Sustainable Mitigation of Coastal and Riverbank Erosions Caused by Severe Storms and Heavy Rainfall due to Climate Change

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ABSTRACT: Global warming is happening now with devastating effect on climate change. The result of climate change can be floods in China, Thailand and Vietnam (to name a few) as well as increasing frequency of strong typhoons and associated heavy rainfall in the Pacific and hurricanes in the Carribean and the U.S.A. These heavy rainfall, high river flow velocity, and wind-driven waves as well as strong water currents are the main causes of coastal and riverbank erosions. Traditional mitigation techniques utilizing rock, concrete, and steel for erosion protection are being increasingly challenged by alternatives offered using geosynthetics in combination with natural fibers and root reinforcement for revetments, groynes, berms, artificial reefs, erosion protection, etc. The various types of geosynthetics can be applied towards the construction of erosion resistant structures in shorelines and riverbanks. This paper points out the erosion damages and demonstrates the various mitigation measures.

1 INTRODUCTION

Global warming is evident with 11 of the previous 12 year (from 1955 to 2006) ranking among the warmest since 1980, according to the Global Environment Outlook: Environment for Development published by the UN Environmental Program. The resulting climate change are indicated by abnormal weather patterns and increased frequency of strong typhoons with the associated heavy rains.

Geosynthetics can play important and vital roles in the protection, mitigation and rehabilitation efforts in affected coastal areas. Geosynthetics have been used in hydraulic and geotechnical engineering for about the past three decades. Their use is well established for the purposes of material separation, filters, drainage, and reinforcement. There are various types of geosynthetics such as geotextiles (GT), geogrids (GG), geomembranes (GM), geonets (GN), geocomposites (GC), geopipe (GP) and geofoam (GF). The functions and geosynthetic types are tabulated in Table 1. The use of geosynthetics has advantages such as speed of construction, flexibility and durability, low mass per unit area, high strength and stiffness, and its cost effectiveness. Geosynthetics can be applied to construct artificial dunes by geotubes, erosion resistant coastal road/railway embankments, earth reinforcement earth slopes and scour resistant coastal structures by geobags and geocells, etc.

Table 1: Function vs. Geosynthetic Type.

Type of geosynthetics	Separation	Reinforcement	Filtration	Drainage	Containment
geotextile	√	√	√	√	
geogrid		√			
geonet				√	
geomembrane					√
geosynthetic clay liners					√
geopipes				√	
Geofoam	√				
geocomposites	√	√	√	√	√

However, the use of geosynthetics requires a proper understanding of soil-geosynthetic interaction mechanisms. The pullout behavior of geogrids and geotextiles has been investigated by full-scale tests, laboratory model tests and numerical analyses (Jewell et al. 1985; Ochiai et al. 1996; Long et al. 1997; Bergado et al. 2002a; Sugimoto and Alagiyawanna 2003). However, most of the previous studies were directed to investigate the interaction parameters (i.e., pullout resistance and shear stress-strain characteristics) between geosynthetics and granular soils. Researches have been done relevant to the evaluation of the interaction parameters between the cohesive soils and the geosynthetics (Bergado et al. 2002b; Long et al. 2006).

The limited life geosynthetics (LLGs) made of natural fibers can be developed into woven geosynthetics. The LLGs have been investigated by many researchers (Sarsby 2007; Lekha and Kavitha 2006; Chattopadhay and Chakravarty 2008). The LLGs can be combined with polymer geosynthetics and root reinforcement for sustainable soil erosion protection and soil stabilization.

The effects of Vetiver Grass roots in combination with Acacia Mangium Willd roots on shear strength of soil have been studied by Voottipruex et al. (2008). The results revealed that there were significant root reinforcement effects of 1.5 times increase by Vetiver Grass and 3.0 times increase by Acacia Mangium Willd in the soil shear strength.

2 BANK EROSION IN THE MEKONG RIVER

The Mekong River flows over 4,800 km from its source on the Tibetan Plateau at an elevation of 5,200 m to the South China Sea in the Mekong Delta of Vietnam. It passes through six countries, namely: China, Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam (MRC 2003). The elevation of the river is 260 m at the Golden Triangle, where Thailand, Laos and Myanmar converge (Sok 2003). The portion from the Golden Triangle to the river mouth at the Mekong Delta has a distance of more than 2,000 km and is referred as the Lower Mekong River (Figure 1)

The Mekong River forms the border between Laos and Thailand, with a length of 1,100 km (Tansubhapol 2005). These 2 countries agreed to define the political border at the deepest part of the river channel (thalweg). The thalweg can be shifted by scouring and sedimentation of the riverbed as well as riverbank erosion patterns on the opposite banks (Miyazawa et al. 2008). This shifting of the border is very sensitive political problem. Riverbank erosion is a major problem from Vientiane to Nongkhai. In this stretch, the Mekong River meanders and consequently scouring the riverbed and eroding the outer banks with sedimentation in the inner banks. JICA (2004) indicated the length of bank erosion is approximately 29 km with erosion rate of 10 to 30 m/yr. Other reaches with severe erosion includes the Mekong Delta in Vietnam (Luu et al. 2004) as well as the Chaktomuk confluence in Phnomphen, Cambodia (MRC 2002)

