

## **STRUCTURAL DAMAGES ON THE COAST OF TAMIL NADU DUE TO TSUNAMI CAUSED BY DECEMBER 26, 2004 SUMATRA EARTHQUAKE**

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### **ABSTRACT**

The December 26, 2004 Sumatra earthquake of Moment Magnitude  $M_w = 9.3$ , the largest earthquake in the world since the 1964 Prince William Sound, Alaska earthquake, generated a widespread tsunami. Soon after the earthquake, the authors visited Tamil Nadu and Pondicherry for a damage survey. This paper describes the structural aspects of damages caused on the coast of Tamil Nadu. The area covered was along the coast from Chennai on the east coast to Thiruvananthapuram on the west coast. There were practically no major evidences of damage due to direct shaking while damages due to tsunami were extensive. Both masonry and concrete structures were damaged, though level of damage varied. In general, structural damages involved: damage to brick masonry, damage to compound walls, collapse of adobe houses, failures of columns and toppling of roofs, damage due to lack of detailing of reinforcement. Causes of damages have been investigated and remedial measures to avoid those in a future tsunami are suggested. A good correlation between run-up height and level of damage is found.

**KEYWORDS:** Earthquake, Tsunami, Brick Masonry, Adobe Houses, Toppling of Roofs

### **INTRODUCTION**

A number of earthquakes in past had caused widespread damages in different parts of India, e.g. recent earthquakes including 1993 Latur, 1997 Jabalpur, 1999 Chamoli, and 2001 Bhuj earthquakes. However, there is little evidence in literature that tsunamis have caused widespread damage in India. Tsunami effects in Japan and Alaska are known for about half of a century (refer the web-site of International Tsunami Information Center at <http://www.prh.noaa.gov/itic/>). The Chile earthquake of 1960 (the largest recorded earthquake in history with  $M = 9.5$ ) produced a tsunami that not only killed 300 people in Chile but also killed 61 people in Hawaii and 22 hours later, more than hundred people in distant Japan (Iida et al., 1967; Watanabe, 1998). A tsunami generated by the Niigata earthquake in Japan on June 16, 1964 caused widespread damage (Day, 2002). Besana and Ando (2004) presented coastal effects of 1992 tsunami in Philippines.

A tsunami is an ocean wave that is created by a disturbance that vertically displaces a column of seawater (Kramer, 1996). Many different types of disturbances can generate a tsunami, such as an earthquake, volcanic island eruption, or submarine landslide. Recent Sumatra earthquake of Moment Magnitude  $M_w = 9.3$  (Stein and Okal, 2005) generated widespread tsunami. Casualties and damage caused by the tsunami were many folds of those due to the direct shaking in an earthquake. The tsunami generated was so powerful that it traveled thousands of miles away from the epicenter of the earthquake and even caused damage in distant Somalia. The casualties caused by this tsunami are the largest in the recorded history of tsunami. The human loss from the tsunami is more than 250,000 with a belated recognition that this great loss could have been avoided (Kerr, 2005; Bhattacharjee, 2005). Harinarayana and Hirata (2005) presented the analysis of the available scientific data related to the Sumatra earthquake and tsunami. The tsunami has caused tremendous damage to the Andaman and Nicobar Islands of India as well as to its mainland. While the damage in the Andaman and Nicobar Islands was due to both ground shaking and tsunami, on mainland it was only due to tsunami. Affected areas on mainland include Tamil Nadu, Pondicherry, Andhra Pradesh and Orissa.

Soon after the earthquake and tsunami, the authors visited the coastal regions of Tamil Nadu and Pondicherry (see the hatched locations in Figure 1) during January 6-14, 2005 for a reconnaissance study. The area covered was along the coast from Chennai (Tamil Nadu) on the east coast to

Thiruvananthapuram (Kerala) on the west coast. The main objectives of the team were to see the effects of tsunami on the built environment in terms of structural and geotechnical damages, to measure the inundation and run-up of the tsunami waves (and their variations), arrival time of tsunami, number of waves, and to model the dynamics of the waves. There are thirteen districts of Tamil Nadu with the seacoast. The authors visited ten districts including Pondicherry. Out of the 45 towns and communities that they visited, 37 sites were directly affected by the tsunami. The Nagappattinam, Kanyakumari and Cuddalore were the worst hit districts while others had relatively lesser damage. Considering the run-up of tsunami, the highest value reported was 12 m (described later in detail in Table 1) in Keelamanakudy and Meelamanakudy towns of the Kanyakumari district, which were structurally worst-hit among the visited communities.

