6th International Conference on Structural Engineering and Construction Management 2015,
Kandy, Sri Lanka, 11th-13th December 2015

SECM/15/050

Comparison of Failure Mechanisms of Coastal Structures due to the 2004 Indian Ocean and 2011 Tohoku Tsunami Events

G. Lim[1], B. Premaratne[1], R. Jayaratne[1*], M. Marriott[1]and T. Shibayama[2]

[1]University of East London, London, UK
[2]Waseda University, Tokyo, Japan
*E-Mail: r.jayaratne@uel.ac.uk, TP: +44 (0)208223 2536

Abstract: By analysing and comparing the results of post-disaster field studies and literature regarding the mechanisms by which coastal structures failed due to the 2004 Indian Ocean Tsunami and the 2011 Tohoku Tsunami events (the focus being on defence structures where applicable), trends were identified and examined. This paper highlights the most commonly occurring / major failure mechanisms identified in the various locations affected by the two tsunami events. The failure modes found in over twenty locations throughout the Fukushima, Iwate and Miyagi Prefectures of Japan were categorised into seven failure modes: a) leeward toe scour, b) crown armour failure, c) leeward armour failure, d) parapet wall failure, e) overturning, f) seaward toe scour, and g) sliding. Leeward toe scour was found to be the major failure mechanism in seawalls and dikes, and sliding was found to be the major failure mechanism in concrete breakwaters. The failure modes found throughout regions affected by the Indian Ocean Tsunami were categorised into five failure mechanisms: a) scouring of foundations, b) beam/column failure, c) joint failure, d) wall failure, and e) total disintegration. The 'total disintegration' caused by seismic forces, debris collision and hydrodynamic forces was the major failure mode throughout the studied regions. Some of the major tsunami induced forces found to have been among the causal factors of structural failure included hydrostatic and hydrodynamic forces. Flow velocities as high as 13.4m/s were found in areas of Japan, and flow velocities of up to 10.4m/s were found in regions affected by the 2004 Indian Ocean Tsunami. Potential strengthening measures were suggested for structures such as seawalls and coastal dikes, which were most vulnerable to scouring at the toe. By producing armoured components to protect the toe of the structures, they would become less susceptible to toe scour failure.

Keywords: Coastal structures, Failure mechanisms, 2004 Indian Ocean tsunami, 2011 Tohoku tsunami, Toe scour, Total disintegration.

1. Introduction

Recent extreme events such as the 2004 Indian Ocean Tsunami and the 2011 Great East Japan Earthquake and Tsunami (2011 Tohoku Tsunami) have been the cause of excessive amounts of damage not only to coastal structures, but also to the lives and economies of many. In order to be able to prevent such large-scale disasters in the future, it is imperative that research on the probable failure modes of the coastal structures is carried out. It is also very important that the relevant findings are used to design, strengthen and refine existing and future coastal structures to resist against such events. The purpose of this study is to compare the various failure mechanisms present in two tsunami events and in turn, to identify correlations between the structures and failure modes present in different locations. This paper also focuses on identifying some of the major destructive tsunami-induced forces that are responsible for the various failure mechanisms observed. By examining the identified trends, this study aims to investigate the vulnerabilities of the coastal structures and suggest viable solutions to strengthen them.

2. Identified coastal structures, failure mechanisms and tsunami-induced forces

The various coastal structures and failure mechanisms identified in this section, for both tsunami events, were obtained by examining and comparing field notes, reports, case studies, photographs and various literature documenting post-tsunami field surveys. Field studies that were analysed and compared included the works of Jayaratne et al. [1, 5], Kato et al. [2], Chock et al. [3], Saatcioglu et al. [4] and Shibayama et al. [6], which collectively covered field surveys that were carried out in over twenty locations throughout the Fukushima, Iwate and Miyagi Prefectures of Japan

and also regions throughout Indonesia, Sri Lanka, Thailand and the Maldives Islands.

2.1 Summary of observed coastal structures

The various coastal structures observed in each of the surveyed locations were studied and analysed to determine by which mechanisms they failed. Only the most commonly observed coastal structures are summarised as follows:

Coastal structures observed in 2011 Tohoku Tsunami:

1) Coastal Dikes
2) Seawalls
3) Breakwaters

Coastal Structures observed in 2004 Indian Ocean Tsunami:

1) Seawalls
2) Residential buildings

2.2 Summary of identified failure mechanisms

This section briefly summarises the different failure mechanisms that were observed in the various coastal structures summarised in Section 2.1.

