Behavior of Building Frames under Tsunami Loading

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Abstract—**The coastal population has increased significantly over the past several decades. The increased coastal population led to increased coastal development, which led in turn to great number of structures at risk from coastal hazards. In this study, a G+5 storey reinforced concrete building is analyzed for earthquake and tsunami considering different earthquake zones and different tsunami heights. Based on results, it is found that with the increase in earthquake zone number and tsunami height, values of response quantities of interest i.e. base shear, shear force in column, bending moment and insterstorey drift increases. However, the values of response quantities for tsunami is quite high as compared to earthquake loading.**

Index Terms—**earthquake, Tsunami, base shear, bending moment, SAP 2000**

I. Introduction

India has witnessed several major disasters such as earthquakes, tsunami, floods, cyclone and blast in the last two decade. An event like a tsunami is rare as compared to other natural hazards. Until December of 2004, the phenomena of the tsunami were not on the minds of most of the world's population. The Great-Indian Ocean Tsunami on 26 December 2004 severely affected communities bordering the Indian Ocean, including the coasts of Indonesia, Sri Lanka, and Thailand, Maldives Island as well as the littoral zones of several West African countries. The moment magnitude of the earthquake which caused this tsunami was 9.1 and this resulted in the displacement of the seafloor in the vertical direction which resulted in tsunami that killed about 2.30 lakh people.

Similarly, on 11th March 2011, a moment Magnitude 9.0 earthquake struck off the northern coast of Japan. This earthquake generated a tsunami that rose up to 133 feet height above sea level and killed over 20000 people and caused billions of dollar economic loss to Japan. Because of Japan's familiarity with earthquake and enforcement of earthquake- resistant building codes, there was minor destruction from the earthquake. But even though a tsunami warning system was in place, the earthquake was so close to the coast that there was little time available for people to reach the safe place.

Recently, on 28 September 2018, a shallow large earthquake struck in the neck of the Minahasa Peninsula, Indonesia with its epicentre located 77 km away from the provincial capital Palu in the mountainous Donggala Regency, Central Sulawesi. The moment magnitude of the earthquake was 7.5. Due to the earthquake, a localized tsunami struck at Palu, sweeping shore-lying houses and buildings on its way. The combined effects of the earthquake and tsunami led to the deaths of at least 2,100 people. In brief, in all the tsunamis occurred in the last 2 decades, the major life loss could be described to structural failure, since it had not planned for vertical evacuation and the resulting debris became an added hazard. Till now, research in the field of tsunami resistant design has been conducted only in a few countries because major tsunamis were perceived to be rare. However public perceptions in this regard are changing. Further, for finding suitable structural solutions, a fundamental understanding of the forces imposed on structures by tsunami inundation, and the response of structures needs to be understood. This will require considerable knowledge about the physical characteristics of the tsunami and its effect on the structure as they penetrate over land.

There has been considerable research undertaken on the design of structure to resist tsunamis in last decade. A brief summary of the work is given. Bandara and Dias [1] carried out non linear static and dynamics analysis of a 2D concrete frame for tsunami forces. Nayak *et al.* [2] determined the tsunami vulnerability of a three storey building. Wang *et al.* [3] using Flow 3D software determined effects of tsunami waves on reinforced concrete building frames. Attary *et al.* [4] proposed a probabilistic framework for performance based tsunami engineering. Petrone *et al.* [5] carried out nonlinear static and dynamics analysis of a ten storey building for tsunami forces in Open Sees software. Chock *et al.* [6], [7] summarized design guidelines used in ASCE 7-2016. Further, Chock *et al.* [8] conducted reliability analysis for tsumani loading using Monte Carle simulation and found that the level of reliability is consistent with the new ASCE 7 tssunami design guidelines. In the present study, design loads for tsunami-resistant structures based on run-up height of waves, arrival time and inundation depth are evaluated. Further, the behaviour of framed reinforced concrete structures under tsunami generated loads is also studied using SAP2000.

Manuscript received April 7, 2020; revised August 25, 2020.