Maheshwari et al. (2005) presented geotechnical aspects of the damages. This paper presents the structural aspects of damages observed, their analyses (correlation with the level of run-up), and suggestions for remedial measures. Major structural damages presented include damage to compound walls, damage to brick masonry, collapse of adobe houses, failure of columns, toppling of roofs, and damage due to lack of detailing of reinforcement.



Fig. 1 Affected and visited area along the coast of Tamil Nadu (see the shadowed portion)

## RUN-UP AND INUNDATION AT DIFFERENT LOCATIONS

Characteristics used to describe a tsunami include tsunami (wave) height, run-up elevation and inundation distance as explained in Figure 2(a). Run-up is the difference between the elevations of maximum tsunami penetration and sea level just before the tsunami attack, while inundation distance is the horizontal distance of the point of penetration (on land) from the seashore. During the field survey, run-up and inundation at different localities were recorded based on the watermarks and interviews with the local people. Table 1 lists the values of run-up and inundation at different localities (as examined in this paper) along with their latitudes and longitudes (these were measured by using a GPS). These are geo-referenced in the map in Figure 2b with corresponding serial numbers given in the first column of Table 1.

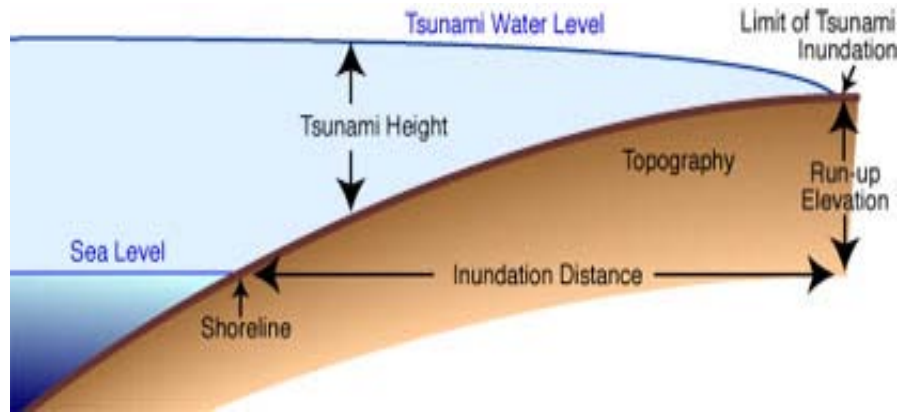


Fig. 2(a) Some of the tsunami characteristics typically measured by the survey team

