Journal of Hydroscience and Hydraulic Engineering
Vol. 26, No.1 May, 2008, 91-112

FIELD INVESTIGATION OF DISASTERS IN SRI LANKAN RIVERS CAUSED BY THE 2004 INDIAN OCEAN TSUNAMI

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SYNOPSIS

The 2004 Indian Ocean Earthquake of magnitude 9.0 triggered a series of lethal tsunamis on December 26th, 2004 that killed over 225,000 people, making it the deadliest tsunami in recorded history. In order to investigate this tsunami and related damages from hydrological and hydraulic aspects, the Committee on Hydroscience and Hydraulic Engineering, Japan Society of Civil Engineers (JSCE) sent its members to Sri Lanka in May 2005. Their fields of study are coastal engineering, river engineering, hydraulic engineering and hydrology as a tsunami investigation team by JSCE. In this paper, the results of a field investigation are shown mainly for tsunami disasters in rivers. The findings of our survey may be useful for preparing for tsunami disaster prevention in Sri Lanka, as well as in Japan, where tsunamis are very likely to occur in the near future.

INTRODUCTION

Sri Lanka incurred extensive damage due to the Indian Ocean Tsunami caused by the earthquake that occurred off the coast of Sumatra in December 2004. The Committee on Hydroscience and Hydraulic Engineering, Japan Society of Civil Engineers (JSCE) conducted an investigation into tsunami propagation into rivers and resulting damages along the rivers. After the occurrence of the Indian Ocean Tsunami, investigations focusing on rivers were not fully carried out up to now. River mouths are more vulnerable to tsunamis compared to other coastal areas protected by coastal structures or natural dunes. Therefore, conducting field investigations which focus on tsunami disasters in rivers is of great significance. The findings of these investigations may not only be useful for future disaster prevention planning in the areas affected, but are expected to contribute to disaster prevention in Japan as well, where there is a serious threat of a large-scale tsunami attack in the very near future.

One of the reasons why Sri Lanka was selected as the site to dispatch the investigation team was that it enabled us to investigate on damages purely caused by the tsunami, since it was free from any influence of earthquake motion.

SITES OF FIELD OBSERVATION

Various investigations have already been carried out concerning tsunami run-up around the Sri Lankan coastal areas (5) (7) (9) (12) (13). According to these findings, the height was over 10m along the east coast facing Sumatra, the source area of the earthquake. Although it gradually diminishes from the southeast coast to the southwest areas, heavy human and physical damages were caused there because there is a concentration of relatively large urban and resorts in these areas. For this reason, the rivers and the areas shown in Fig. 1 were chosen as the area of study in the present field investigation.

In May 2003, heavy rainfall caused extensive damage in the southwest parts of Sri Lanka. JSCE Committee on Hydroscience and Hydraulic Engineering organized and dispatched a survey team to investigate flood disaster in three river basins (6) (11). Some of the areas under investigation in the present study have already been investigated by the JSCE survey team during the investigation in 2003 on heavy rain damages.

Table 1 shows the characteristics of three major rivers in southwest Sri Lanka and two rivers in the east where field observation was carried out. It is possible that the distance of tsunami propagation is dependent more on the scale of flood plains on both sides of the river, rather than on the size of the river-mouth bar.

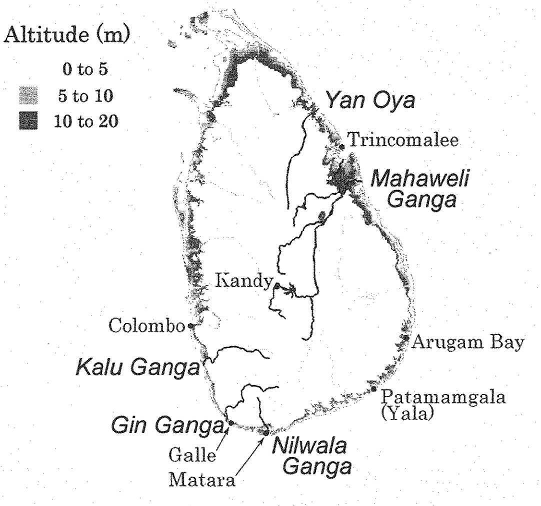


Fig. 1 Study areas

Table 1 Characteristics of rivers

Name of River	Sand bar at River Mouth		Water depth at River Mouth	Status of Both River Banks	Distance of Tsunami Propagation	Degree of Tsunami Energy Dissipation
	Size	Condition				
Kalu River	Large	Stable	Deep	Narrow flood plain	Approx. 20km	Small
Gin River	Small	Stable	Shallow	Vast flood plain, few trees	About 5-6km	Large
Nilwara River	Large	Stable	Deep	Trees covering the vast flood plain	Approx. 8km	Medium
Yan River	Medium	Unstable	Shallow	Dense-growing trees	About 3-4km	Large
Mahaweli River	Medium	Unstable	Deep	Trees covering the vast flood plain	Unknown	Large

TSUNAMI PENETRATION AND DAMAGES IN THE KALU RIVER

The Kalu River has a catchment area of 2,690km^2 and a mainstream length of approximately 100km. The difference in altitude from its riverhead in the mountainous region and its river mouth is approximately 2,250m. Since the altitude drops abruptly from 2,250m to 14m in the first 36km from the riverhead, much of the river channel in the downstream area has a remarkably gentle river slope of approximately 1/5,000. Therefore, it was highly likely that the tsunami waves may have been propagated far upstream from the river mouth. At the Kalu River mouth, there is a sand spit of 3km long covered with thick vegetation, which might have affected the tsunami propagation upstream by dissipating tsunami wave energy. Thus, one of study focuses was on the function of the sand spit at the river entrance for tsunami propagation into the river. Another particular focus of the field investigation was damages of a bridge located at the river mouth.

The satellite images both before and during the tsunami at this river mouth were released by Hitachi Software Engineering Co., Ltd. (3), as seen in Photo 1 and Photo 2. The satellite images do not show any notable changes in the shape of the sand spit even after the tsunami hit, but the field investigation revealed signs of overtopping waves and resulting sediment movement as shown in Photo 3. However, the amount of sediment transported into the river mouth by the overflow was not so distinct, and the washout of vegetation was only partial as shown in Photo 3. In general, similar overtopping waves can be observed during storm waves, not only during tsunamis, and many investigations and studies have been previously carried out mainly in connection with breaching of barrier island due to storm waves (8). The geometric changes shown in Photo 3 are remarkably similar to those caused by overtopping of wind-generated waves reported in previous publications (8).

