Response of Coastal Structures against Earthquake Forces Considering Soil-Structure Interaction and Tsunami Run-Up Forces

P.Kodanda Rama Rao, U.Ranga Raju, K.RamaMohan Rao, S.R.K. Reddy

Abstract** - The catastrophic tsunamis generated by the great Indonesia earthquake triggered on December 26th, 2004, warned the coastal community on preparedness and constructing safe structures to resist against such events. Earthquake occurs suddenly without warning and bulk of destruction takes place within a short period of time. Similarly, when tsunami strikes, there will be a tremendous loss and damage in coastal regions. Apart from having a sound warning system in case of tsunamis, it is necessary to build Earthquake–Tsunami Resistant (ETR) shelters, where residents living in coastal plain regions cannot move to farther distances before tsunami arrives the coast. Hence it is necessary to establish analytical methods for obtaining the response of coastal structures subjected to earthquake forces considering soil-structure interaction and also against tsunami run-up forces. A three storied shelter building with four different cases of structural configurations and another typical structure, an elevated water tank of 6 lakh liters capacity are chosen for the analysis. A comparative study is made on the response of these structures against earthquake forces, when they rest on different soil/rock media. In the analysis, IS 1893-2002 seismic code for determining the base shear values against earthquake loads and FEMA 55 to calculate hydrodynamic and impact forces against tsunami impact are used. From the results, it is observed that the refuge shelters that are chosen are more vulnerable to high tide tsunami loads compared to earthquake loads. In general, it is noticed that Base shears and Displacements increase with the decreases in stiffness of the soil and this increase attributes more due to rocking effect of the soil. Buildings with open storey at bottom and upper stories with heavy mass give significant rise to time period of these structures causing early failures during an earthquake before tsunami arrives. In this study, a useful guideline is evaluated demarcating the heights below which earthquake forces and above which tsunami forces are predominant in the structure.

***Keywords**: Earthquake; tsunami; shelter; soil-structure interaction; time period; base shear; displacement; inundation depth; hydrodynamic force; and Impact force.*

I. INTRODUCTION

India has 7500 Km long coastal belt with different topographical features having different soil or rock media.

Hence, it is felt that the influence of soil-structure interaction plays vital role in obtaining the response of the structures against earthquake forces in particular.

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Past history and geological evidences reveal that the great earthquakes are considered to occur at tectonic plate boundaries, particularly along the coastal belts that rim the Pacific and Cross Southern Asia.

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 earthquake methodologies. Though there are no well established design procedures for tsunami resilient buildings, FEMA 55 provided some guidelines based on the considerations of tsunami forces. A review by Harry Yeh, Ian Robertson and Jane Preuss,2005 (9) suggested that fluid forces exerted on a structure can be evaluated in terms of hydrodynamic and impact forces for a given depth of inundation and the velocity of the approaching tsunami.

Okada et al., 2005 (8) have proposed an empirical method for estimating the forces exerted on structures by tsunami overland flow. 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.

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

The World's population growth which reached seven billion in 2012 is still increasing rapidly and is expected to be nine billion by 2050. Present investigations suggest that Pacific Northwest, Aleutian Island chain, Peru-Chile trench and Indian Ocean Northeast provinces could experience catastrophic earthquakes followed with tsunamis in near future posing a significant threat to the urban environs along the coastal belts. Tsunami protection to some extent can be achieved through the construction of sea walls, beach defenses, shoreline tree plantation and other protection measures. Perhaps the major civil protection measure against a large tsunami is to evacuate the population living close to the coast further inland with high ground. However, Tsunami warning stations are now located at many points in Pacific Ocean and can detect the sea wave when it is first created.

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Indian National Centre for Ocean Information Services (INCOIS) has established Tsunami Warning Centre at Hyderabad, India.

Any discussion on tsunami protection must attempt to identify the distribution of vulnerability in any society and across the world. The evidence shows that if the public can be made aware of the risk of a tsunami and trained to know how to act when a gigantic tsunami strikes the coast, the casualties could be reduced considerably.

A. Earthquake Effects

The Earthquake of December 26, 2004 was the second largest recorded by a strong motion seismograph. Mostly, earthquake damage is due to tectonic surface processes and secondary effects. Surface fault rupture and regional subsidence are tectonic surface processes, where as damages due to liquefaction, earthquake-induced slope failures, landslides, tsunamis, seiches and fire are the examples of secondary effects.

During an earthquake, increased deformation demands on the soft storey columns of the buildings, coupled with lack of confinement and column deformability, resulted in column failures. Sometimes the failure of first storey columns triggered the collapse of entire story.