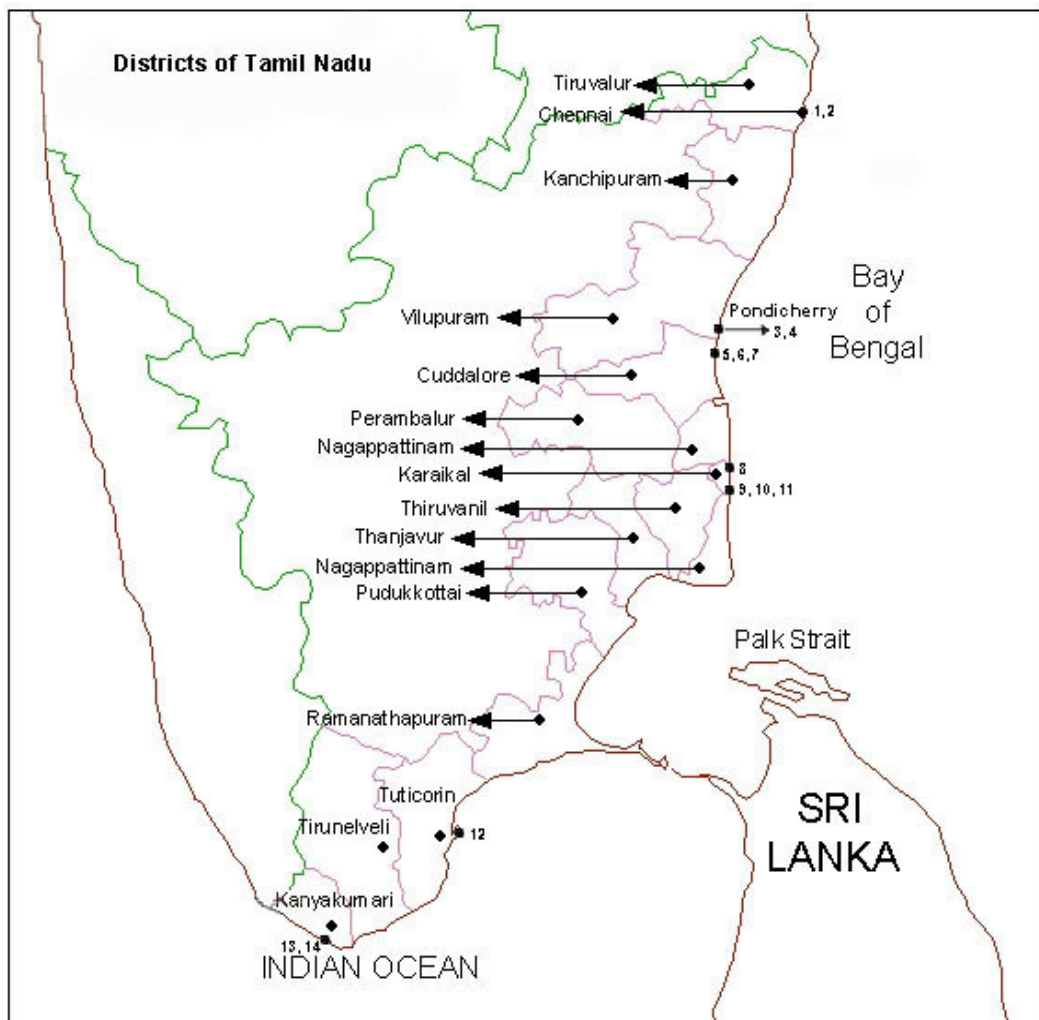


Fig. 2(b) Sites examined in the paper (see the numbered locations with reference to Table 1)

For each locality mentioned here, level of damage is correlated with the tsunami run-up. Damage is also influenced by the inundation distance and in general increases with this distance. However variation in damage pattern with the inundation distance is not considered here. As far as the effects of locations (described by latitudes and longitudes in Table 1) are concerned it is assumed that this effect is reflected in the level of run-up. For example, level of run-up is very high in Nagappattinam and Kanyakumari districts presumably due to the interference of reflected waves from Sri Lanka and Maldives, respectively, with direct waves as shown by Narayan et al. (2005).

**Table 1: Run-up and Inundation of Tsunami at Different Localities Examined along with Latitude and Longitude**

S. No.	District and Locations	Approx. Run-up (m)	Approx. Inundation (km)	Latitude	Longitude
CHENNAI					
1.	Cherain Nagar	3-4	0.1	N 13 <sup>0</sup> 10'13.2''	E 80 <sup>0</sup> 18'48.3''
2.	Madras Lighthouse	4-5	1.0	N 13 <sup>0</sup> 02'22.0''	E 80 <sup>0</sup> 16'51.0''
VILLUPURAM					
3.	Kudukuppam	4	1.0	N 12 <sup>0</sup> 03'02.4''	E 79 <sup>0</sup> 52'41.6''
PONDICHERRY					
4.	Chinapattam	4-5	2.0	N 12 <sup>0</sup> 00'34.7''	E 79 <sup>0</sup> 51'14.5''
CUDDALORE					
5.	Talenguda	5-6	1.0	N 11 <sup>0</sup> 45'54.2''	E 79 <sup>0</sup> 47'39.7''
6.	Devanam Kuppam	6-7	1.0	N 11 <sup>0</sup> 44'18.6''	E 79 <sup>0</sup> 47'17.0''
7.	Kuddukullam	8-9	0.5	N 11 <sup>0</sup> 31'31.3''	E 79 <sup>0</sup> 45'47.0''
NAGAPPATTINAM					
8.	Kuddupattanam	8-9	2.0	N 11 <sup>0</sup> 04'04.2''	E 79 <sup>0</sup> 51'28.1''
9.	Amman Kerapattu	8-9	2.0-3.0	N 10 <sup>0</sup> 56'08.0''	E 79 <sup>0</sup> 59'11.1''
10.	Nagappattinam Beach	10-12	2.0-3.0	N 10 <sup>0</sup> 46'55.5''	E 79 <sup>0</sup> 51'05.8''
11.	Nabiyar Nagar	10-12	3.0	N 10 <sup>0</sup> 46'22.6''	E 79 <sup>0</sup> 50'56.5''
TUTICORIN					
12.	Tuticorin Port	3	0.2	N 08 <sup>0</sup> 44'58.6''	E 78 <sup>0</sup> 11'47.5''
KANYAKUMARI					
13.	Keelamanakudy	12	2.0	N 08 <sup>0</sup> 05'17.9''	E 77 <sup>0</sup> 29'11.4''
14.	Meelamanakudy	12	2.0	N 08 <sup>0</sup> 06'28.9''	E 77 <sup>0</sup> 24'13.4''

