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Tsunami forces acting on ocean structures: A synthetic study

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ABSTRACT

Andaman-Sumatra subduction zone had produced several large and great earthquakes in the past, some of which have generated destructive tsunamis. Tsunami forecast model is used to provide an estimate of wave arrival time, wave height, and inundation area immediately after a tsunami event. Forces caused due to a tsunami on different structures also play an important role. Considerable amount of research has been done on shape, size and strength of near-coastal structures. But, the impact on the ocean structures (like Oil Rigs) has not been addressed. In this paper, the lateral forces due to tsunami acting on a vertical hypothetical wall constructed in an ocean or sea are calculated. The location of the wall is taken in between India and Sri-Lanka due to the large scale destruction of structures on land and in the ocean caused by 2004 tsunami. To address the problem in an organized way, firstly, a hypothetical wall divided into 6 sections has been selected. Secondly, the wave heights are calculated for each section using TUNAMI N2 model. Thirdly, calculation of forces using the wave heights are made separately for each section for a better understanding of forces acting. And lastly, change in forces with time is calculated to bring out varied nature of forces with time. The acquired information is then plotted to explicitly show the changes. Results reveal that the hydrostatic forces acting on the wall structure in the ocean or the sea shall not pose a great threat to the structure. Also, due to the presence of such barriers the tsunami wave energy would get dissipated and less damage would happen to the adjoining coastal region. We have also followed the same approach to calculate the changes in tsunami forces with time on the Oil Rigs in the Ravva Offshore field.

Key words: Tsunami, Hydrostatic force, Wave heights, Vertical hypothetical wall, TUNAMI N2 model, Andaman-Sumatra subduction zone.

INTRODUCTION

A tsunami is a series of water waves caused by the displacement of a large volume of a body of water. Tsunamis have been causing drastic damage to the coastal areas. Their effects on man-made structures are the reasons for a large amount of economic losses. Earlier, the study on Tsunami induced forces was not given significance due to the less frequency of tsunamis. After viewing the destructed buildings and many other damaged structures due to 2004 Sumatra-Andaman & 2011 Tohoku tsunamis, these forces are being given importance and considered in engineering constructions along tsunami prone areas.

Extensive research has been conducted on the impact of hydrodynamic forces on classical coastal protection works (breakwaters, seawalls, reefs, etc.). Mizutani and Imamura (2001) measured the wave force of tsunamis acting on prevention structures along the coast such as seawalls and breakwaters. Kumaraguru et al., (2005) dealt with the impact of the tsunami on coral reefs. Such research studies help in measuring the reduction in tsunami impact while building preventive structural models (Kunkel et al., 2006). But, there is a very limited research on tsunami impact on structures such as buildings and bridges located inland. One such work by Azadbakht and Yim (2014) calculated tsunami loads on bridges using simulations separately with initial impact and impact at full inundation. Failure analysis of several buildings is another effective approach to evaluate design equations for hydrodynamic loading conditions. This approach was adopted by Chock et al., (2011) in his Tohoku Tsunami-induced building damage analysis.

The devastation brought by the 26 December 2004 Indian Ocean Tsunami on coastal communities in Indonesia, India, Sri Lanka, Thailand, and other countries outlined the urgent need for research on the evaluation of structural resilience of infrastructure located in tsunami-prone areas. Nistor et al., (2009) worked on forces generated by tsunami-induced hydraulic bores, including debris impact. Further, he presented the sample calculations of tsunami loading on a prototype structure.

Experimental investigations have been done in the estimation of tsunami-induced hydrodynamic forces on infrastructure located in the vicinity of the shoreline. One such work by Suzuki et al., (2014) has specifically considered the Tohoku-Pacific Ocean Earthquake that occurred in 2011, which has caused a great damage to the bridges in the submerged area. In conventional designs, however, it was not assumed that those bridge girders or other bridge elements would be carried away by tsunami wave forces. Estimation of tsunami wave force was difficult because no load calculations or design methods had been established. Hence, hydraulic model experiments and numerical simulations in 2D and 3D have been carried out to understand the behavior of tsunami waves and the impact of tsunami wave forces acting on the bridge.