Photo 1 Satellite image before the tsunami at the Kalu River mouth (3)

Photo 2 Satellite image during the tsunami at the Kalu River mouth (10:20 a.m. local time) (3)

A bridge across the river is located approximately 2.5 km from the opening of the river mouth as seen in Photo 1. It was found that this bridge was entirely damage-free during the tsunami. As will be explained in detail later, notable bridge damages were observed in small- to middle-sized rivers, but not in large rivers. Thus, it is concluded that the measures against flood disaster functioned effectively for the present tsunami on western coast of Sri Lanka. On the eastern coast in Sri Lanka, however, significantly higher waves of more than 10m were observed, as will be described later, resulting in enormous bridge damage in this area. In Arugam Bay, for example, a bridge approach fill was completely washed out, and displacement of floor slabs occurred due to severe scouring of the bridge piers.

The Kalu River sustained tsunami propagation up to distinct upstream distance because of its extremely gentle bottom slope, as aforementioned. Figure 2 shows the wave heights above mean water level along the river obtained from interviews to local people. There are many sand and gravel mining plants along the Kalu River, and several workers there witnessed the tsunami waves propagating upstream of the river. In the figure, the tsunami height at 0.0km denotes an observation in the coastal area (Koibuchi et al. (5)). It was observed that, once the tsunami entered the river mouth, its height reduced considerably. It is noted that a witness at the 12km point testified that a big wave was immediately followed by 3 to 4 smaller waves traveling up the river, suggesting formation of soliton fission in the river. At the uppermost point, no form of wave motion could be observed, only a slow rise and fall in the water level.

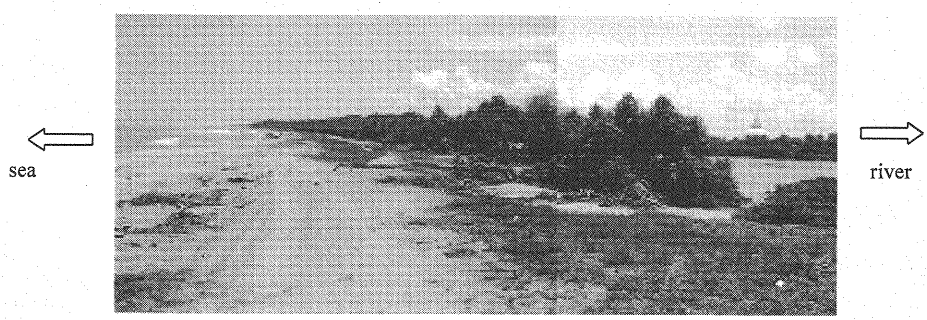


Photo 3 Erosion due to overtopping tsunami on the sand spit

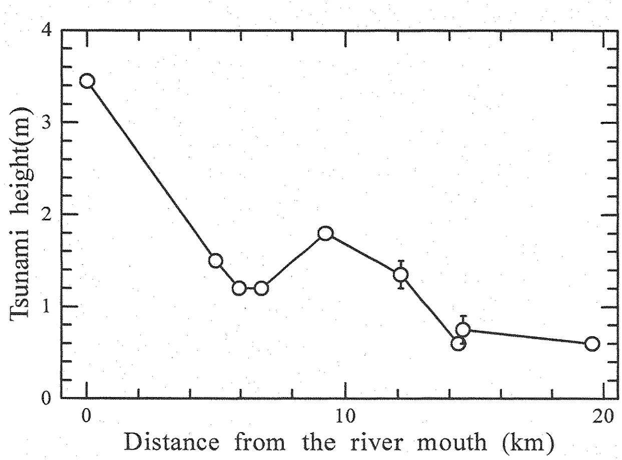


Fig. 2 Tsunami wave height along the Kalu River

TSUNAMI PENETRATION AND DAMAGES IN THE GIN RIVER

Kalutara and Matara are cities located at the river mouth of the Kalu River and the Nilwara River respectively, but there is no city at the river mouth of the Gin River located between Galle, the capital of Galle District, and Hikkaduwa, Sri Lanka's largest seaside resort. The Gin River's catchment area is 947km^2, and its length is 112 km. There is a sand spit of approximately 1.5km in length at the river mouth as shown in Photo 4, but is smaller and has a shallow water depth as compared to those at the Kalu River mouth and the Nilwara River mouth. The upstream region has a vast flood plain with dense vegetation on both sides of river banks, as shown in Photo 5.

River levees along the Gin River were constructed under the support of Chinese Government. The Gintota region on the left bank of the Gin river mouth experienced tsunami flooding 2m deep, but no severe damages were reported (2). According to the field investigation by Yokohama National University (9), the tsunami run-up height was 4m above the mean sea level at the mouth of the Gin River near the bridge. Workers at the estuary barrage construction site, located 3.4km upstream from the mouth, witnessed a tsunami approximately 30cm high, but it caused no damage to the barrage.

In summary, it was found that the tsunami energy in the Gin River dissipated sufficiently due to a vast shallow flood channel with dense vegetation at the river mouth.

Photo 4 Sand bar at mouth of Gin River

Photo 5 Flood plains in the upper mouth of Gin River

TSUNAMI PENETRATION AND DAMAGES IN THE NILWARA RIVER

Matara, the capital of Matara District is located at the river mouth of the Nilwara River whose population is approximately 110,000 as of 2001, and is one of the main cities in southern Sri Lanka. The Nilwara River has a catchment area of 1,077km^2 and channel length of 70km, and flows from the southern to northern regions of Matara District (1). The sand bar at the river mouth is well-developed and has developed into an area with many private houses, hotels, and public institutions.

A coconut farm exists 7km upstream from the river mouth on the right bank. It was reported that the water level rose up to 60cm above the river surface due to tsunami, but it did not cause any severe damage. At a bridge 9km upstream from the river mouth (Photo 6), there was no sighting of propagation of tsunami. Thus, it is likely that the existence of trees on both river banks and a vast flood plain weakened the energy of tsunami.

Photo 6 Levee 9km upstream from the river mouth of Nilwara River

TSUNAMI PENETRATION AND DAMAGES IN GALLE CITY

Galle City is a historical city facing the Indian Ocean with population of approximately 110,000, located about 116km south of Colombo. The Fort Region, which is an old urban area, is located on elevated ground and is protected by a fortress, so it did not incur any damages from the tsunami. The new urban area, however, sustained extensive damage from the tsunami spreading as far as 200-500m inland from the shoreline, since there is no breakwaters or other coastal structures for reducing wave energy along the coast.

The first tsunami reached Galle District at 9:26am on December 26th 2004, and a second wave followed 20 minutes later (2). The second wave was larger than the first one, and as a result Galle City's coastal areas became submerged in water with 6m depth. Figure 3 shows the flooded areas within Galle City surveyed by Galle District Government, in addition to flooded depth data at several points (indicated by dots) obtained from the present field investigation. The damage from this tsunami was extensive with the death toll reaching 4,233 and the number of flood victims reaching 135,389. The damages caused by the tsunami are summarized in Table 2.

