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Nested Modeling Framework for Assessing Tsunami Wave Impact on the Coastal Region of Gujarat, West Coast of India: A Hypothetical Approach

Girishkumar D Jagad[1], M. B. Dholakia[2], V. M. Patel[3], Yashodhar P Pathak[4], Kashyap B Gohil[5]

[1]Research Scholar,Gujarat Technological University, Ahmedabad, Gujarat, India. Email: girishjagadphd@gmail.com
[2]Director and Dean Swarrnim Institute of Technology, Gandhinagar, Gujarat, India. Email: mrug63@rediffmail.com
[3]Asst. prof. Civil Engg Dept, Government Engineering College Patan, Patan, Gujarat, India.
[4]Assistant Professor, Civil engineering, Governement Engineering college Bhavnagar, Gujarat, India. Email: yashodharpathak189@gmail.com
[5]Assistant Professor, Civil engineering, Shantilal Shah Engineering college Bhavnagar, Gujarat, India. Email: kapgohil@gmail.com

A nested modeling framework is designed to evaluate the potential ramifications of tsunami waves on the coastal expanse of Gujarat, with a specific focus on the DevbhumiDwarka District. Initially, the study area was discretized from a coarse 4000 x 4000 m grid to a finer 300m x 300m grid using Delft 3D flow and Delft-Dashboard. Subsequent simulations were executed to replicate tsunami waves generated by a theoretical tectonic earthquake of Mw 9.1 magnitude.The outcomes provide crucial insights into the timing and magnitude of tsunami wave occurrences. The initial wave reached the Gujarat coast at DevbhumiDwarka approximately 2 hours and 20 minutes after its genesis. Within an 80-minute timeframe, two peaks of tsunami wave heights were discerned, measuring 2.9 and 4.5 meters, respectively. This underscores the significant impact such events can have on coastal regions.Furthermore, a comparative analysis with past data reveals a notable alteration in arrival time. In this hypothetical scenario, the first wave reached the coastline 20 minutes earlier than a prior tsunami event along the same stretch of coast.

Keywords: Impact of Tsunami, Tsunami risk assessment, Nested Modeling, Delft Dashboard, Delft 3D Flow, Hypothetical Approach.

1. Introduction

A tsunami is a series of extremely destructive, long, and rapidly moving ocean waves, originating from the Japanese word for harbor waves.Tsunamis, though infrequent, create a substantial threat to coastal communities and infrastructure (e.g., Clague et al., 2003; Jaiswal et al., 2009, 2011; Singh et al., 2012; Merrett and Chen, 2013; Prerna et al., 2015; Patel et al., 2016; Hou et al., 2020). Understanding potential sources of tsunamis in the Arabian Sea is crucial for bolstering disaster preparedness, especially for Gujarat's coastline (Byrne et al., 1992; Jaiswal et al., 2009; Dani et al., 2023). One notable source is the Makran Subduction Zone (MSZ), spanning 800 km along the northern Arabian Sea. The last significant tsunami in this area occurred on November 27, 1945, triggered by an earthquake in the MSZ, registering a magnitude between Mw 8.0–8.3 (Byrne et al., 1992; Jaiswal et al., 2009). This event generated waves as high as 10m, affecting Iran, Oman, Pakistan, and northwest India.Western India's coastline regions are extremely susceptible to tsunami-caused earthquakes along the MSZ, which could have catastrophic effects on a number of coastal communities.

The 1945 tsunami, with reported wave heights of 11.0 to 11.5 meters along parts of Gujarat's coastline, resulted in considerable loss of life. Thermal modeling of the MSZ suggests its potential for seismic activity comparable to the December 2004 Sumatra rupture, capable of triggering an earthquake up to Mw 9.2 (Singh et al., 2012). Given the significant coastal development in the Arabian Sea region, understanding vulnerability to such extreme events, particularly from the MSZ, is paramount. To address this, a nested numerical model of tsunami waves along Gujarat's Coastal Region was simulated following a hypothetical tectonic earthquake of Mw 9.1. The simulation uses Delft Dashboard and Delft3D-Flow to assess tsunami arrival time, wave height at the coastline, run-up elevation, and inland inundation. In view of this an attempt is made a hypoteical approach for assessing Tsunami wave impact on the coastal region of Gujarat, western India

2. Methodology and Study Area

This study employs a quantitative research approach, utilizing a case study methodology that undergoes numerical analysis. Tsunami wave simulation is performed bymodeling in Delft Dashboard and Delft3D-Flow. This research started by studying historical tsunamigenic eventsthat occurred in the north-western Indian Ocean, which is shown in Table 1.

Table 1.Historical Tsunamigenic event in North-Western Indian Ocean(Heidarzadeh et al, 2008)

Sr. No.	Year	Earthquake Magnitude
1	326BC	-
2	1008	-
3	1524	-
4	1819	7.5–8.25
5	1845	>6
6	1897	-
7	1945	8.1–8.3
8	2004	9.3

A simulation grid for the domain is created using the Delft Dashboard. Here three different grid sizes are created in the coastal and offshore areas to achieve accuracy and stability in wave simulation. The tsunami modeling in this research used two simulation scenarios having momentum magnitude 8.1 and 9.1 out of which former was actual event 0f 1945 Makran and later is hypothetical event (Smith et al., 2013). Underwater earthquake parameters which can generate a tsunami of momentum magnitude of 8.1 and 9.1 are tabulated in Table 2.

Table 2.Rupture Parameters

Source: Byrne et al. 1992, Smith et al., 2013

Name	Makran 1945	Hypothetical
Momentum magnitude	8.1	9.1*
Length (km)	200	850
Width (km)	100	200
Rake(°)	89	90
Depth (km)	15	10
Strike (°)	246	260
Dip (°)	7	15
Slip(m)	7	20

The simulation of these two scenarios generates water surface elevation, which is analysed to obtain the height and arrival time of tsunami waves at each predetermined observation point. Meanwhile, the run-up and inundation elevations of the tsunami are obtained from the analysis of the maximum water surface elevation that floods the land area to determine the affected areas in the coastal region of DevbhumiDwarka.

