Response of Coastal Buildings Subjected to Seismic and Tsunami Forces

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Abstract:
A devastating tsunami generated by the great Indonesia earthquake on 26th December, 2004, revealed the importance of constructing seismic and tsunami resistant structures in coastal regions. Hence, it is necessary to establish analytical methods for obtaining the response parameters and comparing them when structures are subjected to both earthquake and tsunami forces.

In this paper a two storied shelter building is chosen for the analysis considering six different types of structural configurations and a comparative study is made on the response of these structures. In this analysis, base shear values are determined using IS 1893(2002) seismic code and hydrodynamic forces are evaluated using FEMA'S CCM. Buildings with open storey at bottom and upper stories with heavy mass give significant rise to the time periods causing early failures during earthquake before tsunami arrives the coast. The authors have also evaluated a useful guideline for demarcating the height of the building below which earthquake forces are predominant and above which tsunami forces are predominant.

1. Introduction

Geological evidences reveal that most strong earthquakes, representing 80% of total energy released by earthquakes, are considered to occur in subduction zones where an oceanic plate slides under a continental plate or another young oceanic plate. On 26th December, 2004, Indonesian submarine earthquake with a Richter magnitude of 9.3 generated catastrophic tsunamis killing more than two lakh people and created a major economic impact on the countries surrounding the Indian Ocean. Such mega events reminded the coastal community alert on the preparedness against initial ground shaking and subsequent effects followed by tsunamis. As most of the tsunamis are earthquake induced tsunamis, it is necessary that coastal structures should be designed against both earthquake and tsunami loads. Seismic and Tsunami resistant analyses are complicated as the motion is transient and the forces are time dependent. Though there are no well established design procedures for tsunami resilient buildings, FEMA CCM provided some guidelines based on the type and nature of tsunami forces. A review by Harry Yeh, Ian Robertson and Jane Preuss(2005) suggested that fluid forces exerted on a structure can be evaluated in terms of hydrodynamic and forces for a given depth of inundation and the velocity of the approaching tsunami.

Okada et al. (2005) have proposed an empirical method for estimating the forces exerted on structures by tsunami overland flow assuming that seaward face of the building will be loaded by a hydrostatic pressure based on an immersion depth of three times the design inundation depth, with no load on the landward face of the structure. The impact of the earthquake reportedly altered the topography in certain regions and strongly warned the community particularly along the Indian coast and Andaman and Nicobar (A&N) Islands. Although tsunamis cannot be prevented its impact can be minimized through mitigation measures like community preparedness, timely warnings public education and enforcement of byelaws. Another concern is lack of integration of seismic codes with other construction codes. The concrete design code (IS 456-2007) does not give cross reference to detailing code (IS-13920-1993) and often the professional engineers are unaware of additional detailing requirements.

The process of long-term planning and civil engineering research should raise to the occasion so that protection measures against earthquakes and tsunamis become ingrained in the designs.

2. Earthquakes and Earthquake Effects

The honor of greatest earthquake of all times goes to the 1960 Chile earthquake which measured 9.5 on the moment magnitude scale where Nazca plate subducted under the south American Continent .The focus of the earthquake was 60 km down below the ocean floor and about 160 km off the coast of Chile out in the pacific. Not only was there damage to the manmade structures during earthquake, but the earth itself was forever changed by enormous amount of energy released. Huge landslides, massive flows of earthen debris and rock material were sent down the mountain slopes and some landslides changed the course of major rivers.

December 26, 2004, Indonesia earthquake was the second largest ever recorded and the duration of the earthquake was long but the focal point was at about 30 km depth. The ocean floor area was covered by soft soil contributing to the implication of seismic waves. The strongest shaking was felt in Banda Aceh, Indonesia, causing significant damage. Many seismic deficiencies of buildings, known to cause poor structural performance, were clearly witnessed throughout the city, Banda Aceh. During earthquake shaking, the R.C. frame buildings which appeared to have been constructed with strong and relatively deep beams supported by weak and smaller dimensioned columns suffered severe damage or collapse showing the signs of formation of early hinging at top level of columns, while the majority of beams remained elastic until the collapse. Lack of joint reinforcement also caused the above failures. Soft stories in most of the commercial buildings suffered increased deformations coupled with lack of confinement and column deformability resulted in column failures at many places. Failure of first story columns attributed the collapse of entire building. Lack of transverse reinforcement in column splice regions, coupled with inadequate splice lengths and seismic design practices also resulted in column failures. Unreinforced masonry constructions used as exterior and interior infill walls increased the building mass and attracted seismic forces.