Riverbank erosion is caused by river meandering, high river flow velocity in the rainy/flood season, less cohesive and dispersive fine-grained soil deposits at the riverbanks, lack of vegetation and root reinforcement at the riverbanks, and human activities (Miyazawa et al. 2008). Human activities include land use, river flow modifications, sand/gravel extraction, navigation in the river, etc. Furthermore, the water level difference in the Mekong River between the flood and dry season is 10 m or more (Bergado et al. 2004). The groundwater level at the banks remains high but the river water lowers rapidly as the flood season ends. Subsequently, seepage pore pressure develops especially when the soil deposits at the riverbank consist of fine-grained and low permeability soil. These excess pore pressures cause riverbank failures. In addition, bank erosion also occurs due to the waves created by passing ships in the river channel (Miyazawa et al., 2008)

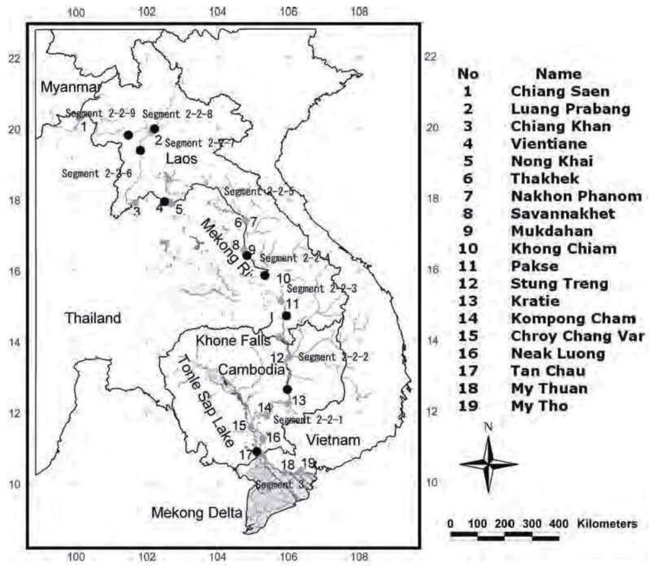

Figure 1: Lower Mekong River and river segment division.

3 COASTAL EROSION IN THAILAND

Prior to the current industrial development and population explosion, the causes of coastal erosion in Thailand were due to natural processes (Siripong 2008). The coastal areas which face the strong monsoon winds suffer severe erosions as follows:

a) During Southwest Monsoon from May to September: erosions occur along the Andaman Sea Coasts, Inner Gulf Coasts and Northeastern Coasts from Chonburi to Trat.

b) During Northeast Monsoon from October to March: erosions occur along the eastern coastlines of Southern Peninsula from Petchaburi to Narathiwat.
In the past, the coastal areas were dynamically stable as tabulated in Table 2. Nowadays, the eroded coastal areas are dominant. In general, the causes of coastal erosion are shown in Figure 2, namely: climate change, coastal processes, sea level rise, human activities, and sediment budget. However, the erosional features from waves and tsunami waves are different. The erosional features of the storm waves are caused by the breaking waves and wind-driven currents (Figure 3) On the other hand, the erosional features from the tsunami waves are much larger due to both run-up and run-down water currents as shown in Figure 4 (Siripong, 2007).

Table 2: The status of Thai coasts (total length of 2637 km) (Sinsakul, et al. 2002)

Status/Length (%)	Andaman	Gulf of Thailand
Severe erode > 5 m/yr	23(2.45%)	181 (11%)
Mid erode 1-5 m/yr	90.5(9.65%)	302(18%)
Deposition/Accretion	35(3.7%)	127(8%)
Changing	148.5(15.8%)	610(37%)
Stable (dynamic)	788.5(84.2%)	1090(63%)
Total length (km)	937	1,700

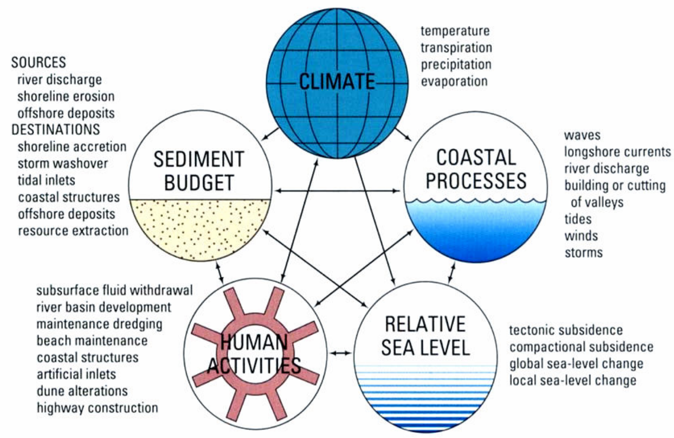

Figure 2: The causes of coastal erosion (Pilkey et al. 1989).