All these studies consider coastal or near-coastal structures. Though we have incorporated calculation of tsunami forces in engineering of coastal structures, no such study is available while engineering the structures in the ocean (like Kalpasar dam). In this paper, we have take up a case study of 2004 Indian Ocean tsunami caused by the Sumatra earthquake and specifically evaluated the different types of forces acting on a hypothetical wall in the Indian Ocean due to the tsunami waves. Also the same approach has been followed in calculating the tsunami wave impact on the Ravva field oil rigs located offshore near East Godavari district, Andhra Pradesh, India.

Mathematical Formulation

Theory of tsunami waves has been discussed by several researchers (Imamura, 1996; Imamura et al., 2006; Yalciner et al., 2005). To obtain the initial surface wave specific details of the initial sea bottom deformation is necessary. Mansinha and Smylie method (Mansinha and Smylie, 1971) has given a complete set of closed-form analytical expressions to obtain the internal as well as surface deformation. To obtain this one needs the information pertaining to the earthquake source parameters such as fault length, width of the fault, focal depth, angle between N & fault axis, dip angle, slip angle and displacement. Once the initial wave is generated one of the wave fronts would start moving towards the deep ocean and another towards the nearest local shoreline.

Since the vertical acceleration associated with tsunami waves is small compared with the gravity acceleration, tsunamis waves are usually resolved using 2D hydrostatic models (Imamura et al., 2006) and mathematically it is expressed as

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} M\sqrt{M^2+N^2} = 0 \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}} N\sqrt{M^2+N^2} = 0 \tag{3}$$

In the above equation M and N are expressed as

$$M = u(h+\eta) = uD \text{ and } N = v(h+\eta) = vD \tag{4}$$

where D is the total water depth given by $h+\eta$, t is time, h(x, y) is unperturbed depth, g is the gravitational acceleration, u and v are components of the horizontal velocities, M and N are the discharge fluxes in the x- and y- directions.

Imamura et al., (2006) used a finite difference technique based on Leap-Frog scheme to develop a code to solve the tsunami wave propagation i.e. TUNAMI-N2. The formulation uses the central difference method with a second order truncation error. The deformation at the sea bottom gives the initial condition, which is computed using Mansinha and Smylie method (Mansinha and Smylie, 1971). This gives rise to the initial wave. The boundary conditions are free transmission in the open sea and the perfect reflector on land is assumed (Imamura et al., 2006).

Waves break at a depth ranging from about 0.8 to 1.4 times their height, depending on their steepness and seabed slope. If the structure is located in this range of water depth then it would be subjected to the action of breaking wave forces. On the contrary, if it is installed in depth deeper than this range, it would be subjected to non-breaking wave forces. Finally, structures in shallower depths would be influenced by broken water action. While non-breaking wave forces are static in nature, the remaining two (Breaking and Broken wave forces) are dynamic or time-varying (Deo, 2013)

Non-breaking wave forces:

On a smooth faced vertical wall, the incident wave would undergo pure reflection and standing waves will be formed. Assuming linear theory to be valid the subsurface pressure at depth 'z' is given by (Sainflou, 1928)

$$p = \gamma h \cos kx \cos \omega t \frac{\cosh k(d+z)}{\cosh kd} - \gamma z$$

Where γz is static and γH costkx $\cos\omega t$ $\frac{\cosh k(d+z)}{\cosh kd}$ is dynamic part.

Choosing x = 0, cos(kx) =1.

Let ρ be the density of water, g be the acceleration due to gravity, d be the depth of water below mean sea level, b be the length of the section of the dam, ν be the velocity of the incoming wave and h be the wave height above mean sea level.

Here $\gamma=\rho g$, H is the vertical distance between the maximum crest and maximum trough, k is the wave number of the tsunami wave, $\omega=2\pi/T$, T is the time period of the wave. Force is calculated by integrating wave pressure on the entire area of cross-section.

CASE STUDY

A Hypothetical Wall

To demonstrate the methodology we have taken a tsunamigenic source in the Andaman-Sumatra subduction zone.

