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COMPARISON OF EROSIONAL FEATURES BY TSUNAMI AND WIND WAVES

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ABSTRACT

The erosion features from tsunami wave and wind wave are different according to the characteristics of the two kinds of waves. The tsunami wave is a shallow water wave, even in Deep Ocean, with very long wavelength and relatively high especially near shore. It does not break when attacking the shore. It composed of run-up and run-down. The waves which can scour the offshore sea bottom and deposit the sediment mostly sand on the coast called storm or tsunami over washes. The erosion features from storm wave are caused by the breaking waves and wind-driven currents. However, the erosion features from tsunami wave are caused by both run-up and run-down. The scouring pit and trough by tsunami run-down usually are larger and deeper than those by tsunami run-up due to the stronger run-down which flow down slope and carrying debris. Examples of these features on Indian coasts are shown. Investigations of these features are important to the preventive measures for coastal erosion by these natural disasters. The characteristics of the flows of tsunami and wind wave cause the different erosion features and degree of erosion. The morphology of the coast modifies the intensity of the flow and the detail features along the coast. Examples of erosion features by strong wind and tsunami 2004 are shown on the Indian coasts.

INTRODUCTION

Strong wind wave and tsunami wave can cause deposition and erosion on the coast. The wind wave is called deep-water wave in deep water and shallow-water wave in near shore where the wavelength is more than twice the water depth. It always breaks and dissipates energy on the shore; therefore it has no run-down component except when it hits the sea wall or cliff, where it reflects the energy back to the sea. Moreover, wind waves change direction according to the wind regime and also cause near shore currents (rip and alongshore currents). Both waves can transport and deposit a large amount of sediment. Their erosional features are different because of the different characteristics of both waves. The deposits from these disasters have potential to record the flow parameters of the waves that created them. Several attempts to estimate wave parameters from tsunami deposits have been made (Moore and Mohrig, 1994; Nott, 1997 and Reinhart, 1991), this subject is still in its infancy. Early studies focused on (Hearty, 1997; Reinhart and Bourgeois, 1989) understanding the hydraulic differences between tsunamis and storms, but most later studies (Chagué - Goff and Goff, 1999, Nanayama et al., 2000 and Tuttle et al., 2004) have adopted a facies approach modern storm and tsunami deposits are compared, and their differences tabulated. Tsunamis are hydraulically different from other coastal phenomena, and this difference affects how their sediments look. The ability to distinguish tsunami deposits from other deposits is a useful tool in hazard planning. The ability to recover aspects of tsunami and storm flow conditions through examination of their deposits and erosional features would lead to a useful information. With knowledge of the tsunami flow depths and velocities, for example, coastal structures could be designed to withstand the associated fluid forces. The topography and bathymetry of the coastal zone are another control factors for the powerful forces of these disasters.

CHARACTERISTICS OF WIND WAVE AND TSUNAMI WAVES

Tsunami waves are primarily associated with the occurrence of earthquakes in oceanic and coastal regions. When a submarine earthquake occurs, the energy generated travels outward in all directions from the source. The directivity of the tsunami wave height depends on the characteristics of the rupture zone (Fig. 1). Waves become larger as they reach the shore, where the water is shallower. When a tsunami wave begins in the deep waters, it may only have a height of about one meter and look like nothing

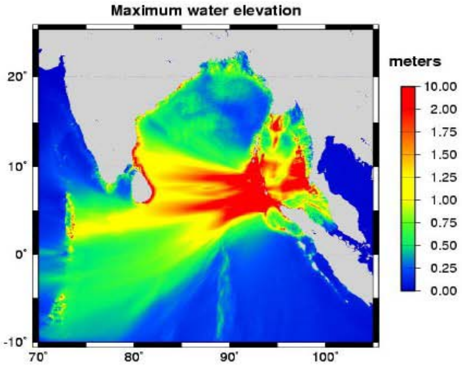

Fig. 1 Directivity of tsunami wave height depends on the rupture characteristics

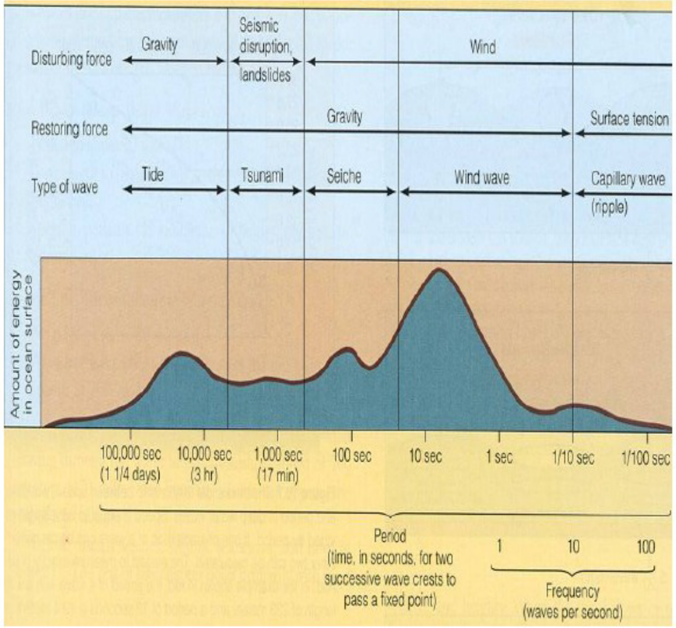

Fig. 2. Wave energy as a function of the wave period

Table 1: Wave Classification

Wave	Period	Wave Length	Wave Type	Cause
Capillary	>0.1 sec	<2.0 sec	Deep to Shallow	Local winds
Chop	1 -10sec	1-10m	---do	Local winds
Swell	10-30sec	up to 100m	-- do--	Distant Storm
Seiche	10min-1hr	up to 100 km	Intermediate	Tsunami
Tsunami	10-60 min	up to 100 km	--do--	Submarine dist
Tide	12-24 hr	up to 1000 km	Shallow	Gr. Sun-moon attraction
Inter wave	1-60min	up to 100m	Shallow	Pycnocline

more than the gentle rise and fall of the sea surface. Tsunamis are characterized as shallow-water a wave which means that the ratio between water depth and wavelength is very small. Shallow-water waves are a different from the wind-generated waves many of us have observed from the beach. Wind-generated waves usually have period (the time between two successive waves) of five to twenty seconds and a wavelength (the distance between two successive waves) of about 100 to 200 m. However, tsunami waves in deep water can have a wavelength greater than few hundreds kilometers and a period of about an hour (Fig. 2 and Table 1). These shallow-water waves move at a speed equal to the square root of the product of the acceleration of gravity (9.8 m/s^2) and the water depth (Figs 3 to 5). The deeper the water, the faster and shorter the wave is. Because a wave loses energy at a rate inversely related to its wavelength, tsunami waves can travel at high speeds for a long period of time and lose very little energy in the process.