II. Numerical Study

India is having 7500 kilometers of coastline and many areas on this coastline come under tsunami hazard. According to the draft of Indian code of tsunami–resistant design, tsunami hazard for Indian coasts range from 0 to 7 meters. A tsunami can be caused by various reasons but with respect to India's geographical locations, it will be caused by subduction zone earthquakes. The east coast of India was affected by the Sumatra-Andaman subduction zone earthquake which caused the deadliest tsunami in the Indian Ocean region in 2004. The west part of India comes under tsunami hazard from Makran subduction zone. Problems and design parameters considered in the study are of tsunami hazards related to Indian coasts and latest available tsunami design guidelines were used to analyse building models.

A. *Description of Problem*

To study the behaviour of a building under tsunami loads, a 21 m height G+5 story building is considered. Three different sets of depth and velocity which are consistent with India's tsunami hazard are considered for the calculation of tsunami load on the structure as per ASCE 7- 2016. The values of tsunami depth and velocity are given in Table I. Hydrodynamic load and impact load in addition to dead and live load are considered in the design of the building. The same G+5 building is also analysed for zone III, IV & V earthquake zones to compare the different analysis results due to earthquake and tsunami force under linear static analysis. Plan and elevation of the building is shown in Fig. 1. Member sizes of the building are decided based on applied tsunami load and drift criteria's as per IS 1893-2016. M 30 concrete grade and Fe 500 steel grade is taken for numerical study. Models are prepared in SAP 2000 software and linear and nonlinear static analysis is performed with the tools given in SAP 2000.

TABLE I. Different Sets of Tsunami Depth and Velocity

Tsunami	Maximum Depth	Maximum Velocity
Scenario - 1	10.5	8.3 m/sec
Scenario - 2	6.2	6.4 m/sec
Scenario - 3	5.2	5.2 m/sec

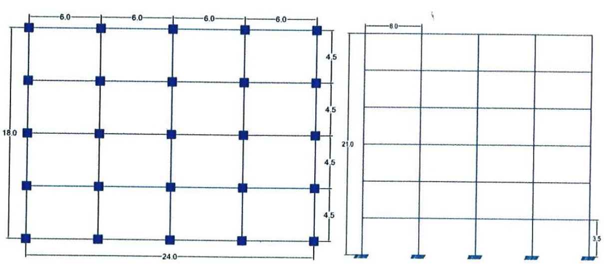

Figure 1. Plan and elevation of the G +5 storey frame.

B. *Analysis of Building for Tsunami Load*

Depth and velocity of the tsunami are selected from the data provided in ASCE 7-2016 tsunami database. Importance factor of 12.5 is considered for tsunami load calculation of building and this corresponds to risk category IV. Closure ratio (C_{cx}) is considered as 0.5 for tsunami load calculation. Tsunami refuge floors are selected based on inundation depth and refuge loading is applied accordingly. Factor like velocity amplification, the directionality of flow, minimum no. of tsunami cycles & seismic effect prior to the tsunami are not considered in this. In this study, it is considered that the building is near to shore and nearby side & front obstructions are there and one cycle of tsunami is considered which consist of incoming and outgoing flow. Soil structure interaction is not considered. The direction of flow is considered perpendicular to the building to avoid directionality provisions of ASCE 7- 2016. Member dimensions are selected based on drift criteria mentioned in the ASCE 7- 2016. Dead load of different components of building frame and live load considered in the present study is given in Table II. Member dimensions for different buildings are presented in the Table III.

TABLE II. Dead and Live Load Data

Components	Data
Thickness of slab	150 mm
Floor Finish	1.5 kN/m^2
Roof Finish Load	2 kN/ m^2
Parapet wall load	4.508 kN/m
Exterior Masonry wall load	15.778 kN/m
Live load (terrace)	1 kN/m^2
Live Load (Typical floor)	4 kN/m^2

TABLE III. Building Configuration for Different Sets of Tsunami Depth and Velocity

