditions created by this extreme rainfall triggered numerous landslides across Guam. The highly plastic soils in the volcanic area in the southern half of Guam are particularly susceptible to landslides. (Doerge, 2008) A major landslide occurred on a hillside just above a subdivision near the town of Piti in west-central Guam. Geotextiles were used in the remediation of this large, geologically complex landslide on the island of Guam. The geotextile application was intended to eliminate the potential for clogging. A conventional sand filter was used between a gravel drain and the overly silty rockfill. (Doerge, 2015)

10.7 Permanent Erosion and Re-vegetation Materials for Hard Armor Related Application

Clearly, fabric-formed revetments (FFRs), which are hard armor materials, clearly recognize that erosion control is the major feature of this system. Numerous concrete block systems are available for erosion control. Hand-placed interlocking masonry blocks are very popular for low-traffic pavement areas. Alternatively, the system can be factory-fabricated as a unit, and placed on prepared soil. The prefabricated blocks are either laid on or bonded to a geotextile substrate. The finished mats can bend and torque by virtue of the blocks being articulated with mechanical jointed weaving patterns, or cable. Pre-fabricated articulating concrete block mats with filter fabrics underneath were used for suburban dam spillways and beach protection projects, as shown in Figure 27 (www.contechES.com, 2016).

Fig. 27: Pre-fabricated articulating concrete block mats underneath by filter fabrics were used for suburban dam spillway and beach protection project (www.contechES.com, 2016)

11. SUMMARY AND CONCLUSIONS

A coastline is the boundary dividing land and sea. A shoreline is the boundary dividing land and seawater. However, coastline and shoreline are common interchangeable terms for each other. In general, the existing coast geometry is the result of long-term interaction between the ocean and land. Typical coast geometry includes rock coastline, sedimentary coastline and river delta coastline. Many of these coastlines have beaches composed of loose sediments such as gravel, sand or mud that are constantly acted upon by waves, currents and winds.

Coastline region activities have increased significantly due to human and industrial activities. These activities also induce coastline associated problems such as ground settlement, coastline erosion, coast pollution, environmental protection, land use concurrence and disaster prevention.

Waves, tides, ocean flow and wind are the major external energy sources for coastline equilibrium system. However, wavesare the most important energy source among them. The sediment carried by waves and currents is referred to as littoral drift.The amount of sediment moved along the coast is the littoral transport, or long shore sediment transport.

Determining the causes of coastal erosion and which coastal protection options should be used requires a comprehensive investigation of coastal processes conducted on a regional scale through every season.

There are few options that can be considered for eroding coastlines. The first possible scheme is retreat by abandoning shoreline development or moving it landward at the same rate as the shoreline recession. The second approach is nourishing the beach with added sediment to stabilize it. The third program is protecting the beach using hard structures such as groins, seawalls or revetments.

For coastline resource and properties protection, hard armor and soft protection technologies are commonly used in the coastline protection applications. Typical protection strategies include retreatment, accommodation and protection. The retreatment strategy involves ceasing human activity and instituting no protection activity. The accommodation strategy allows the necessary development with some limitation. For some high populated areas, heavy economic zones, or natural resource enriched areas, protection techniques would be constructed to protection erosion potential areas.

Offshore levees and artificial headlands are commonly used to control and modify wave and tide direction in order to change the response of beach sands. However, these techniques will not change the amount of littoral sediment. Therefore, the most important tasks for coastline erosion prevention are to maintain the river and ocean littoral equilibrium.

Typical options for combating coastal erosion are traditionally two types, namely hard structural/engineering methods and soft structural/engineering techniques. These solutions have at least two hydraulic functions to control waves and littoral sediment transport. The cost of installing hard structures for coastal protection is very high and brings strong negative public reaction to rock emplacements along the coast. The combination of hard and soft options has become more popular recently for optimum results.

The typical armor protection methods include seawalls, revetments, groins, offshore or detached breakwaters, submerged breakwaters and artificial reef work. The typical soft protection schemes consist of beach nourishment, sand dunes, headland defense work, control beach water level and ecological treatments.

In some cases, the used of several methods is required to control waves, currentsand littoral transportation. The advantages and disadvantages of these engineering protection methods can be evaluated based upon their function, safety, durability, economy, constructability, environment impacts, landscape condition, recreation function and ecological impact. Each method has its typical function. Engineers can choose the necessary protection method based on their needs.

Soft structural/engineering protection options aim to dissipate wave energy by mirroring natural forces and maintaining the natural coast topography. These options include beach nourishment/feeding, dune building, re-vegetation and other non-structural management options.

Geotextiles possess good tensile strength, flexibility and permeability. Geotextiles havebeen widely used for civil, geotechnical, water resource, transportation and environmental engineering projects. Geotextiles have been widely placed under seawalls, dikes and river bank protection works as filters or separators in hydraulic applications.The use of geotextiles as flexible forms in the context of bags, containers, mattress and tubes is growing at an incredible rate. The primary applications are erosion control and dewatering.

In addition to coastline erosion and accretion situations in Taiwan, sea pollution, groundwater saline intrusion, ecological atrophy and near-shore alluvial plain settlement phenomena are also severe coastline problems in Taiwan. Five hundred and ten kilometers of seawalls were built to protect nearly 50,000 hectares of land in Taiwan. Groins and offshore breakwaters were also used in Taiwan coastline protection applications. Geotube and geobag coastline protection applications were recently introduced to government agencies, with several projects under the investigation process in Taiwan.

Many Geosynthetic coastline protection application cases are discussed in this paper, such as: geosynthetics for dike protection, geotextile tube for coastline protection, geotextile tube failures, geosynthetic mattresses for revetment protection, earthen levee strengthening with high performance turf reinforcement mat (HPTRM), geotextile filter for revetment, permanent erosion and re-vegetation materials for hard armor related applications.

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