A devastating earthquake measuring a magnitude 7.3 on the Richter scale struck Haiti on 12th January 2010 and killed more than two lakh people leaving hundreds and thousands homeless. With a gap of few weeks after occurrence of Haiti, another 8.8 magnitude earthquake hit the Chilean coast on 27th February 2010. But a prolonged Tsunami warning issued by the Japanese authorities sent five lakh people fleeing for elevated places thus reducing the death toll drastically to 891. Through Haiti is less powerful temblor compared to chile earthquake, the extent of damage to structures and loss of life in Haiti is much higher. The reason lies not just in Chile's longer experience with geologic adversity, but also the capacity of Chileans' government to enact and enforce the building codes and rescuing operations.

3. Tsunamis and Tsunami Effects

Tsunamis have great erosional ability and they can strip beaches of sand and coastal vegetation. Likewise, tsunamis are capable of inundating the coastal lands. The fast-moving water associated with the inundating tsunami can destroy houses and other coastal structures. A tsunami generated by the Niigatta earthquake 1964 caused damage to port and harbor facilities because of ground failure and liquefaction as a result of ground subsidence. The erosion of soil underneath the foundation during the tsunami caused settlement of many structures during the 1964 Alaska earthquake. Series of tsunamis in Japan in 1986 killed 27000 people. 1992 Nicaraguan earthquake tsunami deposited a vast sediment blanket over many low lands along the affected area. An earthquake occurred in Java trench in 1994, triggered a large tsunami and killed 200 people. 1998 Papua New Guinea tsunami that killed more than 2100 people, with wave heights up to 12 m, was triggered by a submarine slump.

Tectonic Tsunamis tend to have longer wave lengths, longer periods and a larger source area than those generated by mass movement of the earth. The geometry of earthquake fault constitutes a ternary family featuring three fundamental parameters; strike-slip, thrust and normal fault. Strike-slip is a transform fault, which produces horizontal motion of Earth's crust; where as thrust and normal faults entail vertical motion. Generally, the larger the magnitude of an earthquake, the larger the area that is deformed. Hence, submarine thrust or normal faults produce tsunamis as the sea floor lifts up pushing the water up on one side or drops down pulling it down on the other side, and causes triggering wave motion on the ocean surface. Strong earthquakes not only deform larger areas, but they do so by a greater amount of slip, thus producing larger tsunamis than smaller events. Earthquakes deeper than about 30 km, rarely cause sufficient deformation to generate tsunamis. However, truly mega thrust earthquakes, which occur deeper than 30 km, such as 1960 Chile event and recent 2004 Sumatra earthquake can also occasionally trigger tsunamis.

The energy imparted to the water during tsunami formation sets the entire water column in motion. Hence, tsunamis not only possess a lot of energy and move at high speeds, but they can also travel greater distances with little energy loss. In typical ocean depth of 4 km, a tsunami travels at a speed of nearly 700 kmph. When tsunamis enter shallow waters, they slow down; at a depth 30 m, shallow water waves travel at only 60 kmph. Like wise, tsunami transforms as it leaves the deep water of the ocean and travels into shallow water near the coast. The first piece of information required for modeling tsunamis is the size and distribution of seafloor deformation following an earthquake and the amount of energy released. The tsunami speed further diminishes as it travels into the shallower coastal water and its height grows. While tsunami may be imperceptible at sea, the shoaling effect (Fig. 1) near the coast causes the tsunami to grow to be several meters of height. When it finally reaches the coast, the tsunami may develop into a rapidly rising or falling tide, a series of breaking waves.