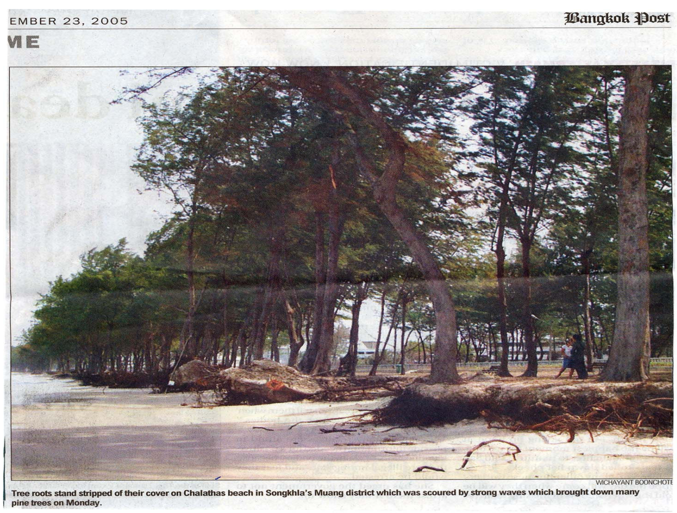

Figure 3: Beach erosion by strong waves.

Figure 4: Beach erosion by tsunami (Siripong 2007).

4 MITIGATION AND REHABILITATION FOR EROSION CONTROL

Rigid sea walls made of reinforced concrete structure may cause wave reflection preventing wave energy dissipation that lead to more erosion at the base of the wall (Figure 5). Moreover, the seawalls may block the sea turtles from laying their eggs in the beach. For severe erosion due to continuous wave action, the shoreline maybe hardened with stone revetment along the coastal area as shown in Figure 6. Revetments are protective surface capable of resisting hydraulic forces that cause erosion. These revetments can only function properly if geotextiles are utilized underneath for separator, filtration and drainage purposes and prevent internal erosion.

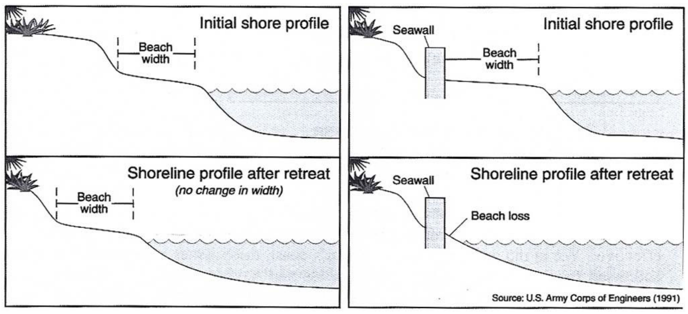

Figure 5: Potential impact of seawalls.

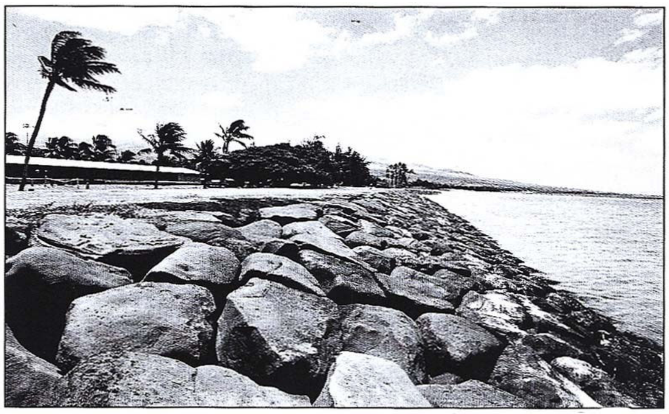

Figure 6: Shoreline hardening with stone revetments.

In recent years, the use of geotextile bags (Figure 7), geotextile tubes filled with sand (Figure 8), and geotextile wrap-around revetment (Figure 9) have been used for erosion control. The sand bags can be stitched together to form a barrier against erosion.

The geotextile tubes are closed-ended geotextile tubes with regular filling ports filled with sand/water slurry. The geotextile consists of high strength and high permeability geosynthetics. Figures 10 and 11 demonstrate the wave energy reduction due to the installation of geotextile tubes parallel to the coastline which can greatly reduce beach erosion. Groynes are geotubes that are oriented at some angle to shorelines for erosion protection in case of oblique currents.

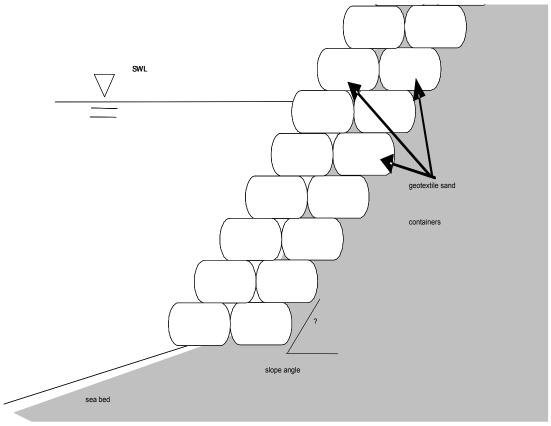

Figure 7: Revetment made with geotextile sand containers.