1945 tsunami event numerical model simulation result shows that tsunamis could reach along the western coasts ~2 hrs to 5.30 hrs after the initial tsunami wave generated with heights from 1 m upto 2.5 m along the MSZ. The most affected coasts of Gujarat are Jakhau, Mundra, Kandla, Okha and Dwarka (Dani, 2023). Further Due to the unavailability of observation data on water level rise along Gujarat coastal belt because of the 1945 Tsunami event, further investigation was inspired, leading to the selection of Devbhumi Dwarka as the study area.

In Fig. 1 as indicated the study area under consideration for proposed research which is located at coastline of DevbhumiDwarka District, Gujarat, India.

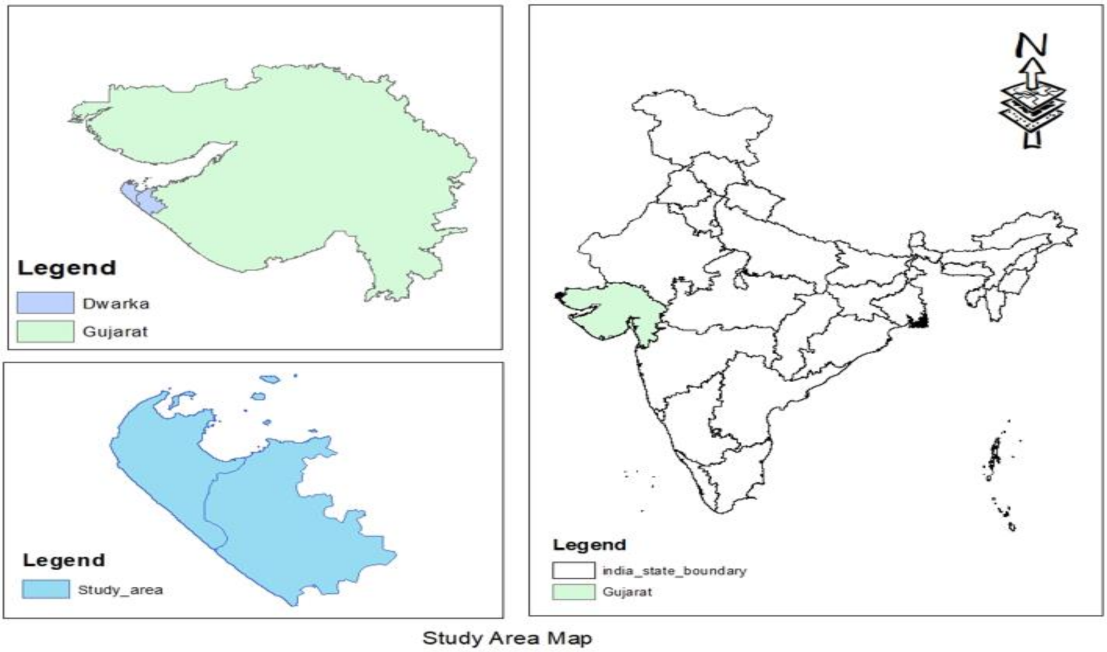

Fig 1.Map for Study Area

3. Numerical Model Development

Delft3D FLOW was used to simulate initial wave generated at source of earthquake to the far field to investigate the wave height along coastline of the study area due to tsunami. Delft3D is an open-source, fully integrated computer software suite developed by Delft3D which predicts well the general hydrodynamic observations associated with tsunami nearshore propagation and inundation measured under a wide range of conditions. This study, combined with previous studies(Deepak et al., 2005;D. Vatvani et al., 2007),that showed Delft3D models studied the deepwater propagation and inundation of the 26 December 2004 Indian Ocean tsunami near Banda Aceh, demonstrates that Delft3D is applicable for modeling long, non-dispersive tsunamis from the source to the maximum extent of inundation. For a 3Dflow simulation the system of the momentum equations in −x, −y direction reads:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \frac{\omega}{H}\frac{\partial u}{\partial \sigma} - fv = -\frac{1}{\rho_0}P_x + F_x + \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left[v_{V,back}\frac{\partial u}{\partial \sigma}\right] \quad \text{(Eq. 1)}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + \frac{\omega}{H}\frac{\partial v}{\partial \sigma} - fu = -\frac{1}{\rho_0}P_y + F_y + \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left[v_{V,back}\frac{\partial v}{\partial \sigma}\right] \quad \text{(Eq. 2)}$$

where f is the Coriolis parameter; uandvare the horizontal velocities in −x and −y direction, ω is the vertical velocity in relation to σ –coordinates (Phillips, 1957), $v_{back}$is the minimum vertical eddy viscosity; P_x, P_y are the horizontal pressure terms approximated by the Bossiness assumptions; $\rho_o$is the reference water density;H = d + ζ with d the water depth below a reference level z = 0 and ζ the free surface elevation above that reference level and F_x,F_y are the viscous forces presenting the unbalance of the Reynold's shear stresses.

The free surface elevation ζ is computed from the depth-averaged continuity equation neglecting the contributions due to discharge/removal of water per unit surface area and evaporation/precipitation effects. So:

$$\frac{\partial \zeta}{\partial t} + \frac{dHU}{dx} + \frac{dHV}{dy} = 0 \qquad \text{(Eq. 3)}$$

Where U and V are the depth-averaged horizontal velocities in the –x and −y directions.An Alternating Direction Implicit (ADI) time integration technique is used to solve the continuity and momentum conservation equations. The accuracy of the ADI solver depends on the Courant-Friedrich-Lewy (CFL) number. In most practical applications, as in the present study, the CFL number should not exceed a value of 10 but may be higher in case of small variations in space and time (Deltares, 2011).