Tsunami Scenario	Component	Storey	Size (m x m)
Scenario - 1	Column	Ground to second storey	0.70 X 0.70
		3rd to 5th storey	0.50 X 0.50
	Beam	All storey	0.35 X 0.55
Scenario - 2	Column	Ground & 1st storey	0.70 X 0.70
		2nd to 5th storey	0.50 X 0.50
	Beam	All Storey	0.35 X 0.55
Scenario - 3	Column	Ground & 1st storey	0.70 X 0.70
		2nd to 5th storey	0.50 X 0.50
	Beam	All Storey	0.35 X 0.55

C. *Tsunami Hydrodynamic Load Data*

Tsunami loading data contains hydrodynamic drag force and impact loading on the structure. Hydrodynamic drag will be calculated for all three tsunami depths for two load cases, namely, A and B. The loading data for different scenario of tsunami is shown in Table IV. Impact load is considered as per ASCE 7 -16 and its value is taken as 597.2 kN. For tsunami resistant design, the following eight load combinations are taken as per ASCE 7 – 2016 [9]:

1) 0.9D + FRSU (INCOMING FLOW)
2) 0.9D + FRSU (RECEDING FLOW)
3) 0.9D + FRSU (IMPACT FORCE, INCOMING FLOW)
4) 0.9D + FRSU (IMPACT FORCE, RECEDING FLOW)
5) 1.2D + 0.5L + FRSU (INCOMING FLOW)
6) 1.2D + 0.5L + FRSU (RECEDING FLOW)
7) 1.2D + 0.5L + FRSU(IMPACT FORCE, INCOMING FLOW)
8) 1.2D + 0.5L + FRSU(IMPACT FORCE, RECEDING FLOW)

Similarly, for earthquake resistant design, following load combinations were used as per IS 1893-2002.

1) 1.5 (D.L + L.L)
2) 1.2 (D.L + L.L ± EQ_X)
3) 1.2 (D.L + L.L ± EQ_Y)
4) 1.5 (D.L + E.Q_X)
5) 1.5 (D.L + E.Q_Y)
6) 0.9 D.L ±1.5 EQ_X
7) 0.9 D.L ±1.5 EQ_Y

III. RESULTS AND DISCUSSION

Fig. 2-Fig. 6 shows base shear, shear force, bending moment and storey displacement for earthquake and tsunami loading in the building frame for earthquake and tsunami loading. Note that the columns considered in the figure are exterior corner columns. It is seen in the figure that for increase in earthquake zone number, base shear increases about 48 to 50 %. Similarly, for increase in tsunami height, base shear increases about 180 to 200 %. Further, base shear for 10.5 meter height tsunami is 5 times than that of zone V. It is seen in the Fig. 3 that for each increase in earthquake zone number, shear force in column increases about 40-50 % for zone III to V. For each increase in tsunami height, shear force in column increases about 195 to 450 %. Maximum shear force for 10.5 meter tsunami is 3 times more than zone V earthquake. It is seen in the Fig. 4 that for each increase in earthquake zone number, bending moment increases about 40 to 50% for zone III to V. For each increase in tsunami height, bending moment in column increase about 340-500%. Maximum bending moment for 10.5 meter height tsunami is 2 to 3 times than zone V tsunami. It is seen in the Fig. 5 that for each increase in earthquake zone, value of storey displacement increase about 45 to 50 % for zone III to Zone V. Similarly, in Fig. 6 it is seen that for increase in tsunami height, storey displacement increases by 7 to 13 times.

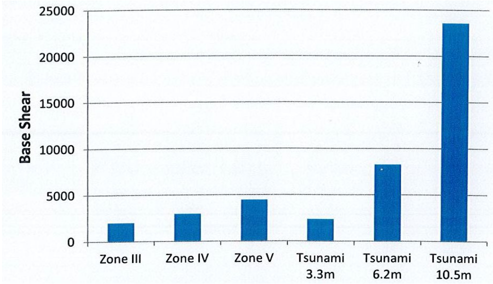

Figure 2. Base shear in the building frame due to earthquake and tsunami loading.