Failure mechanisms found in 2011 Tohoku Tsunami:

1) Leeward toe scour failure
2) Crown armour failure
3) Leeward armour failure
4) Parapet wall failure
5) Overturning failure
6) Seaward toe scour failure
7) Sliding failure

Failure mechanisms found in 2004 Indian Ocean Tsunami:

1) Foundation/Scouring failure
2) Beam and column failure
3) Joint failure
4) Wall failure
5) Total disintegration

2.3 Calculation of tsunami-induced forces

The observed failure mechanisms were often caused by a combination of different tsunami-induced forces which are shown below, along with the method by which these forces were calculated.

Flow Velocity

As tsunami waves have very long wavelengths, they act like shallow water waves. For celerity of shallow water waves Eq. (1) was used:

$$V = \sqrt{gd} \quad (1)$$

where:
V = velocity of the tsunami flow (m/s)
g = gravitational acceleration (= 9.81 m/s^2)
d = flow depth (m)

Hydrostatic Force

According to the Federal Emergency Management Agency (FEMA),USA [7], hydrostatic load can be determined using the following equation:

$$f_{sta} = \frac{1}{2}\gamma_w {d_s}^2 \quad (2)$$

where:
f_{sta}= hydrostatic force per unit width (kN/m)
γ_w = specific weight of fluid(10.1 kN/m^{3}for seawater)
d_s = design still water flood depth (m)

Hydrodynamic Force

Hydrodynamic load can be determined using Eq. (3) (FEMA [7]):

$$F_{dyn} = \frac{1}{2} C_d \rho V^2 A \quad (3)$$

where:
F_{dyn}= horizontal drag force (N)
C_d = drag coefficient (-)
ρ = mass density of fluid (1025kg/m^3 for seawater)
V = velocity of water (m/s)
A = surface area of obstruction normal to flow (m^2)

2.4 Summary of calculated tsunami-induced forces

This section shows the various tsunami-induced forces that were calculated for both events, using the equations given in Section 2.3 above.

Table 1: Inundation heights and calculated flow velocities (2011 Tohoku tsunami)

Location	Inundation Height (m above MSL)	Velocity (m/s)
Otsuchi Town	12.2	10.9
Kamaishi Port	9.0	9.4
Minamisanriku	15.9	12.5
Onagawa	18.4	13.4
Hitachi Port	3.0	5.4

Table 2: Calculated hydrostatic and hydrodynamic forces (2011 Tohoku tsunami)

Location	Hydrostatic Force (kN/m)	Hydrodynamic Force (kN)
Otsuchi Town	750	7513
Kamaishi Port	402	5547
Minamisanriku	1269	9768
Onagawa	1710	11340
Hitachi Port	46	1849

NOTE: 'Surface Area (A)' = 100m^2 was used for hydrodynamic force calculations.

Table 3: Inundation heights and calculated flow velocities (2004 Indian Ocean tsunami)

Location	Inundation Height (m above MSL)	Velocity (m/s)
Kaddhoo	1.3	3.6
Kuchchaveli	6.7	8.1
Palatupana	11.0	10.4
KhaoLak	9.6	9.7
Banda Aceh	7.9	8.8

Table 4:Calculated hydrostatic and hydrodynamic forces (2004 Indian Ocean tsunami)

Location	Hydrostatic Force (kN/m)	Hydrodynamic Force (kN)
Kaddhoo	8	789
Kuchchaveli	227	4129
Palatupana	611	6779
KhaoLak	465	5916
Banda Aceh	318	4893

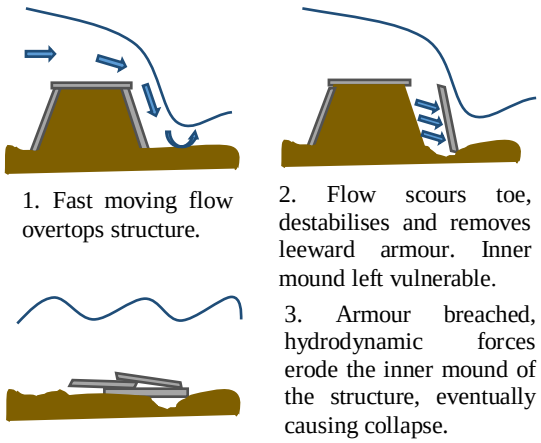
NOTE: 'Surface Area (A)' = 100m^2 was used for hydrodynamic forces calculations.