Reinforced concrete frames, designed and built without seismic design and detailing practices, suffered significant damage due to ground shaking. Extensive use of unreinforced masonry, strong beams and weak columns and lack of column and joint transverse reinforcement could be blamed for seismic damage. Furthermore, soft stories experienced widespread damage often resulting in the collapse of first stories, sometimes leading to total building collapse.

Many of the seismic deficiencies of buildings, known to cause poor structural performance were clearly visible throughout, during 2004 Indonesian earthquake.

B. Tsunami Effects

A tsunami can generate large on-shore currents and move the objects far inland. Tsunami impact forces sometimes can cause collapse of structures. The most interesting tsunami event is that, the ship moved 3 km inland during 1868 Chile tsunami was moved back to the shore during 1877 tsunami.

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.

Although there is no well established design criterion for tsunami resilient buildings, Coastal Construction Manual (CCM) has mentioned the following types of forces may result when tsunami run-up strikes the buildings with high velocities.

- Hydrostatic forces
- Hydrodynamic forces from drag forces in a steady flow
- Buoyant or vertical hydrostatic forces
- Impact forces resulting from debris
- Surge forces from impingement of the leading edge of a surge
- Breaking wave forces

In the analysis only hydrodynamic and impact forces are taken into consideration since these are normally more predominant in nature.

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. Tsunami waves impose dynamic water pressures on coastal structures as well as buildings and bridges near the coastline, inducing serious damage to the entire surrounding infrastructure located up to approximately 4 km inland. 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; whereas 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 of the framed buildings.

II. SOIL-STRUCTURE INTERACTION

In the analysis of structures subjected to seismic excitation, it is usually assumed that the structures are fixed at the base to simplify the mathematical problem, but as the foundation of the structure rests on soil, it is apparent that response depends upon the properties of structure as well as soil. The dynamic response of a structure resting on soft soils in particular, may differ substantially in amplitude and frequency from the response of an identical structure supported on a very stiff soils or rock. However the data available on many failure examples of rigid structures resting on flexible soils and intensive analytical studies in recent years have made considerable advances in the field of soil- structure interaction and analytical techniques are now available. The interaction phenomenon is principally affected by the mechanical energy exchanged between the soil and the structure.

Since seismic waves travel through different soil /rock media, influence of soil-structure interaction plays vital role in earthquake analysis of structures. Whereas, tsunamis travel in the form of waves on ocean surfaces and due to the shoaling effect near the coast, waves rise to greater heights and strike the seaward surface of the structures directly. Hence, in the present study, effect of soil-structure interaction has been considered only for earthquake forces. In case of tsunami, the prominent hydrodynamic and impact forces are taken for the analysis.

III. PRESENTATION OF PROBLEM

In this paper it is mainly focused on the analysis of two categories of structures, one, a three storied shelter building with four different cases of configurations and another, a typical structure, an elevated water tank that are assumed to be located along the coastal belt of Krishna district. A comparative study is made on the response of dynamic parameters like fundamental natural frequencies, time periods, base shears and displacements of these structures for earthquake forces considering soil-structure interaction and also against tsunami run-up forces.

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In present study a useful guideline is evaluated demarcating the heights below which earthquake forces and above which tsunami forces are predominant.

A. *Study Area*

India has a long coast line surrounded by Bay of Bengal, Indian Ocean and Arabian Sea. Andhra Pradesh coast has the second largest coastal belt of length 972 kms, covering 9 districts of Srikakulam, Vizianagaram, Visakhapatnam, East Godavari, West Godavari, Krishna, Guntur, Prakasam and Nellore.

The tsunamis generated during 2004 Indonesia submarine earthquake reached the east coastal belt of India and caused damage to Manginapudi beach at Machilipatnam, a prominent coastal town in southern parts of Krishna district which is situated in central part of A.P. coast. In the present study the above said southern part of Krishna district has been identified as vulnerable zone for such events and hence has been chosen as study area (Fig.1)

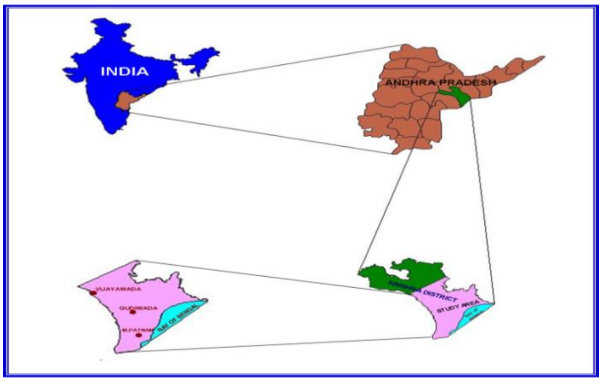

Fig.1 Location Map

The study area is bounded by latitude in between 16°10'N to 16.17°N and Longitude in between 81°09'E to 81.13°E. A map showing spacial distribution of various soils and geomorphic features has been prepared for the study area using satellite based Remote Sensing techniques as shown in Fig.2.