Flood depths were measured from the traces left by the tsunami along the Parana River that runs alongside the bus terminal in Galle City. The river width is about 12m near the bus terminal, about 8m near the China Garden, and about 3m near Weliwatta and these places are also shown in Fig. 3. The findings showed that tsunami flooding occurred even outside the flooded area surveyed by the Galle District Government. The tsunami surged up along the Parana River for approximately 2km upstream and caused flooding. Flood levels reached 30-90cm high which was also observed outside the flood region along Moragoda River. The tsunami propagated up this river for about 1km where the river width is around 10m, causing some localized flooding. Both rivers have rather narrow channel widths but have very mild bed slopes from each river mouth to 1 or 2 km upstream. These findings suggest that measures against tsunami penetration in small and mid-sized rivers running through rather flat areas should be considered seriously when contemplating anti-flood measures.

Table 2 Summary of damage in Galle District (2)

Damages	Impact
Damaged households	26,728 households
Disaster victims	135, 389 people
Death toll (including tourists)	4,233 people
Number of initial evacuees (IDP Camp)	69,000 people
Number of initial evacuated households (IDP Camp)	9,160 households
Number of initial IDP camps	185 camps
Number of present IDP camps	5 camps
Number of current evacuees (IDP Camp)	581 people
Road damage cost (RDA-related*1)	121.1 million Rs.
Road damage cost (PRDA-related*2)	29.2 million Rs.
Communication facility-related damage cost	294 million Rs.
# of outdoor facility damages	5
# of transmission facility damages	1
# of power generating facility damages	1
# of switchboard facility damages	1
Power supply facility damage cost	268.53 million Rs.
Others include:	
Temples, mosques, churches, etc.	51
Hospitals	2
Public Schools	25
Galle Kachcheri, Hikkaduwa, and Habaraduwa Division office buildings Navy camp damage cost*3 Many local public and private offices & trade centers were seriously damaged	191.67 million Rs.
*1 RDA : Road Development Authority, Ministry of Highway. Includes damages of 4 concrete bridges at Akurala, Sinigama, Magalle, and Ahangama. *2 PRDA : Provincial Road Development Authority. Includes damages of bridges, culverts, and approximately 50km of roads. *3 Includes buildings, equipments, cars, etc.	

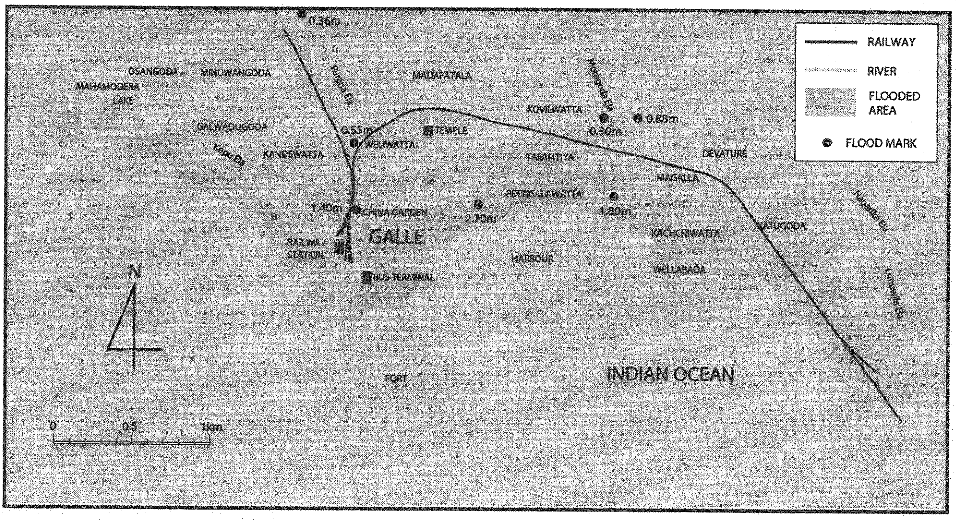


Fig. 3 Tsunami inundation area in Galle City

TSUNAMI PENETRATION AND DAMAGES IN MATARA CITY

Matara City is located approximately 160km south from Colombo. It is a city that has developed on the mouth of the Nilwara River with a population of roughly 65,000. Matara District was seriously hit by tsunami along most of its approximately 51km coastline. The damages were concentrated in the four regions facing the sea: Weligama, Matara, Devinuwara, and Dickwella. Each region is further divided into what is called GN Divisions. The number of damaged houses in these GN Divisions is shown in Fig. 4 (1). Although the number of damaged houses vary depending on the number of those which originally existed in the GN Division, many damaged houses were found particularly in the area facing the bay in Weligama District, and along the coasts of Matara City. In one of the GN Divisions in the Matara District, damaged houses were found not only along the coastal lines but also in the inlands as well. Since the Nilwara River runs through the GN Division, it was concluded that the tsunami penetrated the Nilwara River and caused local floods in the inner low-lying areas along the river.