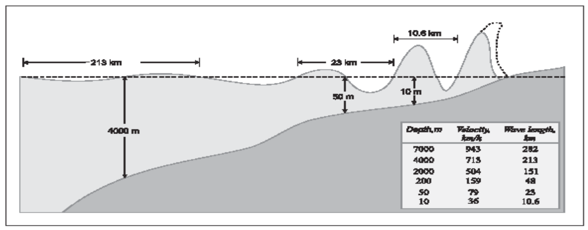

Fig. 1 Shoaling effect of Tsunami

During 2004 Indonesian Earthquake, due to subduction of Indian plate underneath the Burma plate, A & N Islands sustained for both uplift and subsidence. The southernmost tip of Great Nicobar Island, which was on elevated ground before earthquake is now under water, indicating a land subsidence of about 3m. On the other hand, the western coast of Middle Andaman Islands showed emergence of new shallow coral beaches suggesting an uplift up to 0.3m and Diglipur harbor at Northern region of Andaman indicated an uplift of 1.2 m. US geological survey expert, Ken Hudnet said that some of smaller islands off the Southwest coast of Sumatra may have moved to southwest by about 20 m.

In Thailand and Indonesia, it was observed that non-engineering R.C. structures, low rise timber frames, non-reinforced masonry buildings suffered extensive damage due to hydrodynamic pressures generated by tsunami and impact forces induced by floating debris; where as Banda Aceh, Indonesia, suffered extensive damage due to seismic excitation. In Kata Beach, Thailand, the tsunami wave height was measured approximately 6m above sea level. Some of the failure examples that were reported are

- Widespread failure of masonry infill walls within the first storey level of most frame buildings.
- Damage of prefabricated R.C. slab strips due to uplift forces caused by hydrostatic pressures.
- Lack of proper anchorage to the supporting beams was balanced for failure of these slab systems.
- Storage tanks should be well anchored to their foundations to resist tsunami pressures.
- Light timber frame buildings are extremely vulnerable to tsunami pressures.
- Soft stories experienced widespread damage, often resulting in the collapse of first stories some times leading to total building collapses.

While the topographical changes in little A & N Islands are tsunami-related, the failure of many non-engineering structures and poorly constructed R.C. buildings are due to earthquake shaking. Jain et al. (2005) made aerial and field surveys along east and west coastlines of India and A & N Islands, immediately after the occurrence of 2004 earthquake tsunami. Some interesting observations on damage both due to earthquake ground shaking and tsunami impact were analyzed. Damage due to earthquake shaking was recorded mainly in A & N Islands since the long duration of shaking coupled with low water table led to liquefaction at many coastal areas.

Experimental studies were conducted to estimate the tsunami force exerted on damaged coastal structures through in situ strength tests. Strong and flexible objects like handrails of balcony or staircase remained slightly deformed or bent even after being hit by gigantic tsunami. Series of in situ strength tests were conducted by Tsutsumi et al. (2000) on similar handrail samples to determine the forces needed to deform them in a same manner as those of handrails bent during the Southwest Hokkaido earthquake tsunami of 1993. Tests were also performed to estimate the advancing direction, true height and flow velocity of the tsunami on land for the future assessment of tsunami disasters.

4. Design Parameters:

Though there are well established procedures for earthquake analyses, till recent years, no significant research has been undertaken on design of structures to resist tsunamis. The design requirements for seismic response generally depend upon the weight, structural flexibility, ductility and redundancy; while the design parameters for tsunami forces require considerable strength and rigidity of the structure particularly at lower levels. The wave height of tsunami approaching the shore results from the influence of three dimensional bathymetry and coastal topography. Even though use of good engineering techniques and materials will help a structure to resist tsunami forces, in case of large tsunami events such as December 26, 2004 tsunami, they will only reduce losses but can not prevent severe damage. The best way to minimize the tsunami losses is to construct tsunami shelters for vertical evacuation or locate buildings beyond the reach of tsunami run-up for horizontal evacuation.

5. Method of Analysis

In this paper a two storied R.C. shelter building for evacuees is chosen for the study and the analysis for dynamic response against both seismic and tsunami forces is carried out considering six different types of configurations of the shelter.

Type 1 : Both G.F. and F.F. with outer and inner infill walls.
Type 2 : G.F. with outer and inner infill walls and F.F. with only outer infill walls
Type 3 : G.F. with only outer infill walls and F.F. with both outer and inner infill walls.
Type 4 : Both G.F. and F.F. with only outer infill walls.
Type 5 : G.F. with cellar and F.F. with only outer infill walls.
Type 6 : G.F. with cellar and F.F. with both outer and inner infill walls.

5.1 Structural Features

The shelter is 12m x 12m size in plan with three equal bays 4m each and is structured with sixteen columns, the height of each storey being 3.35m. Member dimensions are with 120mm thick floor slabs, 230 x 400 mm beams and 300 x 300mm columns. Thickness of outer infill walls and inner infill walls are taken as 230mm and 150mm respectively.