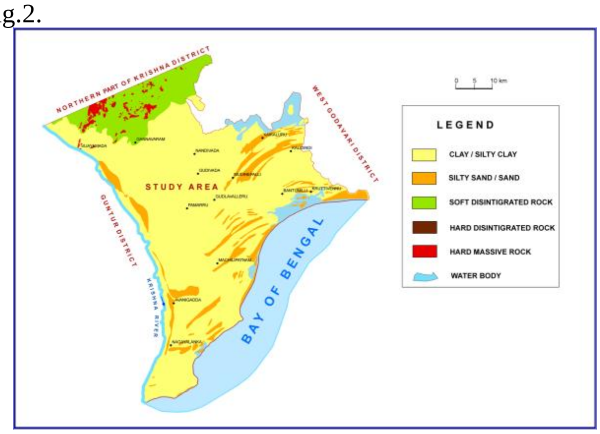

Fig.2. Soils/Geomorphic unit Map

The classification system of these units has been prepared based on geotechnical/geo-engineering properties of different soil/geomorphic units.

The terrain slope near the coast line of the study area ranges from 1 in 40 to 1 in 60 and hence in the present analysis an average slope of 1 in 50 is considered.

C. *Soil Model*

In the present study the following types of soil/ geomorphological units as shown in Fig.2 are considered for the analysis.

Type A : Clay / Silty Clay
Type B : Silty sand / Sand
Type C : Soft Disintegrated Rock
Type D : Hard Disintegrated Rock
Type E : Hard Massive Rock
Type F : Fixed Base

The dynamic properties of above soils/rock media are worked out and the properties are presented in Table I

Table I : Results of Dynamic properties of Different soils / rocks

S. No.	Description of Soil / Rock	Shear wave velocity V_s (m/s)	Mass density ρ (KN-sec²) m⁴	Poisson ratio 'ν'	Shear modulus G (KN/m²x10⁵)
1	Type A	60	1.70	0.45	0.06
2	Type B	150	1.85	0.40	0.42
3	Type C	400	1.90	0.33	3.04
4	Type D	1250	2.10	0.30	32.81
5	Type E	2700	2.60	0.30	189.54

A dynamic model of the soil/rock requires the representation of soil stiffness and damping factors allowing for strain dependence and variation of soil properties. Most rudimentary method of modeling the soil/rock is to use springs located at the base of the structure to represent the appropriate selection of horizontal, rocking, vertical and torsional stiffness of the soil. Since, the structures are usually designed for gravity loads, in the present seismic analysis, only horizontal and rocking spring constants of the soils are considered. These equivalent soil spring constants are worked out for different classified soils or rocks of the study area based on the work done by Whitman and Richart (1967) both for rectangular footing adopted for the building and circular footing for water tank respectively. Accordingly the horizontal stiffness (k_x) and rocking stiffness (k_Ψ) values of different soils are worked out and presented in Table II

Table II: Results of Horizontal & Rocking Stiffness of Soil Springs

Sl. No.	Description of Soil / Rock	Stiffness value in KN / m x 10^6			
		Building		Water Tank	
		Horizontal k_x	Rocking k_Ψ / h^2	Horizontal k_x	Rocking k_Ψ / H^2
1	Type A	1.235	3.257	0.183	0.026
2	Type B	6.434	10.129	1.207	0.165
3	Type C	40.756	50.424	8.446	1.154
4	Type D	327.605	230.400	89.560	11.210
5	Type E	1419.276	561.472	517.333	64.754

The analysis is carried out considering the soil- structure interaction effect when similar structures rest on the above soils/ geomorphic units of Type A to E. The results thus obtained are compared with the results when the same structures are assumed to be fixed at the base (Type F).

D. *Structure Model*

Two types of structures are chosen for the study i) A three storied R.C. shelter building 18.5 m X 11.5 m size in plan with a storey height 3.35 m for evacuees is chosen for the study and the analysis for dynamic response against both seismic and tsunami forces is carried out considering the following four different cases of structural configurations of the shelter.

Case 1: Ground floor(GF) with cellar, First floor(FF) and

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Second Floor (SF) with only outer walls.

Case 2: G.F. with cellar, F.F. and S.F. with outer and inner in-fill walls.

Case 3: G.F. , F.F. and S.F. only with outer walls.

Case 4: G.F., F.F. and S.F. with outer and inner infill walls.