The 26th December 2004 Sumatra earthquake of M_w 9.3 along the subduction zone between Indian plate and Burmese plate triggered a tsunami causing large-scale devastation in the coastal cities across the Indian Ocean. Due to the occurrence of aftershocks, a large

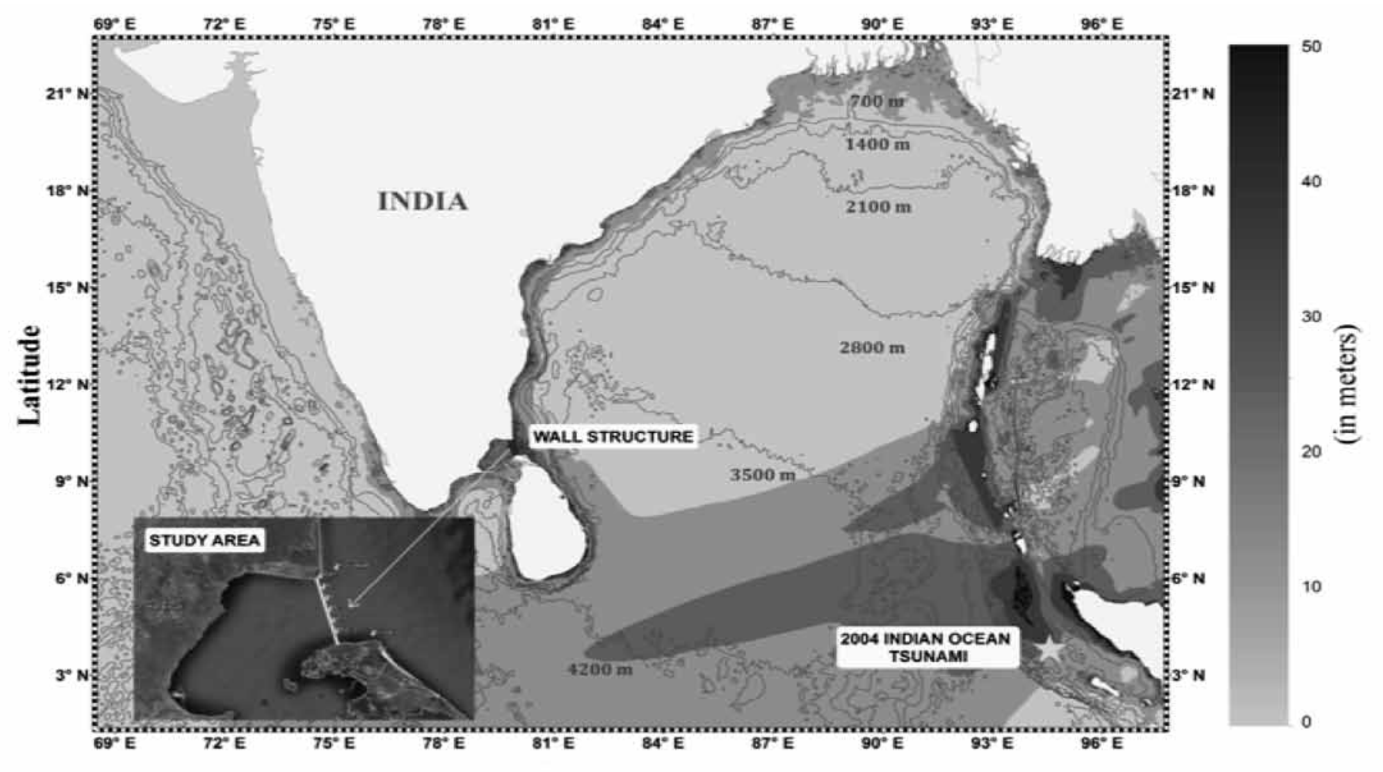

Figure 1. Directivity map of 2004 Sumatra tsunami and the hypothetical location of the wall structure.

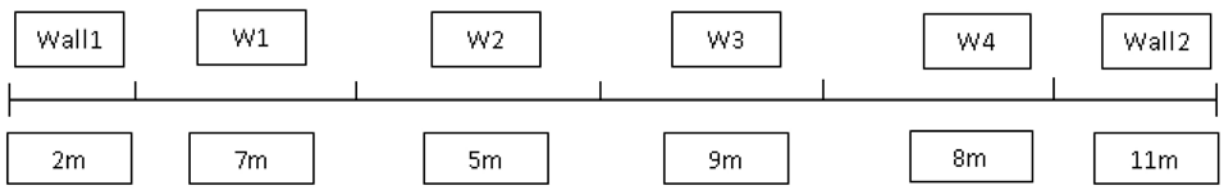

Figure 2. Water depths along different sections of the wall structure.

Table 1. Earthquake source parameters.

