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OCEAN-WIDE TSUNAMIS, MAGNITUDE THRESHOLDS, AND 1946 TYPE EVENTS

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SUMMARY

An analysis of magnitudes and runups in Hawaii for more than 200 tsunamigenic earthquakes along the margins of the Pacific reveals that all of the earthquakes with moment magnitudes of 8.6 or greater produced significant Pacific-wide tsunamis. Such findings can be used as a basis for early warnings of significant ocean-wide tsunamis as a supplement to, or in the absence of, more comprehensive data from other sources. Additional analysis of magnitude and runup data suggests that 1946 type earthquakes and tsunamis may be more common than previously believed.

INTRODUCTION

In the aftermath of 26 December 2004, attention has been focused on strategies for reducing or eliminating those factors that contributed to the Asian tsunami tragedies. In this regard one of the first questions to be asked is whether there exists an earthquake magnitude threshold above which the generation of a significant ocean-wide tsunami becomes a certainty. This question is important because such a threshold might be useful in providing the basis for an early warning of a significant ocean-wide tsunami, perhaps well in advance of comprehensive data from ocean buoys, tide gauges, or other sources.

ANALYSIS

Magnitude Threshold

In an earlier report (Walker, 2000) more than two hundred earthquakes from 1900 through 1999 with epicenters along the margins of the Pacific were analyzed in terms of their surface wave magnitudes, moment magnitudes, and runups in Hawaii. For this report these data have been updated through 2004 (Table 1). Also added is the only known ocean-wide tsunamigenic earthquake in the Pacific prior to 1900 for which a surface wave magnitude (Ms) and moment magnitude (Mw) have been computed (i.e., the 1896 Sanriku earthquake). Data from Table 1 and the earlier report are shown in Figure 1. Smaller runups may actually be estimates from water level recordings. Values through 1999 may be found in Table 1 of Walker (2000).

Earthquakes with Ms/Mw values above the dashed line in Figure 1 appear to have the potential for generating destructive tsunamis in Hawaii. Earthquakes with Ms/Mw values below the line have not generated Pacific-wide tsunamis or have generated only moderate or small Pacific-wide tsunamis. As might be expected, most of the significant tsunamis (i.e., those having runups of 1 meter or more) have large moment magnitudes. All earthquakes with moment magnitudes of 8.6 or greater produced significant ocean-wide tsunamis. However, this does not hold true for two of the five earthquakes with Mw's of 8.5. One occurred in the Kurils with an Ms = 8.1 and runup (A) = 0.4 meters. This earthquake had no obvious characteristics (i.e., location, orientation, depth, or source mechanism) that might explain the absence of a significant ocean-wide tsunami. The other earthquake occurred south of Samoa (Ms = 8.2; A = 0.1 m), close enough to have much of the energy that might have traveled to Hawaii blocked by those islands. Moving further down the Mw scale to 8.4 and 8.3, four of the five earthquakes did not produce significant tsunamis in Hawaii. The orientation of faulting relative to Hawaii could be a factor in explaining the absence of a significant ocean-wide tsunami for the Peru earthquake (Mw = 8.4, Ms = 8.2, A = 0.7 m). No obvious characteristics can explain the absence of significant tsunamis for the other earthquakes (an 8.4 and two 8.3's). Therefore, based on the available limited data, the Mw threshold indicated for the Pacific is 8.6. However, an earthquake in the Central Aleutians with an Ms = 8.2, Mw = 8.7, and A = 1.1 meters is indicative of how close the 8.6 threshold could be to producing "false warnings" (i.e., warnings perceived as false because the maximum runup was less than 1 meter). There are no obvious characteristics that might explain the absence of a larger tsunami for this Central Aleutians event. Aside from values in the source area, the largest runup reported for this earthquake was the 1.1 meters in Hawaii (Iida, Cox, and Pararas-Carayannis; 1967). The central Aleutian earthquake with its 8.7 Mw and relatively small ocean-wide tsunami may be somewhat comparable to the recent 8.7 Mw Sumatra aftershock of 28 March 2005.

Additional 1 April 1946 Type Tsunamis

Other important insights into the relationships (or non-relationships) between tsunamis and earthquake magnitudes may be found in Figure 1. Most disturbing is the fact that of all the significant Pacific-wide tsunamis reported in Hawaii, none had a larger runup (A = 16.4 m), a smaller Ms (7.1), or smaller Mw (8.0). A generally accepted explanation for the size of this tsunami, given its relatively modest magnitudes, has yet to be found. If this earthquake can generate a 16.4 meter runup in Hawaii, would it be possible for earthquakes with Ms and Mw values far less than 7.1 and 8.0, respectively, to produce 1 meter or more runups in Hawaii? Would it be possible for a 1946 type tsunami with Ms and Mw values far greater than 7.1 and 8.0, respectively, to produce runups in Hawaii far greater than 16.4 meters? For years the hope had been that this tsunami was a “one of a kind” anomaly for which an explanation could be found. However, with the publication of an analysis of the 1896 Sanriku earthquake (Tanioka and Satake, 1996), the 1946 event, while still the most prominent, may no longer stand alone. The 1896 earthquake (Figure 1) has the same Mw (8.0) as the 1946 earthquake and a slightly larger Ms (7.2 versus 7.1). The largest reported runup in Hawaii was 5.5 meters at Keauhou on the western coast of the Big Island. This value is larger than the 3.2 meters reported at Keauhou (Lander and Lockridge, 1989) for the much larger (Ms = 8.3, Mw = 8.4) Sanriku earthquake of 1933. The largest runup reported for this larger earthquake was 3.3 meters at Kaalualu on the Big Island (Lander and Lockridge, 1989). An investigation of the differences in the mechanisms of these earthquakes may provide some insights into the unusual strength of the 1946 tsunami.

Another pair of earthquakes similar to, but less spectacular than, the Sanriku earthquakes, occurred in the Kurils in 1963 on the 13th and 20th of October. Both had maximum reported runups of 0.4 meters in Hawaii. However, the 13 October earthquake had an Ms = 8.1 and an Mw = 8.5 while the 20 October earthquake had an Ms = 7.2 and an Mw = 7.8. Like the Sanriku earthquakes, these Kurile events might provide some insights into the unusual strength of the 1946 tsunami. Finally, it should be noted that a small region generating a large number (9) of reported tsunamis in Hawaii is the offshore area of Kamchatka. Many of these earthquakes have nearly identical mechanisms, orientations, depths, and travel paths to Hawaii. For an earthquake with an Ms of only 7.0 and Mw of only 7.0, a runup in Hawaii of 0.3 meters was reported (13 April 1923); yet for an earthquake with an Ms of 8.2 with no available computed Mw, a runup of only 0.2 meters was reported (4 May 1959). The 7.0 / 7.0 / 0.3 m earthquake could also be compared to another Kamchatka earthquake with Ms / Mw / A values of 7.3 / 7.5 / 0.12 m (8 June 1993). Also there are three Kamchatka earthquakes with nearly identical epicenters (i.e., within about 100 km of one another) with values of 8.1 / 8.5 / 6.1 m (3 February 1923), 8.2 / 9.0 / 9.1 m (4 November 1952), and the previously mentioned 8.2 / NA / 0.2 m earthquake. As with the Sanriku and Kurile earthquakes, Kamchatka events could be useful in resolving the enigma of the 1 April 1946 tsunami.

CONCLUSIONS

All shallow earthquakes along margins of the Pacific with moment magnitudes of 8.6 or greater through 2004 produced significant tsunamis in the Hawaiian Islands. This threshold could be used to provide early ocean-wide tsunami warnings as a supplement to, or in the absence of, more comprehensive data from ocean buoys, tide gauges, or other sources. Runup values in Hawaii that are seemingly inconsistent with the magnitudes of the earthquakes that produced those tsunamis are found off Japan, the Kurile Islands, and Kamchatka. These earthquakes suggest that the 1946 tsunami may not be as anomalous as previously believed, possibly providing additional data for resolving the mechanism of the 1946 tsunami. Of the six earthquakes in Figure 1 having the largest reported runups in Hawaii, two (1896 and 1946) have unusually low magnitude values. These findings should serve as a reminder of the potential danger of recurring 1946 type tsunamis.

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Table 1

Additional Pacific-Wide Tsunamis in Hawaii through 2004*

Year	Date	Source Locations	Ms	Mw	A (meters)	Location
1896	06 15	Japan	7.2	8.0	5.5	Keauhou
2001	06 23	Peru	8.2	8.4	0.7	Hilo
2003	09 25	Japan	8.1	8.3	0.4	Kahului
2003	11 17	Aleutians	7.2	7.8	0.7	Kahului

* Data are supplemental to listings in Table 1 of Walker (2000). Magnitudes for the 1896 earthquake are taken from Tanioka and Satake (1996). Other data are from searches of U.S. Geological Survey (USGS), National Geophysical Data Center, or International Tsunami Information Center on-line databases. Surface wave magnitudes (Ms) are USGS values and moment magnitudes (Mw) are those of Harvard.

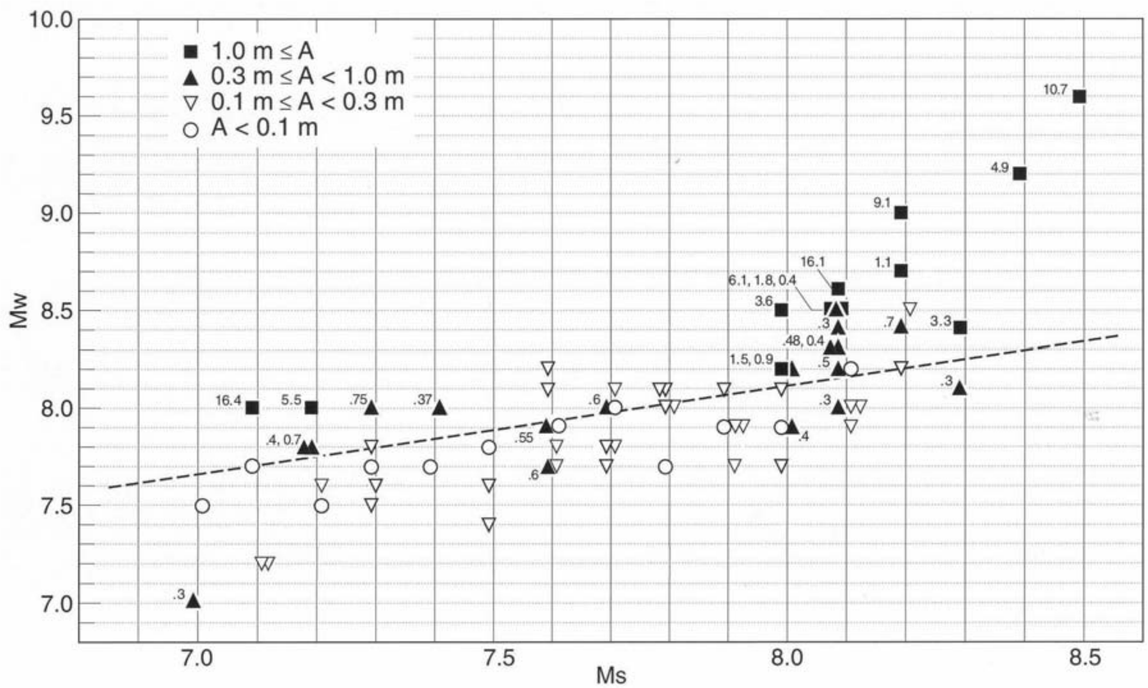

Figure 1. Surface wave magnitudes (Ms), moment magnitudes (Mw), and maximum reported runups or tide gauge readings (A) in Hawaii from Table 1 and Walker (2000). Of the more than 200 earthquakes examined for these regions, most did not generate reported tsunamis in Hawaii or their tsunamis were reported either to be less than 0.1 m or to be "observed". Only the largest of these in terms of Mw for each Ms value are plotted in this figure. The dashed line is an estimated delineation of those earthquakes with (above the line) or without (below the line) the potential for generating significant tsunamis in Hawaii.