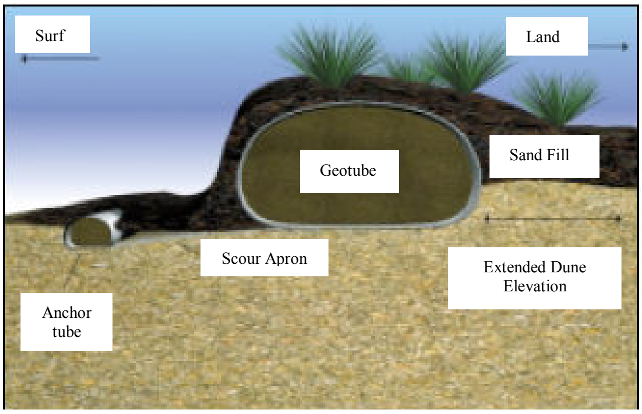

Figure 8: Schematic diagram of geotube.

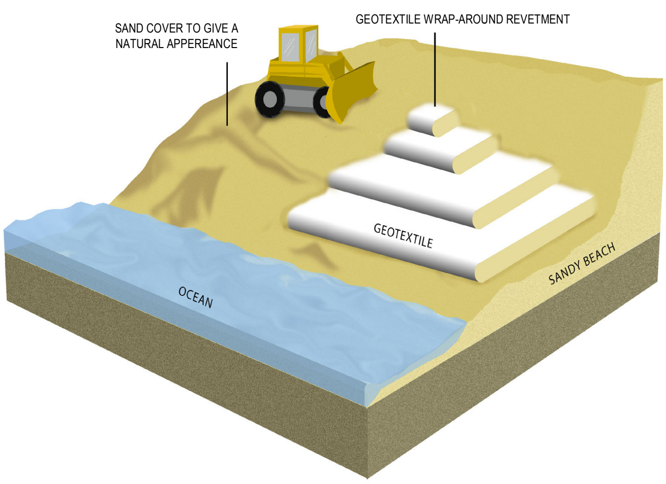

Figure 9: Geotextile wrap-around revetment.

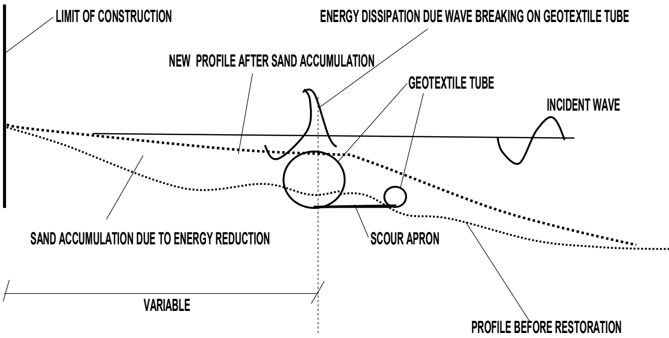

Figure 10: Schematic section of wave energy reduction.

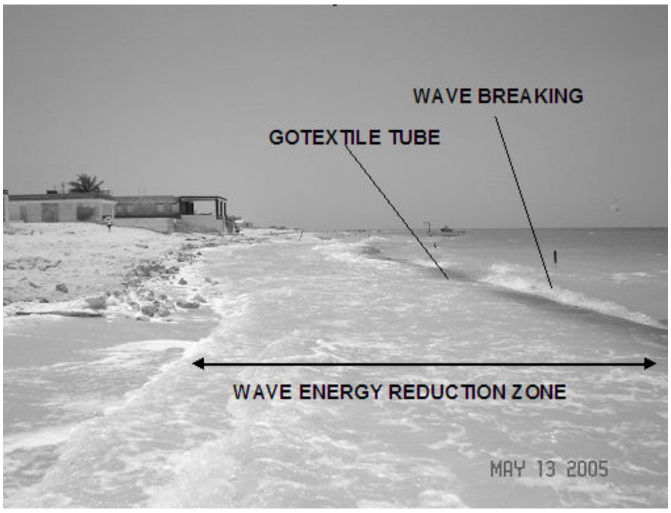

Figure 11: Geotextile tube inducing wave breaking for energy attenuation.

Figure 12: Groyne for prevention of coastal erosion.

Geocells are cellular confinement system for erosion control (Figure 13). The geocells can be stacked together for slope erosion protection. These geocells are usually infilled with gravel, sand, silt or clay. Grasses and shrubs can grow at the infills. The geocells are made of ultrasonically-welded polyethelene sheets.

