



STORM AND TSUNAMI INDUCED SEDIMENT TRANSPORT AND MORPHOLOGY CHANGES IN VICINITY OF TIDAL INLETS

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Abstract: This study comprises of numerical modelling studies on the morphology changes in the vicinity of tidal inlets. Two real case scenarios comprising of a very severe cyclonic storm and the mega Indian Ocean tsunami were considered as case studies. Satellite images before and after the storm were used to study the morphology changes. Sediment transport is estimated utilising available sediment transport formulae and the hydrodynamics forcing obtained from a depth averaged hydrodynamic model.

Keywords: inlet morphology; hydrodynamics; sediment transport; cyclone; tsunami.

INTRODUCTION

Due to its unique nature the Bay of Bengal experiences majority of the storms and cyclones compared to the Arabian Sea in the Indian Ocean region. About 7% of global tropical cyclones occur in the north Indian Ocean region (e.g., Gray, 1985; Mohanty, 1994; Niyas et al., 2009; Singh et al., 2001). On the other hand tsunami-events that occur in the Indian Ocean region are few and far between, the most featured being the 2004 Indian Ocean Tsunami (IOT04). The IOT04 devastated a majority of the coastal habitation along many parts of south-east Asia, Sri Lanka, south east coast of India, and other adjoining coasts. Although many studies exists pertaining to the IOT04 tsunami propagation and inundation (e.g., Jaya Kumar et al., 2005; Synolakis & Bernard, 2006) but very few studies on the hydrodynamics and sediment transport due to this tsunami (e.g., Jaya Kumar Seelam, 2012). Also there are very few studies available on the tropical storm induced hydrodynamics and sediment transport along the Indian coast (e.g., Vinod Kumar et. al., 2012).

Morphology changes on the coast and nearshore are due to the sediment transport variations in the near vicinity. Erosion/accretion either progressive or intermittent depends on the sediment transport gradients in the region. Impacts on coast due to extreme events like storms or tsunamis on the coastal sediment transport can be addressed by studying the sediment transport variations due to such impacts. This manuscript deals with the sediment transport in the nearshore regions along the east coast of India due to a very severe cyclonic storm and the 2004 Indian Ocean tsunami. The coasts of Odisha and Tamil Nadu on the east coast of India are considered to study the sediment transport due to storm and tsunami respectively.

METHODS

The effect of a very severe cyclonic storm, Phailin, which had a landfall on the east coast of

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India (www.imd.gov.in/section/nhac/dynamic/phailin.pdf) and the 2004 Indian Ocean tsunami (IOT04) on the near shore sediment transport is considered individually in this paper. Brief details of the events, the numerical model setup, morphology change observations from satellite images and the numerical model results are given.

Phailin Cyclone:

Cyclone track data for the very severe cyclonic storm Phailin is obtained from India Meteorology Department (<http://www.imd.gov.in>) is used to estimate the storm induced parameters. The basic input data viz., central pressure, neutral pressure, maximum sustained wind speeds, radius of maximum winds obtained from the above mentioned database are used in Rankine vortex parametric wind model (Depperman, 1947) to obtain the wind field over the study region (Figure 1). The cyclone wind fields from the model are compared with available measured winds off Gopalpur during Phailin cyclone. The cyclonic modelled winds over the study region are used to obtain the hydrodynamics of the region over which the sediment transport modelling is carried out. DHI's spectral wind wave model is used to derive the storm induced waves and the wave induced radiation stresses are included in the cyclone wind forced flexible mesh hydrodynamic model (<http://www.dhigroup.com>) and the hydrodynamics of the study region are obtained. The cyclone induced hydrodynamics are used as inputs to the sediment transport model and the near shore sediment transport is estimated.

Indian Ocean tsunami:

The details of 2004 Indian Ocean Tsunami have been widely reported in the literature (e.g., Jaya Kumar et al., 2005; Synolakis & Bernard, 2006). Numerical modeling of the tsunami heights, propagation and hydrodynamics in the vicinity of the coast for this tsunami for the southeast Indian coast has been studied earlier by the senior author (Jaya Kumar et al., 2006; Jaya Kumar, 2012). The inputs and model details for the tsunami induced hydrodynamics and sediment transport is detailed in the earlier paper (Jaya Kumar, 2012).