EFFECTS OF MEDU AND COASTAL TOPOGRAPHY ON THE DAMAGE PATTERN DURING THE RECENT INDIAN OCEAN TSUNAMI ALONG THE COAST OF TAMILNADU

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ABSTRACT

Effects of Medu (naturally elevated landmass very close to the seashore and elongated parallel to the coast) and coastal topography on the damage pattern during the deadliest Indian Ocean tsunami of December 26, 2004 is reported. The tsunami caused severe damage and claimed many victims in the coastal areas of eleven countries bordering the Indian Ocean. The damage survey revealed large variation in damage along the coastal region of Tamilnadu (India).

The most severe damage was observed in the Nagapattinam district on the east coast and the west coast of Kanyakumari district. Decrease of damage from Nagapattinam to Kanchipuram district was observed. Intense damage again appeared to the north of Adyar River (from Srinivaspuri to Anna Samadhi Park). Almost, no damage was observed along the coast of Thanjavur, Puddukkotai and Ramnathpuram districts in Palk Strait, situated in the shadow zone of Sri Lanka.

It was concluded that the width of continental shelf has played a major role in the pattern of tsunami damage. It was inferred that the width of the continental shelf and the interference of reflected waves from Sri Lanka and Maldives Islands with direct waves and receding waves was responsible for intense damage in Nagapattinam and Kanyakumari districts, respectively. During the damage survey authors also noted that there was almost no damage or much lesser damage to houses situated on or behind the Medu. Many people observed the first arrival. The largest tsunami amplitude occurred as the first arrival on the eastern coast and in the second arrival on the western coast.

INTRODUCTION

The deadliest Indian Ocean tsunami originated due to the occurrence of the Sumatra earthquake (M = 9.0, on Richter scale) of December 26, 2004 at 0:58:51 UT or 6:28:51 IST (USGS, 2005). The epicenter of the Sumatra earthquake (3.251^0N & 95.799^0E) was located about 255 km SSE of Banda Aceh, Sumatra, Indonesia at a depth of 10 km. (USGS, 2005). The thrusting type of source rupture generated the killer tsunami, which caused damage as far away as Somalia (Table 1). The damage along the coast of Indian mainland was due to only tsunami.

Table I Life loss in Sumatra Earthquake And Tsunami (UN/OCHA Relief-web*)

Country	Death	Missing
Indonesia	110,229	12,132
Sri Lanka	30,899	6,034
India	10,672	5,711
Thailand	5,303	3,396
Maldives Is.	81	21
Malaysia	68	6
Myanmar	59	3
Seychelles	3	NA
Somalia	150	NA
Total	1,57,464	27,303

**Regional overview data up to 14.1.2005*

Though the Indian subcontinent is in a seismically active region, tsunamis along the coastline of India have been rare, but not unprecedented. The coasts of Indian landmass have experienced at least four attacks of tsunamis in the last 200 years. A tsunami of height of the order of 2 - 3 m in Kutch region was reported during the June 16, 1819 Kutch earthquake (MacMurdo, 1823; Bilham, 1999). The submarine earthquakes of December 31, 1881 and June 26, 1941 beneath the Andaman Islands generated a tsunami, and the later one caused loss of life along the east coast of India (Rogers, 1883; Oldham, 1884; Murthy and Rafiq, 1991). Another tsunami struck on the west coast during the Baluchistan earthquake (M_w = 8.0) of November 28, 1945.

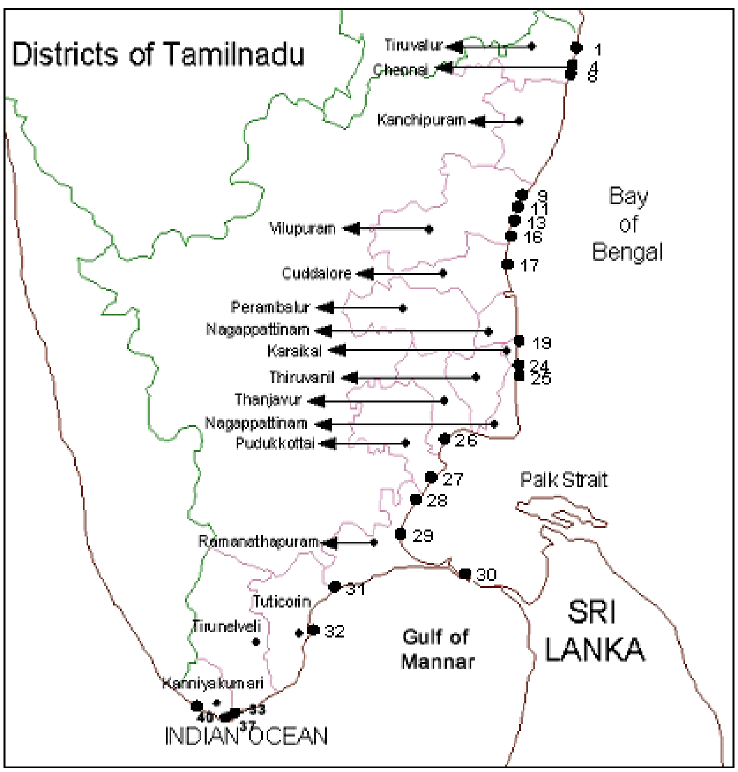

Figure 1: District Map of Tamilnadu showing locations of visited area (black circles). Refer location number in Table 2.

A team from Department of Earthquake Engineering, Indian Institute of Technology Roorkee visited the coastal region of Tamilnadu during January 6-14, 2005 for a post-tsunami damage survey. The main objectives of the team were to see the affects of tsunami on the built environment, to measure the inundation and run up and their lateral variation, to determine arrival time of the tsunami, number of waves, and to model the dynamics of the waves.

Table 2. Name of different locations visited, their serial numbers, run-up and inundation measured at each locality, reported death and arrival time of tsunami (Note: localities with * are plotted in Fig. 1).

SN		Latitude (^{0}N)	Longitude (^{0}E)	Run-up (m)	Inundation (m)	Arrival Time	Death reported	Name of Locality
1*	East coast of Tamilnadu	13.17	80.313	3-4	400		Nil	Cherain Nagar
2		13.145	80.303	3-4	10-20m		Nil	Royapuram
3		13.063	80.287	4-5	800		---	MGR/Anna Samadhi
4*		13.039	80.281	4-5	800	9:05 AM	200	Marina beach
5		13.021	80.28	5-6	1200		30	Srinivaspuri
6		13.002	80.276	4	400		9	Elliot's beach
7		12.991	80.273	3-4	300		Nil	Basant Nagar
8*		12.969	80.267	3-4	200	8:45 AM	Nil	New beach
9*		12.051	79.878	4	1000		Nil	Kudukuppam,
10		12.007	79.861	4-5	2000	8:45 AM	9	Chinnapattam
11*		11.961	79.843	4	200		Nil	Kotakuppam
12		11.931	79.837	4	20	8:30 AM	Nil	Pondicheri
13*		11.857	79.817	3	150		Nil	Nallwarkuppam
14		11.777	79.797	3	150	8:45 AM	4	Manjakuppam
15		11.765	79.794	5-6	1000	8:30 AM	36	Talenguda
16*		11.739	79.788	6-7	1000		Nil	Devanamkuppam
17*		11.525	79.763	8-9	500		130	Kuddukullam
18		11.068	79.858	8-9	2000		38	Kuddupattanam
19*		10.944	79.854	8-9			23	Kilinjal Village
20		10.936	79.853	8-9			31	Amman Kerapattu
21		10.784	79.851	10-12	3000		30	Nagapattinam Beach
22		10.778	79.852	10-12	3000		260	Nabiyarnagar
23		10.773	79.846	10-12	2500		15	Vellaipalyam
24*		10.762	79.851	10-12	1000		---	Nagapattinam Port
25*		10.679	79.854	4-5	500-7000		1000	Velanganni Beach
26*		10.201	79.253	2	700	11:00 AM	Nil	Alatikut Village
27*		9.9082	79.146	1-2.0	50	11:45 AM	Nil	Arpudapattanam
28*		9.7412	79.023	1	20	12:30 PM	Nil	Tondi
29*		9.4798	78.899	1	30	12:50 PM	Nil	Navapasanam
30*		9.1775	79.417	1			Nil	Dhanushkodi
31*		9.0748	78.366	3	20-30	10:00 AM	1	Vember
32*		8.7496	78.194	3	100	9:00 AM	Nil	Tuticorin Port
33*		8.1175	77.56	2-3	1000	10:15 AM	Nil	Aragyapuram Village
34		8.1092	77.558	2-3	300	9:45 AM	Nil	Librahmkuppam
35		8.096	77.566	3-4	450	10:30 AM	Nil	Cinnamuttam Harbor
36		8.0789	77.553	4-5	450	10:40 AM	Nil	Kanyakumari
37*	West coast	8.0883	77.487	9-10	2000	10:30 AM	70	Keelmanakudy
38		8.1414	77.304	6-7	700	10:15 AM	2	Chinnavilai Village
39		8.1557	77.29	6-8	500-1000		---	Pattupetta Village
40*		8.1705	77.256	6-8	500	10:20 AM	---	Colachal harbor

The general observations as reported by many people in the affected coastal areas of Tamilnadu are mainly tsunami crest as the first arrival i.e., the first arrival was a positive wave and the largest tsunami amplitude was observed as the first arrival on the eastern coast and the second arrival on the western coast. IOC (1998) (Intergovernmental Oceanographic Commission) post tsunami survey field guide was used to measure run-up, inundation and other useful information regarding tsunami. The hatched area shown in figure 1 depicts the surveyed locations. The names of localities, their serial number, locations, tsunami run-up and inundation, number of causalities and first arrival time of tsunami are given in table 2.

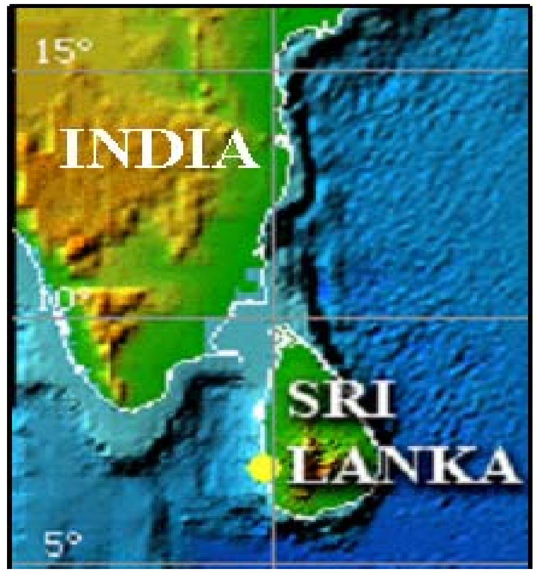

Figure: 2 Coastal and ocean basement topography around Tamilnadu and Sri Lanka.

Analysis of gathered data reveled that the measured run-up values and the damage pattern were highly variable. The districts of Nagapattinam, Kanayakumari and Chennai were the worst hit districts and almost no damage was observed in Pudukkotai, Ramnathpuram and Tuticoin districts. During the damage survey it was noticed that localities with Medu, breakwaters, mangroves, and shelter belt plantations suffered less damage (The Hindu, 2004, 2005). Such peculiar observations along with the possible physics behind the large variation in damage along the coast of Tamilnadu are documented in this paper.

EFFECTS OF WIDTH OF CONTINENTAL SHELF

It can be inferred that the amplitude of tsunami should decrease from south to north along the coast of Tamilnadu, on the basis of location of epicenter of Sumatra earthquake and the orientation of rupture plane. But, the damage survey revealed large variations in the tsunami run-up and damage pattern.

Figure 3: Depicts the damaged children's park, uprooted electric pole, damaged SINGNADH and the collapsed auditorium on Nagapattinam Beach.

Figure 4: Intense erosion of front portion of beach road, facing to the sea coast at Nagapattinum beach.

Figure 5: Uprooting of the trees and washing away of destroyed building materials in Vellaipallyam village

The southern part of Tamilnadu from Kanyakumari to Pudukkottai district, situated in the shadow of Sri Lanka, suffered the least damage (Fig. 1 & 2). But, the damage survey revealed large variations in the tsunami run-up and damage. Further, tsunami damage was highly variable from Nagapattinam to Chennai. Maximum tsunami damage (run-up 10-12 m) was observed along the coast of Nagapattinam. There was decrease in damage from Cuddalore to Kanchipuram district. Increase of damage was again observed to the north of Adyar River from Srinivaspuri to Anna Samadhi Park in Chennai district. Along the coast of Nagapattinam district run-up and inundation were 10-12 m and 2-3 km, respectively. General panic was reported every where and people were unable to understand what was happening. Many people were washed away and lost their life.

