References

Chesworth, W. (1989). Agrogeology in East Africa: the Tanzania-Canada project". Journal of African Earth Sciences (and the Middle East), v. 9 (2), pp. 357–362. Bibcode:1989JAfES...9..357C. doi:10.1016/0899-5362(89)90078-X

Government of India (2023). Contribution of agriculture in GDP. Department of Agriculture and Farmers Welfare. Accessed online. http://www.indiaenvironmentportal.org.in/files/file/winter_session_2023/Loksabha-Contribution%20of%20Agriculture%20in%20GDP.pdf

India economic survey (2018). The Financial Express. 29 January 2018. "Farmers gain as agriculture mechanisation speeds up, but more R&D needed". Archived from the original on 8 January 2019. Retrieved 8 January 2019.

India Water Portal (2021). Healthy soil, crucial for agriculture in India https://www.indiawaterportal.org/faqs/healthy-soil-crucial-agriculture-india?

Mukherjee, A., Bhattacharjee, P., Natarajan, V., Bhatt, A.K., Zakaulla, S. and Rai, A.K. (2017). Lime-kankar as Surface Signature of Concealed Dykes: A Guide to Borehole Planning for Uranium Exploration. Jour. Geosci. Res. Spl. vol. 1, pp. 107-113.

Patra, A.K., Lenka, N.K. and Biswas, A.K. (2015). Soil Health Assessment and Management: Issues and Strategies. Indian Jour. Fert., v. 11 (12), pp. 16-25

Peter van, S. (2007). Agrogeology: the use of rocks for crops. Cambridge, Ontario: Enviroquest. ISBN 978-0-9680123-5-2.

Powell, C.LL. and Jeannette, D. (1978). Mycorrhizal Fungi Stimulate Uptake of Soluble and Insoluble Phosphate Fertilizer from a Phosphate-Deficient Soil. The New Phytol., v. 80 (2), pp. 351–358. doi:10.1111/j.1469137.1978.tb01568.x. JSTOR 2433509.

Singh, B. and Eric, C. (2021). "Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem". SN Appl. Sci., v. 3 (4), 518p. doi:10.1007/s42452-021-04521-8. hdl:1885/267455. ISSN 2523-3971.

Singh, H.M. (2011). "Effect of inoculation with phosphate solubilizing fungus on growth and nutrient uptake of wheat and maize plants fertilized with rock phosphate in alkaline soils". European Journal of Soil Biology, v. 47, pp. 30–34. doi:10.1016/j.ejsobi.2010.10.005.

Yadav, H. (2017). "Enhancement of applicability of rock phosphate in alkaline soils by organic compost". Applied Soil Ecology, v. 113, pp. 80–85. doi:10.1016/j.apsoil.2017.02.004. S2CID 89625691.

Framework for Submarine Geohazard Evaluation and Spatial Screening in Offshore Wind Farm Planning along India's Western and Eastern Margins

Jayant Kumar Sahoo

National Institute of Technology, Rourkela-769008, Odisha, India
(E-mail: jayantks1998@gmail.com)

India has taken significant steps toward offshore wind energy deployment as part of its broader energy transition strategy. Government initiatives led by the Ministry of New and Renewable Energy (MNRE), including the Viability Gap Funding (VGF) mechanism and offshore wind leasing programs, have identified the continental shelves off Gujarat and Tamil Nadu as priority zones for early projects (MNRE, 2024). These areas collectively host several tens of gigawatts of estimated offshore wind potential and are expected to support pilot and commercial-scale developments over the coming decade.

Unlike onshore wind projects, offshore wind farms are exposed to complex seabed and sub-seabed processes that may compromise foundations, inter-array and export cables, and operational safety. Indian continental margins exhibit evidence of submarine landslides, active seismic sources capable of generating tsunamis, weak Holocene sediments prone to liquefaction, and dynamic sediment transport systems driven by monsoon-influenced currents (Bijesh *et al.*, 2022; Prizomwala, 2022; INCOIS, 2025). For early-stage projects supported by public funding, inadequate geohazard assessment can result in cost escalation, insurance challenges and long-term operational risk.

This paper proposes a pragmatic, staged framework for submarine geohazard screening and spatial evaluation suitable for offshore wind farm planning along India's western and eastern margins. The framework emphasizes early hazard identification, proportional escalation of investigations, and direct linkage between hazard assessment, design decisions and regulatory compliance.