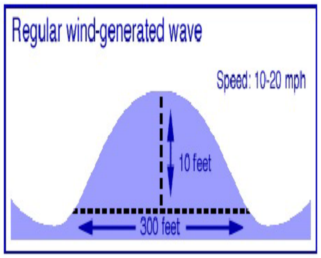

Fig. 3 Characteristics of regular wind-generated wave

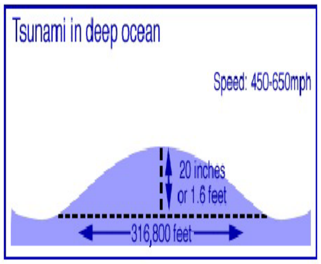

Fig. 4 Characteristics of tsunami wave in deep ocean

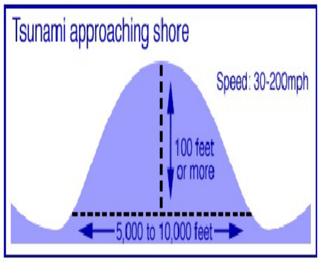

Fig. 5 Characteristics of tsunami wave approaching shore. (http://www.pdc.org/iweb/tsunami-characteristics.jsp)

The transformation of wind waves from generation area (Fig. 6) is different from tsunami wave (Fig. 7). The distribution of wave energy of short period wave and long period waves. While this

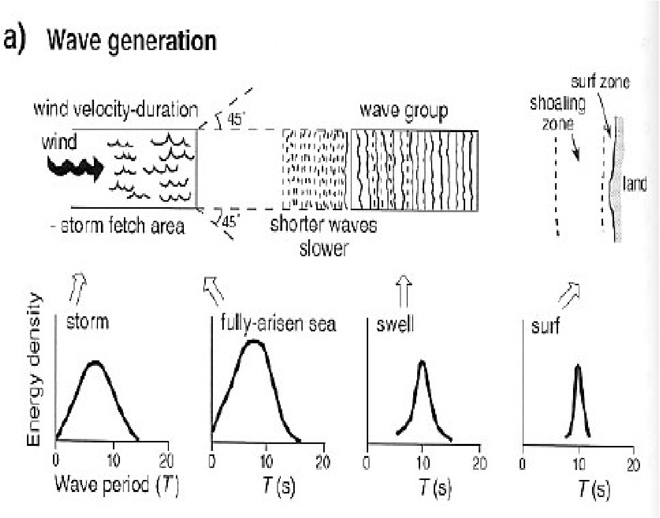

Fig. 6. Wave energy distribution over the entire water column between storm and tsunami waves

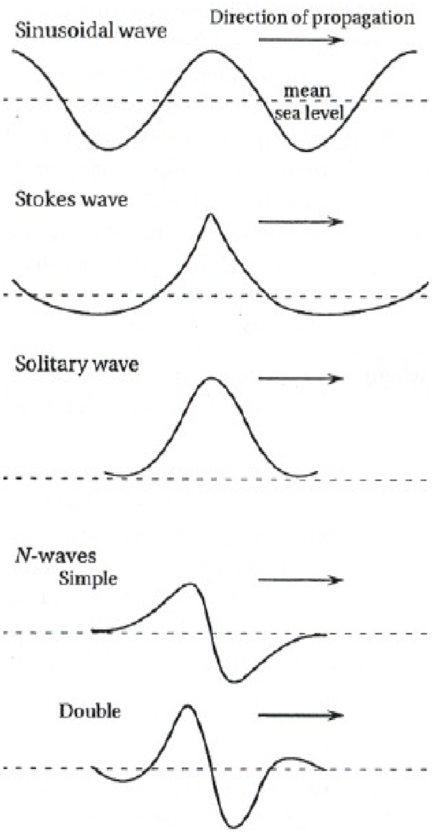

Fig. 7 Orbital flow characteristics of short and long period waves (Pal and Ghosh, 2005).

may not be important on the shelf, it causes the tsunami to take on the shape of a solitary wave in shallow water. Fig. 9 is the orbital flow characteristics of short and between storm and tsunami waves are difference according to the characteristics of both waves (Fig. 8). Tsunami differs from wind-generated waves in that significant water motion occurs throughout the whole water column under the former long period waves.