2.5 Analysis of failure mechanisms

2011 Great East Japan Earthquake and Tsunami

Leeward and Seaward Toe Scour Failure

Failure by leeward toe scour was found to be the major failure mode by which seawalls and coastal dikes failed (see Figure 1).But toe scour did not always lead to the failure of the leeward armour. However it was found that armour failure was commonly caused by toe scour. There were instances where no toe scour was found, but leeward armour still failed. A possible explanation for some of the leeward armour failures may be due to negative pressures caused by fast overflow that imposed suction on the armour and removed it.



1. Fast moving flow overtops structure.

2. Flow scours toe, destabilises and removes leeward armour. Inner mound left vulnerable.

3. Armour breached, hydrodynamic forces erode the inner mound of the structure, eventually causing collapse.

Figure 1: Leeward and seaward toe scour

It is commonly accepted that the shear forces that are induced by rapid flow on the structure toe generated by the overtopping waves are responsible for the toe scour. In order for mitigation methods to be implemented, it would probably be necessary to calculate the shear forces induced by the tsunami waves. Another tsunami induced force that could be useful to calculate in the case of further research would be overturning forces. It was found in the work of Jayaratne et al. [1], Kato et al. [2] and Chock et al. [3]that though leeward toe scour was the main causal factor of failure in seawalls, many seawalls were found to have failed ultimately by overturning. It could be argued that by making the seawalls more resistant to overturning, the scouring would likely have far less of an impact on the structure and may no longer be deemed a mode of failure but simply as some erosion being present. In order to mitigate the problem of scouring completely, the overturning moments induced by the tsunami waves could be calculated and then incorporated into the design process.

Crown Armour Failure

Crown armour failure was found to be one of the more common failure modes in coastal dikes. The major causal factor for this failure mechanism was proved to be negative suction pressure being induced by rapid flow overtopping the structure (Kato et al. [2]). When the suction force was greater than the resisting force (i.e. holding the armour in place), the crown armour was removed and left the inner mound vulnerable to scouring. As shown in Figure 2, once the armour was breached, the enormous hydrodynamic forces often eventually led to complete collapse of the structure.

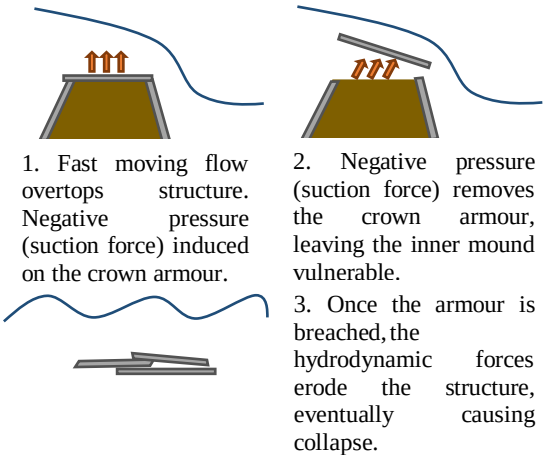
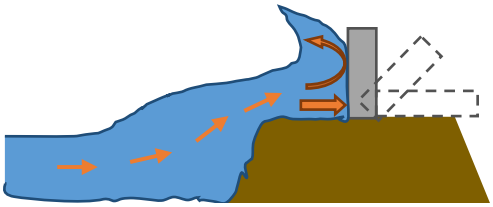


Figure 2: Crown armour failure

Overturning and Parapet Wall Failure

These two failure mechanisms have been grouped together because they work more or less in the same way. It was found that the majority of parapet walls that did fail (this failure mechanism was found to be very common), failed as a result of wave impacting forces. As it is shown in Figure 3, when the impacting forces imposed by the waves exceeded the resisting strength of the parapet wall, the structure was cracked or in some cases destroyed completely. This is very much the same for the overturning of structures such as seawalls and breakwaters. It was found that in many cases where structures failed by overturning, they were caused by the impacting force of the tsunami waves; whether it was the run-up process or the draw-down process. When the overturning moment induced by the waves exceeded the restoring moment, the structure overturned. It was also found that hydrostatic forces induced by differences in water level either side of the structure often resulted in overturning failure.