The shelter building is idealized as mass-spring – dashpot system treating it as one having three degrees of freedom with fixed base condition and five degree of freedom ,when soil-structure interaction is considered, the loads being lumped at the nodes of each floor. According to IS-1893(2002), live load is reduced to 25%and no live load is considered at roof.M-20 grade concrete is used for all the elements of the building, the inter storey stiffness ‘k’ is computed by adding the stiffness values of all columns in that storey.

And ii) An elevated water tank 6 lakh liters capacity, an another typical structure, is considered for the analysis. The tank is intze type with 7.75 m internal diameter' and is supported by twelve columns connected well with a circular ring beam at bottom and with three bracings at equal intervals in the staging of 14.75m high above ground level. It is idealized as mass-spring-dashpot-system with one degree of freedom when it is assumed to be fixed at base and as three degrees of freedom when soil-structure interaction effect is considered. The top circular tank with water is lumped as top mass and the stiffness of staging is worked out as per IS - 1893 code. M25 grade concrete is used for circular tank and M20 for staging elements.

These two structures are analyzed when they are subjected to earthquake forces considering soil-structure interaction and also for tsunami run-up forces separately. Though the 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 and impact forces caused by the impact of different tsunami induced inundations are compared with earthquake forces when these structures are located in different seismic zones.

IV. ANALYSIS FOR EARTHQUAKE FORCES

The present analysis is carried out considering the chosen structures are situated in seismic zones II and III as the majority regions in this study area fall under the category of these two zones according to IS 1893 code.

The stiffness of each storey of shelter building 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 $k_c = 12\, E_c I_c / h^2$ 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 as suggested by the Stafford Smith,1966.(9) Thus the effective width of the equivalent diagonal strut is calculated for obtaining the stiffness of infill wall(k_W).

The total equivalent stiffness of each storey is taken as $\sum k_c + \sum k_w$.

The masses and equivalent stiffness values of both the structures are worked out for the use in the analysis.

In analyzing the structure subjected to time – dependent forces, a mathematical model with masses and springs is used. The equation of motion for a system can be derived by considering the equilibrium of all forces acting at the nodes which can be written as

$$F_i + F_d + F_g = F(t) \quad (1)$$

Where F_i - Inertia force vector

F_d - Damping force vector

F_g - Internal resisting force vector

$F(t)$ - Externally applied dynamic load vector

For linear systems, these forces can be expressed as

$F_i = [M]\{\ddot{x}\}$; $F_d = [C]\{\dot{x}\}$; $F_g = [K]\{x\}$

where $[M]$ - Mass Matrix

$[C]$ - Damping Matrix

$[K]$ - Stiffness Matrix

$\{\ddot{x}\}$ - Acceleration vector relative to ground motion

$\{\dot{x}\}$ - Velocity Vector relative to ground motion

$\{x\}$ - Displacement Vector relative to ground motion

Equation (1) can be written as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = F(t) \quad \textbf{(2)}$$

When the structures are subjected to a ground acceleration $\{y\}$ then,

$$[M]\{x\} + [C]\{x\} + [K]\{x\} = -[M]\{y\} \text{ -- } (3)$$

The dynamic analysis of linear systems of both the structures involves solution of simultaneous equations, which will give rise to displacement, velocity and acceleration time history for the given time dependent load F (t).

The mathematical model for water tank is shown in Fig. 3

For free vibration analysis, the natural periods and mode shapes are determined using the following equation

$$[M]\{x\} + [K]\{x\} = 0$$

Equations of motion for the free body diagram of the water tank model with soil-structure interaction effect is presented in Fig.3

i $m_1 x_1 + k_1(x_1 - x_0 - \theta H) = 0$

ii. $m_0 \ddot{x}_0 + k_x x_0 - k_1(x_1 - x_0 - \theta H) = 0$

iii. $I\ddot{\theta} + k_\Psi \theta - m_1 \ddot{x}_1 H = 0$

Where $I = I_1 + I_2$

Putting these equations in matrix form,

$$\text{Massmatrix } [m] = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & I/H^2 \end{bmatrix}$$

$$\text{Stiffness Matrix } [k] = \begin{bmatrix} k_1 & -k_1 & -k_1 \\ -k_1 & (k_1 - k_2) & k_1 \\ -k_1 & k_1 & k_1 + k_\psi/H^2 \end{bmatrix}$$