Morphology changes:

One site each on the Odisha and Tamil Nadu coasts are considered to study the morphological changes in the coast line in vicinity of tidal inlets, using satellite images. The coast off Konark on the Odisha coast is considered for the Phailin cyclone and the coast off Chennai is considered for Tsunami induced morphology changes. The morphological changes on the coastline in front of the tidal inlets are qualitatively studied and the quantitative estimates and further studies will be reported elsewhere. The types of changes in the coastline, breaching and overwash of the closed inlet mouths are described for both the storm and tsunami events.

Sediment transport model:

Sediment transport is estimated from the main parameters of flow speed, flow direction and sediment size. DHI's MIKE21 software suite is used to obtain tsunami induced flows. More details on the tsunami propagation model, its input, validation and output are presented in Jaya Kumar et al. (2006). Flow field generated in the study region was used in estimation of the sediment transport using the three non-cohesive sediment transport (ST) equations used in MIKE21. Of the three different formulations used in MIKE21 sediment transport model, the

Engelund and Hansen (1972) (hereinafter referred as EH formulation) which is based on total-load transport theory is considered. The dimensionless total load sediment transport (Φ_t) formulation of EH is used in this study which is calculated as:

$$\Phi_t = 0.1 \frac{C^2}{2g} \theta^{2.5} \quad (1)$$

where, C is Chezy number and θ is dimensionless bed shear stress which is based on shear velocity related to total friction (U_f), grain diameter (d) and s is the relative density of the bed material (s).

$$\theta = \frac{U_f^2}{(s-1)gd} \quad (2)$$

The total load (q_t) can be estimated from:

$$q_t = \Phi_t \sqrt{(s-1)gd^3} \quad (3)$$

This formulation assumes that the dimensionless bed shear stress q is much larger than the critical Shields parameter for initiation of transport. The ST numerical model considered provides total sediment transport due to the hydrodynamics of the region. The morphology changes on the coastline and in the near shore waters considering the river discharge and breaching of the barrier are not attempted in this work.

RESULTS

Phailin Cyclone model results:

The parametric wind speed model resulted in wind speeds over the model domain (Fig. 1) which was used further both in wave and flow models. The maximum sustained wind speeds obtained from the model are shown in Fig. 2.

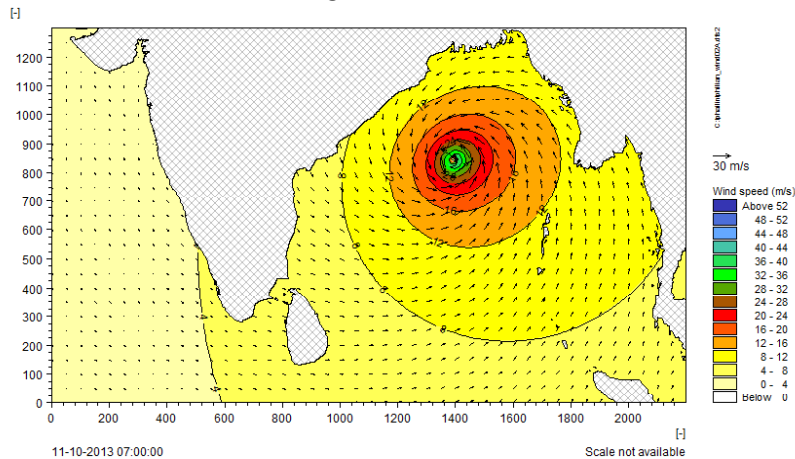


Fig. 1. Model generated Phailin cyclone winds in the Bay of Bengal.