Watts et al, 2007	Segment-1	Segment-2	Segment-3	Segment-4	Segment-5
Coordinates	94.57°E to 3.83°N	93.90°E to 5.22°N	93.21°E to 7.41°N	92.60°E to 9.70°N	92.87°E to 11.70°N
Length (km)	220	150	390	150	350
Width (km)	130	130	120	95	95
Depth(km)	25	25	25	25	25
Dip (degrees)	12	12	12	12	12
Strike (degrees)	323	348	338	356	10
Rake(degrees)	90	90	90	90	90
Slip(m)	18	23	12	12	12

amount of stress was released causing rupture of 1200-1300 km northward from its epicenter up to Andaman region (Swaroopa et al., 2011). The Sumatra earthquake zone has been divided into five segments by Ioualalen et al., (2007) to model the 26th December 2004 tsunami and the initial deformation at the five segments is computed based on the deformation parameters given in table 1.

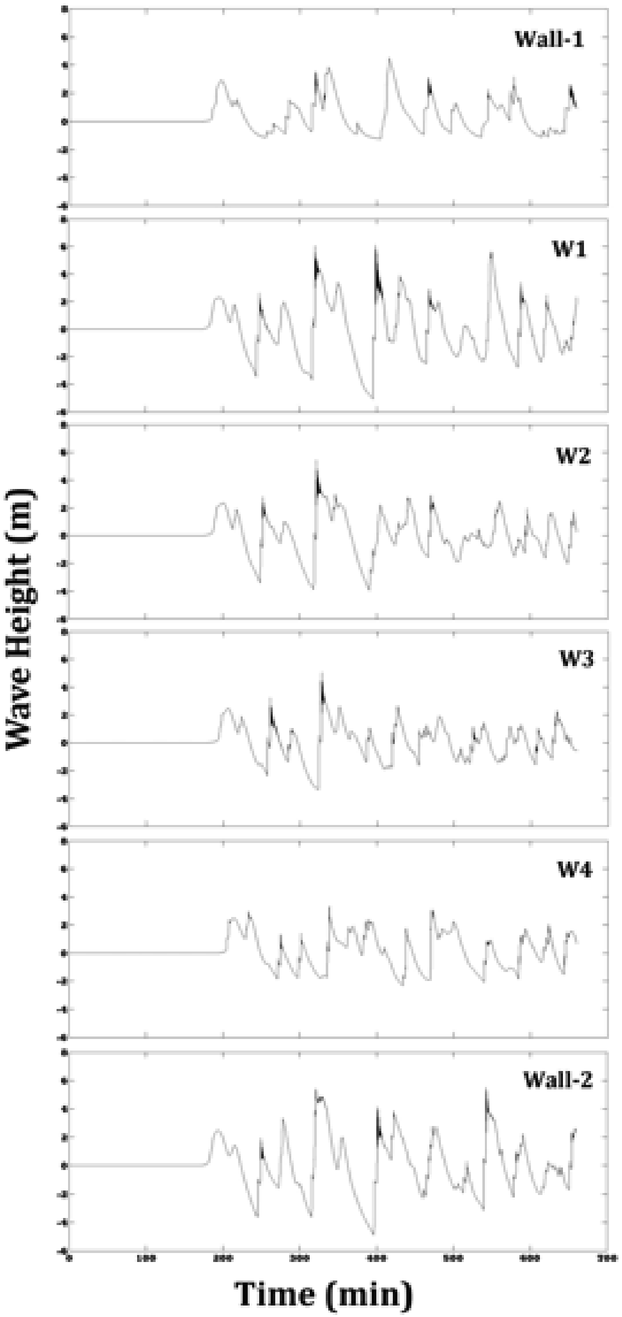

Figure 3. Tsunami wave height versus time at different locations along the wall structure.