3.1 Model Setup for Scenario 1

The past event of the 1945 Makran earthquake (Mw 8.1) was taken as base to validate the tsunami simulation result of Delt3d-Flow. Earthquake parameters for the present study were obtained from(Byrne et al, 1992)Table 2. The initial tsunami wave is generated using the same earthquake characteristics as input parameters in the Delft Dashboard tsunami tool. To achieve the desired momentum magnitude, the regression equation suggested by Wells and Coppersmith 1994 (Wells, 1994) is utilized to derive fault length, width, and dislocation in this model.

Numerical Model parameter for model setup is as shown below;

- Grid Resolution: 4000 m × 4000 m, Total Number of Computational Grid Cells: 56776. Grid Extent: East to West: 61.008 to 73.088 North to South: 17.829 to 25.349.
- The Gebco 19 bathymetry data, characterized by a resolution of 15 arc seconds (450 meters), was employed in the simulation. I choose Riemann as the boundary type in the flow condition setting because when the generated wave has achieved the maximum boundary, it will be reflected and the same process will occur again.
- The forcing type chosen is time-series with gravity values of 9.81 m/s^2.
- Water density of 1025 kg/m3 for seawater.
- Manning roughness coefficient taken 0.03 for deep sea and 0.06 for land having elevation more than 0m. (based on Chow and TR-55)

The numerical parameter settings adopted minimum depth at grid cell centers and mean depth at grid cell faces, threshold depth 0.1 m, and flood advection scheme for momentum to visualize the tsunami inundation on the main land in detail. In a view to validate model output, the simulated tsunami wave height for Pasni and Karachi was compared with the tsunami wave height observation by (Heidarzadeh et al, 2008; Howells, 1982)(Table 3). The present study found A good agreement between the pattern and the magnitude of the sea surface rise near

Pasni and Karachi(Heidarzadeh et al, 2008; Howells, 1982). Therefore, it is said that the present model can predict the sea surface rise with an acceptable level of confidence.

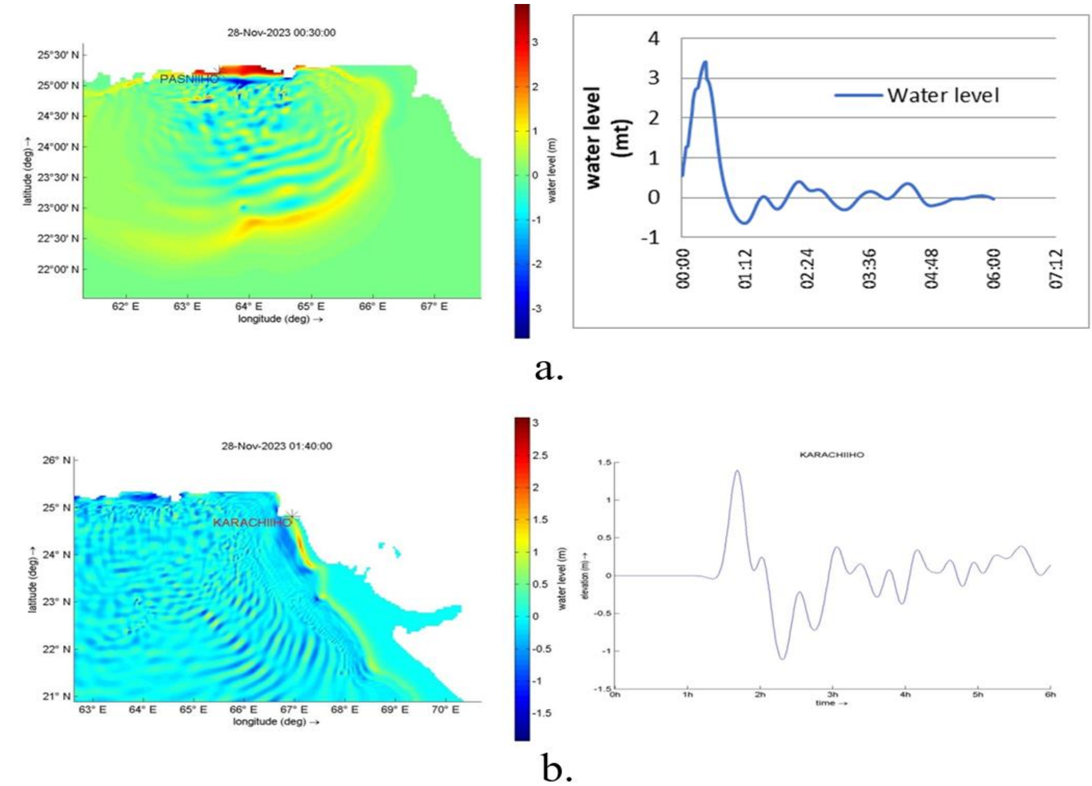

Fig.1: a. Water level rise at pansi; b. water level rise at karachi

Table 3.Comparison of observed water level and model derived water level

Source: Howells1982**; Heidarzadeh et al. 2008a*

Obs. Point	Location	Max Wave height observed	Max. Wave Height (modelled)	Error %
1	Pasni	4 – 5* m	3.4 m	15
2	Karachi	1.5 **m	1.4 m	6.6
			MAPE	10.83

This validation is calculated using MAPE (Mean Absolute Percentage Error), shown in equation (Guo, 2018).