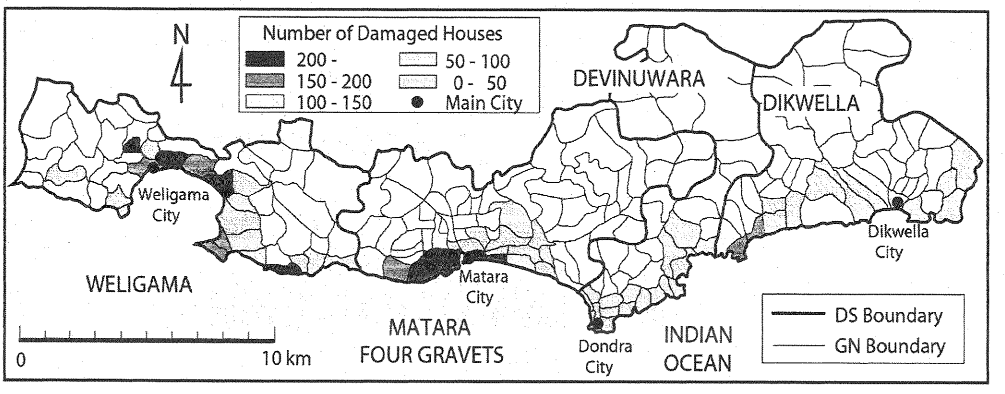


Fig. 4 Number of damaged houses in four Matara GN Divisions

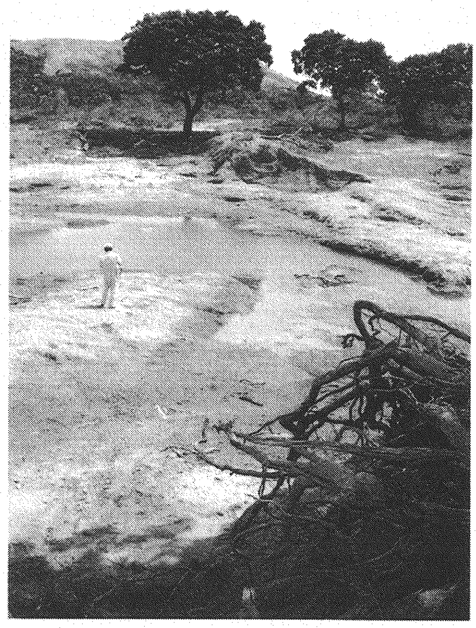
DAMAGES IN YALA AREA

An investigation for the damages in Yala National Park was carried out mainly around the beach where 50 people including eight Japanese were killed. The height of the tsunami penetrating the river was 7-7.5m above the mean sea level, judging from the withered leaves in the trees. Some trees were ruptured at around the height of 2m, and the depth of erosion on the sand surface near the lodge and the trees was around 0.6m.

Photo 7 and Photo 8 show the damages to the road, which also acts as a levee for a small reservoir behind the lodge. The tsunami ruptured the levee as shown in Photo 7. In the ruptured area in Photo 7, there was a channel that had not existed before the occurrence of the tsunami. The water in the channel was stagnant at the time of the field investigation, and its mouth facing the sea was already closed due to sediment deposit by waves.

The destruction of this road was characterized by severe erosion of the slope facing the ocean, whereas the other slope facing the reservoir was not affected by erosion as shown in Photo 8. The distinct difference of erosion on the both sides is probably caused by the following process. When the first tsunami wave reached this area, the water level rose instantaneously far over the height of the embankment, and did not show a form of an overflow during the landwards propagation of tsunami. During the tsunami backwash, however, the sea water which had accumulated in the reservoir was discharged forming an overflow. As it eroded the sea-side slope of the road, it then ruptured the levee and resulted in formation of the channel seen on the left hand side of Photo 7. A more detailed explanation of the mechanism of levee breaching can be found in another study (Tanaka et al. (10)). Such a mechanism conforms to the bridge-damaging mechanism caused by the return flow which will be described in a later section of this paper.

sea



reservoir

Photo 7 Road damage in Yala

reservoir

sea

Photo 8 Road damage in Yala

TSUNAMI PENETRATION INTO RIVERS ON EAST COAST

Elongated sand spits can be observed at river entrances on the eastern coast of Sri Lanka due to predominant longshore sediment movement. For this reason, the water depth around the river mouth is extremely shallow in general, and differs greatly from the downstream of typical Japanese rivers. Although most of the rivers in this region pour into the sea through a lagoon along the coast, the Yan River and the Mahaweli River are one of the few rivers that have simple river mouth topography without lagoons, as shown in Figs. 5 and 6 respectively.

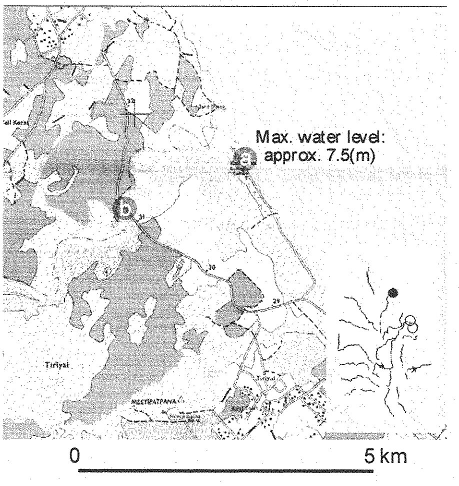


Fig. 5 Yan River estuary (point "b" is approximately 3.5km from river mouth. The river banks in this stretch contain a thick mangrove)

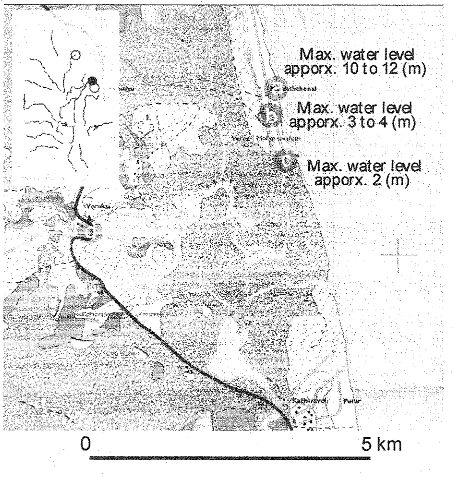


Fig. 6 Mahaweli River estuary (Distance between point "c" and "d" is approximately 3.2 km)

Tsunami penetration and damages in the Yan River

It was revealed that the maximum tsunami height in the coastal area "a" shown in Fig. 5 was approximately 7m. Around the river mouth, on the contrary, the extent of damages was not so noticeable as compared with the coastal area facing the sea, although slight damages of vegetation and erosion and deposition of sediment could be seen. The reason for such a distinct difference of damages between coastal areas and the river mouth areas may be due to the fact that the coastline does not have any obstacles to reduce tsunami wave energy, whereas the tsunami waves remarkably dissipated their energy in the river due to its shallow water depth.

According to local residents, the tsunami height at the point "b" in Fig. 5, located 3.5km upstream from the river mouth was about 0.5m. In addition, they reported that the river bed elevation rose by roughly 4m in some places. Judging from the maximum tsunami water level in the coastal area and the ground elevation at this point "b", the rise in the water level due to tsunami was too small there. This was probably due to dense mangrove forest and extremely shallow water depth at the river mouth, which contributed greatly to suppressing the distance of tsunami penetration. Nevertheless, there is insufficient information to fully explain these processes at the present. Furthermore, there may be other factors which caused tsunami energy dissipation in the study area. Future investigations must be carried out regarding effects of vegetation and river mouth topography on the tsunami penetration.

Tsunami penetration and damages in the Mahaweli River

The Mahaweli River has the largest catchment area in Sri Lanka with two river mouths; one connecting to the Trincomalee Bay and another one to the Indian Ocean. Out of these two river mouths, the present investigation focused on the latter one shown in Fig. 6, which has relatively simpler topography such as the Yan River.