To classify the level of damage in structures, following two parameters are considered:

- Type of structure (as described in Table 2)
- Grade of damage (as described in Table 3).

**Table 2: Types of Structures (Buildings)**

Type of Building	Material Used and Quality of Construction
Type A	Buildings in field-stone, rural structures, unburnt-brick houses, clay houses
Type B	Ordinary brick buildings, buildings of large block, half-timbered structures
Type C	Reinforced buildings, well-built wooden structures

**Table 3: Grade of Damage to Structures (Buildings)**

Damage Category		Extent of Damage in General
Grade 1	Slight Non-Structural Damage	Thin cracks in plaster, falling of small pieces of plaster
Grade 2	Slight Structural Damage	Small cracks in wall, falling of fairly large pieces of plaster
Grade 3	Moderate Structural Damage	Large and deep cracks in walls, widespread cracking of walls, columns, piers, and tilting or falling of chimneys; the load carrying capacity of the structure partially reduced
Grade 4	Severe Structural Damage	Gaps occur in walls; inner or outer walls collapse; separate parts of the buildings lose their cohesion
Grade 5	Collapse	Partial or total collapse of the building

**DAMAGE TO COMPOUND WALLS**

The tsunami has caused widespread damage to compound walls. Usually, a compound wall consists of reinforced concrete posts with masonry infill walls between the posts. In the visited areas, brick masonry was used for infill walls. Compound walls, used as the boundary walls of the buildings and facilities, got severely damaged in all affected areas. Damage to these walls during the tsunami was due to two reasons. Firstly their locations (i.e. being in front they are the first component of a building/structure hit by the waves) made them vulnerable to the tsunami. Secondly in many cases these walls collapsed due to the failure of foundations as often only surface footings (without any embedment) were used for these walls (Maheshwari et al., 2005). Moreover, brick masonry used for these walls could not resist the lateral force of the tsunami. Few of the damages to compound walls are discussed below.



Fig. 3 The boundary wall of about 50 m length damaged in Cherain Nagar (Chennai)

Figure 3 shows the damage to a boundary wall near tollgate in Cherain Nagar (Chennai). Run-up observed in this area was 3-4 m (see Table 1). The wall was located about 50 m from the seacoast after crossing the 10 m wide road. The coast height near this locality was about 3 m only and tsunami waves could cross the breakwater made to prevent it. The boundary wall (made of brick masonry) was severely damaged. Damage was in partial length of wall only where the tsunami struck first and hydrodynamic force of the tsunami exceeded the bending capacity of the wall. Once water entered inside and pressure equalized on both sides of the wall, this reduced the overturning moment and further damage. Wall being unreinforced, this type of damage was inevitable. From Tables 2 and 3, the level of damage may be characterized as of Grade 4 in Type A structure.

Compound wall of the Madras Lighthouse (Chennai) partially collapsed due to the tsunami (see Figure 4). According to Table 1, the run-up in this area was 4-5 m. Boundary wall was of brick masonry with concrete posts. A few concrete posts of the wall (to the south of the lighthouse) were even detached from the wall and damaged. It appears that the tsunami attacked the joints as posts were toppled from the joints with base. As shown in Figure 4, a post got displaced laterally by about 10 cm (after collapse of infill walls). Approximate size of a post was 0.45×0.3×1.5 m, with a weight of about 5 kN. Displacement of such a heavy weight shows that the lateral force exerted by the waves was indeed intense. Also it can be observed that compared to Figure 3, quality of the material used (concrete) here was better and the damage can be classified as Grade 4 in Type B in the 4-5 m zone of tsunami run-up height.