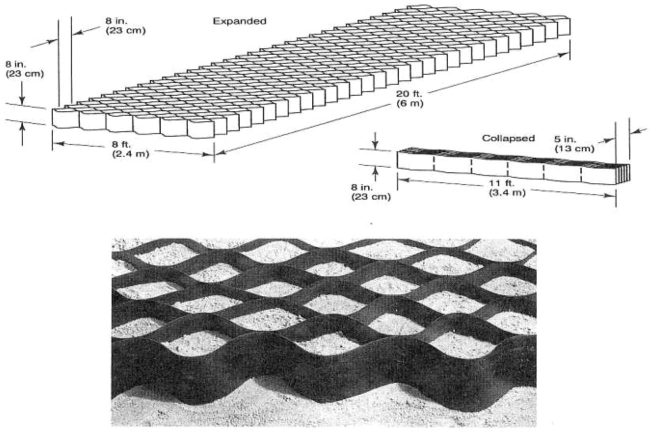

Figure 13: Geocell cellular confinement system.

Gabions and mattresses are rock-filled baskets made of twisted hexagonal wires for erosion control. The wires can be coated by either zinc or PVC. Gabions have thicker dimensions than mattresses (Figure 14). Gabions, geocells, and mattresses can be applied as revetments.

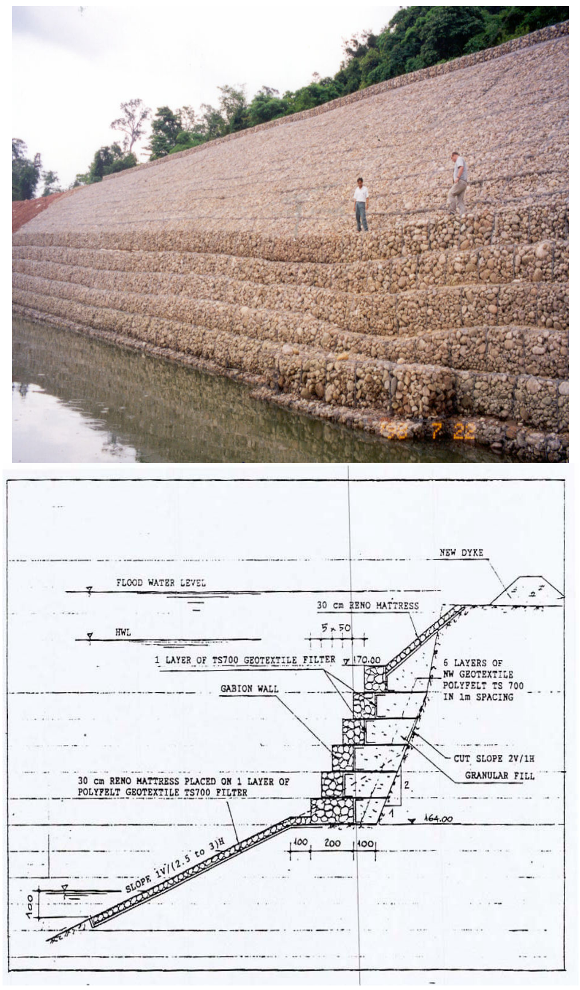

Figure 14: Gabions and mattresses are stone-filled box containers.

Revetments consisting of concrete facing, gabions, and mattresses or rock armour are effective for erosion control and scouring prevention (Figure 15). Geotextiles underneath revetments serve as separators, drainage, and filters.

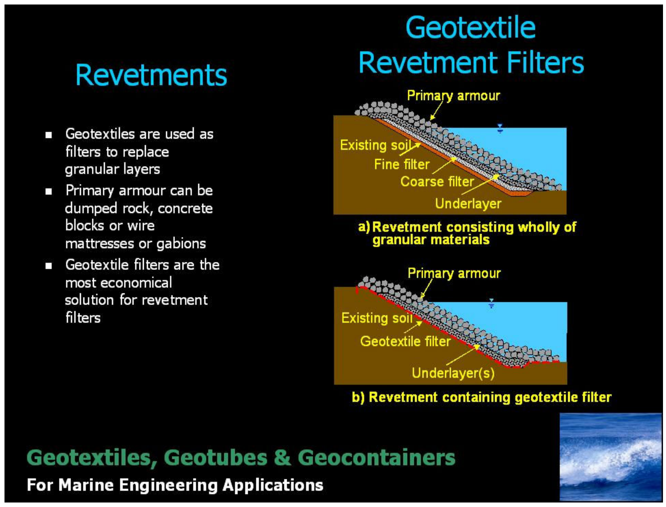

Figure 15: Revetments can have concrete facing gabions or rock armour.

5 ZONING

The zones in the beach are illustrated in Figure 16. The zoning guidelines include the provision of high sand dunes in the buffer zone, setback distance of buildings from the beach, and deep foundations of buildings as shown in Figure 17. The high sand dunes maybe constructed using geotubes or geobags providing flexible structures. Rigid concrete walls are avoided. The setback zone may vary from 50 m to 200 m depending on the location. An example of an ideal zoning arrangement is illustrated in Figure 18. The schematic diagram of a Japanese protection is shown in Figure 19. Man-made high road embankments and artificial elevated sand dunes can be also constructed in buffer zones for coastal protection and flood control. The road embankments should have at least 3.0 m high and 6.0 m wide that can also function as coastal road. The road embankment should be reinforced and protected against erosion through the incorporation of geosynthetics (Figure 20).