The values of Young's Modulus for reinforced cement concrete and masonry are taken as 22360 N/mm^2 and 13800 N/mm^2 respectively.

The six types of structures are analyzed based on the consideration of dynamic forces associated with earthquake and tsunami separately. Normally most of the tsunamis are triggered due to undersea earthquakes and hence the coastal structures are subjected to ground shaking initially followed by tsunamis later.

Though coastal structures are subjected to severe wind pressures, past research results indicate that impact of hydrodynamic impulsive wave pressures are much higher than wind. Hence, in this analysis wind force is not considered. Hydrodynamic forces caused by different tsunami induced inundations are compared with earthquake forces when these structures are located in different seismic zones.

5.2 Analysis for Earthquake Forces

The present analysis is carried out considering the shelters are situated in seismic zones II and III as the majority regions along the east coast belt of Indian peninsula fall under the category of these two zones according to latest IS 1893 code.

All the six types of the chosen structures are idealized as mass-spring models treating each system with two degrees of freedom with an assumption that the structure is fixed at the base. The stiffness of each storey is evaluated considering the effect of stiffness of infill walls also. In case of the storey without infill walls, each column stiffness value is taken as $k_c = 12\ E_cI_c/h^2$ and the stiffness of each storey is worked out. In case of storey with infill walls, the system is modeled as a braced frame approximating the infill wall as an equivalent diagonal strut. The vital approach is to determine the effective width of the equivalent diagonal strut (w_e) which depends on

i) The length of contact between the wall and the column, α_h and
ii) The length of contact between the wall and the beam, α_l.

where

$$\alpha_h = \frac{\pi}{2}\left[\frac{E_c I_c h}{2E_m t \sin 2\theta}\right]^{1/4} \quad and \quad \alpha_l = \pi\left[\frac{E_c I_b l}{E_m t \sin 2\theta}\right]^{1/4}$$

The formulations of Stafford Smith (1966) given below are used to calculate stiffness of infill wall, k_w.

$$k_w = \frac{A E_m \cos^2\theta}{l_d} \qquad (1)$$

In Eq. 1,

$$l_d = \sqrt{h^2 + l^2}\ ; \ \theta = tan^{-1}\left[\frac{h}{l}\right],\ A = w_e \text{ x } t \ and \ w_e = \frac{1}{2}\sqrt{\alpha_h^2 + \alpha_l^2},$$

Where

A – Area of cross section of the member
E_c – Young's Modulus value of reinforced cement concrete
h – Height of the wall/column
E_m – Young's Modulus value of masonry
I_b – Moment of inertia of column element
I_c – Moment of inertia of beam element
l – Length of the wall
t – Thickness of the wall

The total equivalent stiffness of each storey is taken as $\sum k_c + \sum k_w$.
The masses and equivalent stiffness values of each storey for each type of structure are worked out for the use in the analysis. Free vibration analysis software is used for obtaining the fundamental time periods of these structures. The values are presented in Table 2, and the graphical representation has shown in fig.3. Based on these time period values, response spectral curves given in IS 1893 code are used to calculate the shears at ground and first floor levels for all the cases. The base shear values are worked out when these structures are situated in seismic zones II & III and the results are presented in Table 2.

5.3 Analysis for Tsunami Forces

According to Camfield (1994) the following types of forces may result when tsunami run-up strikes the buildings with high velocities.

- Hydrostatic forces caused by partial or fully submergence of structures.
- Hydrodynamic forces caused by high velocity of surging water.
- Buoyant forces caused by partial or full submergence.
- Impact forces caused by driftwood, small boats, lumber, portions of houses and other debris material carried away by surge water.
- Surge forces caused by leading edge of the surge impinging on a structure.

In principle, the calculation of wave force on a structure involves the integration of pressure and shear force over the exposed area of the structure.

In the event of a large tsunami, design codes provide expressions for different forces that may be produced due to tsunami wave impact on coastal structures. When turbulent water flows around the building, hydrodynamic loads are applied to the structure in the direction of approaching tsunami wave. These loads are caused by the impact of moving mass of the water and friction forces as the water flows around the obstructions. In the analysis only hydrodynamic forces are considered and the equations suggested by Harry Yeh et al. (2005) are used.