A village by the name of Mudduchchenal existed in the area near the river mouth marked "a", "b" in Fig. 6, but was completely destroyed by this tsunami and is currently deserted. The maximum tsunami water depth in the palm tree zone "a" along the coast was about 10-12m judging from bending of palm trees. The average tsunami height along the roadside trees in the village "b" was about 3-4m, whereas the maximum water depth on the land areas along the river channel indicated "c" in Fig. 6 was about 2m. Thus, distinct difference of water depth was observed between the two locations. Te reason for this is that the water depth on the side of incoming tsunami flood water rose drastically at "b" due to the effects of roadside trees and structures in the village, while the region "c" along the river channel had relatively fewer obstacles to intercept the tsunami height, resulting in lower tsunami height.

An investigation into the sediment deposit was also carried out in the river bank near "c" in Fig. 6. Local scouring of river banks generated by the return flow was found near the river channel, and sediment deposit of about 0.3m thick was found at 50m inland from the river bank. Both, however, were in their terminal stage, and their formation process is unknown.

BRIDGE DAMAGES

Outline of damage situation of bridges

The extent of damage to 34 bridges, including small scale box culverts and their surrounding structures in the southwest coastal belt from Colombo to Hambantota were investigated. Road Development Authority (RDA) in Sri Lanka has investigated the damages of the river bridges by tsunami waves immediately after the tsunami and the outline was made public on the Internet. However, tsunami waves of such magnitude are extremely rare occurrence in Sri Lanka and a lack of know-how is a big disadvantage in dealing with the situation. Hence, our in-depth analysis of effects of tsunami waves on bridges is crucial in future bridge designing in coastal areas and an examination of undamaged bridges is also very important.

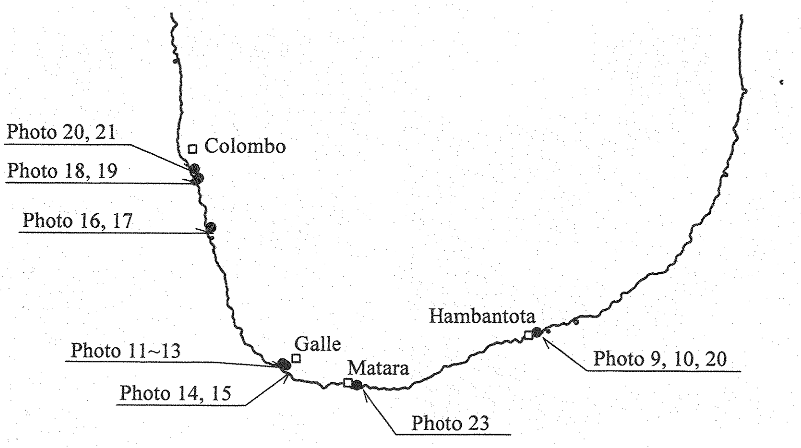


Fig. 7 Location of investigated bridges

The main southbound highway and railway track from Colombo lie very close to the coast and run parallel to it. From Colombo to Payagala, the railway is laid in the sea side of the highway. Our investigation included both road and railway bridges in the area.

The extent of damage to bridges is discussed by taking into account the nature of the damages. Damages were categorized into seven conditions as described below. The seriousness of the damage and the number of structures are listed according to extent of damage.

1) Loss of concrete girder: One pedestrian bridge in Hambantota
2) Loss of wooden girder: One pedestrian bridge in Galle
3) Collapse of the bridge by the destruction of the abutment (due to scouring): Three road bridges
4) Loss of abutment approach: One road bridge and eight railway bridges
5) Loss of the temporary girder which was under construction: One railway bridge
6) Slight damage of abutment: Seven road bridges and one railway bridge
7) Damage of hand rail: Six road bridges

Furthermore, investigations were carried out on five bridges, which apparently had not sustained any significant damage. Figure 7 denotes the location of the bridges expressed in terms of photo number shown hereafter.

Analysis of damage circumstances of bridges

(1) Loss of concrete girder: One pedestrian bridge in Hambantota

This is the only case of loss of concrete girder due to tsunami wave force in our investigation. The span length, the width and the thickness of this bridge are 13.3m, 1.6m and 0.3m, respectively. The pedestrian bridge which was washed away by the wave force is shown in Photo 9. The supporting base columns (abutments) are shown in Photo 10. The left side of the Photo 9 is sea side and the bridge was about 125m far from the shoreline. The tsunami wave carried the concrete girder about 24m upstream without overturning it in the channel about 1.6m deep. However it can be observed in Photo 10 that by the time the tsunami wave struck, the girder had not been connected to the base columns permanently.

Photo 9 Damaged situation of concrete deck

Photo 10 Supporting base columns of a damaged bridge

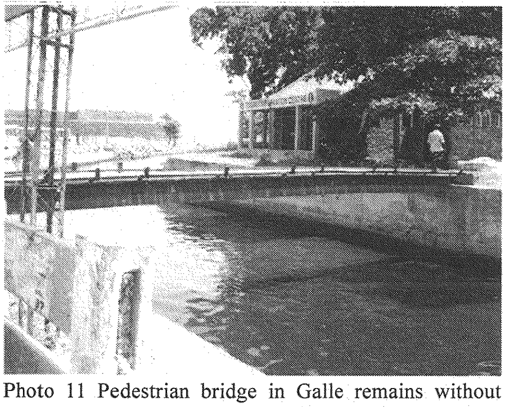


Photo 11 Pedestrian bridge in Galle remains without being washed out

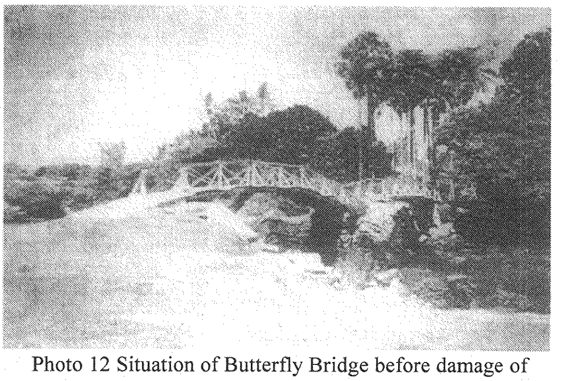


Photo 12 Situation of Butterfly Bridge before damage of tsunami waves

Another pedestrian bridge in Galle (span length=13.9m, width=0.75m and thickness=0.8m), shown in Photo 11 whose width is narrower than the above-mentioned sidewalk bridge but which remained without being washed away was investigated. Since both ends of this bridge are clamped firmly to the base, it did not move due to the drag force induced by the tsunami. However, all the handrails of this pedestrian bridge were broken and washed away as shown in the photograph.