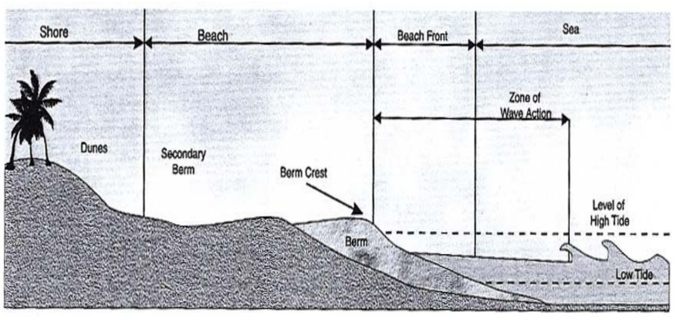

Figure 16: The zones of the beach.

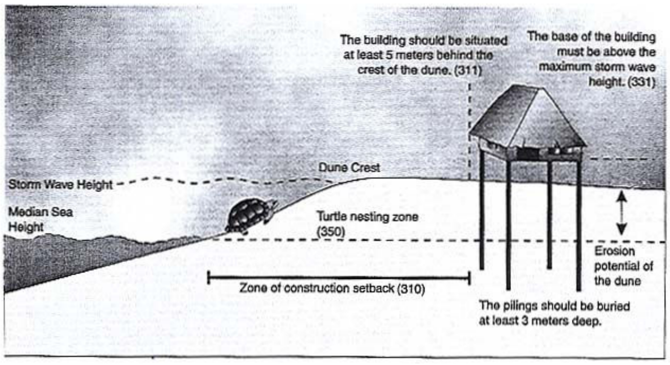

Figure 17: Guidelines for infrastructures.

6 LIMITED LIFE GEOSYNTHETICS

Natural fibers are limited life geosynthetics (LLGs) such as water hyacinth, reed, roselle, or kenaf and sisal. The water absorption of these 4 fibers is demonstrated in Figure 18. The water absorption of sisal and kenaf fibers was much less than the reed and water hyacinth fibers. Thus, the reed and water hyacinth fibers could be used for erosion control while the sisal and kenaf fibers could be applied for soil reinforcement.

Woven geotextiles were made from both water hyacinth and kenaf fibers namely: plain, knot, and hexagonal patters. Figure 19 shows the tensile strengths of water hyacinth woven LLGs while Figure 20 shows the corresponding values for kenaf of LLGs. The superiority of the plain pattern as well as the high tensile strength of the kenaf LLGs has been confirmed.

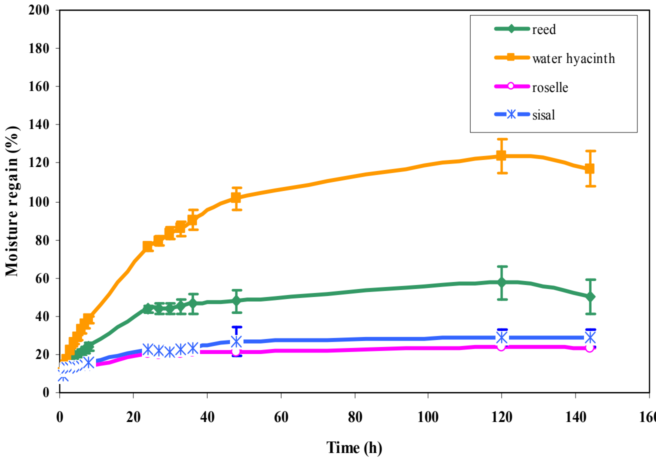

Figure 18: Moisture absorption of the natural fibers at 95%RH, 23 °C.

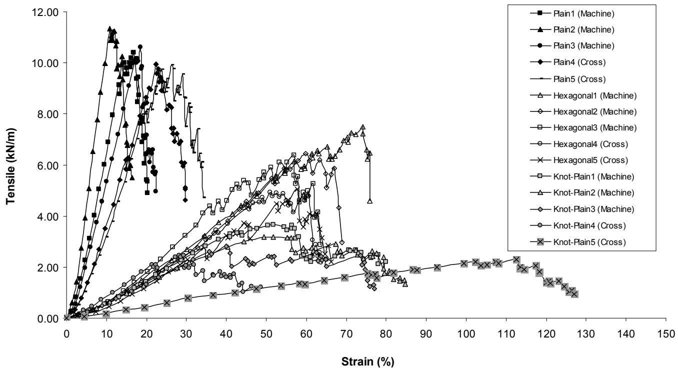

Figure 19: Comparison of tensile strength of water hyacinth for all patterns.