Assuming the beach slope 1 in 50 as in Fig.2, inundation depths (h_{max}) are calculated for different tsunami heights when these structures are located at distances 100 m and 150 m from the shore. Inundation depth and flow velocity of a tsunami wave are the important parameters for evaluation of external forces imparted to the structures.

It may be noted that, if a structure is situated at an elevation of 2m above sea level, the 3m flow (inundation) depth at the building site would be equal to 5m tsunami.

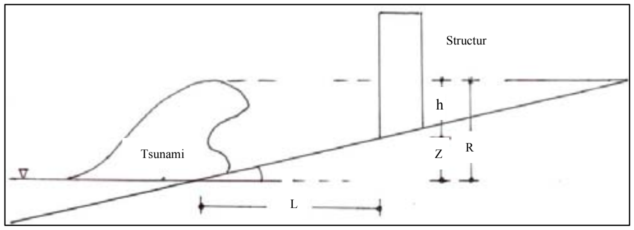

Fig. 2 Run up Zone of Tsunami

Hydrodynamic (drag) force is expressed as proportional to the product of the square of flow velocity and the projected area of the structure. The drag coefficient value, C_D, is taken as 2.0 for rectangular column members and 3.0 for wall members. In the present study C_D value is taken as 2.0 for square colomns. For a given location, the design value of (h_{max} u^2) is computed from Eq.2 and the corresponding drag force, F_D, is obtained from Eq.3.

$$\frac{h_{max}u^2}{gR^2} = 0.125 - 0.235\,\frac{Z}{R} + 0.11\left[\frac{Z}{R}\right]^2 \qquad (2)$$

$$F_D = \frac{1}{2}\,\rho C_D\, b h_{max}\, u^2 \qquad (3)$$

where
L – Distance of location of the structure from shore line
R – Maximum run up height of tsunami above shore line
Z – Height of location point of the structure above shore line
h_{max} - Maximum Inundation Depth above base of the structure
u – Tsunami wave velocity approaching the structure
ρ - Mass density of sea water
b - Breadth of exposed column/wall member
Using Eq.3, the values of hydrodynamic force on all types of structures are calculated for different inundation depths and the values are presented in Table 2.

It may be noted that, the analyses are carried out for independent actions of tsunami and earthquake separately, when the structures are located in different seismic regions. Hence, Eq.3 depends only on the intensity of tsunami and does not depend upon the seismic zone.

Table 2. Time period and base shear values due to earthquake forces and hydrodynamic forces due to tsunami

Type of Structure	Due to earthquake				Due to Tsunami			
	Natural Time Period (sec)	Seismic Zone	Base Shear (KN)		Hydrodynamic force in (kN) when			
			ground floor level	First floor level	h_{max} = 2m	h_{max} = 3m	h_{max} = 5m	h_{max} = 6m
Type - 1	0.088	II	287.0	216.7	72.6	149.4	412.0	575.0
		III	459.1	346.7				
Type - 2	0.091	II	269.5	202.3				
		III	431.3	323.7				
Type - 3	0.107	II	297.64	228.5				
		III	476.2	365.6				
Type - 4	0.110	II	274.5	210.0				
		III	439.2	336.0				
Type - 5	0.385	II	256.0	201.3	28.5	59.84	200.0	310.0
		III	409.6	322.0				
Type - 6	0.400	II	279.8	220.4				
		III	447.6	352.6				

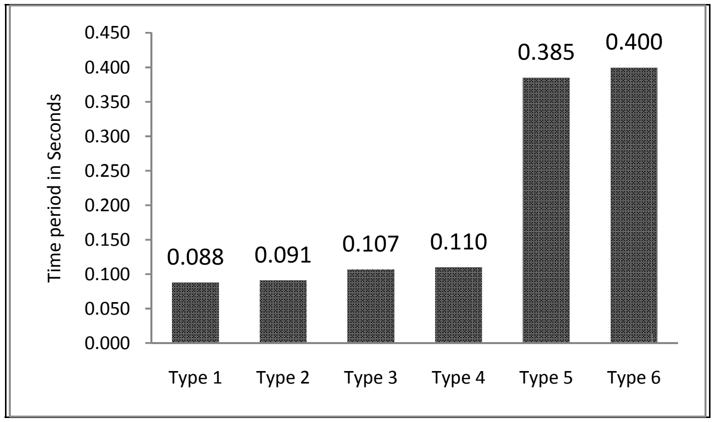

Fig.3 is the graphical representation of Type of Structure Vs Time period due to Earthquake Forces