Submarine Geohazard Setting of the Indian Offshore Region

The Indian continental margins display a diverse range of geological and oceanographic conditions relevant to offshore wind development. Along the western margin, the relatively wide continental shelf off Gujarat transitions into steeper slopes toward the Arabian Sea basin. Geophysical studies have documented large-scale submarine landslides and slide scars, including the Cochin offshore slide system, indicating potential for mass movement and turbidity current activity (Bijesh *et al.*, 2022; Zhang and Wang, 2025). Although such features are often located beyond shallow shelf areas, export cable routes and deeper foundations may intersect zones of instability.

Seismic and tsunami hazards also require consideration. The Makran subduction zone in the Arabian Sea and the Andaman–Sumatra subduction system in the eastern Indian Ocean is both capable of generating tsunamis that may impact Indian coastlines (Prizomwala, 2022; Rashidi *et al.*, 2025). While recurrence intervals for major tsunamigenic events are long, offshore wind infrastructure is designed for multi-decadal lifespans, necessitating inclusion of low-probability, high-impact scenarios in risk assessments.

On the eastern margin, the Bay of Bengal shelf off Tamil Nadu is influenced by large sediment fluxes, seasonal monsoon-driven currents and relict sedimentary structures. Thick accumulations of fine-grained Holocene sediments may exhibit low shear strength and susceptibility to cyclic degradation or liquefaction under seismic or hydrodynamic loading. Seabed scour around foundations and cable exposure due to sediment mobility are additional concerns in both regions (Duguid, 2017).

Principles of Staged Geohazard Screening

Effective geohazard assessment for offshore wind projects should follow a staged, risk-proportionate approach. Early

(Received: 01 October 2025; Accepted: 04 March 2026)

https://doi.org/10.56153/g19088-025-0286-107

screening using existing datasets allows identification of potentially hazardous zones before committing to costly site investigations. Subsequent stages increase data resolution and analytical complexity only where residual risk remains significant. This approach is consistent with international offshore wind practice and supports efficient use of resources during project development (Sun *et al.,* 2025).

Key principles underlying the proposed framework include: (i) early identification of hazard-prone corridors, particularly for export cables; (ii) consideration of cascading hazard chains, such as earthquake-triggered landslides leading to turbidity currents; (iii) integration of geological, geotechnical and oceanographic data; and (iv) alignment of technical outputs with regulatory, insurance and funding requirements relevant to VGF-supported projects.

Proposed Framework for Geohazard Evaluation

Stage 1: Desk-based Screening

The first stage involves compilation and interpretation of existing regional datasets. These typically include bathymetry, publicly available sub-bottom or seismic profiles, earthquake catalogs, tsunami source models and regional sedimentological information. Key screening indicators include seabed slope gradients, proximity to mapped landslide scars or canyon heads, sediment thickness, and exposure to known tsunamigenic sources. The outcome is a preliminary hazard zoning map categorizing areas as low, moderate or high concern (Scacchia *et al.,* 2025).

Stage 2: Focused Site Investigation

Areas identified as moderate to high concern progress to targeted field investigations. High-resolution multibeam bathymetry and sub-bottom profiling are essential to detect subtle seabed features, shallow weak layers and gas-charged sediments. Cone penetration tests and sediment coring provide quantitative geotechnical parameters for foundation and cable design. Where sediment dynamics are important, current and wave measurements over representative seasonal cycles support scour and mobility assessments (Duguid, 2017).

Stage 3: Hazard and Risk Modelling

At this stage, process-based modelling is applied to quantify hazard likelihood and consequences (Varela *et al.,* 2025). Slope stability analyses evaluate the potential for submarine landslides under static and seismic loading, while tsunami simulations assess wave generation and propagation from credible earthquake or landslide sources (INCOIS, 2025). Scour depth estimation and liquefaction analyses inform foundation and cable design. Results are integrated into risk metrics that support engineering decisions and insurer evaluations.

Stage 4: Design, Mitigation and Monitoring

The final stage translates hazard assessments into practical design and operational measures. These may include selection of appropriate foundation types, scour protection systems, optimized cable routing and burial depths, and installation of monitoring systems for seabed movement or seismic activity. Integration with national monitoring and early warning systems, such as those operated by INCOIS, enhances operational resilience and emergency preparedness.

