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GUEST EDITORIAL

From excellence to eminence: the Indian tsunami early warning centre

Tsunamis are gravity-driven water waves induced by the displacement of large volumes of seawater due to submarine earthquakes, volcanic eruptions, landslides or meteorite impacts. Under-sea earthquakes are responsible for more than 70% of the tsunamis. After the 2004 Indian Ocean Tsunami, India set up a tsunami warning system with a 24 × 7 warning centre, operating since October 2007 at the Earth System Science Organisation (ESSO) – Indian National Centre for Ocean Information Services (INCOIS). This system provides tsunami early warning to 27 countries and has established its leadership in the Indian Ocean region.

The Indian Tsunami Early Warning System as detailed by Nayak (Tsunami watch and warning centers. In *Encyclopaedia of Solid Earth* (ed. Gupta, H. K.), Springer, 2020) comprises:

(i) Network of seismic stations for real-time detection of earthquakes, and a network of bottom pressure recorders (BPRs) and tide gauges to detect and monitor tsunamis;
(ii) Simulated scenario database of travel time and run-up heights at coastal forecast points of all possible earthquakes in the Andaman–Sumatra and the Makran subduction zones, generated based on numerical models;
(iii) A Standard Operating Procedure (SOP) and Decision Support System (DSS) to generate tsunami advisories;
(iv) A communication system to disseminate advisories in real-time to all stakeholders;
(v) A data centre having the necessary hardware, software, communication and technical support infrastructure.

The system generates the first bulletin within 10 minutes of the occurrence of an earthquake in either of the two subduction zones – Andaman–Sumatra and the Makran, in a fully automated mode, with no human intervention. Subsequent bulletins are issued by the experts after the analysis of model simulations and sea-level data. The information on estimated arrival time and expected tsunami amplitude at 1800 coastal forecast points, covers the entire Indian Ocean region. An innovative, first-of-its-kind, Standard Operating Procedure (SOP) triggers the warning process based on real-time earthquake detection and is followed by confirmation/upgradation/downgradation/cancellation of tsunami threat at different Coastal Forecast Zones based on the results of pre-run model simulations and real-time sea-level observations. During the past 17 years, several hundred earthquakes have been detected by the system, out of which, very few were tsunamigenic. The tsunami early warning system has performed well, meeting all the key performance indicators set by the UNESCO – International Oceanographic Commission (IOC)'s Indian Ocean Tsunami Warning and Mitigation System (IOTWMS) (see Srinivasa Kumar *et al.*, *Curr. Sci.*, 2012, **102**(1), 110–114). While accurate tsunami warnings generated for all the tsunamigenic earthquakes saved precious lives, timely information that the rest of the large earthquakes were unlikely to generate a tsunami also proved to be very important in avoiding unnecessary panic and public evacuation. As estimated by the National Council of Applied Economic Research, New Delhi, such a system has saved expenditure on each evacuation which can be as high as Rs 3500 crore per event.

There has been continuous advancement in understanding the science of tsunamis and the development of technology to improve further the timeliness and accuracy of the warnings, especially for non-seismic sources. Efforts are underway towards executing tsunami models in real-time. A finite-element-based Advanced Circulation (ADCIRC) model has been set up to compute tsunami wave height and associated coastal inundation. This will enhance the capability of the warning system to provide information on the possible impact of a tsunami in near-real time using realistic source parameters and reduce reliance on the use of pre-run model scenarios that are based on simulation of worst-case scenarios. Murthy *et al.* (*J. Geol. Soc. India*, 2022, **98**, 1356–1364; https://doi.org/10.1007/s12594-022-2183-y), presented a case study of the 26 December 2004 Indian Ocean tsunami by finite element modelling of tsunami-induced water levels and the extent of associated inundation.

Large earthquakes ($M_w > 8.5$) are underestimated based on analysis of data of the first few minutes from broadband seismic sensors. In such cases, real-time measurement of ground deformation using a network of Global Navigation Satellite System (GNSS) stations can be used to constrain the rupture model quickly and accurately. This information can be used to force tsunami propagation and inundation models. To achieve this capability, ESSO–INCOIS has set up a dense network of GNSS Network and Strong Motion Accelerometer sensors on the Andaman and Nicobar (A&N) islands and integrated it with the warning system.

Tsunamis can be detected accurately by measuring sea-level variations through data from bottom pressure sensors, which are transmitted to the early warning centre via a surface buoy and communication satellites. Techniques for inversion of tsunami source characteristics from the tsunami waveforms recorded by bottom pressure recorders and coastal tide gauges have been deployed. Further, ESSO–INCOIS has undertaken to deploy a dedicated cabled observatory off the A&N islands to make real-time measurements of seismic and sea-level parameters close to the subduction zone.