Nagapattinam beach, a newly constructed tourist spot was completely destroyed (Fig. 3). Extensive ground erosion and uprooting of trees was observed every where (Fig. 4 & 5). Many structures suffered damage of grade G4 and some destroyed. Severe damage to lifelines (road, bridges, telephone and electric poles and railway line), port and harbors took place (Fig. 5). Many big boats/vessels were thrown violently towards the coast (Fig. 6). It seems that lesser width of continental shelf near the coast of Nagapattinam district and the interference of the direct waves and the reflected waves from Sri Lanka developed largest tsunami run-up (10-12 m) in Nagapattinam district (Fig. 2). On the other hand, much lesser damage occurred along the coast of Kanchipurum district due to some what wider continental shelf (Besana et al, 2004).

Further, heavy damage was observed from Keelmanakudy village to Colachal Harbor on the west coast of Kanyakumari. Largest tsunami run-up (9-10 m) was reported during the second inundation of the tsunami. The decreasing trend of damage was observed from Keelmanakudy village to Colachal harbor. Around 70 people lost their life in Keelmanakudy Village. A newly constructed bridge on Palyar River suffered severe damage (Fig. 7a).

Figure 6: Damaged structure on the Nagapattinam Port due to the collision of a boat thrown by tsunami.

Figure 7: Damaged bridge on the Palyar River, whose spans of the deck were washed away (left), and partially collapsed Church of Keelmanakudy Village (right).

All the four spans of the deck were washed away by the tsunami and two were missing. Almost every building of good quality along the seashore suffered heavy damage (Fig. 7b). Damage to masonry buildings was quite intense; few of them not only collapsed but were completely flattened. There was intense erosion to a road linking the village to the bridge. Variation in tsunami run-up/damage along the west coast of Tamilnadu can be explained considering the interference of first receded waves with the reflected waves from Maldives Islands and the lesser width of continental shelf (Fig. 2). It has also been reported in the literature that some times the later arrivals cause more sever damage (Bryant, 2001).

It was also noticed that there was local increase of tsunami damage near the mouth of rivers, due to the refraction of tsunami waves (Harinarayan and Naoshi, 2005). The place of local increase of damage was dependent on river orientation and direction of arrival of tsunami. For example damage was relatively more towards the north of Adayar River from Srinivaspuri to Anna Samadhi Park as compared to south of it at Elliot's beach. Similarly more damage was observed at Nagapattinam beach near a river, Nagapattinam Port on Kaduvaiar River, Devanakuppam beach on Kedilum River, Velonganni beach near a river and Keelmanakudy village near Palyar River.

EFFECTS OF MEDU

During the damage survey, it was observed that at many places presence of Medu, breakwaters, mangroves and shelter belt plantations (The Hindu, 2004, 2005) saved a lot of loss of human lives and property. Although, the purpose of the breakwaters was to avoid the impacts of tidal waves but it performed well at some of the locations. Further, it was first time observed by the residents that the presence of Medu near the sea-shore may be so effective to avoid the disastrous impact of tsunami. In the following subheadings, the beneficent role of Medu at Kilinjal village, Nabiyarnagar and Nagapattinam Port, during the attack of killer tsunami is reported.

Kilinjal Medu

The Kilinjal Medu is located to the north of the Kilinjal village. Inundation in this area was around 2-3 km. The estimated tsunami height near the shore was 8 - 9 m. The population of this village is

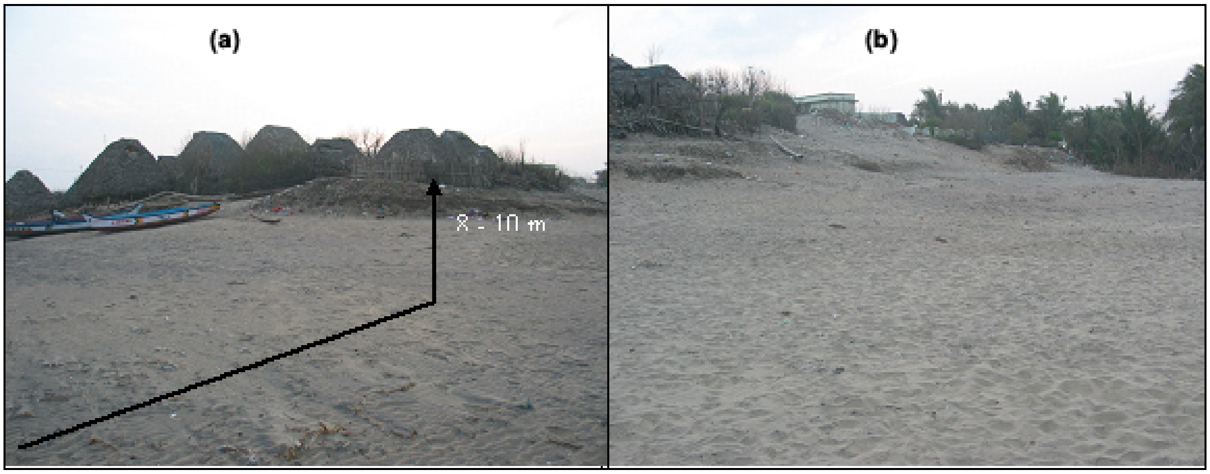

Figure 8: Illustrates the different views of the Killinjal Medu and the little damaged house/huts on the Medu.

about 2000. The loss of human life was 23. The height of Kilinjal Medu is about 8-10 m (Fig. 8a). The width of Medu parallel to the seashore was around 200m. The slope of Medu towards the sea was steep and it was flat up to 50-60 m, and thereafter-gentle slope. Similarly, slope on the north of Medu was more where there was no dwelling and it was gentle on the south side of the Medu. The residents on the Medu reported that sea water was unable to reach to the top of it during the attack of tsunami waves.

Figure 8 depicts houses and the Kilinjal Medu from different locations. We observed that there was no damage to even huts built on the Medu (Fig. 8a). The presence of Medu prevented damage of many huts/houses behind it and finally the loss of human life also. Figure 9a shows a hut, which suffered almost no damage since it was behind the Medu. Severe damage to collapse of houses occurred to the north and south of Medu. Figure 9b depicts damaged houses, which were situated to the north side of the Medu. It was general feeling of the residents of this village that Medu has saved much loss of human life and houses.

Figure 9: Depicts lightly damaged houses behind the Kilinjal Medu (left), and destroyed structures north of the same (right).

Figure 10: A sketch showing the Nabiyarnagar Medu from the left and front side.

Nabiyarnagar Medu

Nabiyarnagar Medu is situated on the northern part of Nabiyarnagar. Tsunami caused death of 260 people and around the same number was missing in Nabiyarnagar having population 5000-6000. Tsunami run-up in this area was around 10-12 m and inundation was around 3.0 km. A sketch of the Nabiyarnagar Medu from north and front side is shown in figure (10). The houses built on the Nabiyarnagar Medu were more or less safe, while others were completely destroyed (Fig. 11a). Most of built houses near the shore (between 50 –100 m) and towards the south of the Medu were either destroyed (B-type) or washed away (huts), and rest was unsafe for living. Intense damage to houses was observed even up to a distance of about 600 –700 m from the coastline.

Very less damage was observed to the buildings behind the Medu. The huts on the Medu suffered no damage, since tsunami waves were unable to cross the Medu. The height of the Medu was around 14 m. It has steep slope towards north and sea but has gentle slope towards south and behind. Some huts were also washed away which were in front of Medu and at lower elevation. It was reported that coastline has come near to the Medu by 50 m. On the south side of Medu where elevation was lesser houses suffered severe damage. Intense erosion towards north of Medu was observed (Fig. 11b).

Figure 11: Lightly damaged hut on the front portion of the Nabiyarnagar Medu (left), and intense erosion of coastal land, north of the Medu (right).

Nagapattinam Medu

Figure 12 depicts the Nagapattinam Medu, existing just in front of the southern part of the Nagapattinam Port. The height of Medu is around 7 m with respect to the port level. Tsunami crossed the Medu. There is Kaduvaiyar River between port and the Nagapattinam Medu (Fig. 13).

Figure 12: Medu in front of the Nagapattinam port.

Lesser damage occurred just behind the Medu, as can be inferred from the figure 13 in which there is lesser damage to wharf in its upper and left corner. Same was the feeling of employees of this port that Medu in front of the port reduced the damage to some extent, particularly to the structures and boats in the Kaduvaiyar River, as reported by Mr. Shajath Ali (Assistant Engineer, Mechanical). On the other hand, Nagapattinam Port suffered heavy damage and it was not in operation for 15 days. Tsunami caused heavy damage to wharfs (Fig. 13), boats (Fig. 6), compound wall and an old jetty constructed in 1972.

CONCLUSIONS

The deadliest Indian Ocean tsunami of December 26, 2004, in the recorded history, developed highly variable damage pattern due to the shadow of Sri Lanka, presence of Medu, variable width of continental shelf and interference of direct waves with the reflected waves from Sri Lanka and Maldives Islands. It seems that maximum damage observed along the coast of Nagapattinam district may be due to the lesser width of continental shelf and the interference of direct waves with the reflected waves from Sri Lanka (Besana et al, 2004).

Similarly, intense damage during the second attack of tsunami, from Keelmanakudy village to Colachal Harbor along the west coast of Kanyakumari, may be due to the lesser width of continental shelf and the interference of receded first waves with the reflected waves from Maldives Islands. It has also been reported in the literature that some times the later arrivals cause more sever damage (Bryant, 2001).

Figure 13: damaged wharf of the Nagapattinam Port.

Presence of Medu at Killinjal village, Nabiyarnagar and Nagapattinam Port reduced the damaging impact of tsunami on the built environment. It was also noticed that there was local increase of tsunami damage near the mouth of rivers, due to the refraction of tsunami waves (Harinarayan and Naoshi, 2005). The place of local increase of damage was dependent on river orientation and direction of arrival of tsunami. The southern part of Tamilnadu from Kanyakumari to Pudukkottai district suffered least damage due to the presence of Sri Lanka in the path of tsunami. Further, the level of damage in the Gulf of Mannar was more than in the Palk Strait, since only diffracted waves were able to enter into the Palk Strait.

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2004 INDIAN OCEAN TSUNAMI ON THE MALDIVES ISLANDS: INITIAL OBSERVATIONS

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ABSTRACT

Post-tsunami field surveys of the Maldives Islands where carried out to document the effects of the tsunami inundation. The study area was situated in the islands of South Male Atoll that were some of the most heavily damaged islands of the Maldive Islands. The tsunami damaged the natural environment, vegetation, man-made structures, and residents. The maximum tsunami wave height was 3-4 m. This level of inundation exceeded the height of most residents. The wave height was greatest on the eastern rim of the South Male Atoll (closest to the tsunami source) and these islands were completely flooded. The islands within the interior of the atoll saw the lowest wave heights, and these were only marginally flooded.

Surveys of flood lines left on the exterior and interior of structures were measured but proved to be substantially less than that reported by survivors. It appears that the highest inundation was not preserved as flood lines. We suggest that the turbulence associated with the tsunami inundation erased the highest lines or that they did not form due to an absence of debris and organic compounds that acted as adhesion during the initial flooding.

Significant erosion was documented. Deposition took place in the form of sand sheets while only desultory deposition of coral clasts in marginal areas was found. Seasonal erosion, and storms are likely to remove most or all of the traces of the tsunami within these islands.

INTRODUCTION

The December 26, 2004 Indian Ocean Tsunami produced considerable damage within the Maldive Islands in the Central Indian Ocean (Figure 1; location map). The maximum tsunami wave heights reached 3 to 4 m and the impacts to these low lying islands in the far-field of the tsunami were considerably less than that observed in the Eastern Indian Ocean, closer to the source region. Nevertheless, the tsunami impact was both widespread and destructive to: the natural environment (rocks, beaches, etc), vegetation, man-made structures, and the island residents. In addition, the location of garbage dumps on the seaward side of the island resulted in the spread of debris that polluted the ground surface and ground water as a direct result of the tsunami.