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{P_{oi}-P_{pi}}{P_{oi}}\right| \times 100\% \qquad \text{(Eq. 4)}$$

While n is the total number of observations, P_{oi}, and P_{pi}. are height of observation and simulation waves. The MAPE value interpretation is categorized into four groups: highly accurate (<10%), good (10-20%), reasonable (20-50%), and inaccurate (>50%)(Lewis, 2012). Therefore, the validation percentage obtained in this model falls within the good accurate range, being less than 20%.

3.2 Model Setup for Scenario 2

To understand the effect of highly intense tsunami along Coastal Region of Gujarat a hypothetical scenario of momentum magnitude 9.1 is simulated. The earthquake parameters that are considered to generate initial wave deformation are tabulated in Table 4. The initial wave was generated using DDB (delft dashboard) and simulated in Delft 3d Flow module.

A multi-scale computational domain was set up to produce better results along the shoreline. Initially, a large-scale model covering an area starting from Makran and extending up to the southwest coast of India was set up with a grid resolution (4000 m x 4000 m). The subsequent grid coveringthe Gujarat coastline modeled 1000m x 1000m heaving extent. Longitude: 67.88 to 70.47, latitude: 21.75 to 23.45. Finally, fine Inner grid of 300m x300m having extent Longitude: 68.85 to 69.36 latitude: 21.97 to 22.52 was prepared as shown in Fig. 3. To understand the effect of tsunami at various observation points were also established along the coastline of Gujarat are tabulated with grid reference in Table 5 and graphically show in Fig. 4. All other Numerical Model parameter is kept same as previous model setup, only the magnitude of earthquake has been increased.

Table 4.Fault Parameters

Dip angle (deg.)	15
Rake angle (deg.)	90
Strike angle (deg.)	260
Slip (meter)	20
Depth (meter)	10
Length (meter)	850
Width (meter)	200

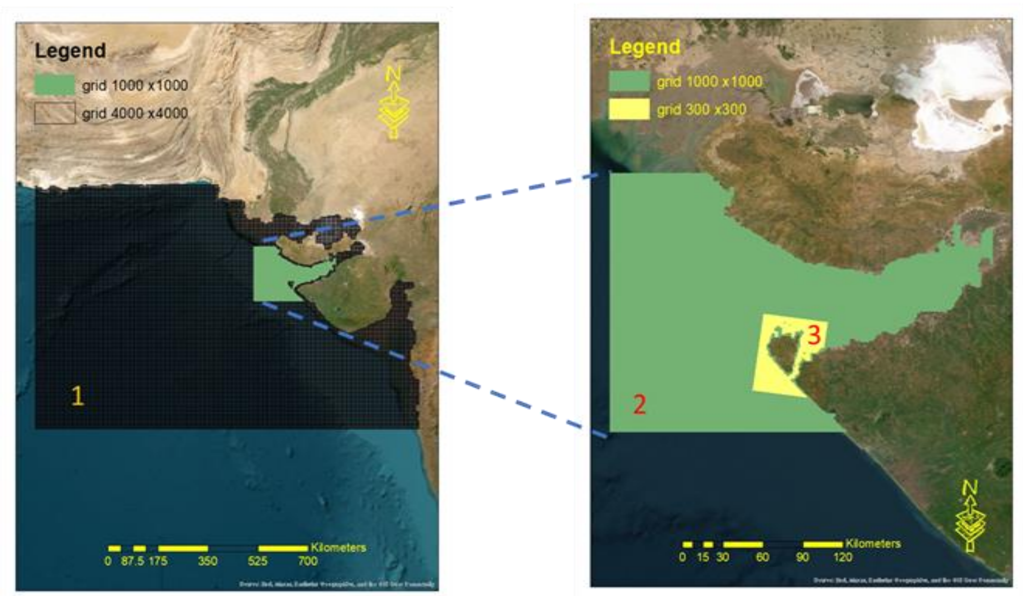

Fig. 3.Multiscale computational domain

1) 4000m x 4000m, 2) 1000m x 1000m, 3) 300m x 300m

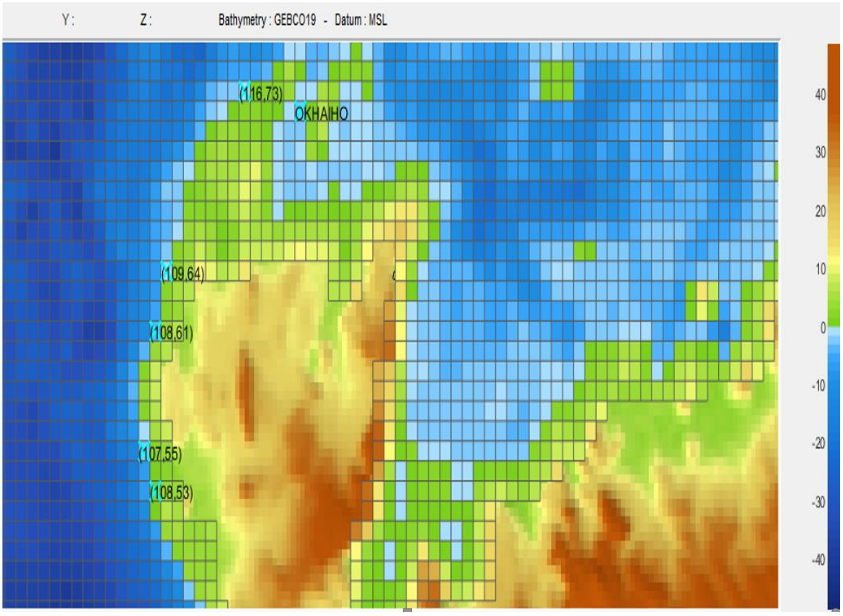

Fig. 4.Observation points along Gujarat coastline

Table 5.Grid Reference for Observation Point

Name	Coordinates	Model Grid
Shiv Rajpur Beach	22.3330° N, 68.9536° E	61, 108
Dwarka Beach	22.2641° N, 68.9544° E	53, 108
Okha	22.48° N,69.05° E	121, 72

4. Results and Discussion

The hypothetical possible worst case of a tsunami of Mw 9.1 results shows that the initial wave height at t=0 time at source was 5.47m as shown in Fig. 5(a), which seems very high compared to actual scenario 1. The resulting output in water surface elevation is analysed to obtain the arrival time of tsunami wave heights at each predetermined observation point shown in Table 7. Furthermore, the simulation of results shows that the first wave reached Gujarat at DevbhumiDwarka after 2h and 20 minutes after the first wave at the source and the run-up height is observed to be in the range of 1.5m to 2m.