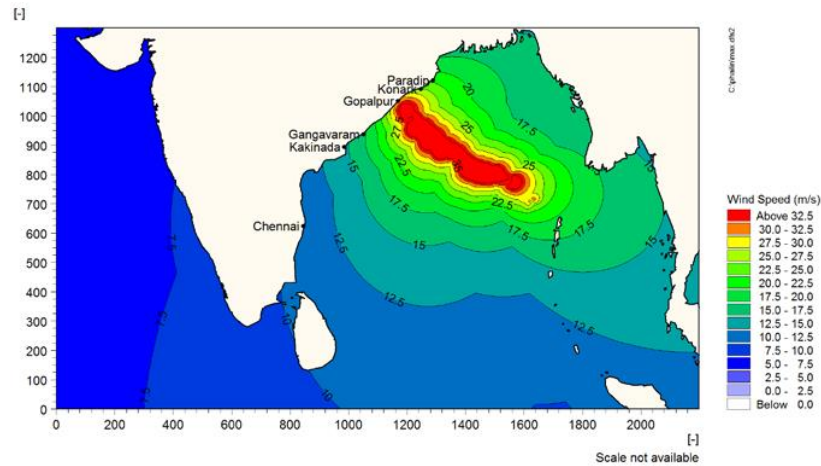


Fig. 2. Maximum wind speeds estimated from cyclone wind model for Phailin Cyclone.

A comparison of the wind speed extracted at Gopalpur, which is in close vicinity of the landfall point is shown in Fig. 3. The modelled wind speed magnitudes compare well with the measurements of wind gusts obtained on the coast of Gopalpur from the automatic weather system data measurement system of CSIR-NIO (Desai et al, 2010). The measured wind speeds could not be obtained just after the storm eye passed through this location due to failure of the instrument. There are discrepancies with the timing of the storm eye passage at the location of data extraction in the model, which could be due to the best track data of the cyclone being based on certain model results, which are beyond the scope of this paper.

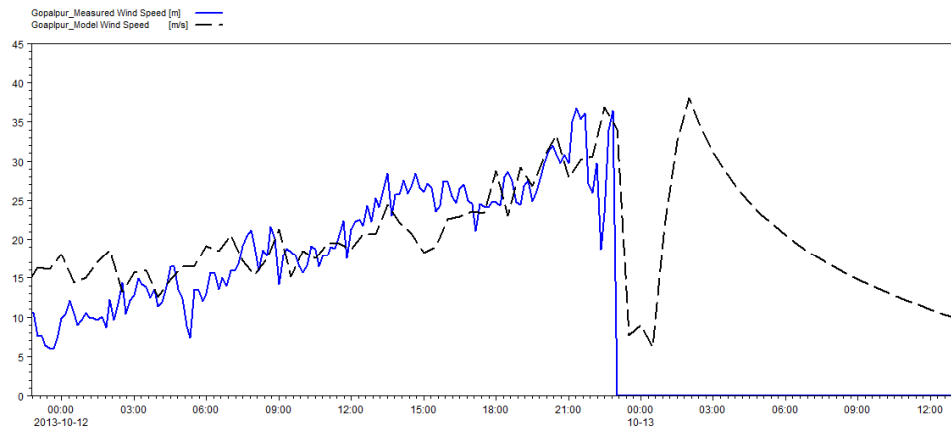


Fig. 3. Wind speeds at Gopalpur for Phailin Cyclone - Modelled wind (dashed line) and measured wind (solid line).

The cyclone wind model results comprising of the wind speed, wind direction and atmospheric pressure were used as input to the spectral wind wave model. The waves were simulated for the period of the cyclone starting from 7th October 2013 till eye of the cyclone was much into the hinterland. The significant wave height from the model results at Gopalpur and Paradip are shown in Fig. 4. The waves from the model are observed to match well with the measurements obtained from a wave rider buoy off Gopalpur (Nair et al., 2014) before the buoy cut loose from its mooring and was adrift.