The nature and scope of the tsunami impact is described here in a general fashion and more details will be the subject of future papers. The narrative of eyewitness reports along with our own observations is intended to give the reader an added dimension and perspective to the impact of the disaster. The tsunami survivors indicated that the flood waters were significantly higher than the flood lines we surveyed.

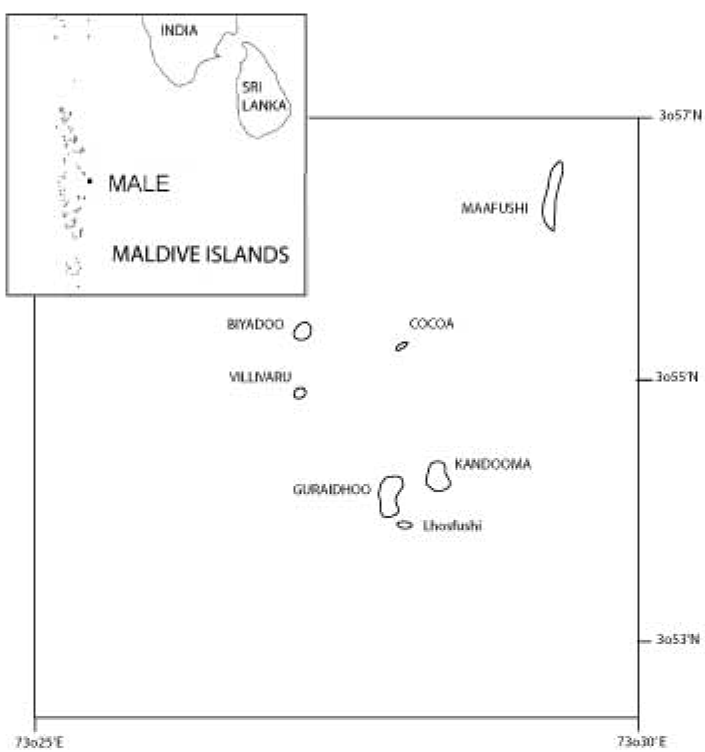

Figure 1. Map of the Indian Ocean (upper left) shows the location of the Maldive Islands relative to Sri Lanka and India, with the location of the South Maldive Islands shown as a bold black dot. The map at lower right shows the location of the islands of South Male Atoll visited during these studies. A small color inset back (bottom) shows the location of the reefs (turquoise color) and the islands (green color). The map is based upon the map of Godfrey (1999).

LOCATION - MALDIVE ISLANDS

The Maldive Islands are situated in the Western Indian Ocean, 2500 km west of the tsunami source area (Figure 1). The island groups lie southwest of India and Sri Lanka along two parallel North-South lines, and form an island archipelago with a total length of a little more than 800 km. Male Atoll, the capital of the Maldives, is situated centrally on the eastern line of atolls. Our observations are restricted to seven low-lying islands of South Male Atoll (both resort islands and residential islands). The islands surveyed are situated on the eastern barrier ring-reef or within the atoll where local pinnacles and micro-atoll are topped with sandy islands only 1.5 m (or less) above sea level (see Figure 2). The islands are composed entirely of reef-derived sediments.

We chose this study area since some of the heaviest tsunami damage was reported in this area. We did not include the island of Male in this investigation although that was our base of operations. Male is a densely populated urban city with high-rise buildings and armored coasts. It was inundated to a depth of about 0.5 m above street level in many places but repairs had been completed prior to our visit and little first hand information was volunteered.

Figure 2. Photograph of Villivaru. These resort room units were flooded due to their proximity to the coast and the fact that this is a very low-lying islands (roughly 0.5 m above sea level).

POST TSUNAMI FIELD SURVEY OBSERVATIONS

Signs of tsunami inundation were numerous (see Table 1). The damage identified falls into five categories including: vegetation, building structures, outdoor structures, people, and natural environment. The damage ranged from severe to light, and reflects proximity to the eastern atoll barrier (ring) reef of the atoll.

Table 1

Tsunami Impacts on Maldives Islands

Impacts on Vegetation

Severe:
Trees up-rooted
Trees undermined and roots exposed
Trees killed by inundation
Roots buried by sand
Trees and low vegetation killed

Moderate to Light:
Salt burnt vegetation
Bark abraded from tree trunk
Debris left in branches, roots, and fork of trees
Leaves stripped
Sand-covered leaves
Burial of grass in sand

Impacts on Building Structures

Buildings Interior:
Flood lines on walls, doors, and mirrors
Changes in finish on furniture
Electrical fixtures damaged
Fixtures corroded
Fine sand deposited
Bathrooms: black mud
Paint sand blasted
Paint peeling from walls

Buildings Exterior:
Flood lines on walls
Scratches on exterior walls
Doors and locks ripped off
Breaks in walls
Effervescence in lime mortar
Windows blown inwards
Air vents blown outward
Changes in paint/finish (blue)

Impacts on Outdoor Structures

Heavy-duty Structures:
Piers- broken
Jetty structures- broken
Ramps- broken
Sea Walls damaged
Heavy objects moved

Light Weight Structures:
Boats moved inland
Jet Ski washed away
Signs and light poles-
Sand adheres
Paint striped
Signboards gone
Soccer goals sand blasted

Impact on People

Impact injuries (Based on first-hand accounts)
Drowning
Illness, e.g. Pneumonia
Phobias

Deaths- 80 initial numbers
Cemetery- more newly dug graves
Trauma, flashbacks, loss of sleep

Impact on Distribution of Rocks

Deposition:
Sand sheet
Coral splay deposit
Coral berm formed
Sand Shallowed harbors

Erosion:
Scarp at back of beach
Erosion roots and structures
Sand bar or cays removed (North & South of islets)
Reef coral moved inland (East)
Beaches incised with gullies (West side)
Subsidence of island by sand compaction/redistribution

Flood lines were measured when encountered on the interior and exterior of buildings. The lines often had small fragments of vegetation (e.g. dry leaves) adhering to the wall probably by organic compounds or oils spread by the flooding. In all cases, the surveyed elevations of flood lines were less than flood elevations described by survivors. The reported "wave height" is summarized in Table 2 (column 3) and compared to the measured flood line elevation (columns 10 and 11) listed as the "Interior" flood height (measured within damaged interiors of homes) and the "Exterior" flood heights (measured on walls and various other exterior surfaces). There are significant disparities between the two levels.

Table 2 **Summary of Eye-witness Reports from all islands surveyed**

Environment	Damage	Wave Ht.	Structural Damage	Locations	Erosion	Type of Inundation	Waves	Vegetation Damage	Int.	Ext.
Island on barrier reef	HD	71-152 cm	Extensive	Guraidhoo	H	Flood	3	H	190 cm	218 cm
Island on barrier reef	H	122 cm	Extensive	Maafushi	H	Flood	3	H	102	244
Back from Reef	H	61 cm	Very light	Cocoa Island Resort	H	Flood**	2	L	15	61
Lagoon	L-M	99 cm	Dive Shop Flooded	Biyaadhoo Resort	M	Marginal Flood **	2	H		122
Lagoon	M	102 cm	Room Unit Damaged	Villivaru Resort	H	Marginal Flood		H		
Island on barrier reef	D	249 cm	No Structures	Lhosfushi Isle	H	Flooded		M		
Island on barrier reef	H	152 cm	Extensive	Kandooma Resort	H	Flooded **	3	H	102	244
Lagoon	M	122 cm	Rooms Flooded	Boduhithi ***Resort		Flood **	2			122

Notes:
** Wave from west side of island, probably due to wrap-around.
Damage: HD- Heavy Damage, D- Damaged, M-Moderately Damaged, L- Light Damage
Run-up measured in cm based upon eyewitness reports. Erosion: H - Heavy Erosion, M - Moderate Erosion. Number of Waves. Vegetation Damage: H - Heavy, M – Moderate, L –Light.
Run-up depth from survey leveling measurements: Int.- Interior Rooms, Ext. Exterior walls of structures. *** These eyewitness reports are from employees on Biyaadhoo Island Resort who were at Boduhithi Resort during the tsunami.

Paint on structures provided important evidence of inundation heights. The paint on the buildings was often abraded from the walls by the sand-lain tsunami waters. The paints on exterior walls (particularly the favored blue color) that remained in contact with seawater for some time appeared to be chemically altered and had changed colors. On interior walls the paints were either abraded or had peeled away from the walls. The paint on the exterior walls often showed scrapes and scratches substantially above the flood lines.

Vegetation

The atolls of the Maldives Islands experienced inundation associated with maximum tsunami wave-heights of 3-4 m. Since the islands of South Male only stand 0.6-1.5 m above sea level (asl), the tsunami flooded all of the land area for the islands nearest the barrier reef and, either totally or marginally, flooded those more removed from the atoll ring reef.

The most obvious tsunami damage was to the vegetation (Figure 3). At the margin of the islands trees were uprooted and laid backwards by the tsunami waters flooding across the island. Corals were found, still held in the roots and branches of the upturned trees. Along the eastern coastlines scrubs, trees, and grasses were killed by the inundation of salt water leaving the leaves and the stalks brown. Broken branches of other plants were found mixed in the branches of still standing trees. Corals were found in the forks of standing trees and in hollows of the trunks.

Figure 3. Photograph of the vegetation that was laid back onto Guraidhoo Island by the tsunami inundation. This shoreline is situated between Guraidhoo and Lhosfusfi Islands. A log (at right) and corals (5-8 cm across) have been thrown up on the island surface.

Within the back-beach area, the bark on some tree trunks had been partially removed by abrasion. On the eastern (barrier reef) sides of the islands, the shrubs were stripped of leaves. Further inland, fine sand covered leaves remaining on plants. Occasionally we observed small areas in the lee of trees that had been shielded from damage, leaving a small patch of green grass in the lee of a tree trunk (a few 10's of cms in area). Generally, the grass was buried by a thin layer of sand with strands of seaweed mixed in. The grass was brown from salt damage. The broad ranging roots of coconut trees were exposed in erosional scarps at the back of many beaches. Up to one half of the root mat of the trees could be exposed to the air, without apparent damage to the living palm tree.

Whilst the roots of palm trees along the beach were very efficient at holding sand in place during the inundation, the palm trees inland provided a minimum barrier to waves, having small cross-sections. Some of the coconut trees were toppled and can be seen lying on the ground in the photographs taken immediately after the tsunami. *Pandanas* trees that have a network of supporting trunks protected the coast well (Figure 4). (In the Pacific Ocean atolls these trees are called upside-down trees because the structure at the base of the tree, mirrors the branch structure above ground). Additionally, in the Maldive Islands, a bushy coastal shrub, 1 to 2 m high, provided excellent protection for the islands. Where present, the vegetation caught coral fragments, sand, and debris and provided substantial protection against the forces of flowing water.

Figure 4. This tree is the *Pandanus* tree. Because the tree proves a broad cross-section to the sea, it stopped corals from being transported onto the surface of the island. These trees were buried in several cms of coral clasts.

Coconuts washed from the islands were observed floating in the sea. Also, more than a month after the event, trees up to 30 m long were floating in the lagoon and proved to be a significant obstacle to navigation. These trees are not native to the Maldive Islands and have floated from Asia. An islander who had worked in Sumatra reported that these types of tree were native to that area.

Buildings and other man-made structures

The tsunami produced the most extensive damage to concrete block structures on the eastern ocean-side of the islands on the atoll ring reef (Figure 5). Structures on islands in the lagoon away from the barrier reef experienced reduced tsunami flooding from 3 m to 2m and then <1m for the islands we visited. The homes situated along the two rows of buildings on the eastern (near) sides of the islands situated on the barrier reef (near-side meaning east, closest to the tsunami source direction) were destroyed on the residential islands of Guraidhoo and Maafushi. Also, many of the buildings on the residential islands were built in an older style of coral rock in a concrete or lime matrix. These structures experienced significant damage, regardless of their location. Newer structures have been built with undersize (relative to the US) concrete hollow blocks with concrete between blocks and compacted lime soil foundations, generally without dug foundations around exterior walls. Since no reinforcing bars (rebar) were used in the walls and the hollow blocks were not filled with concrete, the walls were easily broken and segments were carried as floating or transportable chunks in the tsunami flood waters. These concrete chunks, along with glass, accounted for many of the injuries reported to us.