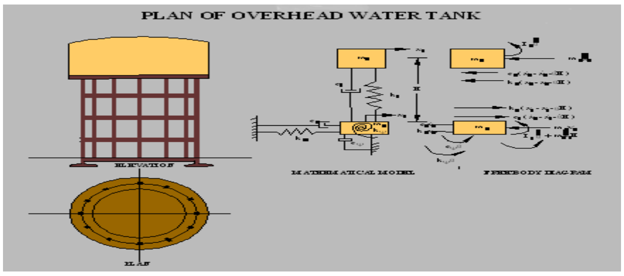

Fig. 3 Elevated Overhead Tank

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Similarly the equations of motion for shelter building with soil-structure interaction are,

i. $m_3 x_3 + k_3 (x_3 - x_2 - \theta h) = 0$

ii. $m_2 x_2 + k_2 (x_2 - x_1 - \theta h) - k_3 (x_3 - x_2 - \theta h) = 0$

iii. $m_1 x_1 + k_1 (x_1 - x_0 - \theta h) - k_2 (x_2 - x_1 - \theta h) = 0$

iv. $m_0 x_0 + k_x x_0 - k_1 (x_1 - x_0 - \theta h) = 0$

v. $I \theta + k_0\theta + m_3x_3 (3h) + m_2x_2 (2h) + m_1x_1 (h) = 0$

and $I = I_1 + I_2 + I_3$

where I - Mass moment of inertia of all storey masses

Putting the above equation in matrix form

$$\text{Mass matrix } [m] = \begin{bmatrix} m_3 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_1 & 0 & 0 \\ 0 & 0 & 0 & m_0 & 0 \\ 0 & 0 & 0 & 0 & I/h^2 \end{bmatrix}$$

StiffnessMatrix [k] =

$$\begin{bmatrix} K_3 & -K_3 & 0 & 0 & -K_3 \\ -K_3 & K_2+K_3 & -K_2 & 0 & K_3-K_2 \\ 0 & -K_2 & K_2+K_1 & -K1 & K_2-K_1 \\ 0 & 0 & -K_1 & K_1+K_x & K_1 \\ -K_3 & K_3-K_2 & K_2-K_1 & K_1 & K_1+K_2+K_3+\left(K_\gamma/h^2\right) \end{bmatrix}$$

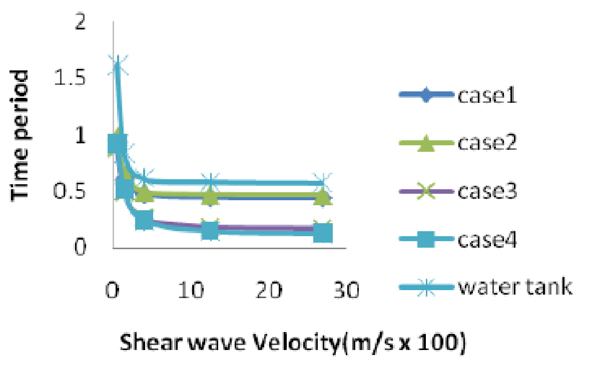
Using mat lab software ,free vibration analysis is carried out to obtain the fundamental time periods and natural frequencies of the two structures when they rest on different soils and the results of time periods are presented in Tab. III

Table III: Results of Fundamental Time Periods

Sl. No.	Description of Soil / Rock	Shelter Building (secs)				Water Tank (Secs)
		Case1	Case2	Case3	Case4	
1	Type A	0.936	0.982	0.879	0.918	1.644
2	Type B	0.619	0.647	0.500	0.514	0.829
3	Type C	0.477	0.497	0.261	0.246	0.612
4	Type D	0.449	0.467	0.187	0.149	0.573
5	Type E	0.444	0.462	0.174	0.129	0.569
6	Type F	0.441	0.459	0.164	0.115	0.568

The variation of fundamental time periods for different shear wave velocities is shown in Fig. 4

Fig.4
VARIATION OF TIME PERIOD WITH SHEAR WAVE VELOCITY



The response spectrum as given in IS 1893-2002 (Fig 2) used for the analysis. For the calculated time periods of different cases, S_a / g values are obtained using the above response spectra. The zone factors for seismic zones II and III are taken from IS 1893-2002 code. In the analysis, for both interactive and non-interactive systems, a constant structural damping ratio of 5% is taken.

Using mode super position method of analysis against earthquake forces, the base shears and storey displacements in seismic zones II and III are obtained separately considering soil-structure interaction and presented in Tables IV and V. These results are compared with the results obtained from fixed base condition. The variation of base shear and displacement of both the structures are plotted and shown in Fig. 5 and 6.for comparision and arriving conclusions.