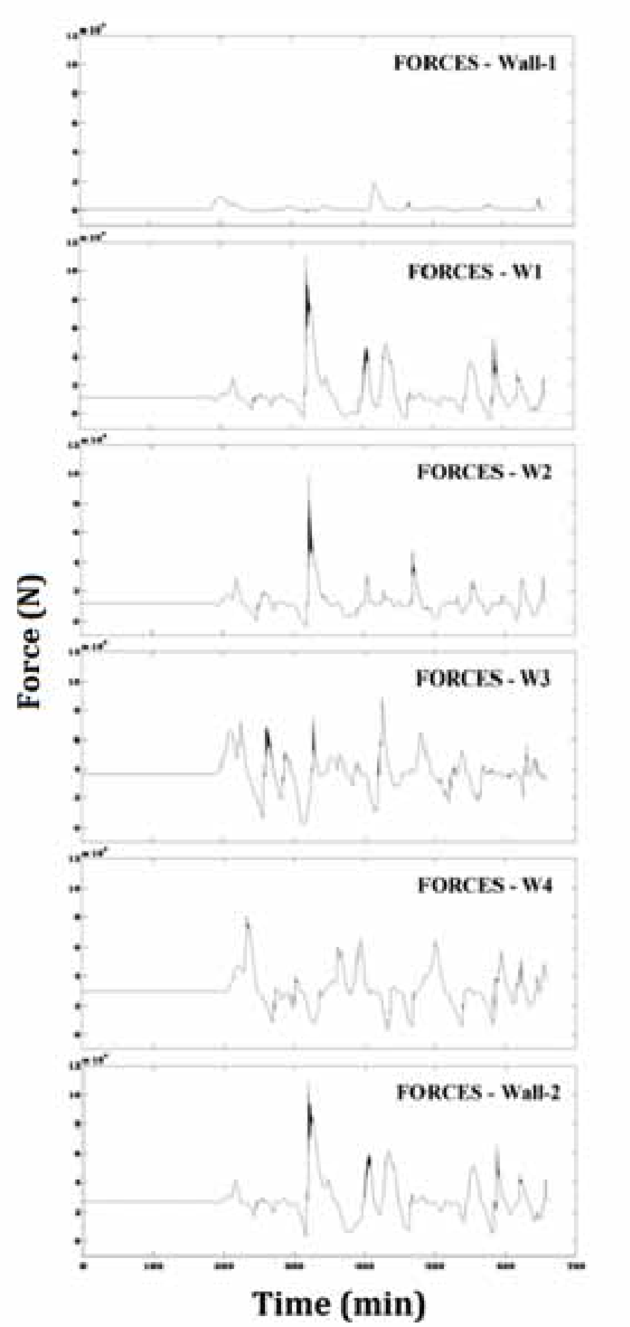

Figure 4. Sum of hydrostatic force and the non-breaking wave forces versus at different locations along the wall structure.

In the present study, the Sumatra tsunami has been simulated to assess the impact of forces on the given wall structure. The TUNAMI N2 code is extensively used in quantifying the tsunami propagation, arrival times, run up and inundation extents. This code is being used by several researchers to simulate the Pacific, Indian and Atlantic tsunamis. Tsunami directivity is computed and is shown in Figure 1. A two-dimensional wall structure is assumed between Kodiyakarai (India) and Illavalai (SriLanka) (Figure 1). The wall is divided into 6 sections along the length (Figure 2) and forces on each section are calculated based on the height of tsunami waves in that section. Tsunami arrival time, wave heights and the arrival time of the maximum wave are all plotted in Figure 3 and the results tabulated in table 2.

Table 2. Depths and maximum wave heights at different locations.

Locations	Depth(m)	Wave heights(m)
Nagapattinam	-11	5.0634
cuddalore	-11	7.1271
Chennai	-7	5.9341
Pallepalam	-10	3.3129
Kodiyakadu	-7	4.3078
Aluvai	-7	3.673
Wall1	-2	4.4368
Wall2	-10	5.2228
W1	-8	5.8136
W2	-5	4.5563
W3	-9	4.0815
W4	-8	3.1891