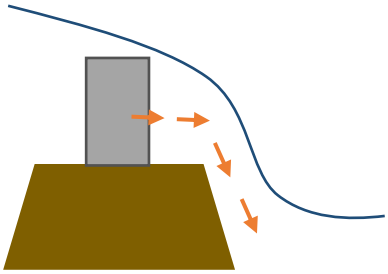


Wave impact causing structure to fail by overturning (Caused by both run-up and draw-down processes).

Figure 3: Overturning and parapet wall failure

Sliding Failure

Sliding failure was the major failure mechanism by which breakwaters failed. As tsunami waves overtopped the structure, a difference in water level on either side of the structure induced lateral hydrostatic forces. These forces pushed the structure, destabilised it and in many cases caused them to fail by sliding.



Pressure difference in either side of the structure causes hydrostatic force large enough to cause the structure to slide (Caused by both run-up and draw-down processes).

Figure 4: Sliding failure

It was noted that scouring would most probably have occurred and destabilised the mound, making it more susceptible to sliding failure. The hydrostatic forces and the presence of scouring were the possible factors in sliding failures. By computing shear forces induced by scouring, relevant measures could be taken to resist these forces. Hydrostatic forces were also calculated in this paper. Based on the calculations, it can be said that structures such as breakwaters would need to be designed to be able to resist against, on average, a maximum force of 1710kN/min regions of Japan, and 611kN/m for regions surrounding the Indian Ocean. Now it would seem that building a structure to resist such large forces would be difficult and expensive. It could also be argued that such a strong structure would not be necessary as hydrostatic forces that high would not occur regularly.

Chock et al. [3] also mentioned that caisson-type breakwaters that were founded on rubble mounds were more susceptible to sliding and overturning failure. It was assumed that this was because of the effects of scouring induced by shear forces on the rubble mound. There are however several different types of breakwaters. It could be interesting to see whether or not other types of breakwaters also failed commonly by sliding and overturning failure or if they failed by different mechanisms. This is an area that could be focused on if further research were to be carried out in future.

Foundation Failure

Saatcioglu et al. [4] found that most of the residential buildings along the shorelines of urban

Thailand had spread footings which are shallow foundations.

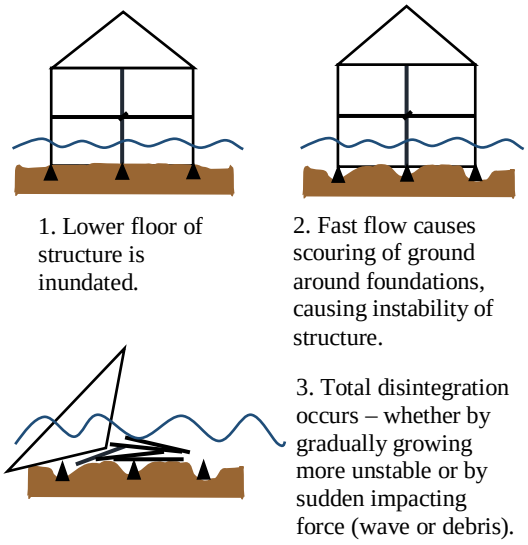


Figure 5: Foundation failure

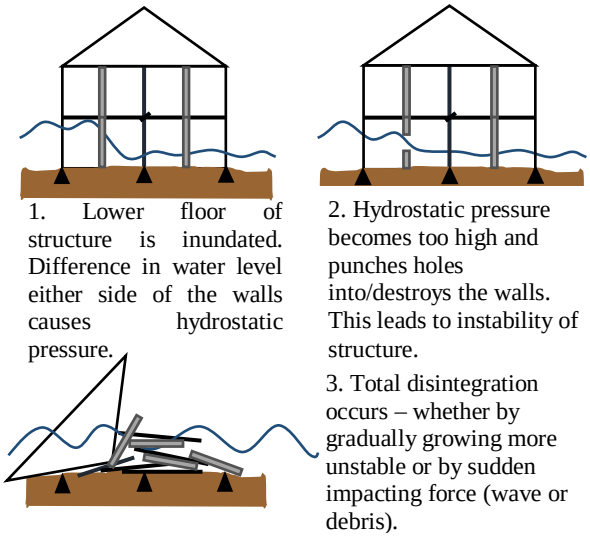


Figure 6: Wall failure

It was found that shear forces were induced by the rapid flow, which in turn scoured the ground around and under the foundations of the structure. This resulted in unsupported foundations. Such lack of foundation support had obvious effects on the stability of the structure and in some cases where the foundation was not quickly repaired, it even led to collapse. In other cases where the structure had already been made unstable, debris impacts and hydrodynamic forces from the waves eventually led to collapse.