Fig.5
VARIATION OF BASE SHEAR WITH SHEAR WAVE VELOCITY

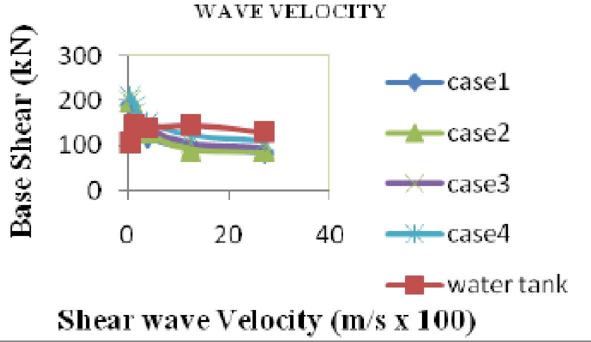


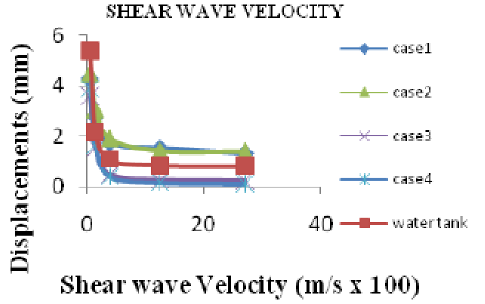
Table IV: Results Of Base Shear

Sl No	Description of Soil / Rock	Building x10 (kN)								Water Tank x10(kN)	
		Zone II				Zone III				Zone II	Zone III
		Case1	Case2	Case3	Case4	Case1	Case2	Case3	Case4		
1	Type A	119.6	124.0	124.7	130.3	191.4	198.4	199.5	208.4	117.0	187.2
2	Type B	94.8	102.6	107.2	116.8	151.7	164.2	171.6	186.9	95.2	158.7
3	Type C	73.2	79.3	86.5	96.0	117.1	127.0	138.5	153.6	92.2	147.5
4	Type D	60.4	58.1	65.8	77.8	96.7	93.0	105.4	124.6	82.5	132.0
5	Type E	51.6	55.0	58.9	69.1	82.6	88.1	94.3	105.1	82.4	131.8
6	Type F	47.3	50.7	51.7	58.3	75.7	81.2	82.8	93.3	82.3	130.8

Table V: Results Of Maximum Displacements

Sl No	Description of Soil / Rock	Building (mm)								Water Tank(mm)	
		Zone II				Zone III				Zone II	Zone III
		Case1	Case2	Case3	Case4	Case1	Case2	Case3	Case4		
1	Type A	2.60	2.70	2.24	2.34	4.30	4.50	3.60	3.90	6.70	10.5
2	Type B	1.70	1.94	0.97	1.03	2.80	3.10	1.57	1.64	1.37	2.20
3	Type C	1.00	1.19	0.29	0.25	1.75	1.92	0.47	0.40	0.54	0.87
4	Type D	0.90	0.89	0.15	0.10	1.54	1.43	0.25	0.16	0.42	0.68
5	Type E	0.80	0.88	0.14	0.075	1.35	1.41	0.22	0.12	0.41	0.66
6	Type F	0.80	0.87	0.12	0.058	1.34	1.40	0.19	0.03	0.40	0.60

Fig.6
VARIATION OF DISPLACEMENT WITH SHEAR WAVE VELOCITY



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V. ANALYSIS FOR TSUNAMI FORCES

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 and impact forces are considered and the equations suggested by Harry Yeh et al. (2005)(9) are used.

Assuming the ground slope 1 in 50 along the coast as in Fig. 7, 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.

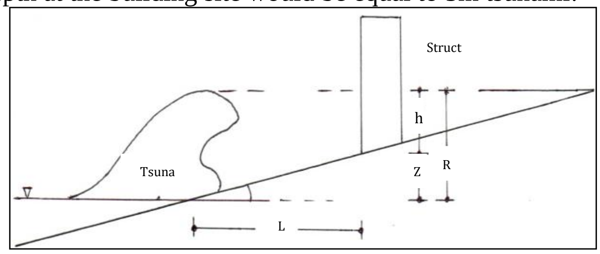

Fig. 7 Runup Zone of Tsunami

Hydrodynamic (drag) force is expressed as proportion 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 columns. For a given location, the design value of ($h_{max}\, u^2$) is computed from Eq. 4 and the corresponding drag force, F_D, is obtained from Eq.5.

$$\frac{h_{max}u^2}{gR^2} = 0.125 - 0.235\,\frac{Z}{R} + 0.11\left[\frac{Z}{R}\right]^2 \qquad (4)$$

$$F_D = \frac{1}{2}\,\rho C_D\, b h_{max}\, u^2 \qquad (5)$$

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.5, the values of hydrodynamic force on all types of structures are calculated for different inundation depths. Impact forces are developed due to debris such as drift wood small boats portions of houses etc ,or any object transported by flood waters, striking against the structures. These values can be calculated from the Eq.6.The values of hydrodynamic and impact forces thus obtained are presented in Tables VI and VII. The base shears due to tsunami forces are compared those obtained due to seismic forces for shelter building are shown in Table VIII.

$$Ft = C_m\, U_{max}\, \sqrt{km} \qquad (6)$$

Where

C_m - Mass coefficient

U_{max} - maximum Tsunami wave impact velocity approaching the structure

$U_{max} = \sqrt{2gR(1\text{-}Z/R)}$

K - Stiffness of the structure

m - Lumped mass

It may be noted that, the analyses are carried out for independent actions of tsunami and earthquake separately, when the structures are located in seismic zones II & III . Hence, Eq.5 and 6 depend only on the intensity of tsunami and does not depend upon the seismic zone.