Fig. 4 Collapse of the compound wall of Madras Lighthouse (Chennai) (concrete posts of the wall separated; second figure shows that another post is displaced laterally by about 10 cm)

The boundary wall of a school in Chinapattam (run-up 4-5 m, see Table 1) was damaged as shown in Figure 5. Some of the parts of the wall were transported up to a distance of about 10 m. The wall was made of brick masonry with concrete posts. At most places the wall got uprooted from the base and toppled as a unit. Level of damage (Grade 4 in Type B) is due to high run-up elevation. Figure 6 shows that front (boundary) walls of few buildings got damaged while the roofs were intact. Brick masonry got damaged even when cement was the cementing material. It could be observed that though the boundary wall collapsed due to the tsunami, it helped to save the other parts of the building.



Fig. 5 Collapse of brick masonry compound wall of a school in Chinapattam (Pondicherry)

#### **DAMAGE TO BRICK MASONRY**

It was observed during the survey that the tsunami has caused widespread damage to brick masonry, which was widely used in the construction of the low-rise buildings. As anticipated, the brick masonry performed very poorly in resisting the lateral forces of the tsunami. Bending capacity of unreinforced

brick masonry was very low against the hydrostatic forces of the tsunami. This type of damage was inevitable and could only be avoided by using reinforced walls designed for the lateral forces of tsunami.



Fig. 6 Collapse of compound walls of residential houses in Chinapattam (these walls protected the houses from damage)



Fig. 7 Collapse of brick masonry houses in Kudukuppam (Villupuram)

Figure 7 shows the collapse of brick masonry houses in Kudukuppam (with run-up of 4.0 m). The huts collapsed as walls and columns were constructed by using mud as a cementing material, and had thatched roofs. The collapse was as anticipated due to the use of very poor cementing material in the construction. The damage can be characterized as of Grade 5 in Type A buildings.

Some of the typical structural damage in the Talenguda village (Cuddalore) is shown in Figure 8. This area had the run-up of 5-6 m. It can be observed that even though the run-up is higher than that shown for Figure 7, the damage is not so severe because of the better quality of construction. Level of damage in the left photograph can be characterized as of Grade 4 in Type B. Joints of a compound wall (made of brick masonry) with the main wall opened and tilted due to settlement of the soil below. Right photograph of Figure 8 shows that the collapse was due to opening of joints and low bending capacity of the brick masonry. This indicates vulnerability of brick masonry to tsunamis.

Opening of brick joints was observed at many other places also. For example Figure 9 shows collapse of a house in Amman Kerapattu village (in Nagappattinam district) near Karaikal due to breaking of bricks even when lime mortar (not mud) was used as a cementing material. This area had the run-up of 8-9 m (see Table 1), which is consistent with the breaking of bricks and collapse of walls observed here and thus with the damage of Grade 5 in Type B.

Tsunami caused heavy damage to brick masonry buildings not only on the east coast but also on the west coast. Figures 10 and 11 show heavy damages to the brick masonry buildings in Keelamankudy and Meelamankudy villages, respectively. Both villages are located on the west coast in the Kanyakumari district, and had run-up equal to 12 m. These villages are about 100 km North-West of Kanyakumari

city. It can be noticed that this damage was severe even with the use of cement mortar. Level of damage may be characterized as “many buildings of Type B subjected to damage of Grade 5”, which is consistent with the high level of run-up.



Fig. 8 Damage to boundary walls in Talenguda (Cuddalore) due to damage to brick masonry



Fig. 9 Damage to brick masonry in Amman Kerapattu village (Nagappattinam) near Karaikal (even bricks used with lime mortar got broken here and wall collapsed)



Fig. 10 Collapse of a brick masonry building under construction at Keelamanakudy (Kanyakumari)





Fig. 11 Widespread damages to buildings in Meelamanakudy (Kanyakumari) (most of the houses were of brick masonry which performed poorly during the tsunami attack)

### COLLAPSE OF ADOBE HOUSES

Much damage was caused by the tsunami to the villages near seashore. Many fishermen's villages called Kuppam were completely devastated as the quality of construction was very poor. Often fishermen's houses are made of bricks with mud mortar and thatched roofs (adobe houses). Due to lateral forces applied by the tsunami, these houses suffered heavy damage and even collapsed. This may be characterized as "many structures of Type A subjected to damage of Grade 5".