As there are not many other studies focussing on the failure mechanisms of coastal structures in Thailand due to the 2004 Indian Ocean tsunami, it is difficult to evaluate the views of Saatcioglu et al. [4]. It can however, in this case, be seen quite evidently from photographs that there wash eavy erosion around the footings of marine buildings. It would be logical to say that the erosion of the footings would have had a large effect on the stability of the structure, and inturn have been a governing factor in the overall collapse of the building.

Wall Failure

Wall failure occurred as a result of differences in water levels on either side of the wall, which imposed hydrostatic forces. These forces, when greater than the resisting strength of the walls, led to punching failures. As the walls serve as part of the structures' frame to support roofs, floors and ceilings, failure of these walls often led to instability of the supported components and eventually to the collapse of the structures.

Total Disintegration

Total disintegration was found to be the major failure mechanism by which structures failed in regions of Indonesia and Thailand especially, under the 2004 Indian Ocean tsunami. It was found that these failures were often caused by systematic failure whereby foundation failure, beam and column failure, joint or wall failure eventually led to the total collapse of the structure. Unlike the wall failures shown in Figure 6, beams, columns and joints serve an essential role in the distribution of loads in a structure. In many cases, when the beams or columns or joints were damaged (due to seismic action, hydrodynamic forces, debris impact etc.) the overall stability of the structure was severely affected. Such instability, when not repaired quickly, often led to collapse. In other cases structures were made unstable and vulnerable by beam, column and/or joints being damaged, and then completely swept away (totally disintegrated) by wave or debris impacts. In other cases structures completely disintegrated under seismic excitation alone, before the waves even reached them. It was more commonly observed however where structures that had already been weakened by seismic excitation from the earthquake, were completely swept away by the tsunami waves.

One of the fundamental reasons why so many structures were devastated by this failure mechanism was the poor quality of design and construction. It was observed that even though a few structures were structurally well-engineered,

they were not built to withstand seismic forces. This may have been because the surveyed areas were previously not as prone to seismic activity as Japan.

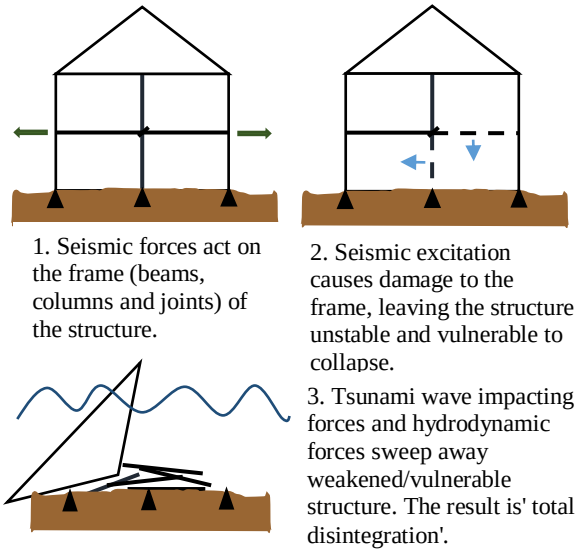


Figure 7: Total disintegration

Thus, when designing for future structures, it would be necessary to incorporate concepts of earthquake engineering into the structures to be at the least somewhat resistant to seismic action. It was discovered that many structures had strong beams and weak columns, which is seen to be one of the worst possible combinations in earthquake engineering. Ideally, a structure would need to remain stable and strong enough to withstand the hydrodynamic forces imposed by tsunami waves even after seismic excitation. According to the calculations carried out by the authors, a structure of surface area 100m^2 in the Indian Ocean regions would need to be able to withstand drag forces of up to about 6.8 MN. Now as was the case with the hydrostatic forces, it would be difficult to design a structure to withstand such a force, and even if it were possible it would likely be very expensive and inefficient. An alternative would be to develop methods of minimising the hydrodynamic forces to some extent and also to incorporate strengthening measures to structures so that the combination of the two methods would allow for structures to resist the hydrodynamic forces without failing.