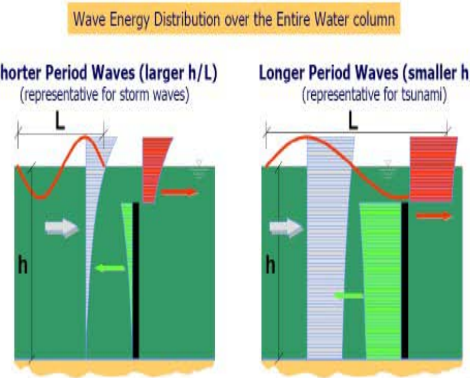

Fig. 8 Energy loss due to flow separation and vortices at wall crest

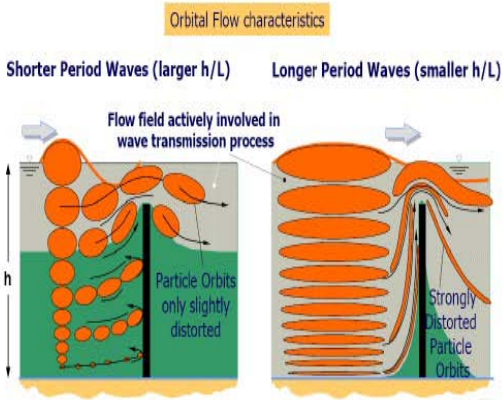

Fig. 9 Orbital flow characteristics of short and long period waves

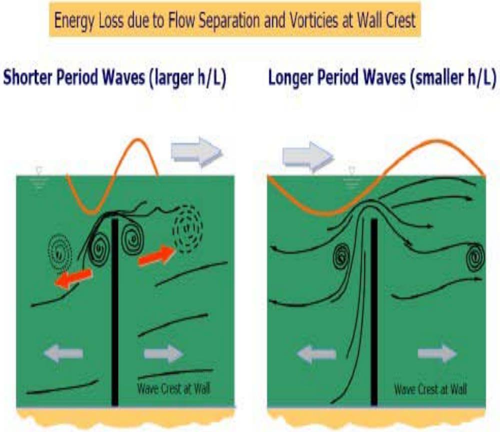

Fig. 10 Energy loss due to flow separation and vortices at wall crest

occurs throughout the whole water column under the former long period waves. A solitary wave maintains its form in shallow water, and because the kinetic energy of the tsunami is evenly distributed throughout the water column, little energy is dissipated, especially on steep coasts (Bryant, 2001). Fig. 10 shows the energy loss due to flow separation and vortices at wall crest. The barrier may cause turbulent Mach Stem wave. When a wave finally reaches the shore, it may appear as a rapidly rising or falling tide, or a series of breaking waves. The bottom bathymetry, coastal topography and configuration of the coastline such as entrances to rivers, reefs, bays, undersea features and the slope of the bench all to modify the tsunami wave as it approaches the shore (Fig. 11). The tsunamis rarely become great, towering, breaking waves like wind waves. Sometimes the tsunami may break far offshore. On occasion, a tsunami may form a bore, a step-like wave with a steep breaking front, which happens if the tsunami moves from the deep water into a shallow bay or river.

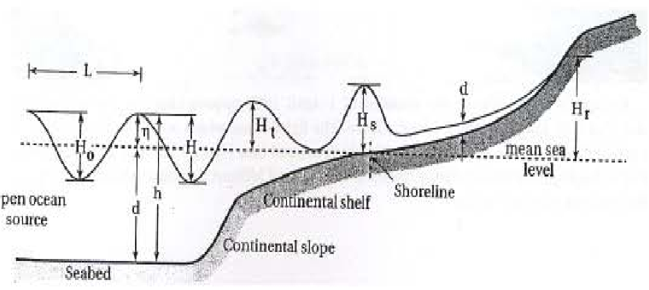

Fig. 11 Various terms used to express the wave height of a tsunami wave (Bryant, 2001).

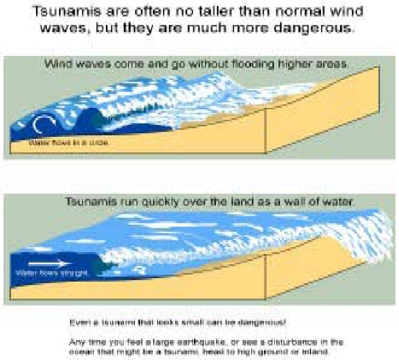

Fig. 12. The wind waves and tsunami wave reach the shore. (http://www.ess.washington.edu/tsunami/images/tsulg.jpg)

The regular wind waves are the most important forces for sediment erosion and transport to the coastal zone. They introduce energy to the coast and also a series of wave-driven currents that move sediment along the shore (long shore drift) and normal to the shore (cross - shore transport i.e. rip current, under toe-over wash). The study of sediment budget can quantify how much the beach accrete or erode from overall processes. Coastal morphology, type, slope, configuration, bottom bathymetry, offshore barrier, sediment characteristics, lithology and land-cover modify the degree of erosion and accretion from wind wave.

The difference of both waves when they reach the shore is the wind wave usually breaks but tsunami wave does not break (Fig. 12). When the wind wave breaks, its energy is absorbed and converted into heat. The gentler slope of the beach, the more energy is converted. Steep slope such as cliffed coast, the waves do not break but reflect back to the sea. The wind waves usually break when their wave heights are approximate half of the water depth. The sheltered locations on the lee side of islands appear particularly vulnerable to tsunami run-up. Solitary waves propagate easily along steep shores, forming a trapped edge wave. Laboratory models show that the maximum run-up height of this trapped wave is greatest towards the rear of an island.

Finally, tsunami run-up can also take on complex forms. Video images of tsunami waves approaching shore show that most decay into one or more bores. A bore is a special waveform in which the mass of water propagates shoreward with the wave. The leading edge of the wave is often turbulent. Waves in very shallow water can also break down into multiple bores or solitons. Soliton formation can be witnessed on many beaches where wind-generated waves cross a shallow shoal, particularly at low tide. Such waves are paradoxical because bores should dissipate their energy rapidly through turbulence and frictional attenuation, especially on dry land. However, tsunami bores are particularly damaging as they cross a shoreline. Detailed analysis indicates that the bore pushes a small wedge-shaped body of water shoreward as it approaches the shoreline. This transfers momentum to the wedge, increasing water velocity and turbulence by a factor of two. While there is a rapid decrease in velocity inland, material in the zone of turbulence can be subject to impact forces greater than those produced by ordinary waves. Often objects can travel so fast that they become water-borne missiles. This process can also transport a large amount of beach sediment inland. Tsunamis that degenerate into bores are thus particularly effective in sweeping debris from the coast (Bryant, 2001).

While wind waves break and dissipate energy on near shore zone, tsunami wave can penetrate deeper inland. The bigger the tsunami, or the longer its wave period, the greater the volume of water carried onshore and the greater the extent of flooding. The strong velocities of tsunami wave have the potential to move sediment and erode bedrock, producing geomorphic features in the coastal landscape that uniquely define the present of tsunami.

COASTAL TYPES

Coastlines comprise the natural boundary zone between the land and the sea. Their natural features depend on the type of rocks exposed along the coastline, the action of natural processes and the work of vegetation and animals (Fig.13). The intensity of natural processes formed their origin – either as erosional or depositional features. The geological composition of a coast determines the stability of the soil, as well as the degree of rocky

Fig.13 Tsunami bore

materials and their breakdown and removal (Garrison 2002).