Figure 12 shows the collapse of fishermen's houses in Kuddukullam village just south of Cuddalore. Construction material used was very poor and the collapse of these houses due to the tsunami was obvious. Level of run-up in the area was also considerably high (8-9 m).

Figure 13 shows damage to the houses in Kuddupattanam (south of Chidambaram city) in the Nagappattinam district. Though level of run-up is high (8-9 m), damage is not so severe especially for the house in the left photograph of Figure 13. Reason for this is attributed to the Medu effect as described by Narayan et al. (2005). As these houses were situated on Medu (naturally elevated landmass), those were saved from collapsing. Fig. 14 shows collapse of the adobe houses in Nabyarnagar (Nagappattinam). The level of run-up was 10-12 m and the collapse of these poorly constructed houses was as expected.



Fig. 12 Collapse of adobe houses in Kuddukullam village (near Cuddalore)

### FAILURE OF COLUMNS AND TOPPLING OF ROOFS

In many buildings, columns (mostly of reinforced concrete) failed and even collapsed due to poor quality of construction, inadequate reinforcement, or due to lack of detailing. Failure of these columns led to falling and toppling of the supported roofs. A few of the observed cases are discussed below.



Fig. 13 Damage to small houses in Kuddupattanam (south of Chidambaram), Nagappattinam



Fig. 14 Collapse of adobe houses in Nabiyar Nagar (Nagappattinam) due to tsunami

Figure 15 shows one of the collapsed columns of Sri Karneshwara Natraj Temple in Kudukuppam (Villupuram), where the run-up was 4.0 m. Damage may be classified as of Grade 5 in Type B, which is on higher side and not correlating well with the run-up. There are many reasons for this inconsistency. Though details about the amount of reinforcement were not available but general observations suggest that the reinforcement was inadequate with respect to cross-sectional area of the column. Thus flexural capacity of column was not enough to resist the hydrodynamic forces of tsunami. Moreover, at the base of the columns, isolated footings were used instead of combined footings, and failure of foundation also contributed to the collapse of these columns. Once columns collapsed, this led to toppling of roof and it moved few meters away. Here the run-up was not very high; however primary reason of the collapse was foundation failure as shown in Figure 16.



Fig. 15 Left: One of the failed reinforced concrete columns of Sri Karneshwara Natraj Temple, Kudukuppam (Villupuram); Right: Toppled roof, which moved few meters away



**Fig. 16** Foundation of collapsed Sri Karneshwara Natraj Temple (Kudukuppam) (only isolated footings under the columns were used)

Figure 16 depicts the foundation of collapsed Sri Karneshwara Natraj Temple (Kudukuppam). It can be observed that foundation below the structure was very abnormal. Only isolated spread footings below the column bases were provided. There was no embedment/foundation below the square ring joining the column bases. No combined foundation was provided below these columns. It appears that the base ring (except below the columns) was directly placed on the soil (without any embedment) as can be seen in the photographs. Such footings cannot withstand the forces of tsunamis and the collapse was as expected.

Figure 17 shows the collapse of a monument in Devanam Kuppam (Cuddalore), with a run-up of 6-7 m. Level of damage can be classified as of Grade 5 in Type B and many reasons of this damage could be observed. First, erosion and settlement of soil due to the tsunami tilted the base of the structure. Second, the roof was supported by just one column at the center, which collapsed. It may be observed that reinforcement used in the column was inadequate. Third, the roof was toppled and washed 20 m away. For the roof, quality of construction was relatively better and it remained relatively intact. Beams of the roof performed well and they kept the roof intact even after its displacement by a few meters.