(2) Loss of wooden Bridge: One pedestrian bridge in Galle

Butterfly Bridge (Photo 12) leading from the esplanade to Dharmapala Park in Galle City is about 175 m upstream of the above-mentioned undamaged pedestrian bridge shown in Photo 11. Photo 13 depicts the situation after the tsunami wave struck. Photo 12 indicates that it is a wooden structure. The drag force acted on this bridge is presumed to be similar to that acted on the narrow undamaged pedestrian bridge downstream in Photo 11 because of the small distance between these two bridges. The destruction of the wooden bridge is attributed to its relatively light weight and wooden structure as well as to the fact that it might have not been firmly clamped to the abutment.

Photo 13 Struck situation of Butterfly Bridge

(3) Collapse of bridge by destruction of the abutment: Three road bridges

The majority of the road bridges dealt in this investigation consists of two bridges standing side by side for two way traffic. Among three bridges which collapsed because of destruction of the abutment, both of the bridges for two way traffic were destroyed at two places, while at the rest only the land side bridge was collapsed. The lengths of these three bridges are 8.3m, 27.6m, and 30m, and the height of the girder from the water surface is 0.7m, 1.8m, and 1.5m respectively. The upstream catchment areas of these rivers are relatively small and hence river flows are also comparatively small.

Seaside of the 8.3m long bridge that handles one way traffic left undamaged by the tsunami is shown in Photo 14. The damaged sustained to landside is clearly visible in Photo 15. This bridge is located in a beach shore protection area. The left bank side was destroyed and the river bed around the bridge was eroded.

Photo 14 Undamaged sea-side bridge

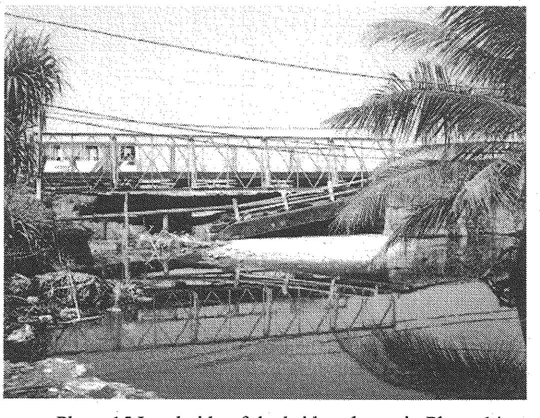


Photo 15 Land-side of the bridge shown in Photo 14

A comparison concept chart of discharge and flow velocity of a flood induced by torrential rain and tsunami waves in small and large rivers are shown in Fig. 8. The catchment area is bigger in wider rivers, hence the discharge is large and also the river depth is greater. The tsunami wave inundates an almost same area from the shoreline toward inland with a similar height. Thus, flow rate of the tsunami traveling upstream of the river does not change significantly according the size of the river: Q_2=Q_4. The water mass which travels up along the land and the river channel with the tsunami wave returns to the sea mainly via the rivers. The return discharge of the tsunami wave Q_2 is less than that of a flood Q_1 in the large rivers. However, the return flow discharge of the tsunami wave Q_4 increases more than the flood discharge (Q_3) in small rivers. Therefore, due to tsunami waves, the damage sustained by a bridge of a large river is relatively small compared to the damage sustained by a bridge of small rivers.

Furthermore, several other factors such as nearshore bathymetry, inland elevation, morphological and topographical features in the area, existence of sandbars and breakwaters control the height of the tsunami wave and tsunami wave travel distance on land. Strength of the abutment also plays an important role to withstand large return flow.

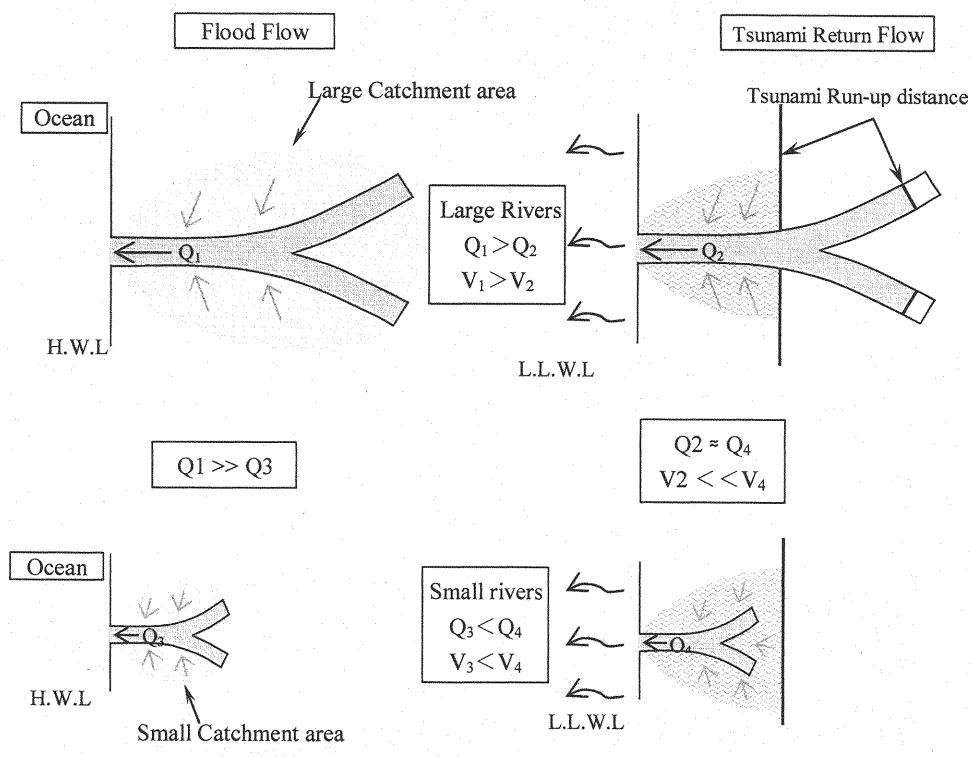


Fig. 8 Comparison concept chart of flood and tsunami flow at catchment areas of large and small rivers

(4) Loss of abutment approach: One road bridge and eight railway bridges

At the time of the field investigation, it was possible to identify one road and eight railway bridge sections where loss of the abutment approach due to tsunami forces has occurred. According to a study of Ishino et al. (4) on damages sustained by road and railway bridges in Fukui, Japan due to heavy flooding in 2004, in the case of road bridges the abutments and access road are concrete paved and hence, resistance to flowing water is higher, whereas in the case of railway bridges, the approach consists of a railroad track floor which uses rubble with weak resistance to the rapid flowing water. Most of the railway bridges investigated in the present study are located on the landward side of the road bridges with a distance of several meters to several ten meters. The railway track floor where the abutment approach was being placed was washed away by the rapid tsunami flow over the tracks, especially the bridges in small rivers. An example of a repaired railroad abutment section is shown in Photo 16.