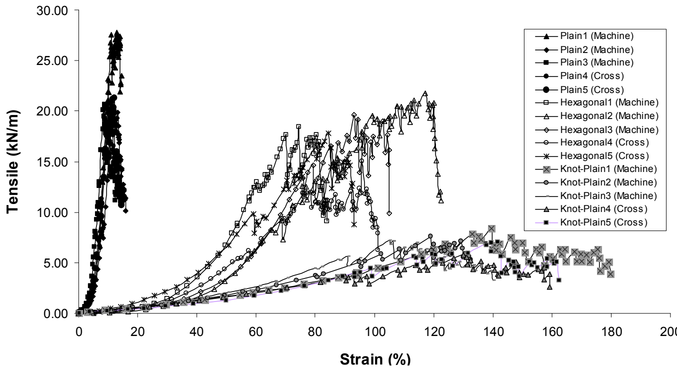

Figure 20: Comparison of tensile strength of Thai kenaf for all patterns.

7 CONTRIBUTION OF ROOT REINFORCEMENT

The ability of plant roots to strengthen the soil mass is well known. The inclusion of plant roots with high tensile strength increased the confining stress in the soil mass by its closely spaced root matrix system. The soil mass is bound together by the plant roots and the shear strength is increased. The contribution of root reinforcement to shear strength is considered to have the characteristics of added cohesion or adhesion (Wu et al. 1979). Soil-root shear strength is directly proportional to root cohesion. This means a soil with high root cohesion will increase the soil-shear strength, adding to slope stability. Roots of plants increase soil cohesion by binding to soil particles. The number, depth, size, and growth patterns of roots affect the soil cohesion. A few models quantify the interaction between the roots and the soil matrix such that root cohesion is limited by the thread strength of the roots themselves, not the bond between root and soil. This procedure is adopted and the following equations for determining the increase in shear strength from Waldron (1977) and Wu et al. (1979).

Assuming the root crosses the shear zone perpendicularly and the ultimate tensile strength (T_r) is mobilized, the total tensile root strength of a given species per unit area of soil, t_r, is expressed as:

$$t_r = \sum T_{ri} (A_{ri} / A_s) \tag{1}$$

where (A_{ri} / A_s) is the root area ratio or proportion of root cross-sectional area to soil cross-sectional area (A_s), and n is the number of roots in area (A_s). The ratio of the total cross-sectional area of all roots to soil cross-sectional area is expressed by A_r / A_s. In Figure 21, the schematic diagram of elastic roots is shown extending perpendicularly across a shear zone, displaced laterally by an amount X, and distorted by angle of shear, α. The mobilization of tensile resistance in the fibers in the soil can be translated into a tangential component ($t_r \cos\alpha \tan\phi'$) and a normal component ($t_r \sin\alpha$). Expressed as a reinforcement strength per unit area of soil, the root, CR, cohesion is:

$$CR = t_r (\cos\alpha \tan\phi' + \sin\alpha) \tag{2}$$

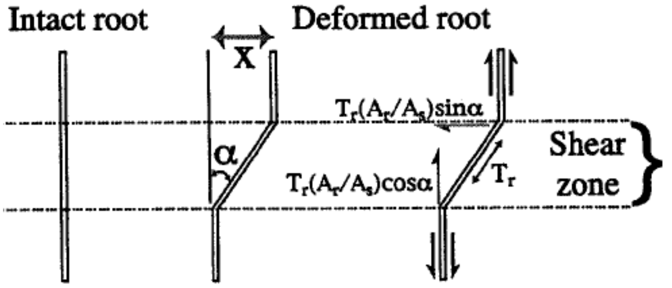

Figure 21: Cross sections of roots across the shear zone on the root reinforcement model.

Sensitivity analyses indicate that the values of $\cos\alpha \tan\phi' + \sin\alpha$ in Equation 12 can be approximated as 1.2 for $25^o < \phi' < 40^o$ and $40^o < \alpha < 70^o$ (Wu et al. 1979). In addition, experimental direct shear tests on dry, fiber-reinforced sand by Gray and Ohashi (1983) indicated that the greatest reinforcement occurs when a fiber is oriented at 60^o with respect to the deformation zone. It is unclear how saturated conditions may alter α and relative fiber reinforcement. Equation 1 is modified to determine the root cohesión arising from root reinforcement of a given each species. Schmidt et al. (2001) employed the following model:

$$CR = 1.2 \sum T_{ri} (A_{ri} / A_s) \tag{3}$$

Greater values of CR arise from high-strength root threads, larger diameter roots, and (or) increased root densities.

Mechanisms of shear strength increase include: 1) fiber deforms when shearing occurs, 2) deformation causes fiber to elongate, provided there is enough interface friction and confining stress to lock the fiber in place and prevent slippage, and 3) fiber elongation mobilizes tensile strength in fiber. The tangential component of the tensile force directly resists shear, while the normal component increases the confining stress on the shear plane (see Figure 21). On the basis of the field observations, laboratory research, and previously published research by Schmidt et al. (2001), the following assumptions were made:

1) The tensile strength of individual root fibers is fully mobilized (not just bond failure between the soil and root). The calculation of root cohesion includes only those roots in landslide scarps which broke as a result of landslide, evidence that their strength was fully mobilized.