Cliff Coast

It is a natural seawall or hard coast, typically has a shore platform which is usually exposed during the low tide. Natural erosion is attributable to slope instability, weathering and wave action and leads to regression of the shoreline. As shown in Fig. 14, extreme wave conditions such as storm waves and tsunamis will have a less erosive effect. Owing the "hard" structure, both wind and tsunami waves will not break but reflect the energy back to the sea and promote sediment transport offshore. Moreover, they scour the toe of the cliff or seawall. Traces of tsunami wave height can be found on cliffs as a trim line where trees or shrubs on the cliff had been erased. Strong wind wave can overtop the low seawall and scour the area at the back of it. It also causes the retreat of the adjacent beach of the seawall or cliff.

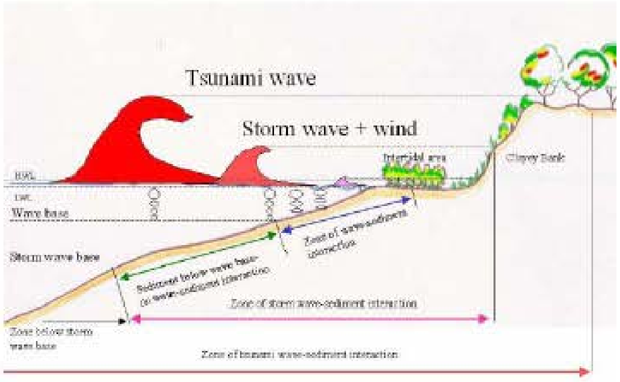

Fig. 14 Cliff coast (Prasetya, 2007)

Clayey Bank Coast

This is a "semi - hard" coast, consisting of cohesive soils; it is common on estuarine coastlines and often has nearly vertical banks ranging from one to five metres in height. The rate of erosion is relatively high compared to the hard coast because it is composed of weaker and less resistant material. Erosion is mostly due to coastal processes, weathering and loss of vegetation cover (ARC, 2000). For extreme events such as storm and tsunami, as shown in Fig. 15, vegetation cover plays a significant role in protecting the coast from flooding and inundation by reducing wave height and energy and decelerating tsunami flow speed; hence, erosive forces and inundation distance are decreased.

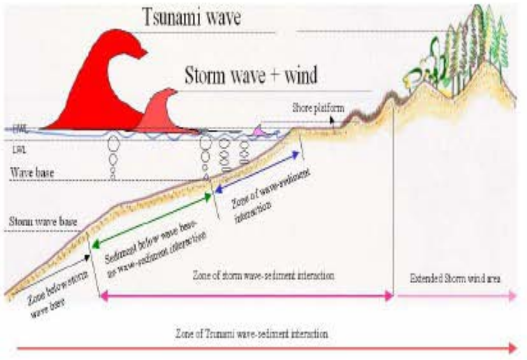

Fig. 15 Clayey bank type coast (Prasetya, 2007)

Inter-tidal/Muddy Coast

This is characterized by fine-grained sedimentary deposits, predominantly silt and clay that come from rivers; it can be classified as a "soft" coast. It has a broad gentle seaward slope, known as an inter-tidal mud flat where mangrove forest, salt marshes, shrubs and other trees are found. Most erosion is generated by river damming that reduces sediment supply, diminishes vegetation cover (usually mangroves and salt marshes) and exposes vegetation roots by lowering the mud flat (Fig. 16) that leads to their final collapse. During storms, healthy and dense vegetation/coastal forest and trees can serve as barriers and reduce storm wave height, as well as affording some protection to the area behind them. In the case of tsunami, coastal forest and trees can decrease wave height and tsunami flow speed to some extent if the forest is dense and wide enough.

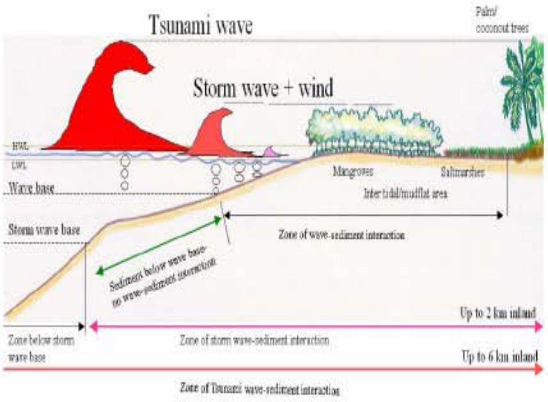

Fig. 16 Inter-tidal/Muddy coast (Prasetya, 2007)

Both extreme events can cause severe erosion and scouring on the coast and at the river mouth.

Sand Dune Coast

It consists of unconsolidated material, mainly sand, some pebbles and shells; it can be classified as a soft coast. It has a gentle seaward slope – known as dissipative beaches that have broad fine sand and gradually steep slopes at the backshore/foredunes, its profile depends on wave form and energy and wind direction; hence, profiles can be adjusted to provide the most efficient means of dissipating incoming wave energy. This coast experiences short-term fluctuation or cyclic erosion - accretion and long- term assessment is needed to identify erosion as a problem here. Often accretion and dune rebuilding take much longer than erosional events and the beach has insufficient time to rebuild before the next erosive event occurs. Erosional features are a lowered beach face slope and the absence of a near shore bar, berm and erosional scarps along the fore dune. Generally, erosion is a problem when the san dunes completely lose their vegetation cover that traps wind-borne sediment during rebuilding, improves slope stability and consolidates the sand. During extreme events such as storms and tsunamis (Fig. 17), this type of coast can act as a barrier for the area behind the dunes. Sand dunes and their vegetation cover are the best natural protective measures against coastal flooding and tsunami inundation.