Furthermore, the majority of the Sri Lankan railway bridges are through bridges, whereas the majority of the road bridges are deck bridges. Thus, the clearance height between the girder and the water surface of railway bridges is higher than that of the road bridges. Therefore, the flow velocity becomes low and some of the locations tsunami flow did not reach the bridge span level to damage the girder.

In Photo 17, the case of a railway track floor of the abutment approach being washed away and the repaired railway track is shown. The abutment was newly constructed and there is strong possibility that the abutment had been destroyed by the tsunami wave. Furthermore, in coastal areas of Sri Lanka, the railway tracks are laid on earth fills inside the lagoons and small bridge openings provide the passage for small magnitude of river discharge. As aforementioned, these small openings are not sufficient to pass high water volume. Therefore, the risk of damages to bridges and approach embankments is high.

In the case of Fukui flooding in 2004, road surfaces and pavements around submerged bridges were removed (Ishino et al. (4)), whereas the tsunami high flows were not sufficient to cause similar problem in Sri Lanka. Future studies need to be carried out to explain the cause of this phenomena.

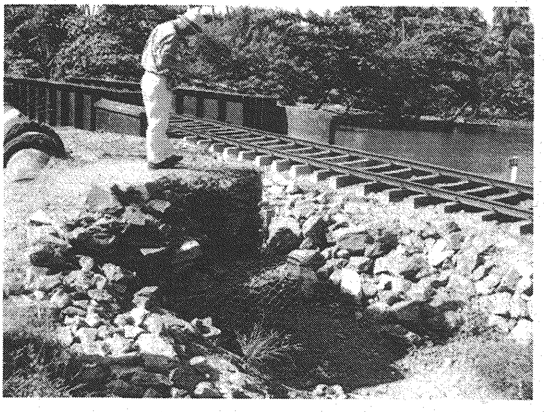


Photo 16 Railway bridge where abutment installation has been damaged

Photo 17 Railway Bridge where bridge installation part flows out

(5) Loss of the temporary girder under construction: One railway bridge

A steel girder plate type railway bridge under construction had been washed away by tsunami force. Girder of the destroyed bridge has carried away about 30m and was visible during the time of field investigation. This bridge is only about 50m far from the shoreline. Insufficient opening and a weak structure was identified as reason for the collapse of the bridge. A new truss bridge was under construction in May 2005 as shown in Photo 18. Part of the middle pier was visible under the center of the new bridge.

Photo 19 depicts the circumstances of the vegetation around another truss railway bridge which is about 75m upstream of the bridge in Photo 18. As shown in the photograph, the vegetation on the banks of the river are torn apart and pushed towards land side, indicating clearly the velocity of the tsunami wave as well as its returning flow.

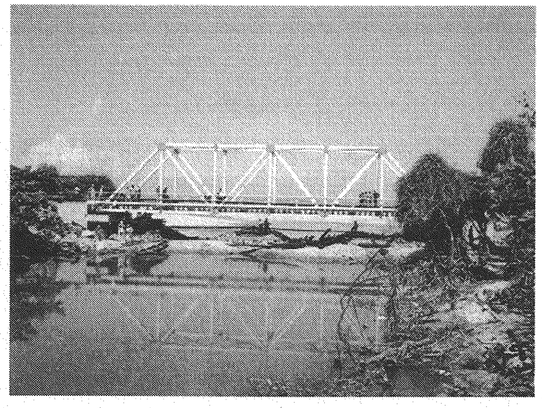


Photo 18 A temporary girder bridge near the river mouth

Photo 19 Undamaged truss railway bridge in the upstream of bridge in Photo 18

(6) Slight damage of abutment: Eight places

In Photo 20 a relatively large bridge of 205m in length, and height of 3.0m from the water surface to the girder is shown. The damaged situation of the left bank protection located just downstream of this bridge is shown in Photo 21. Because of the greater height between the bridge bottom and water surface in large rivers the tsunami wave did not reach the girder, hence there was no apparent damage to the girder and to the hand rails. However, the damages to the bridge approach are observed in many places.

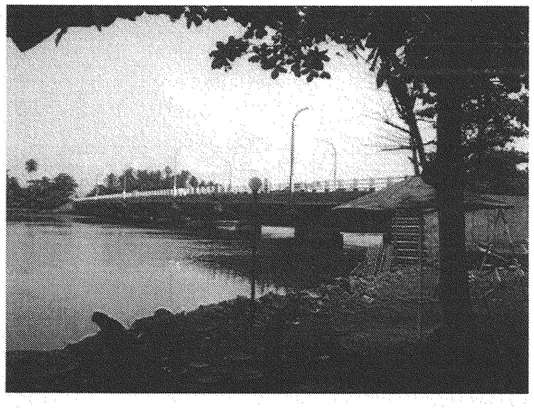


Photo 20 A road bridge across the Panadure River

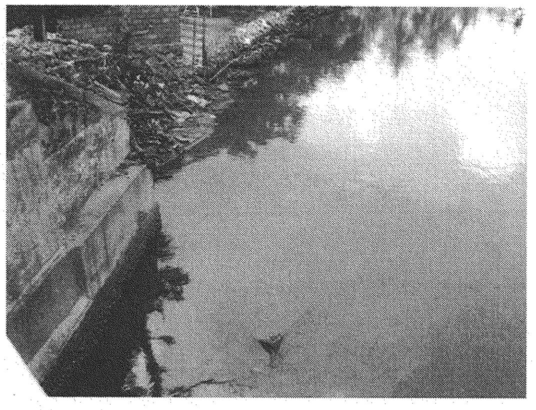


Photo 21 Damage of left bank downstream of the bridge shown in Photo 20

(7) Damage of hand rails: Six road bridges

One example of damaged hand rails of a bridge in Hambantota is shown in Photo 22. The bridge is about 320m far from the shoreline. The hand rail on the lagoon side tilted towards the seaside. It was surmised that the gigantic tsunami wave that flowed into the lagoon was returned seaward direction with strong velocity. On the other hand, the hand drail on the seaside has fallen on the lagoon side. Therefore, hand rails on both sides of the bridge have fallen on the sidewalk hindering the pedestrians. Even after four months tsunami wave struck, the destruction of infrastructure is quite obvious.

Moreover, the damage situation of column handrail in six other road bridges was investigated. The damage situation of a seaside high column handrail of a road bridge of 6.7m in length and 1.7m in height from the water surface is shown in Photo 23. The waterway is perpendicular to both shoreline and road. Therefore, high speed tsunami wave stuck the hand rails and damaged the structure.