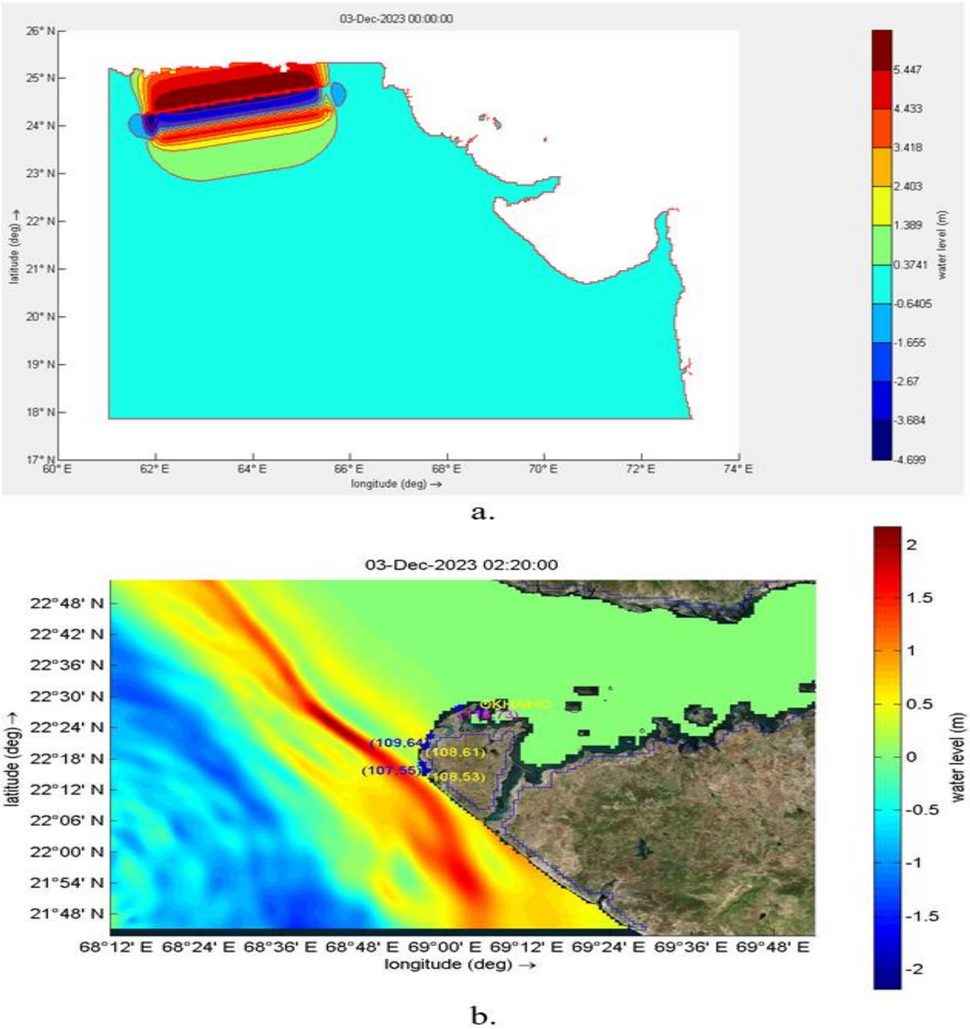

Fig. 5.a. Water level at t=0; b. Water level at t=2hr 20 min

Table 6.Grid Location for Observation Point

Name	Coordinates	Model Grid
Shiv Rajpur Beach	22.3330° N, 68.9536° E	61, 108
	22.3722° N, 68.9633° E	64, 109
Dwarka Beach	22.2641° N, 68.9544° E	53, 108
	22.2825° N, 68.9430° E	55, 107
Okha	22.48° N,69.05° E	121, 72

The first wave of the tsunami is expected to reach Shivrajpur beach in 2 hours and 39 minutes. The second wave arrives 1 hour and 26 minutes later, at 4 hours and 5 minutes, resulting in a more than 1 hour gap between successive crests. Along the Dwarka beach, out of two observation points located at 22.2825° N, 68.9430° E (55,107) encounter two subsequent wave picks at an interval of 80 minutes (Table 7) having wave heights 2.97 and 4.5 meters, respectively (fig. 6) also the first wave pick approaching the shoreline with velocity of 1 to 1.4 m/s and second wave approaching with higher velocity around 1.3 to 2.6 m/s which is seem higher than the first wave velocity (fig.7).