**Fig. 17** Damage and collapse of a small monument in Devanam Kuppam (Cuddalore) (top left: tilted base due to settlement and erosion of soil; top right: heavy roof supported by a single column only; a collapsed RCC column without adequate reinforcement; bottom: displaced roof that toppled and moved away but remained relatively intact due to adequate reinforcement)

A memorial column at Nagappattinam beach, which was erected to celebrate Republic Day after the Kargil war got severely damaged (see Figure 18). It may be seen in the photograph that the Singnadh is broken from the post inside the memorial column. Broken post and its base can be clearly noticed. Also different parts and pieces of the memorial column, and an uprooted electric pole may be observed. Severe damage to the concrete post and many other concrete structures (i.e., Grade 5 in Type B) at the Nagappattinam beach is consistent with the high level of run-up (10-12 m in Table 1). It may be observed in Figure 18 that the depth of embedment of the footing was not adequate and that this also contributed to the damage.



Fig. 18 Memorial column at Nagappattinam Beach that got uprooted, and Singnadh (on top of it) that got broken and moved away (the column was erected to celebrate Republic Day after the Kargil war)

### GENERAL DAMAGE TO STRUCTURES

Widespread damage to masonry buildings, including those with good quality of construction, was noticed especially in the Kanyakumari district. Most affected villages were Keelamanakudy and Meelamanakudy (where the run-up measured was about 12 m). Some of the damages to the brick masonry in these villages have already been discussed in Figures 10 and 11. Further, Figures 19 and 20 show general collapse of newly constructed buildings in the Meelamanakudy village of Kanyakumari.



Fig. 19 Heavy damage to a building in Meelamankudy: (a) complete failure of joints at lintel band, (b) a close up view showing that there was lateral displacement of top part towards the right side



Fig. 20 Collapse of another building in Meelamanakudy (Kanyakumari) (close-up view of the collapsed front wall shows how vulnerable the brick masonry was to tsunami)



Fig. 21 Damaged bridge on the river Palyar in Keelamanakudy: (clockwise from top left) (a) the substructure left after 4 spans of the deck got washed away; (b) a span washed away by about 20 m; (c) another span moved by about 50 m; (d) bare substructure (with 2 spans still missing)

There were spectacular damages to the residential buildings in the Meelamanakudy village. All the houses, which are of single story, appeared to be modern type constructions. These were not fishermen’s huts, but reinforced concrete frame buildings with masonry infills. Almost every house along the seashore suffered heavy damage even though the buildings looked relatively new. Damage was all over, from foundation to the roof level including walls and columns. Figures 19 and 20 show few of the damaged houses. All these damages were due to the tsunami only and patterns of damages even suggest that these were more severe than those due to an earthquake. In fact almost all houses of this village suffered intense damages with a few having partially/fully collapsed. This intense damage may be attributed to low-lying area and a high value of run-up (12 m). Inundation was very high (see Table 1). It caused heavy erosion to road also. Thus level of damage (of Grade 5 in Type C) is very much consistent with the level of run-up.

A bridge on the river Palyar, connecting the Keelamanakudy and Meelamanakudy villages has been badly damaged (see Figure 21). All the four spans of the bridge got washed away. Out of these four spans, two were still missing (up to the date of the survey) and two spans have moved away by about 20 and 50 m (see Figure 21). These spans got displaced from the bearings and separated from the substructure (pile foundation including pile cap). No damage was observed in the substructure and it appeared intact. It seems that the deck got separated due to the bearing failure. Broken parts of the bearings indicated that

mechanical bearings were used. With the help of the measured dimensions, it is estimated that the weight of a span would be about 200-300 tonnes. Displacement of such a heavy structure indicates the intensity of the hydrodynamic force applied by the tsunami. It was a tremendous pressure that washed away the spans. Washing away of bridge's deck may be classified as the damage of Grade 5 in Type C structure, which is again consistent with the level of run-up.

### NO DAMAGE TO ERD STRUCTURES

In the above sections it was observed that many structures were significantly damaged due to the tsunami. The authors have also visited few communities where no damage was reported to the ERD (Earthquake Resistant Designed) Structures. For example, Figure 22 depicts the scene of Tuticorin Port. The harbor is in about 6 km<sup>2</sup> area. Mainly the oil and coal industries are making use of this harbor. This harbor is operated by Tuticorin Port Trust (TPT), Ministry of Shipping, Government of India, and no damage was reported by the Deputy Chairman of the harbor.