Further, from the Figures,8,9,10 and11, it is noted that at some specific height, h_c, the tsunami force and earthquake force are equal in magnitude. Such h_c values for the four cases shelter building when situated in seismic zones II and III are presented in Table IX. 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 VI Tsunami forces on structures located at 100m away from the coast line with a slope 1:50

Forces →	Hydro Dynamic Force (KN)			Impact force (KN)			Total Tsunami Force (KN)		
hmax (m) → / Type of structure ↓	3.35	6.70	10.05	3.35	6.7	10.05	3.35	6.70	10.05
Cellar	109.0	586.2	1068.4	533.0	753.2	922.9	642.0	1339.4	2426
No Cellar	279.9	1081.2	2405.0	533.0	753.2	922.9	812.9	1834.4	3327.9

Table VIII Base shear values due to earthquake forces and tsunami forces

Forces →	Hydro Dynamic Force (kN)			Impact force (kN)			Total Tsunami Force(kN)		
hmax (m) → / Type of structure ↓	2.35	5.70	9.05	2.35	5.70	9.05	2.35	5.70	9.05
Cellar	57.6	532.8	1250.5	446.3	695.0	875.8	503.9	1227.8	2126.3
No Cellar	148.1	803.2	1980.3	446.3	695.0	875.8	594.4	1498.2	2856.1

Table IX Proposed guideline for design

Type of structure	Seismic Zone	Due to earthquake			Due to Tsunami					
		Cumulative storey Shear (KN)			Total Tsunami force (kN)					
		G.F	F.F	S.F	h_{max} 2.35	h_{max} 3.35	h_{max} 5.70	h_{max} 6.70	h_{max} 9.05	h_{max} 10.05
Case – 1	II	471	325	148	503	642	1227	1339	2126	2426
	III	753	519	236						
Case – 2	II	507	348	152						
	III	811	554	244						
Case – 3	II	517	396	197	594	812	1498	1834	2856	3427
	III	828	632	316						
Case – 4	II	583	445	215						
	III	933	711	345						

Fig 8 Case 1 shelter building

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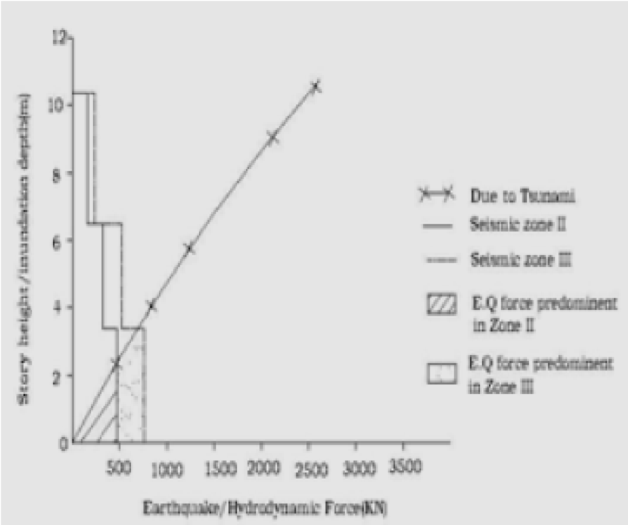