3. Viable solutions and strengthening measures

Scouring

In this study, it was found that toe scour posed a significant threat not because the scouring itself rendered the structures unusable, but because they led to the destabilising of the structures and made them more susceptible to overturning and sliding failures. As this is the case, two logical approaches could be taken in order to strengthen the structures against failure:1) Strengthen the toe region of the structures to avoid/resist erosion in the first place,2) Second approach would be to make the structure more stable so that even if scouring were to occur, it would not be enough to cause the structure to fail.

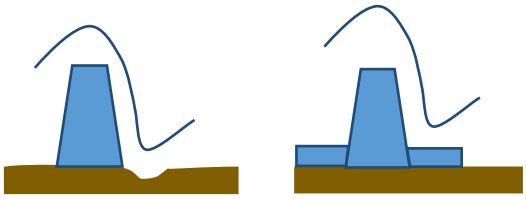


Figure 8: Toe scour (left), Protected toe (right)

If the first approach were to be taken, various materials could be used to create an elongated toe part that would come into contact with the rapidly overtopping flow. If the toe of the structure is elongated as shown in Figure 8, the structure is more stable in two ways;1)The elongated toe part will be the part of the structure the rapidly overtopping flow will impact [as opposed to ordinary soil as shown in Figure 8 (left)]. This means that worst case scenario, the elongated toe part will be damaged, but the soil underneath will not be scoured and the structure will therefore remain stable. The elongated toe effectively works as a sheet of armour protecting the soil on either side of the structure against scouring. Considering that such methods could prove to strengthen the structure against failing completely, it could be deemed a worthwhile investment despite the costs. 2) The elongated toe part of the structure is directly connected to the base of the structure, giving it more stability against overturning failure. It is commonly known that structures or objects with a wider base are more difficult to overturn. By implementing such elongated toes to these structures, they would be protected against the effects of both scouring and overturning failure. In order to make this method affordable and sustainable, cheap but durable materials could be used, perhaps materials that are recycled/recyclable or reusable such as aggregates.

These elongated toe parts could also be designed to be removable/ attachable to the main structure. This would allow for just the toe parts to be replaced in the event of one of them being damaged, rather than having to repair/replace the whole structure which would be more expensive and inefficient. This would also be beneficial as such parts could be added to already existing

structures as well as ones that are to be built in future. One thing that should be considered however is the method by which these attachable parts will be held in place. In crown armour failure, it was understood that the tsunami-induced negative pressures lifted and removed the crown armour from their existing places. It is possible that such negative pressure could remove these attachments if they are not securely fixed to the structures.

The second approach mentioned above, involved making the structure more stable so that even if scouring were to take place, the structure would remain unaffected. This could be done by embedding the foundation of the structure deeper into the ground, much like pile foundations, which would give the overall structure greater stability than if a structure has shallow foundations. This approach could be somewhat problematic however, especially for existing structures. Such methods could be implemented into proposed new construction. An alternative method would be to increase the self-weight of the structure which would make it more resistant against overturning forces.

Total Disintegration

It is fundamental when designing for structures to be resistant against seismic excitation, to have a frame with strong columns and weak beams (the opposite of that found in the structures in Indonesia). The reason for this is earthquakes usually cause a lateral movement of the earth. Such excitation is known to cause stiff columns to snap and flexible columns to sway in the direction of the seismic movement. If columns are strong, they are able to withstand the seismic action without snapping/breaking. Beams on the other hand connect column to column. When columns begin to sway due to seismic excitation, the beams if too stiff would simply snap. By adopting a strong columns and weak beams configuration, the structures would become more resistant to seismic excitation. This configuration could easily be applied to future design and construction and also to already existing structures by using various methods of reinforcement. It was found through interaction diagrams that the columns observed in regions of Thailand could not even sustain half of the moments that were imposed, before failing. But columns that had lateral bracing provided by in-plane infill walls were found to survive against the seismic action as well as the tsunami waves. Such information could be taken into consideration and additional lateral bracing could be applied to columns, whether by infill walls or by alternative methods.

Other practises included in earthquake engineering could also be incorporated into design. Factors such as stiffness and orientation of the building's shape could also be considered in designing process. For example though uniform distribution of stiffness is ideal (i.e. the top through to the bottom of structure have the same stiffness,) when this is not possible, lower floors of the structure should be made stiffer and the upper floors should be made increasingly less stiff to avoid a 'soft storey mechanism', in which case the lower floors would simply snap or collapse and bring down the rest of the structure. The changes in stiffness between each floor should also be gradual. It must also be ensured by careful design that there is a balance in stiffness of the columns and structure in both directions. Again these strengthening measures could be applied to structures being designed and built in the future, and they could also be implemented by methods of reinforcement to already existing structures.