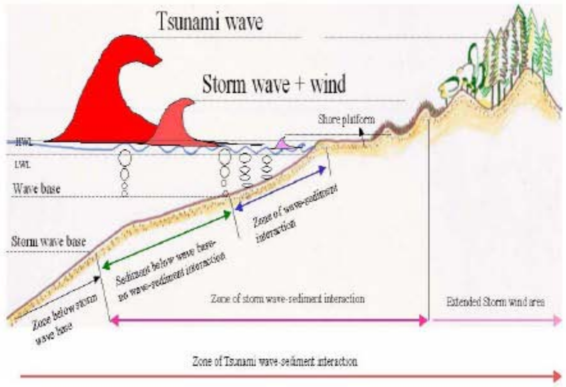

Fig. 17 Sand dune coast (Prasetya, 2007)

Sandy Coast

It consists of unconsolidated material – mainly sand from rivers and eroded headlands, broken coral branches (coralline sand) and shells from the fringing reefs. It can be classified as a soft coast with reef protection offshore. The beach slope varies from gentle to steep slopes depending on the intensity of natural forces (mainly waves) acting on them. Coconut trees, pine trees and other beach woodland trees are common here. Most erosion is caused by loss of: (a) the protective function of the coastal habitat, especially coral reefs (if exist) that protect the coast from wave action; and (b) coastal trees that protect the coast from strong winds.

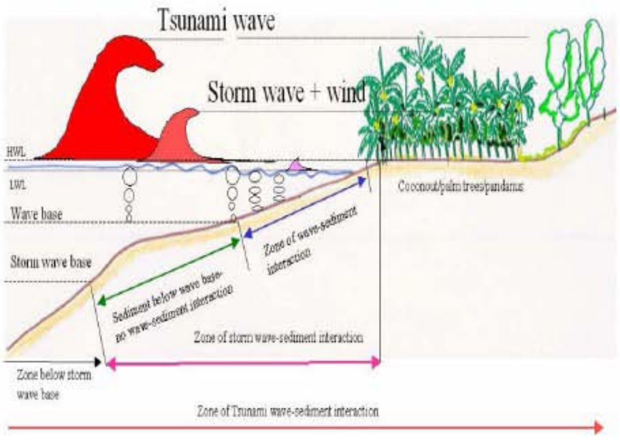

Fig. 18 Sandy coast (Prasetya, 2007)

During extreme events (Fig. 18), healthy coral reefs and trees protect coasts to some extent by reducing wave height and energy as well as severe coastal erosion (Prasetya, 2007).

MAGNITUDE OF THE TSUNAMI

The magnitude of the tsunami is measured by the maximum wave height and the amount of destruction it causes. It depends on several factors:

1. Magnitude of the earthquake and its focal depth. Only rarely do earthquakes of a magnitude lower than 7 and with focal depths greater than 40 to 50 km produce destructive tsunamis; however, far smaller earthquakes, but with shallow focal depths, have been known to generate Tsunamis. These are called Tsunami – earthquakes (Fig. 19).

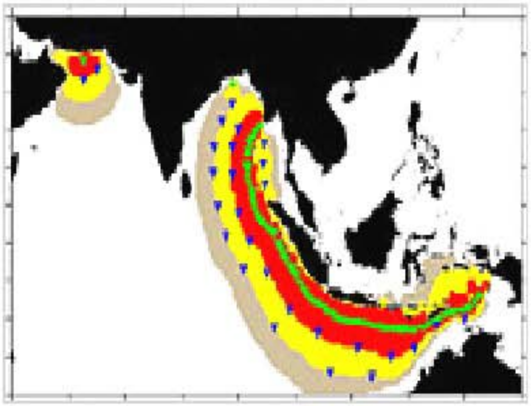

Fig. 19 Tsunami - Earthquake sources in Indian Ocean.

2. The area of earth's crust dislocated on the sea bed depends on the length of the area dislocated, the speed of dislocation, and the way in which the ocean bed becomes deformed.

3. Propagation route of the Tsunami. The effect of the bathymetry of the ocean bed, whose irregularities can act as obstacles or may cause the convergence of the waves' energy.

4. Variation in direction. In the case of near-source tsunamis, the angle that the axis of the bay forms with respect to the direction of the tsunami's source influences the wave height significantly. The effect is given greater in bays that open directly toward the source of the tsunami.

5. Topography of the flooded area. If the land slopes gently and does not have irregularities, the tsunami invades the zone more or less uniformly with greater or less violence depending whether the tsunami waves are of short or long period respectively (Fig. 20). As the gradient of the terrain increases, both the wave height and its propagation speed diminish; however, when the mass of water returns to the sea, it tends to gain speed and causes severe erosion. If there are strips of low - lying land facing the sea, such as the mouth of a river, the tsunami channels itself through them and can travel extensive distances inland (Pal and Ghosh, 2005).

If a short-period tsunami encounters obstacles with a steep or almost vertical gradient, the great kinetic energy it carries is converted into potential energy and the wave can rear up, attaining three or four times its original height (Kuroiwa, 2004). The example is when tsunami wave attacks the offshore breakwater, it can cause Mach-Stem wave, which causes turbulence.

EROSIONAL FEATURES

The different erotional features and their end effect on Tsunamis are studied in detail. Based on that the precautionaries measurements can be taken so that repetation can be avoided. They are:

Tsunami Erosion

Tsunamis intensely erode shore and sea bottom and supply large amount of sediment in coastal areas due to their high flow velocities at shore of 15 m/s or more. Sediments deposited by tsunamis are presented as a geologic record of the event. Reconstruction of ancient tsunamis from geologic record contributes to understanding the risk. The depositional signatures of tsunami can be further subdivided into sedimentary deposits and geomorphic forms. The most commonly recognized depositional signature is the occurrence of anomalous sand sheets or lamina sandwiched in peat or mud on coastal plains. The sedimentary deposits, except for imbricate boulders, are less dramatic because they do not form prominent features in the landscape. Their attribution to other processes. can not be confirmed without examination. Many factors, such as aligned stacks of boulders, reveal the direction of approach of a tsunami to a coastline. In many cases, tsunamis have approached at an angle to the coast because of the configuration of the coastline.

Small Scale Features

Tsunami can also sculpture bedrock in a fashion analogous to the s-forms produced by high - velocity catastrophic floods or surges. The s - forms include features such as muschelbrűche, sichelwannen, V - shaped grooves, cavettos and flutes (Fig. 21). Tsunami flow over rocky headlands has the hydrodynamic potential to generate cavitations or small vortices capable of producing sculptured forms.