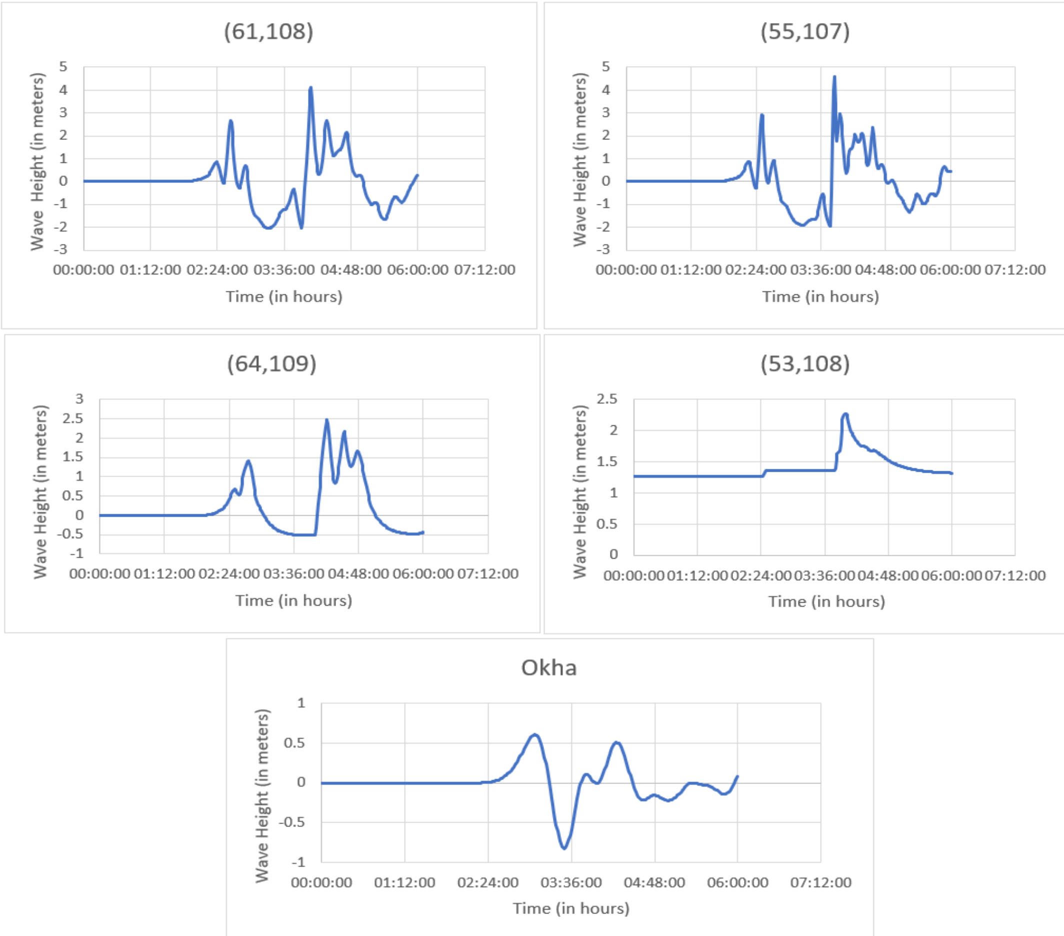

Fig. 6.Water level at Grid locations with Time interval

Table 7.Water level at different grid locations with arrival time

Name	Model Grid	Max. Run-up height [m]	Arrival Time [hh:mm]
Shiv Rajpur Beach	61, 108	2.5853	02:39
		4.12971	04:05
	64, 109	2.48021	04:06
Dwarka Beach	53, 108	2.25376	04:01
	55, 107	2.97259	02:34
		4.51474	03:54
Okha	121, 72	0.756601	03:15
		0.816009	04:51