Application to Indian Offshore Wind Zones

For Gujarat, the framework highlights the importance of early desk-based identification of shelf-edge instabilities and dynamic sediment zones along potential cable corridors. Focused investigations can then prioritize stable shelf areas for foundations while routing export cables away from submarine channels. On the Tamil Nadu margin, emphasis is placed on understanding seasonal sediment transport and the geotechnical behaviour of fine-grained shelf sediments. In both regions, staged evaluation reduces uncertainty and supports cost-effective design.

Policy and Financing Relevance

The VGF mechanism aims to reduce financial barriers for early offshore wind projects, but its effectiveness depends on robust technical due diligence. Incorporating staged geohazard screening into eligibility and permitting requirements can help ensure that publicly supported projects are sited in geologically suitable areas. Clear documentation of hazard assessments and mitigation measures also facilitates engagement with insurers and lenders, improving project bankability.

Conclusions

Offshore wind development along India's western and eastern margins presents both significant opportunities and notable geohazard challenges. The staged framework outlined here provides a practical approach to identifying, evaluating and mitigating submarine geohazards in a manner proportionate to project risk and aligned with national policy objectives. Early desk-based screening, followed by targeted investigations and modelling where necessary, can substantially reduce uncertainty and long-term operational risk. Adoption of such frameworks will enhance the resilience and sustainability of India's emerging offshore wind sector.

Acknowledgements

The author acknowledges the support of the National Institute of Technology, Rourkela, for academic resources and research facilities, and gratefully recognizes the contributions of previous geological studies and reports that formed the basis of this work.

References

Bijesh, C.M., Damodharan, T., Susanth, S. and Kurian, P.J. (2022). Large-scale submarine landslide in the Cochin offshore region: preliminary geophysical understanding. Landslides, v.19, pp.123–135.

Duguid, L. (2017). Offshore wind farm substructure monitoring and inspection. ORE Catapult Report.

INCOIS (2025). Tsunami modelling and Indian Tsunami Early Warning System. Indian National Centre for Ocean Information Services, Hyderabad.

MNRE (2024). Offshore Wind Energy Policy initiatives and Viability Gap Funding scheme. Ministry of New and Renewable Energy, Government of India.

Prizomwala, S.P. (2022). Geological footprints of the 1945 Makran tsunami along the Indian coastline. Mar. Geol., v.439, 106553.

Rashidi, A., Nouri, M., Montazeri Namin, M. and Shugar, D.H. (2025). Submarine landslide tsunami hazard assessment for the western Makran margin. Natl. Hazds., v.77, pp.1–18.

Scacchia, E., Casalbore, D., Gamberi, F., Spatola, D., Bianchini, M. and Chiocci, F.L. (2025). Shallow-water submarine landslide susceptibility map: the example of a sector of the Capo d'Orlando continental margin (southern Tyrrhenian Sea). Jour. Mar. Sci. Engineer., v.13, pp.1350. https://doi.org/10.3390/jmse13071350

Sun, M., Liu, Y., Zhao, L., Xie, W. and Mao, W. (2025). Advances and challenges in assessing submarine landslide risks to marine infrastructure. Natl. Hazds., v.121, pp.7811–7837.

Varela, P., Medina-Cetina, Z. and Hernawan, B. (2025). Bayesian model calibration of submarine landslides. Landslides, v.22, pp.2169–2197. https://doi.org/10.1007/s10346-025-02486-y

Zhang, J. and Wang, A. (2025). Responses of offshore wind turbine foundations to consecutive submarine landslides. Ocean Engineer., v.332, pp.121384.

Guidelines for Exploration and Development of Geothermal Energy in India

P.B. Sarolkar

Formerly with Geological Survey of India, Nagpur-440001, Maharashtra, India
(Email: pbsarolkar@gmail.com)

The development of a country is mainly dependent on the energy security. The main energy sources are mostly conventional energy sources contributing to greenhouse gases leading to global warming. The important Fossil fuels are i) Coal, ii) Petroleum, iii) Natural Gas and iv) Coal Bed Methane, besides this the alternate energy sources like biodiesel and biomass contributed marginally. The climate change perspective required to control the global warming required use of non- conventional, non-polluting sources of energy like i) Hydropower, ii) Nuclear, iii) Wind, iv) Solar and v) Tidal. The largescale installation of these energy sources revealed that these sources are mostly site specific and have particular time window for production. Considering the use of fossil fuels to net zero by the year 2070 (www.investindia), new technology sources like Hydrogen Cells, Electric Vehicles and Hydrogen vehicles have been introduced to substitute the petroleum-based transport system. Similarly, the geothermal energy is also being encouraged to replace the conventional energy sources. Geothermal energy is the heat stored inside the interior of the earth. Geothermal energy is a new and alternate, continuous and site-specific source of energy. The heat is stored in deep seated rocks which is brought to surface by the deep circulation of water. Geothermal energy is a renewable and environment friendly energy source as there is no burning of the fuel.