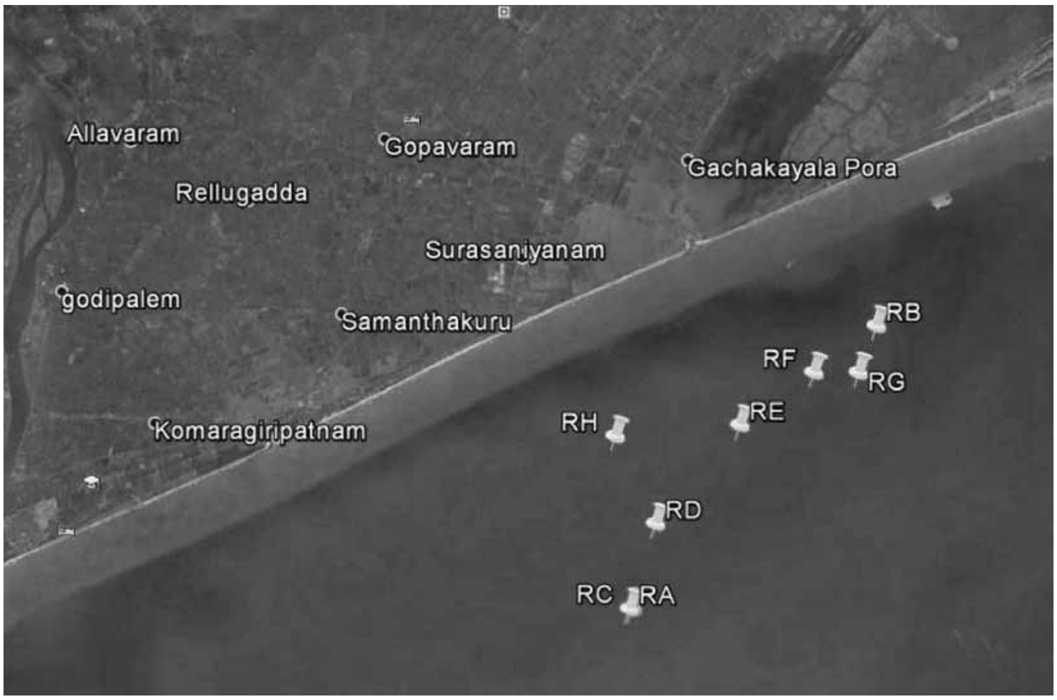

Figure 5. Locations of the Oil Rigs.

Taking into consideration the maximum wave heights and comparing the water depth in each section we clearly know that the wave breaking criteria is not satisfied. So, we calculate the non-breaking wave forces for each section using Equation 5 (where h, k and ω are calculated from the wave data generated by TUNAMI N2).

To compute the forces on the wall structure we take the values b=30km, g $=9.8 m/s^2$,$\rho=10^3 kg/m^3$. Here we have taken the total forces to be the summation of hydrostatic force and the non-breaking wave forces. Figure 4 shows the plot of forces versus time at different locations near and around the hypothetical wall structure.

Application: Offshore Ravva Field Oil Rigs

The Ravva field is one of the most efficient fields in the world and has maintained its low-cost operating base by focusing on oil field life-cycle planning, continuous monitoring of operational costs and the innovative application of operating technologies. The Ravva oil field platforms (RA to RH) are located offshore about 4.1km from the coast. The oil and gas production has declined over the years due to the aging of the oil field. Figure 5 shows the locations of the oil rigs. We have applied the same method in calculating tsunami forces on the oil rigs