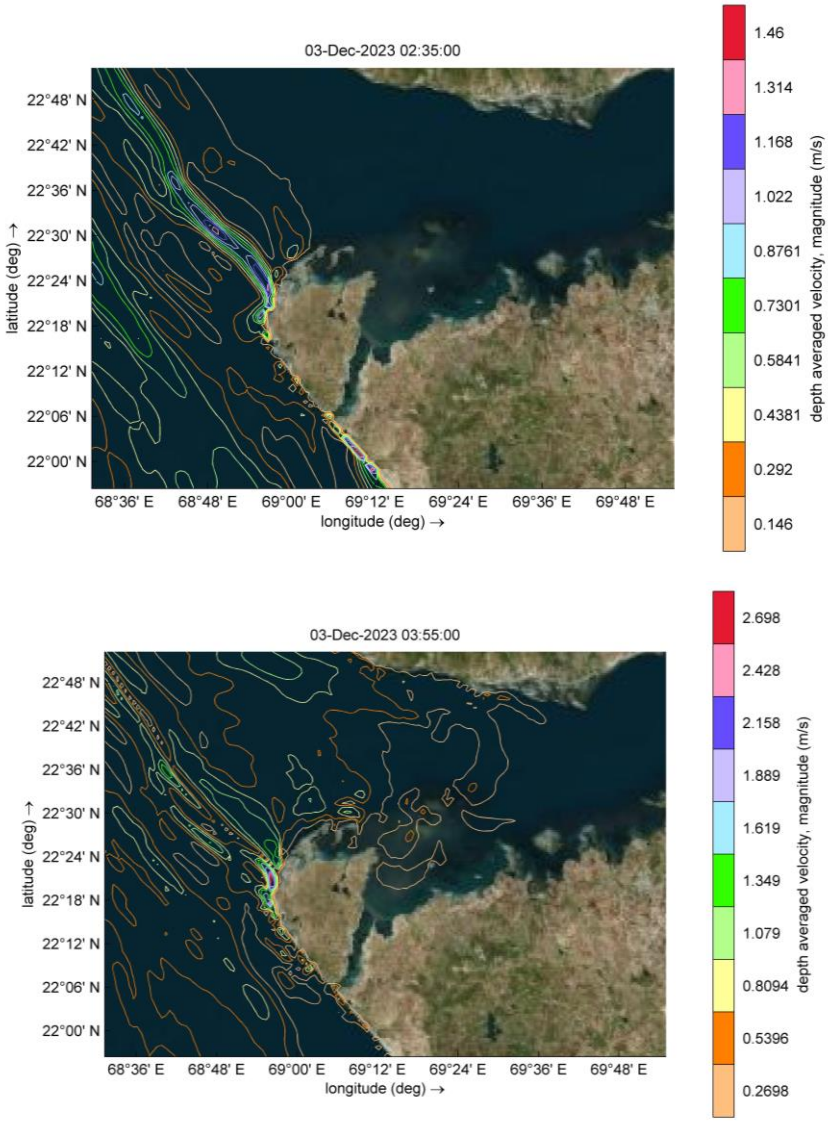

Fig.7 Wave Velocity Contour for 9.1 Mw

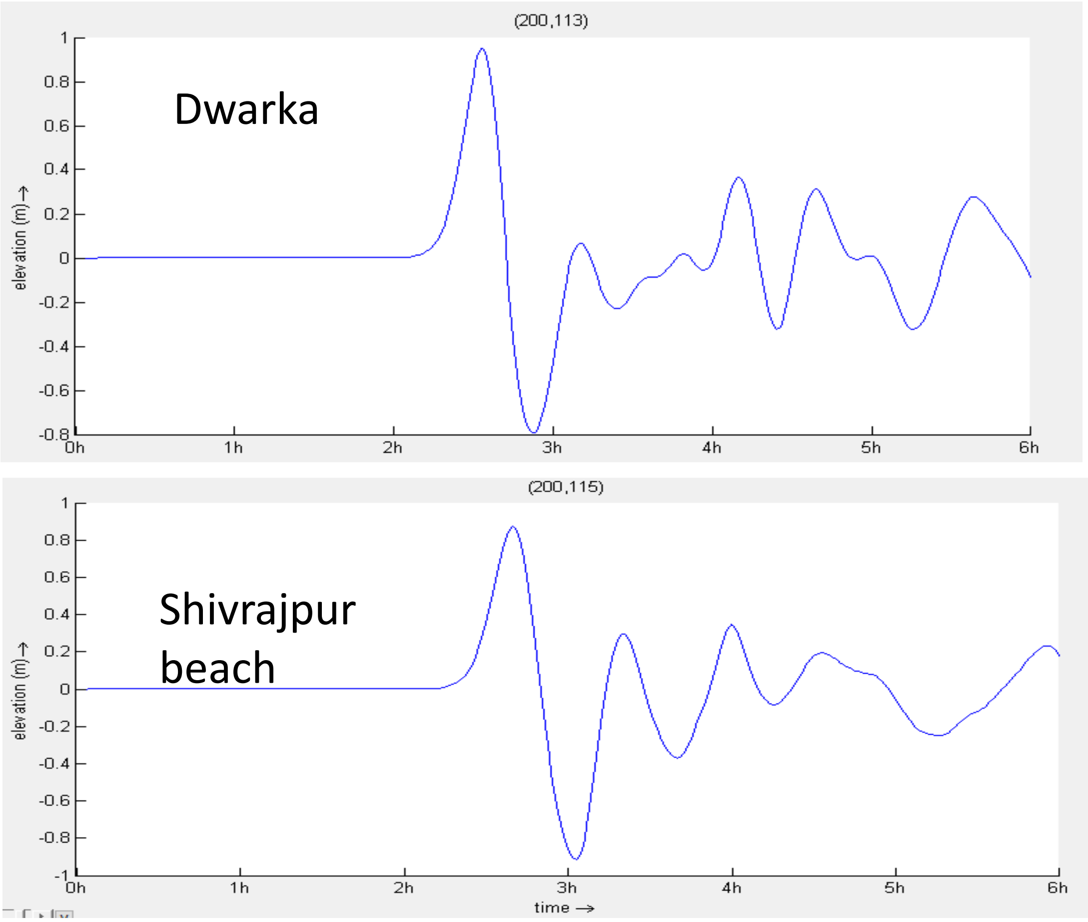

Fig. 8.SimulatedWater level of1945 Tsunami event

5. Conclusion

The development of a hypothetical nested grid model for assessing tsunami wave impacts on the coastal region of Gujarat, specifically the DevbhumiDwarka District, has provided valuable insights into potential scenarios and their consequences. Using Delft3d-Flow, the simulation of tsunami waves resulting from a hypothetical tectonic earthquake of Mw 9.1 has been achieved. The findings reveal that in the hypothetical scenario, the first tsunami wave reached the Gujarat coast at DevbhumiDwarka approximately 2 hours and 20 minutes after the initial wave at the source. The observed run-up heights ranged from 2.9 to 4.5 meters. Also the second wave approaching the shoreline with quite high velocity in the range of 1.3 to 2.6 m/s has the potential to erode the shoreline. The hypothetical event is also capable of producing multiple wave spikes. It is understood from simulation that the second wave is more hazardous than the first wave. The A noteworthy comparison to previous data indicates that the first wave in this hypothetical event arrived 20 minutes earlier than a Historical tsunami event (1945) along the same coastline, with the previous event registering a first wave height of 0.9 meters after 2 hours and 40 minutes from the source. These results underscore the importance of proactive measures and preparedness in coastal regions susceptible to tsunami threats. The nested modeling framework employed in this study offers a valuable tool for assessing potential tsunami impacts.