Interferometric Synthetic Aperture Radar (SAR) along with optical imagery, can provide data on elevation changes following sub-aerial landslides. The planned joint NASA and ISRO Synthetic Aperture Radar (NISAR) mission in 2025 will provide information on minor changes on the land surface that could be used for hazard assessment and early warning for non-seismic tsunamis.

Sound waves in the oceans produced by an earthquake, propagate through water eight times faster than the tsunami waves and reach the land several minutes before tsunami, depending on the distance of the source from the tsunami impact point. The identification of specific tsunami signatures of tsunami-generating earthquakes could lead to a faster-acting warning system for tsunamis as pointed out by Kozdon and Dunham (*Bull. Seismologic. Soc. Am.*, 2013, **103**(2B), 1275; doi:10.1785/0120120136).

The study of palaeo-tsunamis provides information on recurrence interval of tsunamis. Studies by Malik *et al.*, *Sci. Rep.*, 2019, **9**, 18463; https://doi.org/10.1038/s41598-019-54750-6) utilized geological features, sand deposits, coral debris, etc. on A&N islands to infer historical tsunamis of 1881, 1762, 1679 CE and pre-historic tsunamis in 770–1040 CE, 1300–1400 CE, 2000–3000 BCE and 3000–1780 BCE. Rajendran, C. P. *et al.* (*J. Geophys. Res.*, 2013, **118**, 1–18; doi:10.1029/2012JB009541) reported the ages, and relative sizes of pre-2004 tsunamis in the Bay of Bengal region inferred from geologic evidence in A&N islands. A recurrence interval of 420–750 years for mega-earthquakes and a shorter interval of 80–120 years for large magnitude earthquakes, has been suggested. Primrozwala (*Sci. Rep.*, 2018, **8**, 16816; doi:10.1038/s41598-018-35193-x) and Rajendran, C. P. (*Pure Appl. Geophys*., 2020; https://doi.org/10.1007/s00024-020-0257-0) gathered geological evidence of palaeo-tsunami deposits from the West coast of India related to AD 1008 earthquake and Orphan tsunami of 1524 respectively. Based on these palaeo-tsunami deposits, it was inferred that the Makran Subduction zone has experienced major thrust-related earthquakes ($M_w > 8$) in the historical past.

Tsunami cannot be prevented, but their impact can be mitigated through community and emergency preparedness, timely warnings, effective response and public education. Various studies and surveys have indicated the importance of preparedness and public education in saving lives in coastal areas. The 2024 Palu tsunami of Indonesia demonstrated that educating the coastal population about tsunami hazards and strengthening of early warning chains and capacities of local institutions is critical. Various tsunami exercises have been organized in the Indian ocean region to monitor their operational lines of communications, review their tsunami warning emergency response procedures and promote emergency preparedness. The UNESO-IOC Tsunami Ready Preparedness Programme (TRPP) has been implemented by Odisha State in 26 communities, which were recently recognised as 'Tsunami Ready' communities. Such programmes need to be extended along the entire coastline and could help development of community preparedness for all types of coastal inundation.

The current systems very effectively work for earthquake-generated tsunamis. There are still challenges in the detection and warning of tsunamis generated by submarine volcanic activity such as Anak Krakatau and landslides at Palu of Indonesia and near-field tsunamis. Improved understanding of the subduction zones, the Makran coast and Andaman–Sumatra zone will further improve tsunami forecasting. UNESCO-IOC IOTWMS efforts in developing a Probabilistic Tsunami Hazard Assessment (PTHA) is a welcome step. ESSO-INCOIS has recently developed a Standard Operating Procedure (SOP) for addressing tsunamis generated by volcanoes which uses information from Volcanic Ash Advisory Centres and sea-level anomalies detected from tide gauges and tsunami buoys.

Considering that tsunami events are infrequent, ESSO-INCOIS has established state-of-the-art Synergistic Ocean Observations Predictions and Services (SynOPS) system to address all oceanographic hazards. Dissemination of these integrated warnings to the public through SAMUDRA mobile application has ensured wide public reach of these life-saving services.

As we recall the 2004 Indian Ocean Tsunami, it is important to recognise the progress made and to identify the challenges ahead. There is a need for enhancing existing seismic, GNSS and sea-level observing networks, SAR interferometry, acoustic sensing, improved techniques for real-time modelling, etc. to improve the accuracy and reliability of forecast and quantify uncertainties associated with tsunami forecasting. Regional and global cooperation is required to develop tsunami warnings for all sources of tsunami by 2030 and prepare the entire community to be resilient as a part of the Ocean Decade Tsunami Programme of UNESCO-IOC. We should continue to improve our knowledge about tsunami science and forecasting and improve the resilience of coastal communities.

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