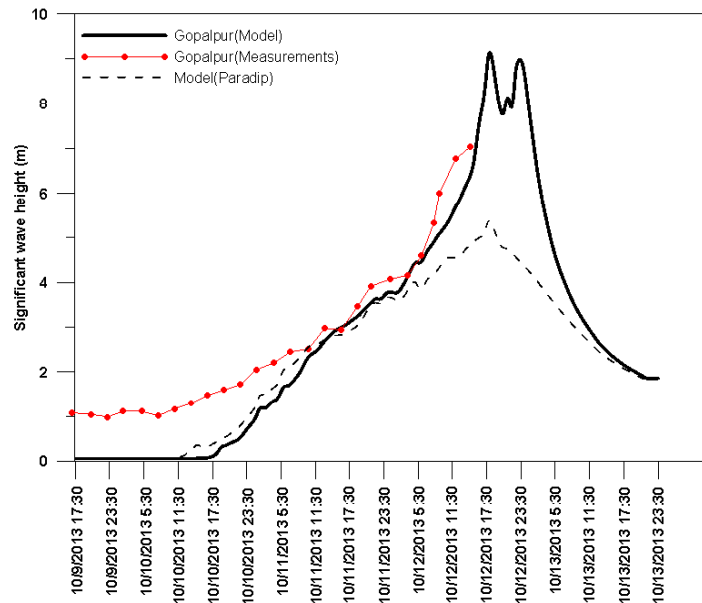


Fig. 4. Wave heights obtained from Phailin Cyclone wind wave model for Gopalpur (solid line) and Paradip (dash line) compared with measured wave heights at Gopalpur (dot-dash line).

Morphology changes due to Tsunami:

The Adayar River confluence with the Bay of Bengal along the Chennai is considered to qualitatively understand the morphology changes due to the 2004 December tsunami. The tsunami run-up height south of the Adayar River mouth was about 5m (Jaya kumar et al, 2005) which was caused by an estimated tsunami height of about 3m near the coast (Jaya kumar et al, 2006). The pre-tsunami river mouth (□ig. 5a) clearly shows its closure owing to higher alongshore sediment transport prevalent in this region. The breaching of the sand barrier and opening of the river mouth and flooding of tsunami water about few kilometres into the estuary can be seen clearly observed from the post-tsunami satellite image (□ig. 5b). The shape of the edges of the breached barrier clearly indicate that the wave influence was far greater than the river flow thereby allowing majority of the sediments to get transported into the river and forming curved edges. Also wave overwash on the northern end of the river mouth is clearly visible. □nlike the storms which have limited area of influence on the coast near their landfall point, tsunami under consideration had a much greater region of influence covering the whole of southeast coast of India. It would be interesting to study the impact of this tsunami on each of the tidal inlet *vis-a-vis* the strength of tsunami encountered near the coast.

Morphology changes due to Phailin Cyclone:

Phailin cyclone was one of the very severe cyclonic storms that had its land fall along Gopalpur coast on the Odisha coast within a period of 14 years, the previous one being in 1999. A comparative study of the coastal morphology along the tidal inlet off Konark showed interesting features along this coast. Three regions demarcated as A, B and C in □ig. 6 indicate the three regions vi□, A-inlet opening B-sand barrier in front of inlet having a wider

backwater region and C-sand barrier in front of the meandering inlet having a narrow backwater region. The cyclonic storm had a greater impact on certain stretch of the coast in this region whereas there wasn't any change to the beach width or the sand barrier at another part of the same coast. The region A, the inlet opening prior to the storm is found to be closed after the storm. The region B, sand barrier in front of the river with wider backwater has breached and a new inlet opening is created with clear wave dominated inlet configuration, similar to the tsunami induced morphology change to the river mouth; whereas, at location C, no significant effect of the storm on the sand barrier is seen. Without much information on the measurements in this region, it would be inappropriate to discuss further on the reasons for varying influence of storm on this coast.