Figure 5. The interior of this resort room unit on Kandooma was destroyed by the tsunami. The building lost the sidewall; and the window units were forced in by the force of the tsunami. The air conditioning units above the windows, and the lighting and electrical fixtures were filled with seawater. The contents of the room were spread over the island. The exterior doors (front and back) on many units were torn away or damaged.

On Biyadoo Island, the sand walkways between buildings had been lined with narrow concrete blocks and concrete block walls. The concrete block edging along the paths restricted the flood inundation. These low obstacles to the tsunami flooding restricted the water damage to the outer margins of the island, seemingly preventing damage to the vegetation and buildings in the interior of the islands.

Substantial scouring was found around the corners of many building structures. The scour pits conformed to the walls, and were 0.6-1.5 m deep and the walls above were generally abraded by sand.

Sea Walls

As is typical on any island, different types of sea walls were built over a long span of time. Sea walls come in all sizes and types. Some do not protect, e.g. concrete ramps at Biyadoo allowed the water to run up the ramp and onto the island surface thereby endangering buildings and people. Other sea walls, e.g. vertical poured concrete walls, provided amazing protection, where adjacent land without any protection was deeply eroded. There were breaks in some seawalls that were probably decades old. While reinforcing bars (rebar) are generally absent in locally constructed buildings in the low-islands of the Maldives, many of the sea walls have been there a long time and served the purpose of protecting people and property.

One of the frequent observations was heavy erosion on the land side of harbor sea walls. Typically the area behind and adjacent to the concrete sea wall was heavily eroded from behind. Some, walls remained in place while others were excavated and toppled seaward. The concrete seawall protected the island but the tsunami waters inundated the inland and erosion became focused behind the harbor seawalls, probably during the drain-back phase of the wave.

Erosion due to the tsunami in the Maldive Islands was very heavy. Coastline retreat of 15 m or more occurred is some areas that were not protected by sea walls (Kandooma). The islanders reported that the tsunami came from the east, and then came from the western (lagoon) side of the island. Often the lagoon-side of the island was the most heavily eroded.

Piers

Like the sea wall, the boat piers throughout the low islands vary in age. Most were completely inundated by the tsunami. Occasionally the support structures were removed and the concrete slab surface fell into the sea. But, it was more common to see the piers that were little affected, in this portion of South Male Atoll (Figure 6). Elsewhere in the Maldives, photographs show wooden pier supports in the water with the wooden planking missing.

Figure 6. It was common to see piers like this one damaged or toppled by the drawdown. The waters draining from the islands eroded behind the piers and the concrete structures were heavily damaged or destroyed. This photograph shows the damaged pier at Maafushi.

IMPACT ON THE NATURAL ENVIRONMENT

Sand sheet

The tsunami in general left a thin sand sheet on the surface of the flooded islands. Sometimes individual corals lay on the ground on the sand sheet; generally this was restricted to the several meters adjacent to the margins of the islands. Typically the greatest sand movement was associated with harbors, shallow lagoon areas, sand bars, and reclaimed beaches. Resort managers (at Biyadhoo and Kandooma) reported that a great deal of sand was lost from shoal areas around these islands and into the deep waters.

Corals

The transport and deposition of coral clasts (blocks) was generally limited to the margins of the islands. We sporadically saw evidence of movement of corals (0.2 m in diameter) in the surf zone on the side of the islands closest to the tsunami source. Within the inter-tidal zone we frequently saw evidence of the movement of small corals (up to 0.1 m in diameter). And, individual corals of this size were strewn (10 m) inland but in a very desultory fashion (Figure 7). No large boulders of coral or cemented beach rock were found displaced onto the reefs or islands by the tsunami.

Figure 7. The vegetation was heavily damaged by the tsunami. At right a shrub has been toppled and laid back onto the surface of the island. The thick root mat of the trees has been undermined by sand erosion and blocks of coral were caught in the vegetation. In the background is one of the room units on Kandooma Island, where doors and windows were removed by the tsunami flooding.

On Guraidhoo Island, the residents reported that the boat harbor was shallower after the tsunami, than before. The sands and other debris that washed across the island filled in the harbor to some degree. An image from a cellular telephone showed a boat sitting on the harbor floor when waters withdrew during the tsunami.

On the east side of Kandooma Island, corals were carried by the tsunami onto and over the beach berm (Figure 8). Behind the berm, a low wetland was found with three scour pits. The back beach appears to have experienced erosion as the waters drained from the island, and deposition of coral clasts occurred on and over the berm and pits. Inland of this low-lying back beach area there was a broad sheet of sand with isolated coral clasts on the sand-covered grass.

Figure 8. On the east side of Kandooma Island, coral clasts were washed over a berm and onto the surface of the island. The trees are buried in corals about 20 cm in depth. The coral rubble extends about 20 m inland from the sea. Broken trees can be seen to the right.

Beach erosion

While the deposition of sediments was limited on these islands, there were abundant erosional features including: scarps cut at the back of the beaches, undermining of vegetation and structures, and incised gullies cutting through the back beach and the shore face.

Erosional scarps cut into the sands at the back of the beach that extended 0.25 to 0.5 m vertically were common, on all islands. Many of the scarps expose the roots of coconut trees or other vegetation (Figure 9). On Cocoa Island where the beaches are raked daily we know that these features were formed by the tsunami. Employees of the Cocoa Island resort reported that the sand under the vegetation was undermined. On the seaward side of Lhosfushi Isle, trees were toppled and undermined and several dead trees remained offshore, partially buried by sand.

Figure 9. The most obvious tsunami damage was to the vegetation. This photograph demonstrates the extent of erosion and under-mining of the vegetation. The tree in the photograph is now standing in the sea. The roots of the trees are now exposed above sea level. Many trees were killed, undermined, damaged by salt, and their leaves stripped.

On Guraidhoo Island we were informed that some of the erosional scarps existed prior to the tsunami. And, on Biyadhoo Island we saw a similar scarp formed between our first survey at low tide and our second survey at high tide. Clearly, normal current induced erosion events can produce scarps just like those reported by local residents as being due to a tsunami origin and observations even a month after the event cannot distinguish between the two origins. Photographs taken of the islands prior to the tsunami indicate that many of the erosions scarps were present prior to the tsunami and thus seasonal erosional processes must have formed some of them.

Scouring

Residents of the islands reported that numerous scour pits were left after the tsunami flood waters drained. The pits were large, 2.5-4m in diameter and 0.5 to a meter or more in depth. Some scour pits occurred around the periphery of the island, e.g. on Kandomma, others formed in the midst of residential areas (on Maafushi and Guraidhoo) perhaps due to subsidence or perhaps due to focused erosion during either flooding or drain-back. On Cocoa Island, a large cay (sand bar) that extended to the north of the island was largely removed and or moved 150 m during the tsunami with the sand being lost into the deep water, thus removing a significant volume of sand from the local beach environment.

Incised gullies

Kandooma Island was one of the worst damaged islands that we visited. It was completely inundated by waters that flooded higher than the height of the residents (160 to 180 cm). The flood waters from the eastern and the western sides of the island met near the center of the island. This compounded flooding led to significant erosion particularly on the west side of the island. The flood waters sculpted a broad area of reclaimed beach, leaving it scoured and incised into hummocks. The draining waters incised gullies, 30 m long and up to 1 m deep across the beach. The draining waters also undermined the beach sand from two jetties extending offshore into the surf and a plastic lawn chair was found wedged under the remains of one of the two damaged jetties (Figure 10). On the north side of the island in a reclamation area, a pre-existing channel that had been filled with dredged material was heavily eroded.

Figure 10. The reclaimed beach on the east side of Kandooma Island was heavily eroded, with incised gullies (shown at center of the photograph) removing a meter of sediments. The erosion undermined the two concrete jetties so that the inland portions of the structures are entirely missing. A plastic lawn chair was wedged underneath the closer jetty. A great deal of beach and lawn furniture was permanently lost during the tsunami.

Subsidence

On Guraidhoo Island, residents reported that the island has subsided. Since the island is only slightly above sea level (roughly 1-1.5 m elevation) this is an important observation. The walls of the buildings on the island were cracking weeks after the tsunami. The flooding of the island followed by the draining is likely to have caused rearrangement and repacking of sand resulting in subsidence.

Ground Water

Impact of the tsunami on the island groundwater supply was variable. Those resort islands that utilized reverse osmosis to generate drinking water, recharged the ground water to some degree and thus the existing fresh ground water lens was full and close to the surface, and these islands displayed little impact to the ground water supply. In contrast, on the residential islands, where the water lens was depleted from use, the islanders reported substantial salt-water contamination of the ground water.

IMPACT ON PEOPLE

The 2004 Indian Ocean tsunami reached the Maldives Islands shortly after a low tide but not the lowest tide of the day and during day light hours. The coincidences of the low tide, the low tsunami wave height, and the time of day were fortunate. Many Maldive islanders are short in stature and, on the islands that were fully inundated everyone faced drowning (Figure 11). The survivors suggested that if the tsunami inundation had been just a meter greater, or if it had occurred at night it is likely that many more people would have drowned.

Figure 11. This photograph illustrates the flood lines preserved on the interior walls of a partially destroyed residence on Maafushi. The waters flooded this home to roughly 1.5 m. The occupants were forced to swim in order to survive the tsunami.

While we were conducting leveling surveys to determine the elevation of tsunami flooding, members of the communities often came up to us and related their experiences. Clearly the residents were traumatically affected by their experiences. They volunteered their observations and when their comments were unclear only limited questioning asked for clarifications. During these conversations, notes were taken (Appendix 1) and occasionally pictures were taken. But we did not try to take formal interviews for we decided that it was unnecessary to have the residents relive the trauma of the tsunami unless they chose to do so by volunteering to talk with us.

Eyewitness Reports

Throughout the islands we visited we were told that the tsunami inundation was greater than the elevation of the flood lines we measured. The absence of flood lines or other evidence on walls at the height of the maximum water level as reported by eyewitnesses is somewhat puzzling. It was very common for residents to report inundation at levels up to a half-meter or meter higher than the flood lines. Occasionally, we could verify this greater inundation by the presence of a residual dusting of very fine sand with an abrupt upper boundary. But the general absence of evidence of this higher flooding level possibly could be explained in various ways. It might reflect: great turbulence in the waters associated with the highest waves scrubbing surfaces at the same time they were being wet by the wave; temporary short duration superposition of waves approaching from different directions, splashing associated with the inundation being capable of erasing the trace; or the absence of compounds in the water which allow debris to adhere to surfaces and structures.

An example of a splash level without an associated flood line can be seen on the walls of the reception building on Cocoa Island resort (Figure 12). Video footage of the tsunami inundation is available from the Maldives Disaster Center Web Site (http://www.tsunamimaldives.mv). The footage shows very clear seawater inundating the island. (The seawater is free of debris and the clays that make the tsunami waters appear brown at other Indian Ocean inundation zones.) The flood waters can be observed to splash along and wet the walls, but they left no obvious high flood lines. It would appear the combination of the splashing of the water and the absence of debris and oils for adhesion may explain this discrepancy between the measured flood lines and the reported flood levels.

Figure 12. Employees of the Cocoa Island Resort, in the Maldive Islands, took this photograph of the tsunami flooding. The tsunami flooding at the time of this photograph is roughly 20 cm deep. The seawater is laden with sand, resulting in a milky appearance. The wall at right has been wet by the tsunami inundation. The splashy or turbulent nature of the inundation is evident from the uneven splash lines on the wall. The splash is roughly 1 m above the island surface. The buildings on the island were inundated by water. The flooding damaged computer equipment, bedding, and furnishing but very little structural damage occurred.

DISCUSSIONS

Discrepancies between leveling results and eyewitness reports

The most significant reports the residents made was that flooding had been significantly higher than the elevation of the flood lines we were measuring on the walls. They reported the water was generally 0.25 to 1 m higher. They also reported that the tsunami flood waters drained episodically, with noticeable standstills. They reported that the flood lines represented various standstills. In retrospect, observations of the elevations of scrapes on the exterior walls might have provided us with more representative inundation measurements. These marks were excluded, since they could have been made during the clean up after the tsunami.