2) The effective internal friction angle, ϕ', is unaffected by root reinforcement. Although laboratory analyses by Endo and Tsuruta (1969) substantiated assumption 2, it is unclear how scale effect modify the contribution to the soil mass frictional strength in the field.

3) All broken roots failed simultaneously. During landsliding, it is unlikely that all roots are simultaneously loaded to their ultimate tensile strength; hence we may overestimate root cohesion in the landslides characterized by slow deformations where roots progressively fail over time.

4) Roots are flexible and are initially oriented perpendicular to the shear zone (Figure 21). Laboratory tests reveal that the reinforcing fibers oriented perpendicular to a shear zone provide reinforcement comparable to that of randomly oriented fibers (Gray and Ohashi 1983)

5) Root cohesion increases are directly proportional to A_r / A_s. Field measurements of root extraction force (Riestenberg 1994) and laboratory analyses on the effects of roots on shearing resistance (Waldron and Dakessian 1982; Gray and Ohashi 1983) substantiated this assumption, as root reinforcement expresses a positive relationship with root cross-sectional area. The results of Gray and Ohashi (1983) indicated that shear strength increases are directly proportional to A_r / A_s, whereas Shewbridge and Sitar (1989) argue that the strength increase in reinforced soil is slightly nonlinear. That is, we may overestimate root cohesion at sites with high root densities (values of A_r / A_s >0.005).

6) The potential effect of pore-water pressure on CR is neglected. Any variation on CR arising from changes in surface tension in the unsaturated zone is also neglected.

7) Root cohesion neglects the bending moments of the individual root threads. Experiment by Shewbridge and Sitar (1990) indicated that the methods based on the development of tension within the reinforcing fibers (neglecting bending moment) are sufficient to represent root reinforcement.

The focus of this research is on that of CR, the strength added to soil from roots. To address this, the tensile strength, root diameter and root density were measured for selected species. Since the mechanical effect of plant roots is to increase the cohesiveness of the soil mass, root reinforced soil shear strength (Sr) can be considered as equivalent to an apparent cohesion of the soil known as apparent root cohesion (CR). Typical values of apparent root cohesion range from 1 kPa to 17.5 kPa (Coppin and Richards 1990). These values were obtained from the studies of several investigators using different techniques including back-analysis, direct shear test, root density information combined with vertical root model equations, and back-analysis combined with root density information. The values of apparent root cohesion (CR) are dependent on the type of vegetation and field soil conditions.

Wu et al. (1979) incorporated the effects of vegetation in slope stability analysis by using conventional limit equilibrium method. In limit equilibrium methods, the shear strength (Sr) of the soil along a potential slip surface is assumed to be fully mobilised at the point of failure (τ). The Mohr-Coulomb equation is used to describe the shear strength of the soil:

$$Sr = \tau = c' + (\sigma - u)\tan\phi' \tag{4}$$

where c' is the effective cohesion; σ is the total stress; u is the pore water pressure; ϕ' is the effective internal friction angle. By incorporating the effect of root reinforcement due to combination root system, Equation 14 becomes:

$$Sr = \tau = (c' + CR1 + CR2) + (\sigma - u)\tan\phi' \tag{5}$$

where $CR1$ is the apparent Vetiver Grass root cohesion and $CR2$ is the apparent Acacia Tree root cohesion

The apparent root cohesions ($CR1, CR2$) can be incorporated in infinite slope analysis to increase the factor of safety (FOS). In the field the shear stress of root free soil at 16 months period is 19.62 kPa while the shear stress of Vetiver Grass penetrated soil is 29.43 kPa which is 1.5 times higher than the former. Besides, the shear strength of soil reinforced with both Vetiver Grass roots and Acacia Tree roots at the same period of time is 58.86 kPa which is 3 times higher than root free soil. The results indicated that the roots of Vetiver Grass and Acacia Tree can improve the stability of soil slopes.

8 CONCLUSIONS

Global warming is already occurring with consequent climate change spawning abnormal weather conditions such as more frequent strong typhoons and hurricanes. Subsequently, heavy rains, high velocity flow and strong currents caused soil erosion along riverbanks and coastal areas. Traditional methods such as seawalls may not be the most effective mitigation measures. The use of flexible geosynthetics such as geobags and geotubes and geocells as well as gabions, mattresses and revetments are advisable techniques to prevent beach erosion and scour. Root reinforcement from Vetiver Grass and Acacia Mangium Willd Trees in combination with Limited Life Geosynthetics (LLGs) can be incorporated in the mitigation measures. Furthermore, zoning includes provision of artificial sand dunes in the buffer zone and setback space between the beach and the residential buildings as well as the requirement of deep foundations for buildings. The provision of additional protection in the buffer zone by construction of high road embankments reinforced and protected against erosion by geosynthetics is also recommended.

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