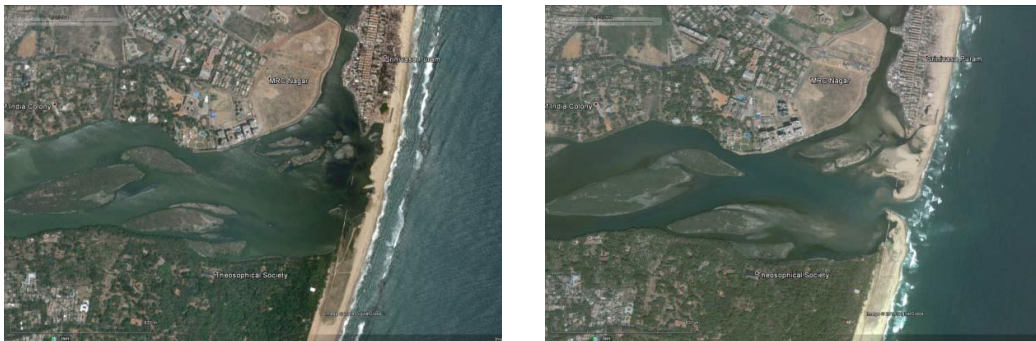


Fig. 5. Morphology of Adayar River inlet off Chennai (a) before tsunami (b) after tsunami.

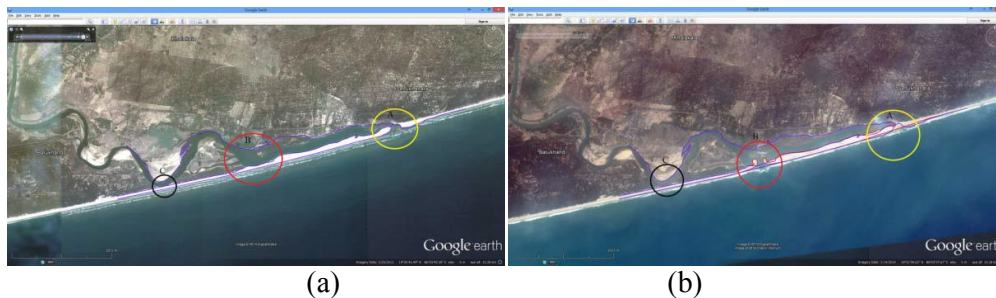


Fig. 6. Morphology of Odisha coast off Konark (a) before Phailin (b) after Phailin cyclone.

Tsunami induced Sediment transport:

Sediment transport rates are estimated for the nearshore regions of north Tamil Nadu coast due to the first two tsunami waves. The bathymetry of the nearshore region and the sediment size adopted in the model are shown in Fig. 7. The total load sediment transport due to tsunami shows that the maximum sediment transport is in the nearshore waters less than 20 m depth (Fig. 8a). The average sediment transport vectors (Fig. 8b) show that due to the initial two tsunami waves, the sediment transport is onshore very close to the coast and for depths between less than 10m and 20m it is in offshore direction. The onshore and offshore total load transport in this region is slightly in contrast with the sediment transport south of this study region, in vicinity of a submarine canyon, where the total sediment transport was mostly offshore (Jaya Kumar, 2012).

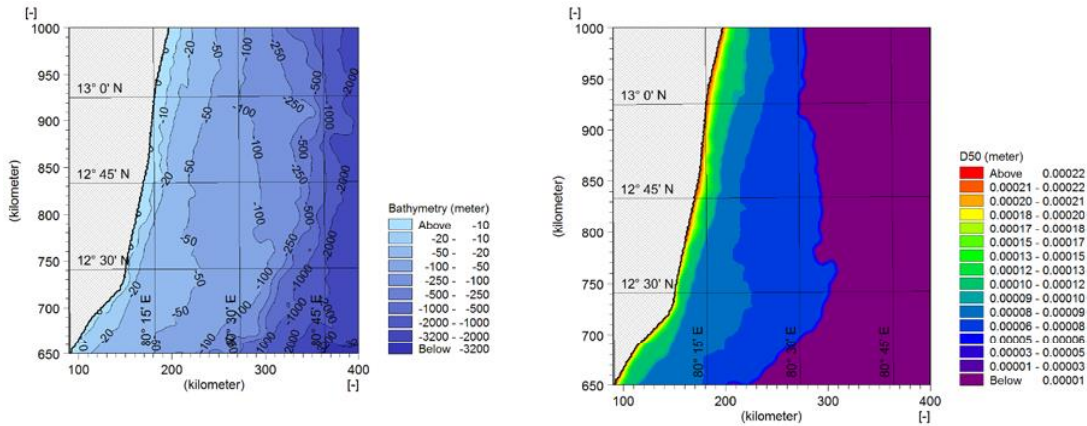


Fig. 7. (a) Bathymetry of the sub-tsunami model region and (b) median grain size considered in model.