The tsunami behaved as an extreme flood event. Two young men reported that they saw the sea boiling (our interpretation of this statement was that it became very turbulent offshore due to flow between and around coral heads and other bottom features), then the water withdrew, and then the tsunami came ashore (Appendix 1, conversion 11). No crashing waves were reported although several people noted that the splash of the flooding wave as it hit the shore sent water up to palm frond levels. Instead the tsunami catastrophically flooded the islands, either completely or marginally. The flooding seawater rose quickly and in most places the flooding was strong enough to knock people off their feet. The survivors reported that the flood waters seemed to pause before receding and that the drain-down was episodic and strong. The survivors report that the flood lines were left by standstills of the retreating flood waters. Depending on the location of the eyewitnesses, the water came from different directions. Residents generally report that the flooding came from the east (side nearest to the tsunami source) then from the west (far side). These reports are consistent with the tsunami wrapping around the islands or spreading out after going through passes and channels between the islands and in the barrier reef.

Draw-down of flood waters

Drawdown of waters was severe, between 5-7 m in the reef channels. One tsunami survivor was washed down into a reef channel and had to climb out. Thus, these reports are reliable. During the maximum drawdown the reefs were bare and sharks, fish and manta ray were left marooned on the top of the reef. Scuba divers from two resorts reported being forced down to 30 ft (9m) by the strong currents during the tsunami. Currents were so strong that a return trip to the island that normally took 15 minutes instead took one hour.

The protection provided by vegetation

In the Maldive Islands, the coastal vegetation provided important protection to the residents of the islands. Where the vegetation was thick, it provided significant protection to the buildings, and limited the damage by tsunami impact (Figure 13). Where vegetation was missing the tsunami flood inundated the buildings, breaking down concrete block walls, breaking in windows, tearing off front and back doors, etcetera as well as flooding the buildings.

Figure 13. The thick vegetation along the shore at Lhosfushi Islet trapped much of the coral at the back of the beach and in around brush. Much of the brush on the island was killed by salt water or torn away by the tsunami. The shallows bank east of the island was stripped of coral and sand, and exposed well-cemented beach rock in the surf.

Many people have recommended that mangrove vegetation is useful for coastal protection in similar disasters. Conceptually that is a valid suggestion, but in practice it has proved problematic. Mangroves are extremely invasive plants. Furthermore, the plant is a nuisance plant, since it becomes so thick that it often becomes a barrier that makes it impossible to reach to the ocean. Although it might protect portions of the coastline, it would virtually consume all of the land area on these small islands if left unchecked. During our surveys, we did not note any mangroves on the islands we visited.

Mangroves were introduced to Hawaii and they have become a real nuisance, because the plant is so invasive, it greatly reduces access to the water in many beach parks. The mangrove plants are detrimental to many local indigenous species, and when the plants have been removed from beach parks, the environmental damage done by siltation along the shoreline is very heavy.

Protection provided by walls and seawalls

During the passage of tsunami waves over the coral reef and beach the tsunami can dissipate a great deal of energy. After the 1946 Tsunami in Hawaii, scientific papers of the time, favored the use of sea walls for protection from tsunami. Considering the amplitude of wave and tsunami experienced by the Maldives, seawalls in most cases provided a means of reducing the wave energy before it reached residents. The concrete structures in places dissipated energy at the coast rather than allowing the energy to be dissipated in areas where people live in the interior of these very low-lying islands.

In addition, in the Maldive Islands, where there are no highlands and no continent to back up to, the sand islands tends to move with time and seawalls are a necessity to assure the island remains in one place for the lifetime of a structure. In some places within the Maldives, barriers have been placed under the sea to restrict sand from migrating into deep waters and this may be an effective means of minimizing sand loss as well as tsunami and storm damage. Although these barriers were installed to control strong seasonal sand movement, they also reduce the strength of waves reaching the shore and they deflect currents away from the soft sandy coastline. Clearly, armored coastlines provided protection to the island communities. Even the low edging along walkways saved a vast amount of resort landscaping and allowed the resorts to get back to business quickly after the tsunami. Furthermore the lined walkways restricted the flooding, and reduced salt water mixing with the ground water and thus preserved a portion of the freshwater lens.

Damage to man-made structures

The hollow blocks walls with poor footings or without foundations were toppled by the tsunami flooding on Guraidhoo and Maafushi Islands. In part the walls were undermined and in part the walls were simply pushed over by the force of the water since they lacked reinforcing rods and interior cement. Both metal roofs and glass windows dislodged by the tsunami inundation became hazards to the general population, causing injuries during and after the tsunami flooding. Guidelines for safe foundations and construction techniques need to be adopted, but must be appropriate for construction on limestone and sandy coastal soils.

Garbage dumps

The residential islands use the eastern coasts of the islands as open garbage dumps. The tsunami emptied these coastal dumping grounds onto the surface of the islands and dumped the garbage as well as the flood debris from the tsunami into the lagoon on the other side of the island. The unfortunate location of the dumps contributed to the contamination of the island surface and the water supply.

SUMMARY

The 2004 Indian Ocean tsunami was a very significant geologic event that generated devastating tsunami near the source region (near-field) and on distant shores (far-field). Eyewitness accounts indicate maximum wave heights reached 3-4 m throughout the Maldive Islands. The wave heights varied significantly through the islands, often having sufficient wave height to drown all of the residents. The coincidence of the tsunami arriving at the Maldive Islands at low tide, during daylight hours, the variability of the wave height, and the resourcefulness of the local people contributed to the low numbers of fatalities.

The tsunami impact to the vegetation on the islands was significant. The salt water flooding killed the fruit trees and the tsunami inundation tore out coastal trees. Inland vegetation was stripped of leaves and killed or damaged by the salt water. Coconuts washed off the islands and floating trees from elsewhere that washed into the lagoon have proven to be hazards to navigation, particularly to the high-speed boats used to deliver guests to resort islands.

The tsunami damage to buildings varied according to location of the island relative to the exterior atoll ring reef and according to the location on the island. The tsunami totally destroyed concrete block buildings adjacent to the coast of the eastern side of Guraidhoo and Maafushi Islands. It also destroyed buildings built using the older style of construction without regard to location. Building debris (concrete blocks, sections of wall, coral clasts from older buildings, metal roofs, glass from windows) and the contents of the homes (televisions, furniture, books, etc.) were spread across the surface of the most-damaged islands. Residents have gradually removed the debris, reestablishing the dump on the eastern sides of the islands. Current plans are to remove contaminated soils and ship them to Male, and eventually to an uninhabited island. Several islands within the Maldive nation were so heavily damaged that the residents have been relocated to other islands.

The resort islands experienced less damage in term of structures being destroyed by the collapse of walls and total destruction of structures. This is probably due to the use of different construction techniques. The resort designs generally were formulated by architects and engineers from abroad rather than individual local builders as are most residences. But on Kandooma Island, the room units were so damaged by flooding, and in some cases by wave impact, that they may be destroyed rather than rebuilt. The two story room units on the resort islands faired well. While they had flooding on the ground floor that destroyed the contents of the rooms, the structures themselves were not heavily damaged.

Both residential and resort islands have extended the islands by reclaiming land from the sea. While the islands have been exposed to natural weathering, compaction and cementation, the fill material has not undergone this natural compaction. We observed more erosional damage to the reclaimed land than to the natural landscape. The fill material is loose, mostly transported from other islands or from the surrounding seafloor. Seasonal changes naturally move the sand around the islands and even during storms little is permanently lost for a subsequent episode brings it back again. Unfortunately the residents reported that much sand from shallow waters was moved to the deep waters by the tsunami. These sands are permanently removed from the normal littoral cells, decreasing the overall sand budget to beaches.

In some areas, the tsunami deposited sand on the surface of the islands. Since the grass was still visible through the sand sheet, the thickness of sand was not great. Coral clasts were also deposited on the surface of the islands, particularly along the eastern coastlines. These were individual coral clasts, most of pebble to cobble size. On Kandooma Island, cobble size corals were thrown up on to one beach berm. Scouring of the littoral zone and the islands was common and gullies were incised into the reclaimed beaches. Much more erosion occurred on the islands than deposition. Normal beach processes are likely to obliterate the traces of the tsunami so that little or no geologic record of the tsunami will be left on the islands, but a significant depositional event should be preserved in the offshore sedimentary record.

ACKNOWLEDGEMENTS

The 2004 Indian Ocean Tsunami produced catastrophic effects on the residents of these low-lying atolls. Most residents faced drowning. Many residents were washed from the islands and fortunately rescued at sea. Friends and family were lost and injured. The homes and businesses of many islanders were destroyed, as well as their jobs. In many cases all their belongs were destroyed.

Many survivors are now afraid to go to the beach. After six weeks, the residential islands still look like ghost towns with residents clustered together in tent camps. Many residents reported that they experience trauma, flashbacks, and nightmares of the tsunami returning. Many resorts were able to make quick repairs and return to business. A few resorts were damaged to the point that they remain closed.

In order to assist the government of the Maldive Islands we shared our observations and recommendations with them in written reports and oral presentations (Keating et al., 2005) in the hope that they can use the information to make their community more tsunami resistant. We thank the residents and officials of the Maldive Islands for their hospitality and assistance in this work.

Dale Dominey-Howes would like to thank Aon Re Australia for their financial support to be able to participate in the post-tsunami surveys. Travel support for Dr.

Keating and Dr. Helsley was provided through the University of Hawaii Vice Chancellor for Research. Aloha.

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Keating, B., Helsley, C. E., Dominey-Howes, D., and Waheed, Z. (2005) Preliminary Report of the US-AUS International Field Team "Post-Tsunami Field Survey in Kaafu South Male Atoll, The Republic of Maldives," pp. 1-9.

Video footage of the tsunami inundation is available from the Maldives Disaster Center Web Site (http://www.tsunamimaldives.mv).

Appendix 1

Narrative of Eyewitness Reports from the Post-tsunami Field Survey South Malé Atoll, Republic of Maldives

Dr. Barbara Keating, SOEST, University of Hawaii, Hawai'i, USA
Zaha Waheed, Marine Research Center, Maldives Islands
Dr. Charles Helsley, SOEST, University of Hawaii, Hawai'i, USA
Dr. Dale Dominey-Howes, Risk Frontiers, Macquarie University, Australia

Unless otherwise noted the conversations were conducted by B. Keating and Z. Waheed. The dimensions cited in the conversations were in feet, with the metric equivalents added for clarity. The locations of the islands can be found in Figure 1 of the text.

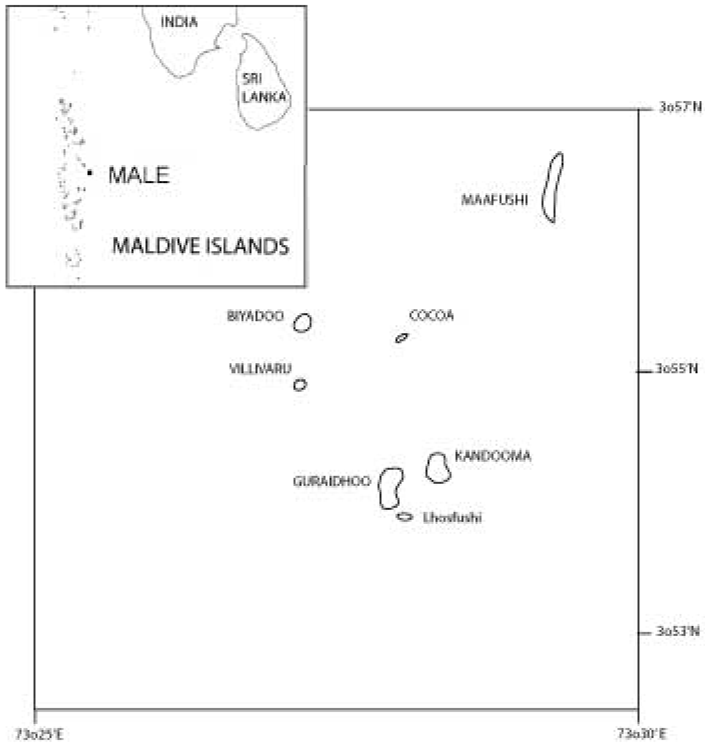

Figure 1. Upper left- Map showing the location of the Maldive Islands relative to India and Sri Lanka. The South Male Atoll is shown by a bold black circle. Lower right- map showing the distribution of the islands of the study area of South Male Atoll.