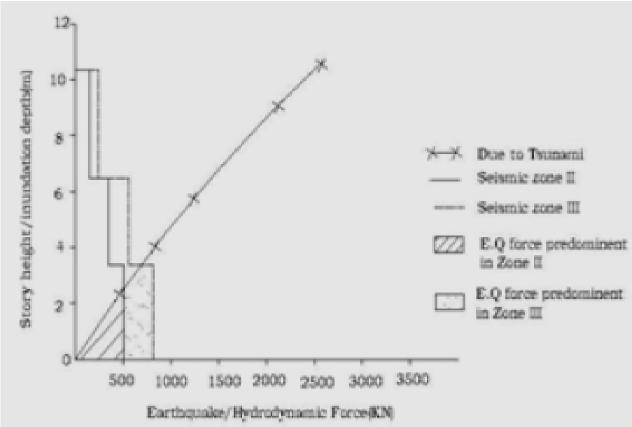

Fig 9 Case 2 shelter building

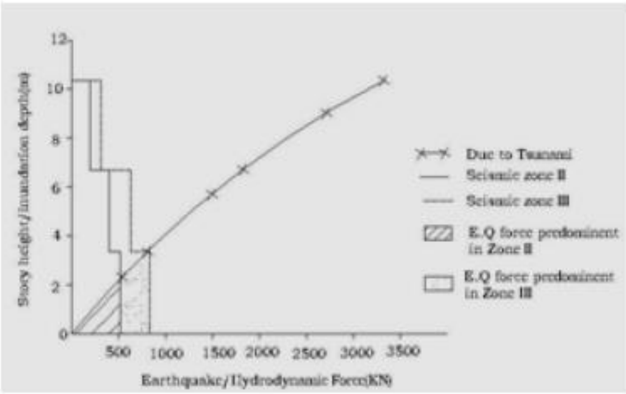

Fig 10 Case 3 shelter building

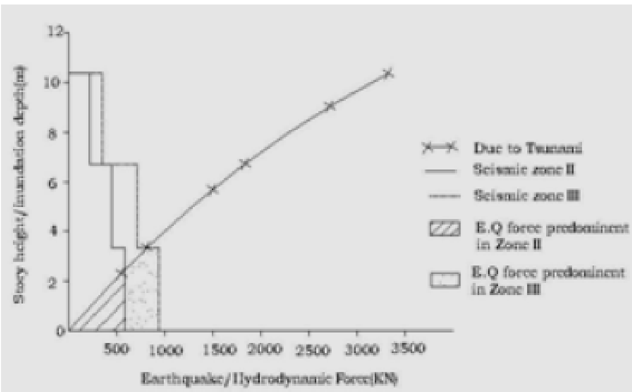

Fig 11 Case 4 shelter building

VI. SUMMARY AND CONCLUSIONS

A. Summary

In-spite of many scientific and technological advancements during last century, the threat of natural disasters, particularly earthquakes and tsunamis, has remained untamed. History and geological evidences show that the rate of occurrence of earthquakes and tsunamis will increase in future. With rapid increase in rate of population and construction activity along coastal towns and cities, the potential for massive destruction increases against earthquakes and tsunamis and hence the risk also increases.

In the event of a major submarine earthquake, not only severe ground shaking but also high tsunami waves are expected posing a significant threat to coastal community and structures.

Keeping in view of these facts and as a deviation from the normal study, it is proposed to study the response of coastal structures against earthquake forces considering the effect of soil-structure interaction and also against tsunami run-up forces.

B. Conclusions

Against Earthquake forces

- From the present study, it is observed that structures resting on hard rock or firm soil behave well during earthquake than the structures resting on loose soils.
- It is observed that shear wave velocity influences significantly the change in shear modulus of soil when it changes from static state to dynamic state and accordingly the horizontal and rocking stiffness values increase exponentially from loose soils to firm soils/hard rock..
- The fundamental time period of the structure invariably decreases with the increase of soil stiffness and this decrease is observed more in case of flexible structures like water tank. However, for shelter buildings with cellar floors given in cases 1 & 2, this variation is not much; whereas for the same shelter buildings without cellars given in case 3 & 4, the time period the variation is significant. This attributes that the decrease in stiffness of lower level floors (soft-storey) increases the time period of the structure.
- Base shears and maximum displacements of both structures (shelter building and water tank)decrease with the increase of soil stiffness. However, this variation is not much in case of water tank compared to that of shelter building. This is because of the structural configuration of water tank with slender staging and top heavy mass.
- It is also noticed that the above said decrease in displacements with the increase of soil stiffness is mainly due to the contribution from the effect of rocking compared to horizontal stiffness of soil/ structure stiffness.

Against Tsunami forces

- R.C. frame buildings with open ground storey (soft story) are considered effective to reduce the tsunami force; where as such soft story buildings tend to fail under severe seismic conditions. In view of this a balanced design approach is necessary in planning ETR shelters.
- Weight of the 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.

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General conclusions

- Depending upon the intensity of tsunami and earthquake, the design criteria should be such that, a demarcating height of the structure shall be identified below which earthquake forces and above which tsunami forces are to be considered.
- Awareness about tsunamis and their impact on coastal structures has to be created not only among the public but also among the officials, scientists and field engineers. Early warning systems are to be installed at various coastal regions
- Protection against tsunamis can be achieved through construction of sea walls, beach defenses, tree plantations And buffer zones like raised land masses and forests.
- Mooring methods should be developed for the fishing boats along the coasts of towns and villages where there is no harbor facility.
- Enforcement of bye-laws and Coastal Regulation Zone (CRZ) norms should be strictly implemented to minimize tsunami damage.
- Tsunamis are secondary effects of earthquakes. Hence, a clause on "Secondary effects of Earthquakes"shall be incorporated in relevant seismic codes.

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