Photo 22 Handrail column on land side of bridge

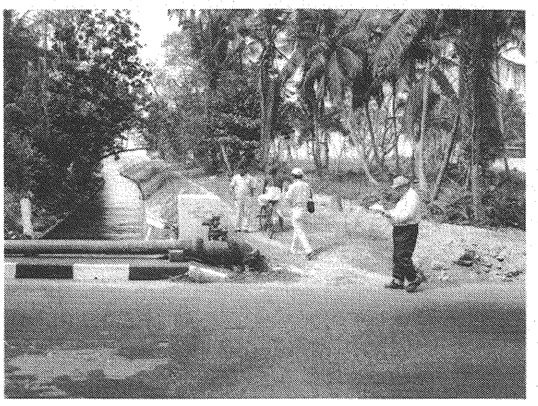


Photo 23 Damaged seaside guardrail of a road bridge

Relationship between damage situation of bridge and tsunami height

In Fig. 9, the relationship between "ratios of travel upstream height of the tsunami wave/clearance height of the bridge" and "distance from the river mouth to the bridge" is shown. As observed in the figure, extent of the damage increases with the ratio. In addition, it is clearly seen in the graph that when the bridge is located near by coastline, the damage becomes severe (girder washed out and deck collapsed). The relationship between the ratio of tsunami wave height to bridge clearance height and length of the bridge is shown in Fig. 10. This finding shows that damage is greater where the bridge span is shorter.

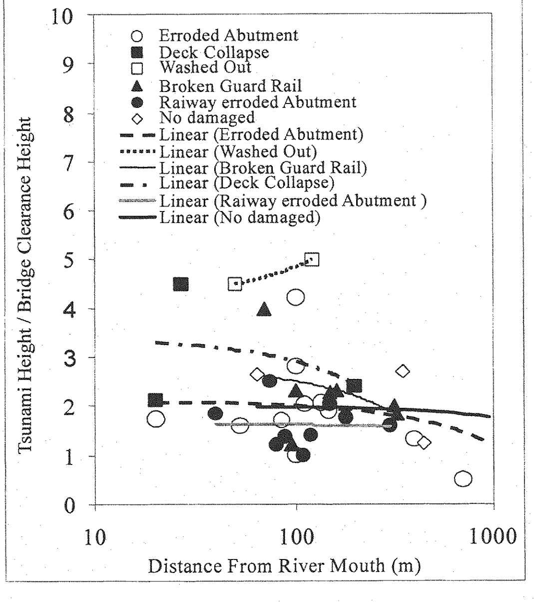


Fig. 9 Relations between distance from river mouth and ratio between bridge clearance heights to tsunami wave height

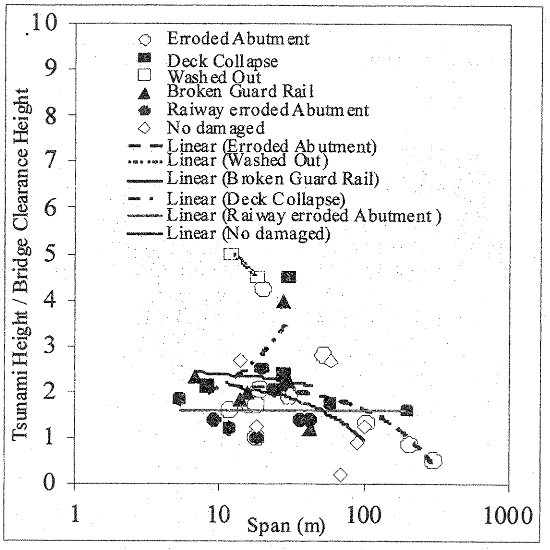


Fig. 10 Relation between Tsunami wave height/bridge clearance height and the length between of bridge

Figures 9 and 10 clearly indicate that the damage become more severe (girder washed out and deck collapsed) as "ratio of tsunami height/bridge clearance height" exceeds 2.0. Moreover, it can be concluded that severity of the damages diminishes when the bridge span is longer than 30 m and distance from the river mouth are longer than 200m. Therefore, it is possible to estimate roughly damages that bridges might sustain by a tsunami wave in the future.

It should be noted that most of the rivers in Sri Lanka have very mild slope and bridge damages due to tsunami waves propagated along the mild waterways can be identified. On the other hand, there are many rivers with significant river bed slope in the coastal areas of Japan. Therefore, in case of a similar tsunami wave struck in Japan, the flow velocities and discharge of return flow of the tsunami wave will be larger, and as a result the damages to the bridges will be larger than those in southwest of Sri Lanka. Thus, the damage to the river bridges caused by the tsunami wave in the Sri Lankan southwest is thought provide lessons that can be learned for planning and implementing necessary prior measures in bridge designing in Japan.

CONCLUSIONS

The results drawn in the present investigation are summarized as follows.

(1) Tsunami penetration into rivers presents different aspects depending on the geological formation around the river mouth and on the characteristic features of the river. Many signs were discovered that suggest the dominant effect of the geological formation of the river mouth and the effect of vegetation on the tsunami penetrations in rivers in all regions.

(2) In Galle City, the tsunami penetration along the small river that flows inside the city caused some flooding that generated some local damages. The same phenomenon may very likely occur in Japan. Detailed management is required in future calculations on tsunami penetration which take into consideration the small and mid-sized rivers.

(3) In the old urban area of Matara that developed around the mouth of the Nilwara River, damaged areas were observed not only along the sea front, but also spread deeper inland. From this finding, it was inferred that the tsunami had climbed up the river and generated localized floods in the low-lying areas in the inlands.

(4) The causes of bridge damages were presumed and measures for river bridges to withstand future tsunami forces have been proposed. Flow velocity of the tsunami traveling upstream of the river does not change significantly with the width of the river. However, the water mass which travels up along the land and waterways returns to the sea mainly through waterways. Thus, the return flow velocity is higher than tsunami run-up velocity, especially in narrow waterways. Therefore, damage sustained by a bridge of a large river is relatively minor compared to the damage sustained by a bridge of small rivers. This is main reason for the destruction of land slide abutments which led to bridge collapses in small rivers. Finding of this study shows that bridges which have span longer than 30m and are located beyond 200m from the river mouth are capable of withstanding the tsunami force if the ratio of tsunami height to clearance height is less than 2.0. Finally, different ranges of ratio between tsunami height and clearance height are identified for damage categories of the bridges.

ACKNOWLEDGEMENTS

The authors would like to express their grateful thanks to Foundation of River and Watershed Environment Management for their financial support to the present field investigation. The authors' appreciation should be extended to Japan International Cooperation Agency (JICA) and various other organizations and institutions for their kind assistance in conducting the field investigation for this paper.

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(Received Jul 02, 2007 ; revised Sep 27, 2007)