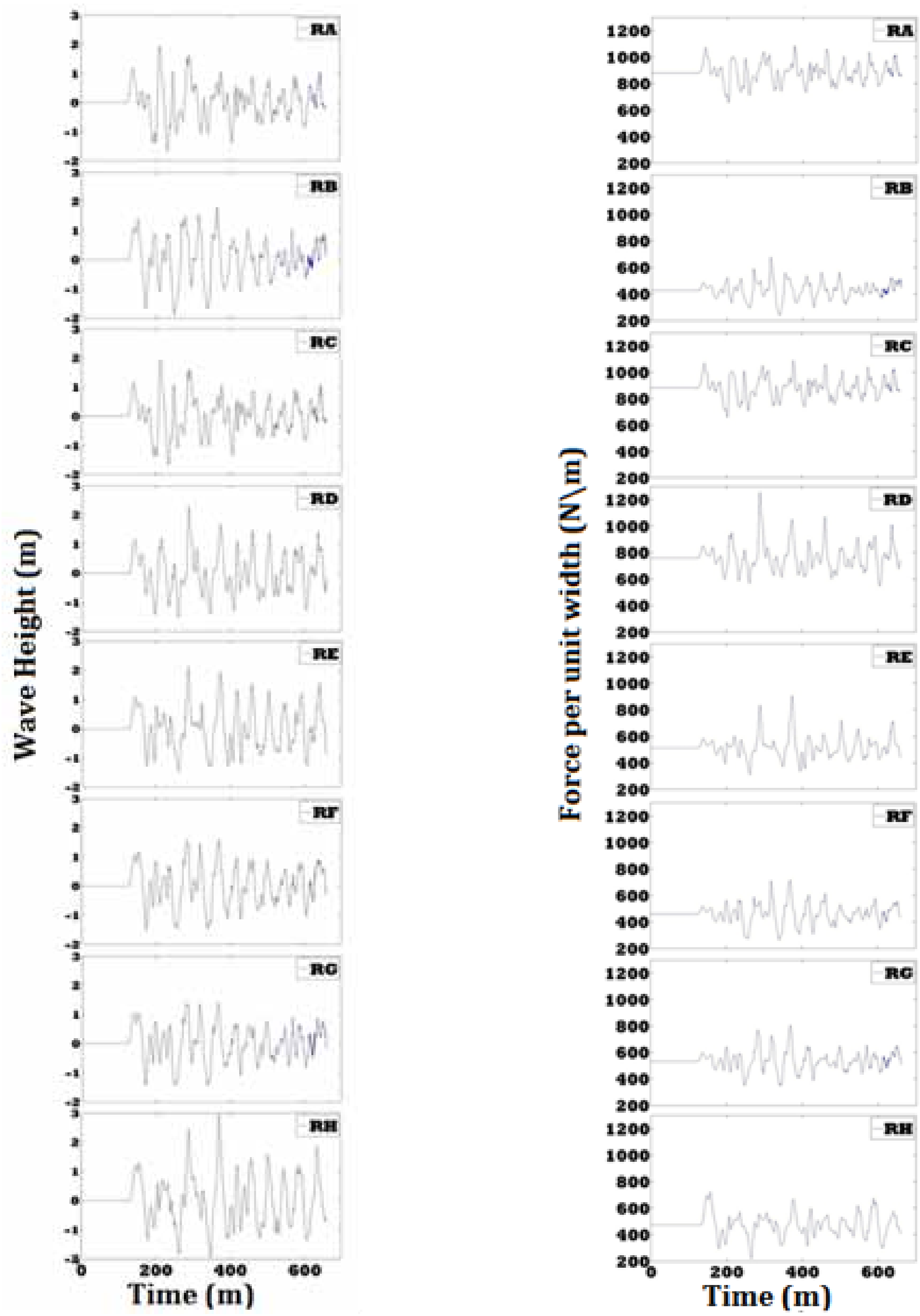

Figure 6. Wave herights and Wave forces per unit width versus at different Oil Rigs.

Table 3. Depths and maximum wave heights at Oil Rigs.

Locations	Depth(m)	Wave heights(m)
RA	-13	1.932
RB	-9	1.7791
RC	-13	1.9193
RD	-12	2.2708
RE	-10	2.0983
RF	-9	1.5971
RG	-10	1.4198
RH	-9	2.9295

mentioned in Table 3. The 2004 Indian Ocean tsunami, which has been discussed earlier is applied and the tsunami wave heights at different rig locations are computed.

From the Table 3 we understand that the wave breaking criteria is not satisfied. So we calculate the non-breaking wave forces for each location using Equation 5 (where h, k and ω are calculated from the wave data generated by TUNAMI N2). The maximum wave height at each rig location is computed and tabulated in Table 3.

Taking $g = 9.8 m/s^2$ and $\rho = 10^3 kg/m^3$ we obtained the forces per unit width at each location. Here we are calculating the forces per unit width, as the width of the rigs is not known. However, the width could be of the order of 100m, which implies that the forces could be of the order of 10^5N. The tsunami wave heights and forces are plotted in Figure 6.

CONCLUSION

Great earthquakes in the sea have often generated the devastating tsunami waves. Tsunami is a very complex natural phenomenon to understand, and its complexity lies in all its stages, i.e., generation, propagation, run up and inundation. Assessment of tsunami hazard along a particular coast is the focus in this study. A study is made for understanding the impact of tsunami forces on the ocean structures. We can see that a large amount of the force acting on the wall is due to the hydrostatic force, which will be surely considered during the wall construction. Due to its proximity to the source one expects to observe a major impact on the wall, yet the forces are much lesser compared to the cyclone-induced wave. Cyclone induced wave forces are almost 2-5 times more than the tsunami induced forces. Since the sizing of the wall protection in such locations will be made depending on the wave conditions exerted during the cyclone action, we opine that the tsunami would not pose any threat to the wall structure. The study on the oil rigs in the ocean shows that tsunami wave forces did not cause any damage to the rigs due to their location in the deep ocean.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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"The sea loved the moon
When she was supposed to love the shore.

The moon knew
And hence made his intentions known.

That she should love the shore
Who was destined for her.

Yet his protests seemed weak.
And even when he pushed her towards the shore-
She always retreated back.

To want, to need, to love the moon
For all she's worth.

Everyone said, it wasn't meant to happen.
Yet, the Tsunami rose that night for their union."

— Saiber *- an young Indian story teller by choice and a poet by heart*