4. Conclusions and further studies

4.1 Conclusions

The failure mechanisms by which coastal structures failed in two extreme events were identified; both patterns identified by researchers in the past and new patterns were found. Some of the major tsunami induced forces responsible for the failure patterns were identified and quantified through theoretical models and simple calculations. Trends regarding these forces were also found and linked back to the failure mechanisms. Numerous weaknesses, vulnerabilities and patterns in the coastal structures were discovered and some basic strengthening measures and concepts were produced in order to account for these vulnerabilities. The major failure mechanism found in coastal dikes and seawalls was leeward toe scour and sliding failure was most common in breakwaters for the 2011 Tohoku Tsunami. For the 2004 Indian Ocean Tsunami the major failure mechanism found in coastal and residential structures was total disintegration.

Some of the major tsunami induced forces were identified and quantified. These included:

- Flow velocities
- Hydrostatic forces (lateral)
- Hydrodynamic (drag) forces

Numerous vulnerabilities were discovered in the coastal defence structures. Seawalls and coastal

dikes were found to be weakest at the toe of the structures. The toe must be strengthened to withstand overturning failure. Concrete breakwaters (caisson-type) were weakest where the toe of the structure linked onto the mound. Again the toe must be strengthened to resist scouring and sliding in breakwaters.
Residential structures found in Indonesia and Thailand were poorly designed against seismic action. A 'strong column, weak beam' configuration must be adopted. Reinforcing measures must be implemented to the columns and joints especially.

4.2 Further studies

Sediment characteristics, geomorphology and terrain should be analysed to see if these have an effect on the stability of structures. Perhaps this could be done by carrying out sieve analyses and by studying the samples. Also the failure mechanisms of ordinary residential coastal structures in Japan (not defence structures) should be compared with those found in residential structures that failed due to the 2004 Indian Ocean Tsunami event. It would be interesting to see how the failure mechanisms differ between well-engineered and non-engineered structures.

Acknowledgement

The authors would like to acknowledge the financial contribution of the "REF 2020 Research Funding" from the University of East London for presenting this paper at the 6th ICSECM conference in Kandy, Sri Lanka. They are also grateful to the University of Peradeniya for waiving the registration fee of the conference.

References

[1]. Jayaratne, R., Premaratne, B., Mikami, T., Matsuba, S., Esteban, Shibayama, T. and Marriott, M. (2013).Probable failure modes of coastal structures in Miyagi and Fukushima Prefectures due to the 2011 Great East Japan Earthquake Tsunami, 4th Int. Conf. on Structural Engineering and Construction Management, Kandy, Sri Lanka.

[2]. Kato, F., Suwa, Y., Watanabe, K. and Hatogai, S. (2012). Mechanisms of coastal dike failure induced by the Great East Japan Earthquake tsunami, 33rd Int. Conf. Coastal Engineering, Santander, Spain.

[3]. Chock, G., Robertson, I., Kriebel, D., Francis, M. and Nistor, I. (2011). Tohoku Japan Tsunami of March 11, 2011 Performance of structures, ASCE.

[4]. Saatcioglu, M., Ghobarah, A. and Nistor, I. (2006). Performance of structures in Thailand during the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami, Earthquake Spectra, 22(S3), pp.355-375.

[5]. Jayaratne, R., Mikami, T., Esteban, M., and Shibayama, T. (2013). Investigation of coastal structure failure due to the 2011 Great Eastern Japan Earthquake Tsunami, Coasts, Marine Structures and Breakwaters Conference, Institution of Civil Engineers (ICE), Edinburgh,UK.

[6]. Shibayama, T., Okayasu, A., Sasaki, J., Wijayaratna, N., Suzuki, T., Jayaratne, R., Masimin, Ariff, Z., and Matsumaru, R. (2006). Disaster survey of Indian Ocean Tsunami in South Coast of Sri Lanka and Ache, Indonesia, 30th Int. Conf. on Coastal Engineering, ASCE, San Diego, USA, pp. 1469-1476.

[7]. Federal Emergency Management Agency. (2011). Coastal Construction Manual, Vol. II: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Buildings in Coastal Areas, 4th Edition.