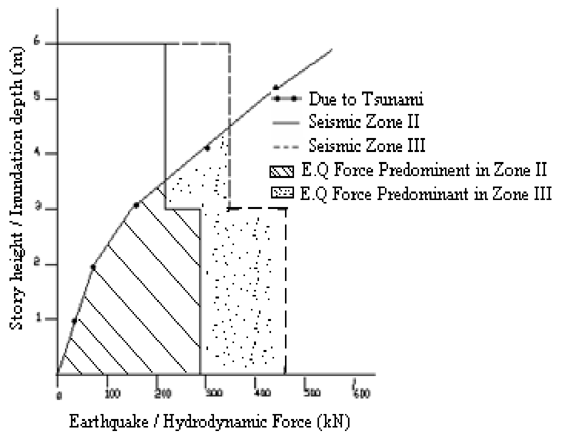

Fig.4 Type - 1 Structure

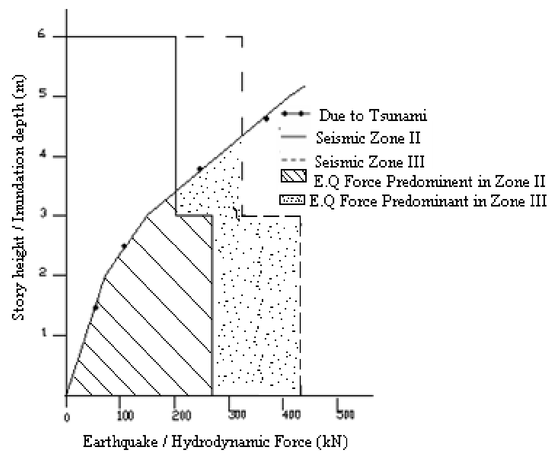

Fig.5 Type -2 Structure

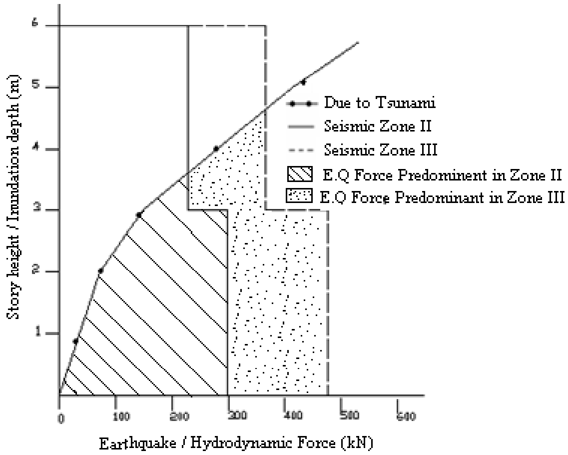

Fig. 6 Type - 3 structure

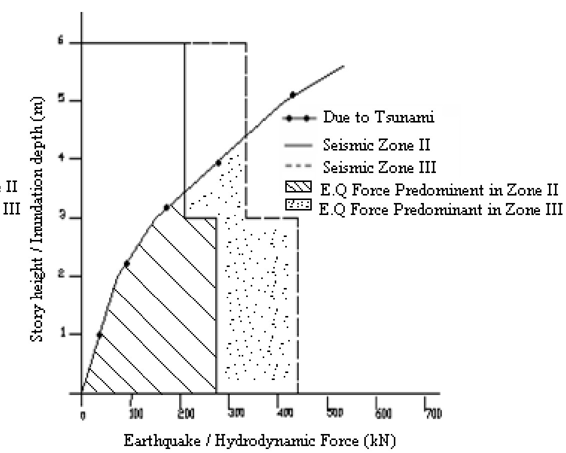

Fig.7 Type - 4 Structure

Fig. 4 is the graphical representation of Storey height vs Shear force due to earthquake and Inundation depth vs Hydrodynamic force due to tsunami for Type - 1 structure. Corresponding results for Types 2 - 6 structures are shown graphically in Figs. 5~9.