Geothermal Manifestations

A geothermal area is characterized by following manifestations 1. Hot water springs (Fig. 1), 2. Steam emission or Fumaroles, 3. Marshy land, 4. Mud pools, 5. Deposition of silica, sulphur, arsenic, borax, calcite on surface and 6. Local subsidence.

Geothermal resources are categorized as- i) Single phase-A field where only hot water or only steam is found, ii) Two Phase –In two phase flow hot water mixed with steam is found in the reservoir, iii) Dry phase- Hot dry rock where no fluid or steam is found as the rock is hard and compact. The rock is hot but the heat is not transferred to surface by water or steam, iv) Enhanced geothermal system- A hot rock system which is used for production by artificial fracturing for hot water production and v) Advanced geothermal system- In this system, a deep borehole is used to flush out heat /geothermal energy by deep circulation of water which collects heat and pumped to surface for power generation. This method can be used in old, unproductive oil boreholes if temperature in the boreholes is satisfactory. The main utilization methods are i) Steam based power plant, ii) Binary cycle power plant, iii) Greenhouse cultivation, iv) Refrigeration, cold storage, v) aquaculture, vi) Tourism and Bath centers, vii) Food processing, viii) Space heating *etc.*

Geothermal energy is considered as an Environmentally friendly energy as the CO2eq emission is about 45 to 65 g/Kwh (IPCC). The hot water contains boron, Arsenic, Fluorine, which need to be monitored to avoid adverse effect on production. A deposition of silica, calcite, arsenic compound, sulphur is reported generally around hot springs and borehole vents. Hot water may contain dissolved sulphur, borax, Cs, Li, which can be separated as a byproduct during production. The hot springs / geothermal boreholes generally show emission of CO_2, SO_2, NO_2, NH_3, H_2, N_2, He, Ar, gases, which need to be studies before production planning. The other main irritant is continuous noise produced by steam emission/ production. Sometimes, there can be marshy ground, local subsidence due to pressure changes in underground caused by water movement. Besides this, during drilling, there is possibility of caving in the boreholes, steam emission and water flow during drilling operation. The drilling site is generally restored to normal to avoid environmental damage.

Geothermal resources can be utilized for electricity generation as well as direct heat uses, depending on the local geology, geography, economic conditions and discharge parameters. The utilization of heat content to various industrial application is called as direct heat uses. The electricity generation is

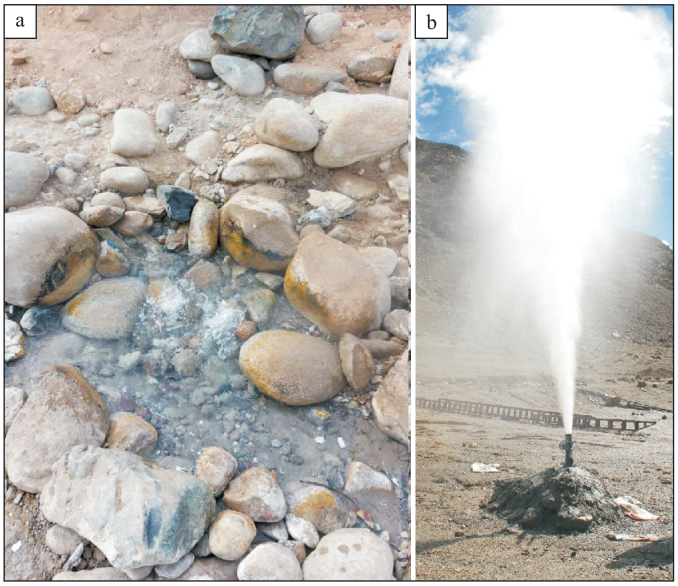

Fig. 1. a. Hot-spring at Chumathang, Ladakh; **b.** Sprout of borehole at Chumathang, Ladakh

(Received: 10 May 2026; Accepted: 10 June 2026)

https://doi.org/10.56153/g19088-026-0306-113