INTERVIEWS: BIYADOO ISLAND

Conversation 1 with WOOD WORKER on Biyadoo Island

The resort employee stated that the first inundation was about 4 ft. or 1.2 m deep and the other inundations were about 2 ft or 0.6 m deep. When the water receded the reef was exposed and bare. The water came in slowly and smoothly but it went out very quickly and powerfully. He said that when the flooding began, he fled inland. He said all the children were crying and screaming. After the flooding, everyone on the island was upset for a long time.

C**onversation 2** with young Resort Employee (a girl from the Philippines) on wharf on Biyadoo Island

The young lady told us she had been on Buduhiti (another island where there is a sister resort owned by the same operator). She was working in the Reception Center, when two inundations took place. The first wave reached chest high (about 4 feet) and the second wave was about 2 ft. deep or 0.6 m. The water receded rapidly, "at a run." The draw down of water left the reef dry, stranding fish and manta rays on the surface and the water deep within the channels.

When the sea began flooding on to the island, the flooding only lasted a short time but reached chest high. The resort had a swimming area of the lagoon that was used by children since it was very shallow. When the flood inundated the lagoon, that was full of children, they became frightened because they were drowning by the flooding waters.

She and all the adults on the island ran to rescue the screaming children. Afterwards, the employees ran to the individual rooms and then to the shore to see if they needed to rescue anyone. The rooms were flooded and the bedding was all wet.

When asked if the flooding frightened her, she said, "no" that she interpreted the flooding as some kind of extreme high tide. Others were panicked, but she said she was very impressed by the people on the island helping each other. Everyone immediately ran to the aid of the screaming children and then ran to help with any rescues. People were working together and helping one another.

Conversation 3. Dale Dominey-Howes' conversation with the clerk at the Biyadoo Resort Reception Desk

There were 2 inundations that took place a little after 9:00 a.m. Both waves completely submerged the jetty. The first wave went up to the first building [the Dive Shop] (about 25 m inland, horizontally). It was a rapidly rising surge not a wall-of-water. The first flood lasted about 2 minutes and then receded and the second flood began about 2 minutes later. The next inundation flooded inland further, reaching the reception building, [the reception area was raised two steps above ground level] without entering the building.

MAAFUSHI ISLAND

Conversation 4:

Conversation with a young woman (and her husband) who owned a home and shop on the atoll barrier reef side of the island (eastern side). She was inside her home and heard a very loud noise. She tried to leave the room to check out the noise but the flooding outside the home was so strong that she could not push open the exterior door. The water quickly rose to her neck (4 feet or 1.2 m). The interior of the room was full of water so she held on to the bed. She and the bed were carried around the room by the turbulent waters, repeatedly colliding, and leaving many bruises. [With the rapidly rising flood, the windows and window frames of many homes were pushed out of the walls by the force of the water and destroyed.] She was able to climb out of the window (because the doors would not open). When she got outside she saw that everyone was hanging on to things (trees, yard walls, etc.) trying to keep from being washed away. When the water receded to ankle depth, everyone went to the mosque at the center of the island. Even the mosque had flooded so they immediately cleaned it up, despite the on-going disaster.

The young mother reported that she did not see the first inundation. Her small child came to her, warning the waves were coming in. The mom was inside the house working on the sewing machine and told her child, "don't go too close to the water, that it was normal." But, by then her older 13 year-old daughter was crying so she realized something was wrong. Her husband tried to get out of the house but could not. She was in shock when she saw the water.

A wall collapsed, then the water tower in her yard was toppled. The mother and grandmother went back into the house. Her little girl was hanging onto the bed screaming "Save, me! Save me!" Both her grandmother and daughter were drowning. She desperately tried to pull her mother and her daughter up to get their heads above the water. They tried to swim. The bed was floating around the room, with the little girl hanging on to it (a bunk bed).

When they could get out of the room they ended up on top of an outside masonry yard wall that did not fall down. Water from the flooding was strong and high because it funneled between her home and the adjacent buildings. The water in this passageway reached the roof eaves.

Marks on the wall in the front room of the house/shop were shoulder- high about 5 ft. 6 inches or 1.5 m. The buildings outside (adjacent to the sea, in the atoll reef direction) were completely gone! The floor tiles within their home came up off the floor and the walls cracked.

She reported that many people were cut by the sheet metal that came off the homes when the walls collapsed. One man cut his foot on glass from the tsunami damage as he rescued a boy being washed out to sea. [They could not see the glass in the water, because it appears transparent in the sea water.]

5. Conversation with woman:

She felt the earthquake. She reported that the flooding was about 40 inches (100 cm) deep and it left a mark on the wall of her home. But, she reported that the first wave reached 12 inches (30 cm) higher than the mark left on the wall. During the flooding water was coming over the walls that were about 5 feet high (1.5 m) and that there was no warning. Two later waves flood the island and left marks at 30 and 18 inches (75- 45 cm). She reported the seawater came over the beach at palm tree height [somewhere on the trunk of the palm trees.] And the waters were splashing as they came. She reported the second wave was even higher. It went up to the palm fronds of the coconut tree [it splashed up into the fronds].

The inundation level at her house was reached about 4 ft. (1.2 m) deep but she reported that the flooding was even higher (up to 5 ft. (1.5 m) deep) further down the beach. The second wave was bigger. The second wave splashed onto the island.

6. Conversation with Island Chief

The community leader reported that the tsunami inundation was all flooding, with “no breaking wave”. The seawater went completely over the island and then the waters washes back\ on to the island from the lagoon side and was about 2 ft (0.6 m) deep. There was scouring of the land that left big pits. The reclaimed land around the prison was heavily damaged, scoured, and eroded. In large part, the erosion resulted because the retaining wall (on the barrier reef side of the island) was damaged.

The floodwaters moved away in ripples. Waters came straight over the island and through the buildings. When the floodwaters moved down the streets, the flood knocked people down. They could not walk in the rising water. The flood swept everything out of the houses including refrigerators, television sets, and everything.

The garbage in the landfill was removed by the tsunami, and left dump empty. Garbage was washed over the island and into the lagoon. The ground has now settled (6 weeks after the tsunami). The residents think the island has subsided. Cracking of building walls is ingoing and probably is the result of the ground settling.

The water supply was contaminated by the seawater that flooded over the island and also by the landfill, leaving the fresh water lens contaminated. The chief concluded that even with rain, the water lens was ruined.

On the seaward side of the island, the chief reported that there is a lot of offshore reef damage. Lots of the corals are washed upon the island. The reef is wide; comparable is size to the island. After the water receded the reef was completely exposed. A person on a boat at sea, said they could see the exposed reef.

On the opposite side of the island, the entrance to the harbor was exposed completely. [A picture we viewed on a camera cell phone showed a boat sitting on the harbor bottom.] A boat anchored in the harbor was loose and the ships moved out of the harbor and then back into the harbor. All the other boats on land that were being repaired were moved 300 ft. inland from the boat yard at the shore.

Interview on **VilliVaru** (off Biyadoo Island)

7. Conversation with repairman on beach.

He reported that he experienced two waves, each lasting only a couple minutes. The seawater reached a maximum of 1.5 ft deep or 0.4 m deep on the leeward side of the island and it flooded the room units, destroying bedding while none of the room units of the windward side were significantly damaged.

Interview on Kandooma Resort Island

8. Conversation with Resort Manager Mohammed

Note- The resort on Kandooma was visited on two occasions in order to document the damage and then to carry out a leveling survey that documented the height of tsunami flood lines. The tsunami occurred as a series of three flood inundations at this location. The Resort Manager Mohammed, who provided us with a tour of the resort, made these comments. The employees also used paint to mark flood levels on trees.

At the time of the tsunami there were 210 guests and 180 employees on the island. The staff is now down to 30. The manager was in his room in the staff quarters (Figure 2) when an employee came to his door and told him to leave. He grabbed his shirt and turned to leave but found he couldn't open the door so he broke the window out and climbed out of the window (cutting his hand in the process). Then the door burst inward from the force of the tsunami waters within the building. The water was up to eye level (about 5 feet, 1.5 m) everywhere on the island for about 5 minutes. He said he would have drowned inside the building if he hadn't gotten out when he did.

Figure 2. The interior of the employee quarters is shown in this photograph taken after the 2004 tsunami. The building was flooded to about 3 m depth and the

manager escaped through a window. The sand in the tsunami wave abraded the white paint on the interior wall.

Outdoors, the ground was cluttered with white coral everywhere. Even the dark corals carried up onto the beaches turned white the next day. On the east side of the island, vegetation had been overturned (Figure 3) despite having roots of several meters wide and the shrubs and trees were rolled backward onto the island. A beach berm (or ridge, Figure 4) of as much as 3.28 ft or 1 m high was present on the east side of the island (Figure 5), with broken corals and whole coral heads mantling the berm. Sand was in large part absent from eastern side of Kandooma Resort Island, having been redistributed over the island and into the lagoon. Coral clasts (blocks) were strewed inland on east side (Figure 6) inland of the storm berm, in a very spotty fashion.

Figure 3. The vegetation on the east side of Kandooma was crushed by the tsunami and laid backyards toward the center of the island. The leaves were stripped from the trees. The roots of the vegetation were undermined and the coral from the littoral zone was trapped within the vegetation. But, the vegetation provided important protection to the buildings nearby.

Figure 4. The manager of the resort reported that 15 m of sand (horizontally) was stripped from this beach. A beach ridge or berm can be seen at the back of the beach, where the vegetation is seen.

Figure 5. On the eastern side of Kandooma Island, coral clasts were left along the back of the beach by the tsunami. The maximum coral clast size is roughly 10 cm across. The clasts bury the roots of some trees along the coast. These trees are roughly 5 m inland from the ocean.

Figure 6. On the eastern side of the Kandooma Island, coral clasts were carried up onto the island surface in one area, by the tsunami. The typical coral clast size was roughly 10 cm across. The clasts bury the base of the trees along the coast up to roughly 20 cm.

A row of palm trees planted on a reclaimed beach on the lagoon side was heavily damaged and many were lost. Along this part of the island, in places, the beach sand was completely washed away. The leeward beaches experienced severe erosion, retreating as much as 5 m (Figure 6). The resort jet-ski was washed into the channel and observed traveling at full speed, and rider-less after the tsunami. Two hours later, the jet-ski was seen again in the channel, going the opposite direction (toward the lagoon). Two days later, the jet-ski was found on the next island (Guraidhoo).

The ground water was still fresh on the Kandooma Resort Island after the tsunami. The leaves on trees and brushes show salt burn. A luxuriant garden featuring topiary was completely stripped of leaves (Figure 7).

Figure 7. The leeward side of the Kandooma resort island experienced significant erosion. The roots of coconut trees are exposed to the air. A comparison of satellite pictures taken before and after the tsunami shows that a large number of coconut trees were missing after the tsunami and 5-15 m of beach sand had been removed.

Scuba divers on resort excursions, diving in the water at 16 ft depth, were pushed down to 30 ft. both on the lagoon side and in the seaward side of the resort island. The clarity of the seawater increased after the tsunami. The particulate matter in the water column seemed to be gone.

Interviews: GURAIDHOO Island (Note- this flood level survey was made at low tide)

9. Interview with the Chief of Guraidhoo Island

According to the community chief, the tsunami came as a series of floods. They did not see the initial wave. There were a total of three waves, with about 5 minutes between waves. It took 15 minutes for the water to recede. The second water wave was seen crossing the reef.

The interior of power plant had water in it 36 in. or 0.9 m deep that knocked out the generators. The tsunami flood moved the large air/noise suppressor units still in shipping crates inside the power plant walls (Figure 8). Four days were spent before the power plant became operational.

Figure 8. The island of Kandooma was completely flooded by the tsunami. The tsunami arrived from the east and wrapped around the island and flooded inland from the west, meeting near the center of the island. The resort manager reported that he broke out a window in order to escape from the flooding in the employees housing on the east side of the island, where the waters were neck-deep. The entire surface of the island was covered by sand, forming a sheet. In many places the sand sheet does not completely bury the grass. The tsunami flooding abraded paint from the concrete walkways and buildings and the salt water killed the vegetation in the foreground. This topiary form (shape of a peacock) was part of a luxuriant garden that was completely stripped of vegetation.