Cavitations

It is a product of high-velocity flow as great as 10 m/s in water depths as shallow as 2 m deep. At these velocities, small air bubbles appear in the flow. These bubbles are unstable and immediately collapse, generating impact forces up to thirty thousand times greater than normal atmospheric pressure. Cavitations bubble collapse is highly corrosive. In tsunami environments, cavitations produce small indents that develop instantaneously, parallel or at right angles to the flow, on vertical and horizontal bedrock surfaces. Cavitations features are widespread and consist of impact marks, drill holes and sinuous grooves (Fig. 21). Impact marks appear as pits or radiating star-shaped grooves on vertical faces facing the flow. Such features represent the impact mark of a rock hurled at high velocity against a vertical rock face; however, such marks have also been found in sheltered positions or tucked into undercuts where such a process is unlikely.

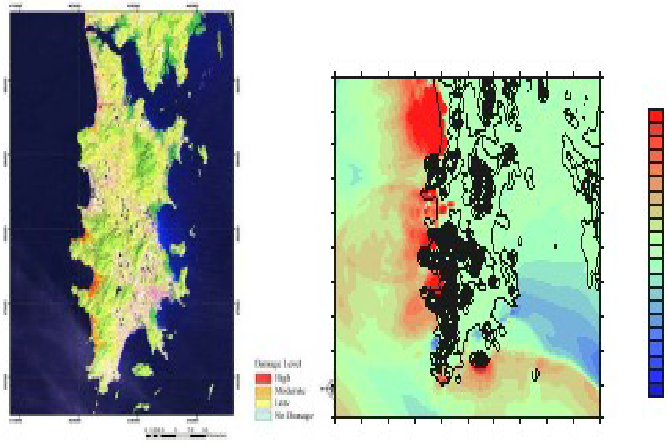

Fig. 20 Inundation distance from MOST model

Drill Holes

These are found over a range of locations on tsunami-swept headlands. Their distinguishing characteristic is a pit several centimeters in diameter bored into resistant bedrock. Drill holes appear on vertical faces, either facing the flow or at right angles to it. Such marks also appear on the inner walls of large whirlpools. They often occur profusely above the limits of high tide. The most common type of drill mark appears at the end of a linear or sinuous groove and extends downwards at a slight angle for several centimeters into very resistant bedrock. Sinuous drill marks are useful indicators of the direction of tsunami flow across bedrock surfaces. Sinuous grooves tend to extend no more than 2 m in length and have a width of 5 to 8 cm at most. Depth of cutting can vary from a few millimeters to several centimeters. Often they form echelon in a chainlike fashion. They are not a product of storm waves or backwash because they evince internal drainage and do not join down slope (Pal and Ghosh 2005).

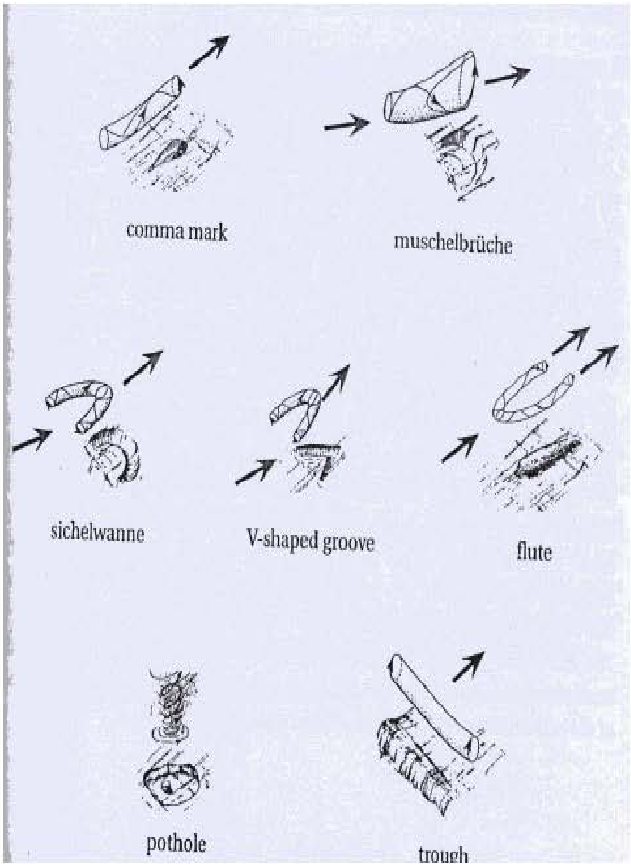

Fig. 21 Types of vortices responsible for bedrock sculpturing by tsunami (Kor et al., 1991 and Shaw, 1994)

S - Forms

It also develop on surfaces that are smoothed and polished. This polishing appears to be the product of sediment abrasion. However, high water pressures impinging on bedrock surfaces can also polish rock surfaces. Flow vortices sculpture s-forms that can be categorized by the three-dimensional orientation of these eddies. The initial forms develop under small roller like vortices parallel to upslope surfaces. In this case, muschelbrüche, sichelwanne and V-shaped grooves are created. Muschelbrüche (literally mussel - shaped) are cavities scalloped out of bedrock, often as a myriad of overlapping features suggestive of continual or repetitive formation. While the features appear flat-bottomed, they have a slightly raised pedestal in the centre formed by unconstrained vortex impingement upslope onto the bedrock surface towards the apex of the scallop. They vary in amplitude from barely discernible forms to features having a relief greater than 15 cm. Their dimensions rarely exceed 1.0 to 1.5 m horizontally. Coastal muschelbrüche inevitably develop first on steeper slopes and appear to grade upslope into sichelwanne, V - shaped grooves, and flutes, as the vortices become more elongated and erosive. Sichelwanne have a more pronounced pedestal in the middle of the depression, while V-shaped grooves have a pointed rather than concave form downstream.

S - forms spatially change their shape depending upon the degree of flow impingement and vortex orientation. In coastal environments, the flow by tsunami over washing bedrock surfaces neither is nor confined. The high velocity and sudden impact of the vortex on the bedrock surface causes the vortex to ricochet upwards, and the unconfined nature of the flow permits the vortex to lose contact rapidly with the bed. This produces features that begin as shallow depressions, scour down flow, and then terminate suddenly; leaving a form that is gouged into the bedrock surface with the steep rim downstream. The helical vortices, besides eroding vertical stacks, have the capacity to bore caves into cliffs and form arches (Pal and Patra, 2009).