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References

1. Byrne D. E., Lynn R. Sykes, and Dan M. Davis, 1992, "Great thrust earthquakes and aseismic slip along the plate boundary of the MakranSubduction Zone", Journal of Geophysical Research: Solid Earth, vol. 97, pp. 449-478.
2. Clague, J.J., Munro, A. & Murty, T. (2003) Tsunami Hazard and Risk in Canada. Natural Hazards 28, 435–463
3. Dani, B., Srivastava, V., Singh, A.P., Bhatla, R., 2023,"Tsunamis in the Past and Recent Years over Indian Coasts: A Review". In: Sandeep, Kumar, P., Mittal, H., Kumar, R. (eds) Geohazards. Advances in Natural and Technological Hazards Research, vol 53. Springer, Singapore. https://doi.org/10.1007/978-981-99-3955-8_10
4. Deepak &Schrama, Ernst & van KesterVatvani, 2005, "Hindcast of tsunami flooding in Aceh --- Sumatraceh", in The Fifth International Symposium on Ocean Wave Measurements and Analysis (WAVES2005), Madrid, Spain.
5. Deltares D., 2011, Delft3D-FLOW Simulation of multi-dimensional hydrodynamic flows and transport phenomena, includingsediments.:Deltares.
6. George. Pararas-Carayannis, 2006, "The Potential Of Tsunami Generation Along The MakranSubduction Zone In The Northern Arabian Sea. Case Study: The Earthquake And Tsunami Of November 28, 1945". https://api.semanticscholar.org/CorpusID:56313036
7. Guo, T.; He, W.; Jiang, Z.; Chu, X.; Malekian, R.; Li, Z, 2018, "An Improved LSSVM Model for Intelligent Prediction of the Daily Water Level", Energies, vol. vol. 12, no. no. 1, p. 112.
8. Heidarzadeh et al, 2008, "Historical tsunami in the MakranSubduction Zone off the southern coasts of Iran and Pakistan and results of numerical modeling", Ocean Engineering, Volume 35, Issues 8–9, pp. 774-786.
9. Hou, J., Yuan, Y., Li, T., & Ren, Z. (2020). Tsunami hazard analysis for Chinese coast from potential earthquakes in the western North Pacific. Geomatics, Natural Hazards and Risk, 11(1), 967–983.
10. Howells,D.A.,1982 "A history of Persian earthquakes, by N. N. Ambraseys and C. P. MelvilleCambridge University Press, Cambridge, 1982", Earthquake Engng. Struct.Dyn., 11, pp. 591-591.
11. Jaiswal R. K, A.P. Singh, Rastogi, B. K. and T.S. Murty, 2011,. "Aftershock Sequences of Two Great Sumatra Earthquakes of 2004 and 2005 and Simulation of the Minor Tsunami Generated on September 12, 2007 in the Indian Ocean and Its Effect on Indian Coast", Natural Hazards, 57(1): 7-26; DOI 10.1007/s11069-010-9637-z.
12. Jaiswal R. K,, A. P. Singh and B. K. Rastogi, 2009,"Simulation of the Arabian Sea Tsunami Propagation Generated due to 1945 Makran Earthquake and Its Effect on Western Parts of Gujarat (India)", Natural Hazards, 48(2): 245-258.
13. Lewis, C.,2012, " Demand Forecasting and Inventory Control. Routledge: Woodhead Publishing Ltd.

14. Merrett, H. C., & Chen, W. W. (2013). Applications of geographical information systems and remote sensing in natural disaster hazard assessment and mitigation in Taiwan. Geomatics, Natural Hazards and Risk, 4(2), 145–163
15. Murty, T. S., 1991, "A tentative list of tsunamis in the marginal seas of the North Indian Ocean", Natural Hazards, Vol 4, pp. 81-83.
16. Patel V. M., H. S. Patel and A. P. Singh. 2011,"Comparative Study of Earthquake and Tsunami Loading On Vertical Evacuation Structure at Dwarka". International Journal of Earth Sciences and Engineering, 04 (04), 659-668
17. Patel V. M., M. B. Dholkiya and A.P. Singh, 2016, "Emergency preparedness in the case of Makran tsunami: a case study on tsunami risk visualization for the western parts of Gujarat, India", Geomatics, Natural Hazards and Risk, 7(2), 826-842.
18. Pendse, CG, 1946, "A short note on the Mekran earthquake of 28th November 1945", J SciInd Res volv5, pp. 106-108.
19. Phillips,N. A., 1957"a Coordinate System Having Some Special Advantages for Numerical Forecasting.", Journal of the Atmospheric Sciences, vol. 14, pp. 184-185.
20. Prerna, R., Srinivasa Kumar, T., Mahendra, R.S. et al. (2015) Assessment of Tsunami Hazard Vulnerability along the coastal environs of Andaman Islands. Nat Hazards 75, 701–726
21. Rastogi B. K., 2006, "A Historical Account of the Earthquakes and Tsunamis in the Indian Ocean," in The Indian Ocean Tsunami. December.3-18.
22. Singh A. P., T. S. Murty, B.K. Rastogi, and R. B. S. Yadav , 2012,"Earthquake generated Tsunami in the Indian Ocean and probable vulnerability assessment for the east coast of India", Marine Geodesy, 35, 49-65; DOI: 10.1080/01490419.2011.637849
23. Smith, G., Lisa McNeill, Kelin Wang, Jiangheng He, and Timothy Henstock, 2013 "Thermal structure and megathrustseismogenic potential of the Makransubduction zone", Geophysical Research Letters, vol. 40, pp. 1528-1533.
24. Srivastava V., A. P. Singh, and R. BhatlaB. Dani, 2023, "Numerical Modelling of tsunami wave to assess the possible impacts along western coasts of India", MAUSAM, vol. 74, no. 4, pp. 1131–1140.
25. Van Ormondt, Maarten and Nederhoff, Kees and van Dongeren, Ap, 2020, "Delft Dashboard: a quick set-up tool for hydrodynamic models", Journal of Hydroinformatics volume 22, pp. 510--527.
26. Vatvani D., B. Jaffe, and F. Dekker G. Gelfenbaum, 2007, "Tsunami inundation and sediment transport in vicinity of coastal mangrove forest", in 6th International Symposium on Coastal Engineering and Science of Coastal Sediment Processes, New Orleans, LA.
27. Wells, Donald & Coppersmith, K, 1994, "New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement", Bulletin of the Seismological Society of America. 84. , pp. 974-1002.