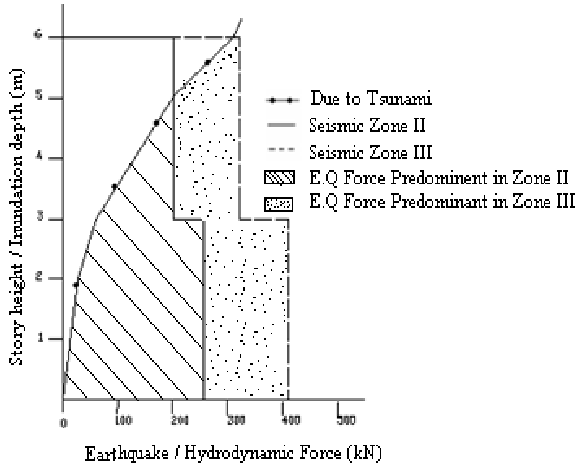

Fig.8 Type - 5 Structure

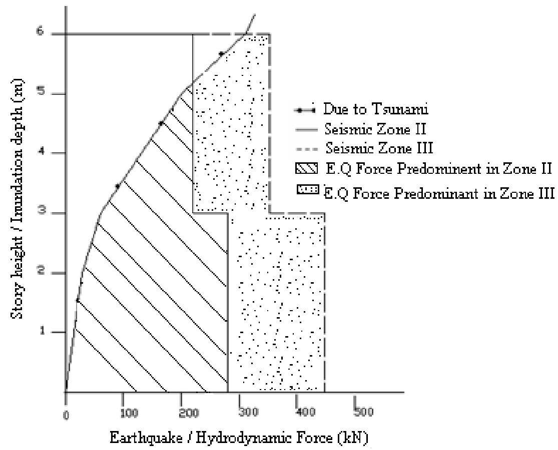

Fig. 9 Type - 6 Structure

6. Result Analysis

The time period values of the chosen six buildings with different structure configurations are shown in fig.3
The time period values of Type – 1 to 4 structures are found less compared to Type 5& 6 structures which indicates that reduction of stiffness in ground storey increases the time period of the structure, particularly when ground floors are with cellars.

The earthquake force mainly depends upon the characteristics of ground motion, stiffness, seismic weight and configuration of the structure; while in case of tsunami, the imparted forces on the structure depend upon the velocity, inundation depth and the exposed area on the wave side of the structure. From the results, it is observed that slender structures produce less base shear compared to those of rigid structures. It is also observed that reduction in mass at lower floor levels decrease the base shear value.

Further, from the graphs, it is noticed that at some specific height, h_c, the tsunami force and earthquake force are equal in magnitude. Such h_c values for the six types of structures when situated in seismic zones II & III are presented in Table 3. For values below h_c, earthquake forces and values above h_c, tsunami forces are predominant. This could be an effective guideline for better design in future.

Table 3. Proposed guideline for design

Type of Structure	Seismic Zone	h_c (in meters)	Design criteria
Type - 1	II	3.4	i) for heights > h_c, the design shall be for tsunami forces and ii) for heights < h_c, the design shall be for earthquake force
	III	4.4	
Type - 2	II	3.3	
	III	4.2	
Type - 3	II	3.5	
	III	4.6	
Type - 4	II	3.4	
	III	4.2	
Type - 5	II	5.1	
	III	6.0	
Type - 6	II	5.2	
	III	6.0	

7. Conclusions

- The shelter should be designed both for ground shaking initially and for subsequent triggered tsunami.
- Decrease in stiffness of lower level floors (soft-storey) increases the time period of the structure.
- Base shear values against seismic conditions increase with increase of stiffness in upper floors and decrease

with increase of stiffness in lower floors, justifying the general conclusion that flexible structures are more resistant to earthquakes forces compared to rigid structures.

- R.C. frame buildings with open ground storey are considered effective to reduce the tsunami force; where as such soft stories tend to fail under severe seismic conditions. In view of this a balanced design approach is necessary in planning Earthquake – Tsunami - Resistant shelters.
- Weight of structure plays vital role under seismic conditions, while the exposed area on seaward side of the structure in run up zone is a major factor to resist tsunami wave pressures.
- The shelter should be designed to allow the waves to pass through by braking the walls (non-structural elements) at tsunami reached level, mostly at ground floor, while the structural elements (column, beam, lateral bracing and other structural connections) are designed to withstand the tsunami impact.
- Depending upon the intensity of the tsunami and the seismic zone in which the structure is located, the design criteria should be such that, below the height (h_c) earthquake forces are to be considered, while above the height (h_c) the tsunami forces are to be considered

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