Flute

The term flute describes long linear forms that develop under unidirectional, high-velocity flow in the coastal environment. These are noticeable for their protrusion above, rather than cutting below, bedrock surfaces. In all cases, the steeper end faces the tsunami, while the spine is aligned parallel to the direction of tsunami flow. Flutes span a range of sizes, increasing in length to 30 to 50 m as slope decreases. However, their relief rarely exceeds 1 to 2 m. Larger features are called rock drumlins. Flute topography always appears on the seaward crest of rocky promontories where velocities are highest. Flutes often have faceting or cavettos superimposed on their flanks. Cavettos are curvilinear grooves eroded into steep or vertical faces by erosive vortices. While cavetto like features can form due to chemical weathering in the coastal zone, especially in limestone, their presence on resistant bedrock at higher elevations above the zone of contemporary wave attack is one of the best indicators of high velocity tsunami flow over a bedrock surface. Large-scale fluting of a headland can also occur, and on smaller rock promontories, where the baseline for erosion terminates near mean sea level, the resulting form looks like the inverted keel of a sailboat. While technically a sculpturing feature, the cockscomb looks as if it has been hydraulically hammered. On narrow promontories, vortices can create arches. Many are formed by vortices. These horizontal vortices form in the lee of stacks and erode promontories from their landward side (Garrison, 2002).

Flat Surface

On flat surfaces, longitudinal vortices give way to vertical ones that can form hummocky topography and potholes (Fig. 22). Potholes are one of the best features replicated at different scales by high-velocity tsunami flow. While large-scale forms can be up to 70 m in diameter, smaller features have dimensions of 4 to 5 m. The smaller potholes also tend to be broader, with a relief of less than 1 m. The potholes tend to develop as flat-floored, steep-walled rectangular depressions, usually within the zone of greatest turbulence. While bedrock jointing may control this shape, the potholes' origin as bedrock-sculptured features is unmistakable because the inner walls are inevitably undercut or imprinted with cavettos. In places, where vortices have eroded the connecting walls between potholes, a chaotic landscape of jutting bedrock with a relief of 1 to 2 m can be produced. This morphology -termed hummocky topography - forms where flow is unconstrained and turbulence is greatest. These areas occur where high-velocity water flow has changed direction suddenly, usually at the base of steep slopes or the seaward crest of headlands. The steep - sided, rounded, deep potholes found isolated on inter-tidal rock platforms, and attributed to mechanical abrasion under normal ocean wave action, could be catastrophically sculptured forms. Many of these latter features evince undercutting and cavettos along their walls.

Crest

At the crests of headlands, flow can separate from the bedrock surface, forming a transverse roller vortex capable of eroding very smooth-sided, low, transverse troughs over 50m in length and 10 m in width. Under optimum conditions, the bedrock surface is carved smooth and angular. In some cases, the troughs are difficult to discern because they have formed where flow was still highly turbulent after over-washing the crest of a headland. In these cases, the troughs are embedded in chaotic, hummocky topography. This is especially common on very low - angled slopes. Transverse troughs can also form on up flow slopes where the bed locally flattens or slopes downwards. Under these circumstances, troughs are usually short, rarely exceeding 5 m. The smoothest and largest features develop on the crests of broad undulating headlands.

Sculpture

Large Scale Features can usually be found sculptured or eroded on rock promontories, which protrude seaward onto the continental shelf. Such features require extreme run – up velocities that can only be produced by the higher or longer waves (mega tsunami) generated by large submarine slides. One of the most common features of high - velocity over washing is the stripping of joint blocks from the front of cliffs or platforms forming inclined surfaces or ramps. In many cases, this stripping is aided by the detachment of flow from surfaces, a process that generates enormous lift forces that can pluck joint-controlled rock slabs from the underlying bedrock. Where standing waves have formed, then bedrock plucking can remove two or three layers of bedrock from restricted area, leaving a shallow, closed depression on the ramp surface devoid of rubble to the open ocean when unconnected. Ramps are obviously structurally controlled and have an unusual juxtaposition beginning in cliffs up to 30 m above sea level and, sloping down, flow often into a cliff. If these high velocities are channelized, erosion can produce linear canyon features 2 to 7 m deep and pool – and - cascade features incised into resistant bedrock on the lee side of steep headlands. These features are most prevalent on platforms raised 7 to 8 m above modern sea level. Wave - breaking may also leave a raised butter like structure at the seaward edge of a headland, separated from the shoreline by an eroded depression. This feature looks similar to an inverted toothbrush.

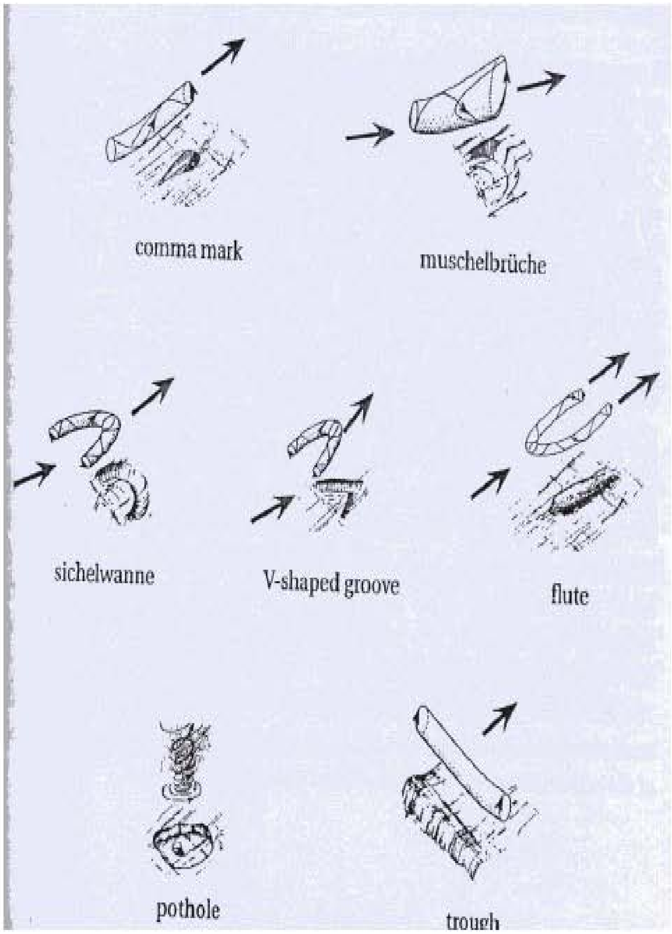

Fig. 22 Types of vortices responsible for bedrock sculpturing by tsunami (Kor et al., 1991 and Shaw, 1994)