Size of the harbor area is approximately 4450×1250 m. On one side of this area is seashore, where administrative buildings of TPT are located while out of the two other sides, one is for pipeline and another is for approach road (see Figure 22). Closing these two sides are breakwaters (with large boulders) thus encompassing the whole area. Harbor was designed and constructed according to Indian Standard seismic codes and was commissioned in 1978. No damage has been reported to the harbor and facilities here, as the quality of construction is very good (based on personal communication with the TPT authorities). Moreover, being shielded by Sri Lanka, this area had a very low run-up (3.0 m). Here the level of damage may be categorized as of Grade 1 in Type C, which is very consistent with the run-up.

### RUN-UP VERSUS LEVEL OF DAMAGE

Usually three parameters, namely type of buildings (see Table 2), grade of damage (see Table 3), and quantity (as described below) are used to classify the level of damage in structures such as used in IS 1893 (BIS, 2002) to define the intensity scales. Though during the present tsunami damage survey, first two parameters were adequately used to classify the level of damage, the third parameter is used only approximately as the number of cases examined in this paper is not very large. The third parameter may be defined as: Few (about 5%), Many (about 50%), and Most (about 75%). A summary of the sites investigated in this paper is presented in Table 4.



Fig. 22 Pictures taken at Tuticorin harbor showing no damage to the facilities there and life remaining normal at the port (clockwise from top left: an oil storage tank; very heavy stones (about 10 tonnes each) to protect the break-water; a ship moored near the seashore; close-up view of another ship)

**Table 4: Correlation Observed between Run-up and Level of Damage**

Run-up	Level of Damage	Example Figure Numbers
10-12 m	Few buildings of Type C with damage of Grade 5 or Grade 4; many buildings of Type B with damage of Grade 5	10, 11, 14, 18, 19, 20, 21
7-9 m	Few buildings of Type B with damage of Grade 5; many buildings of Type A with damage of Grade 5	9, 12, 13, 17
4-6 m	Few buildings of Type B with damage of Grade 4; few buildings of Type A with damage of Grade 5	4, 5, 6, 7, 8
3-4 m	Few buildings of Type A with damage of Grade 4	3

It may be observed from Table 4 that, in general, a good correlation exists between the run-up and the level of damage and that the level of damage is gradually increasing with the run-up. However, there are a few exceptions such as Figures 15 and 16, which are not fitting well into this correlation due to one reason or the other as discussed earlier.

## DISCUSSION AND REMEDIES

With the damage survey presented in the above sections, it may be observed that there were significant damages to buildings and structures due to the tsunami. Most of the damaged buildings were of brick masonry construction. As the flexural rigidity of unreinforced masonry is very low, there was heavy damage to the brick structures due to the tsunami. Compound walls acted as barriers in the passage of the tsunami and in most of the cases these walls collapsed. However, these walls helped to reduce the damage to the main structures/buildings. Along the coast, fishermen houses (normally adobe houses) got collapsed due to lateral force applied by the tsunami; such kind of damage was inevitable. Damage was inflicted not only to the brick masonry and adobe houses but also to good quality modern construction. In many cases, concrete structures also sustained severe damage and even collapsed. The damage in these structures was related to the failure of joints (between two components), lack of reinforcement and detailing, poor quality of concrete, and lack of ductility coupled with the high level of run-up. Based on this discussion, following remedial measures are suggested.

- Collapse of compound walls should be avoided. Adequate depth of foundations for compound walls should be provided and erosion of soil should be checked.
- Brick masonry should be designed to avoid its collapse. Though it may not be designed to be totally tsunami-resistant but to avoid its collapse, adequate reinforcement should be provided.
- There was widespread collapse of adobe houses due to the tsunami. Though these structures, made of poor quality of material, are good in fulfilling the functional needs of economically weaker sections, those are not expected to perform well during a lateral loading. Construction of these houses should be avoided. Else, these should be designed such that roof and walls act as a single unit. This would improve their performance against a tsunami of low run-up.
- Damage to the modern construction (concrete buildings/structures) can be avoided by introducing earthquake-resistant design concept, and thus by giving full attention to their detailing and ductility requirement according to the latest seismic codes.
- In general, to avoid damage to structures due to tsunami, some special measures, e.g. constructing a breakwater should be devised. During tsunami these breakwaters may get damaged but those would help to protect the main buildings/structures by reducing the force of tsunami.

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