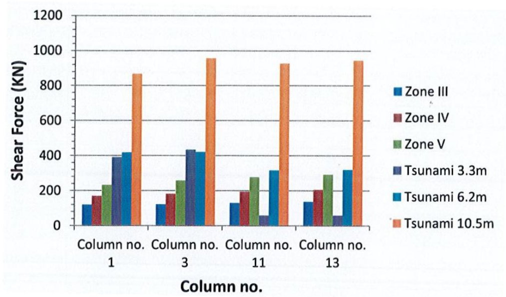

Figure 3. Shear force in columns due to earthquake and tsunami loading.

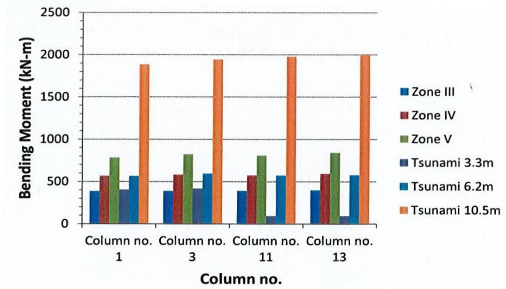

Figure 4. Bending Moment in the building frame due to earthquake and tsunami loading.

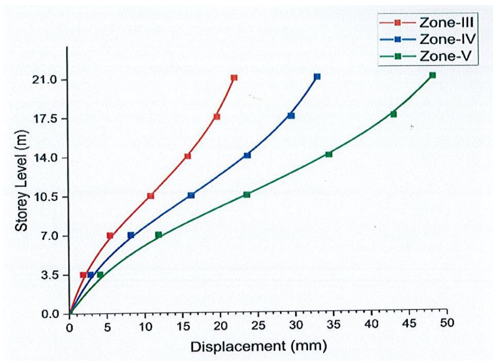

Figure 5. Storey drift in the building frame due to earthquake loading.

TABLE IV. LOAD CASES

Load Case	Scenario-I		Scenario-II		Scenario-III	
	Tsunami Depth	Tsunami Velocity	Tsunami Depth	Tsunami Velocity	Tsunami Depth	Tsunami Velocity
A	7 m	8.3 m/sec	6.2 m	6.4 m/sec	2.2 m	4.7 m/sec
B	10.5 m	2.7 m/sec	6.2 m	2.1 m/sec	3.3 m	1.6 m/sec

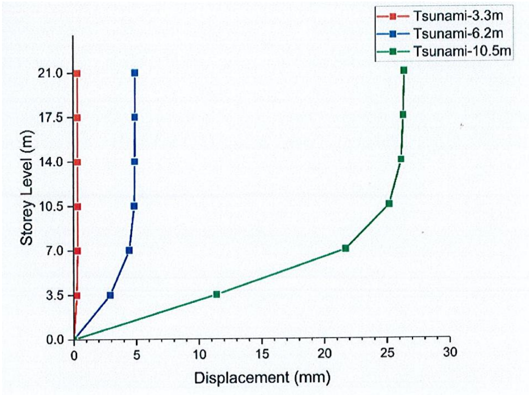

Figure 6. Storey drift in the building frame due to tsunami loading.

IV. Conclusion

A G+5 storey building with its longer side perpendicular to tsunami flow is analysed for earthquake & tsunami loading and results were compared. Based on results it is found that with the increase in earthquake zone number, values of response quantities of interest i.e. base shear, shear force in column bending moment and storey drift increases. Similarly, with the increase in tsunami height, values of response quantities of interest i.e. base shear, shear force in column and bending moment increases. However, the values of response quantities for tsunami is quite high as compared to earthquake loading. Hence, a structure should be designed for both earthquake and tsunami forces because the earthquake force will be applied on all floors but tsunami force will be applied on lower inundated area of building. Further, to reduce effect of tsunami breakaway walls can be used in lower inundated portion because it will help in force reduction during tsunami. Moreover, outer column should be designed for debris impact on the structure.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

Author Contributions

A. J. Shah conceived of the presented idea. Both A. J. Shah and Vishisht Bhaiya contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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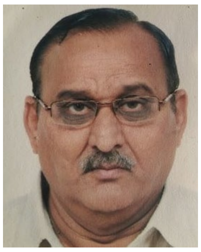

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