Bedrock sculptured features are created by six flow phenomena: Mach-Stem waves, jetting, flow reattachment, vortex impingement, horseshoe or hairpin vortices and multiple-vortex formation. Mach-Stem wave occurs when waves travel obliquely along a cliff line. The wave height can increase at the boundary by a factor of two to four times. The process is insensitive to irregularities in the cliff face and is one of the mechanisms allowing tsunami waves to overtop cliffs up to 80 m high are considered to be optimum.

Whirlpool

The whirlpools formed in bedrock on the sides of the headlands. In coastal environments, whirlpools often contain a central plug of rock and show evidence of smaller vortices around their rim. The counterclockwise rotation of the overall vortex, produces downward – eroded helical spirals that undercut the sides of the pit, forming spiral benches. Circular or sickle-shaped holes were drilled, by cavitations, horizontally into the sides of the pothole and into the wall of the plug (Bryant, 2001).

Multiple-vortex formation occurs at the largest scale and includes kolks and tornadic flow. Kolks are near-vertical vortices whose erosive power is aided by turbulent bursting. They are produced by intense energy dissipation in upward vortex action. The steep pressure gradients across the vortex produce enormous hydraulic lift forces. Kolks require a steep energy gradient and an irregular rough boundary to generate flow separation. These conditions are met when the tsunami waves first meet the steeper sides of headlands; however, the process does not account for the formation of whirlpools.

Whirlpools form when flow velocities increase first through convergence of water over bedrock and then through funneling at preferred points along the coast. Critical rotational velocities required to erode resistant bedrock also take time to build up; however, the flow under the crest of a tsunami wave is only sustained for a few minutes at most.

Once a critical velocity is reached, bedrock erosion commences. The spin-up process causes vortex erosion to develop and terminate quickly, as some potholes are only partially formed. Whirlpools are formed instantaneously in the space or minutes rather than by the cumulative effect of many wave events. Whereas mini vortices in tornadoes can freely circumscribe paths around the wall of the tornado, those in whirlpools are constrained by the bedrock they are eroding (Bryant, 2001).

Flow Dynamics

Any hydrodynamic models responsible for tsunami-sculptured bedrock terrain must be able to explain a range of features varying from sinuous cavitations marks several cm wide to whirlpools over 10 m in diameter. One of the controlling variables for the spatial distribution of these features is bed slope that can be higher than 100 at the front of promontories. Even a slight change in angle can initiate a change in sculptured form. For instance, sinuous cavitations marks can form quickly, simply by steepening slope by 1 to 20. Similarly, flutes can develop with the same increase in bed slope. This suggests that new vortex formation or flow disturbance through vortex stretching is required to initiate an organized pattern of flow vortices able to sculpture bedrock. Because bedrock sculpturing features rarely appear close to the edge of a platform or headland, vortices did not exist in the flow before the leading edge of the tsunami wave struck the coastline. Tsunami because of their long wavelength, behave like surging waves as they approach normal to a shoreline. Jetting is caused by the sudden interruption of the forward progress of a surging breaker by a rocky promontory. The immediate effect is twofold. First, there is a sudden increase in flow velocity as, momentum is conserved and vortex formation is initiated. Second, the sudden velocity increase is sufficient for cavitations and creates lift forces that can pluck blocks of bedrock from the bed at the front of a platform.

Fig. 23 Types of vortices responsible for bedrock sculpturing by tsunami (Kor et al., 1991 and Shaw, 1994)

The third phenomenon occurs if flow separates from the bed at the crest of a rocky promontory. This occurs at breaks of slope greater than 40. Rock platforms over washed by tsunami have changes in slope much greater than this. Some distance downstream, depending on the velocity of the jet, water must reattach to the bed. Where it does, flow is turbulent and impingement on the bed is highly erosive. Standing waves may develop in the flow, leading to large vertical lift forces under crests. The bedrock plucking at the front of platforms and in the lee of crests is a product of this process.

Sedimentary Structure

In some places, the tsunami deposits show multiple graded units that bounded by erosion surfaces. The detail of lateral changes was observed of the units in trenches aligned parallel and perpendicularly to the flow direction. Units in the sediment recode the tsunami waves. Grading structures are formed by fall out of suspended sediments during stagnant water period between run-up and run-down stage. The units of run-up are composed of white colored very course-very fine sand that contains shell fragments and foraminifera's. The units of run - down are composed of very fine sand – silt, and relative thin. This results from the difference of sediment supply between run – up and run-down of tsunami. Run-up current erodes beaches and sea bottoms, supply large amounts of sediments on coast like storm over wash by big wind wave. On the other hand, run - down current has little sediment because it has no sediment resource except sediments suspended in water. The erosion surfaces bounding the units are undulating, and the thickness of units changes rapidly. The unit of the first run - down is commonly eroded out by the next run - up current.

About 35 tons of corals were transported landward from around the reef edge by the 2004 Indian Ocean Tsunami (Go to, personal communication). The tsunami wave converged at the tip of the promontory and cut it off. The erosional features from wave run-up are seen in Fig. 23.

CONCLUSIONS

The characteristics of the flows of Tsunami and wind wave cause the different erosional features and degree of erosion need to be measured. The morphology of the coast modifies the intensity of the flow and the detail features along the coast. Examples of erosional features by strong wind and Tsunami December 2004 have shown that the Indian Ocean coasts are equally vulnerable like Western Coasts. The further studies may be useful for coastal zone management and design criteria for structures on the risk coasts.

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