Damage to buildings was heavy. There were many masonry walls that were left leaning throughout the island. The rows of houses of masonry block closest to the eastern coast were destroyed and most of the houses in the second row away from the sea were destroyed or highly damaged (Figure 9). Many building with the older construction style of cemented corals and limestone blocks cemented together (with lime mortar) were heavily damaged or destroyed. Everyone left their homes and followed one another to the care home (which became the triage center). Two children died and two were lost.

Figure 9. These wooden crates of equipment for the Guraidhoo Island Power Plant had been delivered and placed in side the concrete garden wall surrounding the power plant. The tsunami flood picked up and moved the heavy equipment and crates inside the 1.5 m high concrete block garden walls.

Erosion that exposed tree roots on the east side of the island took place before the tsunami occurred, according to the Chief.

10. Conversation with woman in a home adjacent to the east coast of Guraidhoo Island.

She was about 60 years old, and her picture was taken inside her home (Figure 10). The outer wall of her masonry home fell off. The inside walls of her heavily damaged home had flood marks at 6 ft 3 inches or 1.8 m. She reported that her husband was away at the time of the tsunami. She said 2 more rows or blocks of buildings near her were damaged. The remains of her house is now situated on the outer row of structures left standing on the eastern side of the island, it used to we part of an inner row of structures.

Figure 10. This wall is what remains of a building damaged by the tsunami on Guraidhoo Island. It shows the typical construction of blocks without reinforcing rods, and without interior fillings of concrete.

At first she heard sound and thought to herself that it was the wind, then she saw the sea as it came through the palm trees. She told her granddaughter to run. She saw the tsunami waters coming over the houses splashing in the fronds of the palm trees. The first wave tore up her metal roof, and since she couldn't run she climbed up the wall to the roof. The second inundation took the roof away. When the water receded she went to the home of a friend and then they went to the Health Care Center. Although her friend had no obvious injuries to her body, she was hospitalized and did not recover. She said her friend died of trauma not injury.

She said she could not sleep anymore since the tsunami. She had a hopeless feeling because everything they had was destroyed. Her eyes were blood red- from six weeks of crying. She reached out. I held her hand.

11 Conversation with 2 young men.

Two young men came to speak to us of their tsunami experiences, while we were carrying out a flood line survey. The younger of the two said he felt the earthquake at 6:20 a.m. and there was 10-15 minutes of shaking. He worried that it would generate a 10 ft. high wave (3 m). His friend told him not to say that to anyone – " that a 5 ft [1.5 m] wave would be more than enough for them all to drown."

Later in the morning, they saw the ocean waters boiling (becoming turbulent) offshore. Then the water withdrew. The tsunami came as a flood. It was strong enough to knock them down. On the cemetery (eastern) side of the island the water level was immediately over their heads (about 5 ft or 1.20 m).

The younger man was tortured by his memory and flashbacks to the flood. He said he saw the body of a 9-month old boy in the water. He went after it and was carrying the boy when the second wave flooded the island. He saw his wife and his son drowning. He felt he had to save them but he could not let go of the boy in his arms. So he held on to the boy and struggled to help his wife and son get their heads up out of the water so they could breath.

He was very upset and angered by the memories of chunks of concrete block wall that were rafting around in the floodwater and hitting people in the tsunami waters. He felt the concrete block yard walls should have been strong enough to stand up to the water and protect the people. They were not (Figures 11 and 12). [The walls were built of small concrete blocks (undersized by US standard, Figure 13) with no reinforcing bars and no foundations. The floodwaters toppled the walls and without concrete filling the hollow blocks the walls were swept along in the flood.]

Figure 11. Residents of the Guraidhoo Island assisted us during our surveys and allowed us to enter their homes and measure the flood lines left on the interior walls. The flood lines can be seen on this wall, as dark horizontal lines on the white paint. The tsunami flooding exceeded the height of most residents.

Figure 12. Guraidhoo islanders set up a tent city on one end of the island and have remained there during the reconstruction and our survey (six weeks after the tsunami). The large blue garden wall (at the lower right in this picture) was undermined by the tsunami flood and toppled.

Figure 13. At the center of this picture is a toppled hollow block wall. Reconstruction of new walls appears to enclose the old wall.

The young man took the small boy he rescued to the health center when the waters drained to about 1 ft deep. But, no one there could revive the boy. Each time the young man closed his eyes and pressed his fingers over his eyes to cover them, you could see him reliving his experience.

He reported that the initial flooding of the tsunami literally washed over the entire island from east to west. Fifty-five houses were destroyed and at least 4 children died. The water withdrew after 25 minutes. The second wave came in from the west or lagoon side and destroyed the health center walls, about 20 minutes after the first. Looking offshore the young men reported that every reef looked like a mountain. The reef tops were fully exposed. Two turtles and a shark were dead on the reef. The third wave had very little effect and came about 30 minutes later.

The young men told of another man who went into the sea to save a small boy being washed away. He was able to grab the boy and swim back in with him, but cut open his foot on glass carried into the sea by the tsunami. The glass in the sand and surf is transparent, so he and others found they we cut by the glass in the beach sand. Both of these individuals survived the tsunami.

12. Conversation with a young mother.

A young mother who lived in a home in the second row of buildings back from the sea on the east side of Guraidhoo Islands took me to see the tree that saved her life.

The young mother was outside her home when she was caught by the floodwaters and dragged away. There were many empty water cans floating in the flood with her. As the water drained she desperately looked for her daughter. She saw the second wave coming in and crushing buildings as it came. Her home was demolished and the waters were pulling her away but she desperately clung to a tree in her yard. Somehow she managed to climb into the tree, saving her life. [Objects in the tsunami flood that hit the tree heavily scared the tree.]

Cocoa Island Resort

13. Conversation with two hotel employees [Sobah and Fareen]

Some guests at the beach resort felt the early morning earthquake and asked about it at the reception desk. One of the guests went to his bungalow and used his computer to check for information on CNN via the Internet. He found out that there had been a big earthquake near Sumatra but that there was no other information about a tsunami. The manager regretted that they had not received an Internet warning so that they could prepare for a tsunami and warn the adjacent islands, thereby saving people from drowning.

Flooding was reported to be about 6 inches or 0.15 m deep in buildings (Figure 14). The employees quickly turned off the electrical generator and water pumps, thinking at first that the flooding was coming from a plumbing problem. But, the water quickly rose to 1 ft or 0.3 m on the island (Figure 15). The pressure of the incoming seawater wasn't very strong. The second wave was similar; it was a sustained flood event. The reef water level dropped to at least 2-3 ft. or 0.6-0.9 m down below the reef edge. Fish and sharks were left dry on the reef. Sobah (one of the employee we spoke to) took the stranded sharks and fish, and put them back in the sea. The flood inundation lasted 1-2 minutes. There was roughly 5 to 6 minutes between the first and second wave. The second wave was the only one they saw coming.

Figure 14. The hollow blocks used for construction in Guraidhoo are about 12 cm wide. This photograph above shows the construction blocks at right and a newly repaired building at left. The small building has new construction on the right side where the wall was lost during the tsunami, but the remainder of the structure pre-dates the tsunami. The roof is corrugated metal. The buildings are being constructed in the pre-tsunami manner and still lack reinforcing and foundations.

Figure 15. An employee on Cocoa Island took this photograph during the tsunami. It shows that tsunami flooding inundated buildings, and damaged the interior furnishings but did little harm to the building structures. Note that more than one flood line was left on the walls of the building at left.

A great deal of furniture from the rooms was damaged by water. A lot of the outdoor furniture (even heavy teak furniture) was lost to the sea and some came up onshore on the next island. There were strong currents offshore. Scuba divers from their resort were diving when the tsunami arrived. They were diving at 20 ft. or 6m [bsl] and were taken down to 30 ft or 9m by the tsunami. When they came back up from the dive, they saw the next wave approaching the island from the sea. When they tried to return to the island, the strong currents made the 15-minutes boat ride back to the island into an hour-long return boat ride.

The drain-back was stronger than the initial flooding. The smoothly sloping beaches that were manicured daily by the beach employees became stepped and the roots of the trees were left exposed when they were undermined by the waves.

Approximately 1600 ft or 500-600 m of sand cay was removed from the north side of the island (Figure 16). The sand that was removed was washed away into the deep water. The employees reported that the sand cay (or sandbar) that extends either north (or south) of the island changes seasonally. Throughout the years, it is present on the north side one season and then is eroded and accumulates again on the south side and continues to shift (north then south) on a yearly basis.

Figure 16. In another photograph taken by a resort employee, a person can be jumping out of the tsunami flood waters on to a porch of one of the Cocoa Island Resort buildings during the tsunami. In the background the bungalows lining the lagoon can be seen in the distance. During the tsunami, the water rose to the floor of the bungalows without damaging the building structures significantly or the raised walkways. The bungalows were designed to sit above sea level.

The second tsunami wave seemed to stop a while, staying at the same depth before draining away. The water offshore turned cloudy after the tsunami. [This was probably due to the large amount of sand erosion.]

The tsunami eroded steps about 20 inches high on either side of the jetty. The sand was eroded and removed undermining vegetation. The vegetation appeared to show signs of being pulled seaward by the draining water but they reported that it resulted from sand being removed from under the vegetation. The erosion was very strong around the corners of the buildings. One employee said a deep pit about 5 ft or 1.5 m deep was left around the lagoon-side corner of the reception building (Figure 17).

Figure 17. The Cocoa island resort is situated on a small island that is connected to extensive sand bars. A large segment of the sand bar was removed from the north side of the island by the tsunami. The bungalows situated over the lagoon fared extremely well. The bottoms of the bungalows were about 3 m above the floor of the lagoon. The buildings on the island were flooded with about 30 cm of water. Scour pits were cut as deep as 1.5 m around the corners of the reception building. Extensive erosion was reported to have occurred in the lagoon below the bungalows, without damaging the building structures.

They did not see the coming tsunami they reported that they heard it. They heard the sound of an impact- THUD. One of them reported that he opened the door and the water came in. The water went from 1 foot to 2 ft. 0.3- 0.6 m in a second.

[The employees we spoke to provided us with copies of the pictures taken during the tsunami. The digital photographs (from Sobah and his friend who ran the resort computers) showed us that the reception area (concrete foundation and open porch) was covered with sand and small shells after the tsunami.]

14. Conversation with Manager of Resort

(Najmie Ibrahim, Resident manager, Cocoa Island, South Male)

[Note: The jetty and reception and other buildings on this island are well built with tight construction joints, strong materials, etc. Designers in Singapore did the engineering.]

The manager spoke with us about the resort facilities. The resort has a long boardwalk (or pier) raised above the lagoon, which leads to offshore wooden bungalows. The bungalows survived the tsunami very well with minimal damage. The bungalows sit above the lagoon on stilts 10 ft or 3 m above the lagoon floor. The lower half of the support poles (5 ft.) is covered by lagoon water; the upper half of each support is exposed above the water level. On one bungalow the bottom decorative trim was washed and broken off by the tsunami (Figure 18).) But, the manager explained that there was a great deal of erosion in the lagoon below the walkway and bungalows. One support [out of hundreds] had shifted on the corner of one bungalow.

Figure 18. This picture was taken during the 2004 Tsunami on Cocoa Island. The tsunami flooded the island as can been seen in this picture (provided by a resort employee). The water was milky in color due to the suspended sand in the water. No flood line was preserved on the building's exterior wall. The waters rose over a meter above the ground but the flood was turbulent enough that the trace left by the water appears irregular. Episodic draining of tsunami flood waters from the islands left the flood lines, according to the survivors.

The bungalow support-poles were supported on concrete bases about 18 inches 0.4 m in diameter in the lagoon bottom (Figure 19). The manager said he would suggest that the designers double that dimension when they add a new phase of bungalows in the future. [Several engineering teams have visited the resort since the tsunami.]

Figure 19. These are the bungalows built on concrete poles within the Cocoa Island resort lagoon. The walkways and the bungalows survived with very little damage. Fortunately the tsunami only reached the base boards of the bungalows, leaving the structures intact.

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