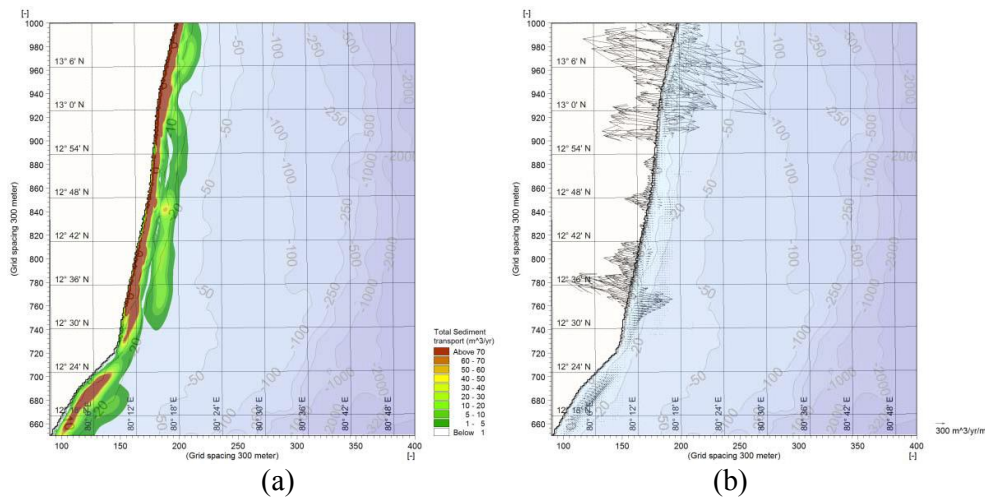


Fig. 8. Total load sediment transport due to tsunami on the north Tamil Nadu coast (a) magnitude of total sediment load (b) average total load transport vectors.

The bed level changes associated with the tsunami waves indicate that the initial rate of change of bed level is greater in regions close to the coast compared to that in water depths of 10m (Fig. 9). An average value of the order of 3 mm for the two waves over a half hour is observed which would amount to about 53 m/yr erosion rate, which is very severe. But due to the this tsunami acting for a short term the prolonged erosion did not occur due to the tsunami waves, unlike the storm waves which could persist for about 2 to 3 days or even more.

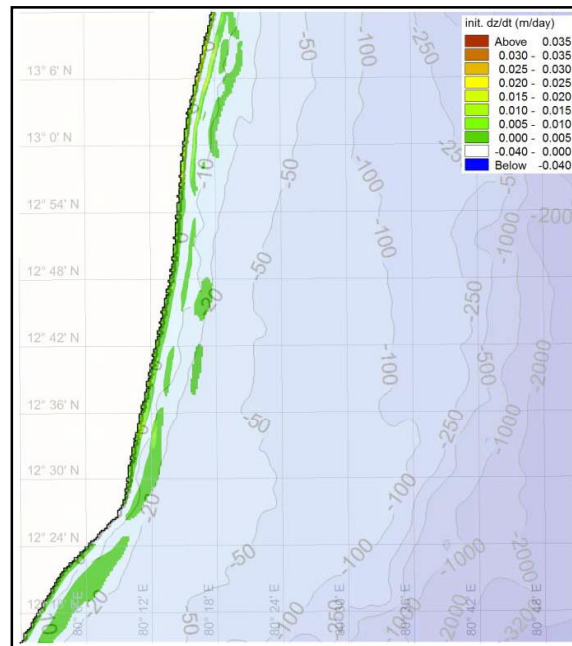


Fig. 9. Bed level change estimates due to tsunami on the north Tamil Nadu coast.

Storm induced Sediment transport:

The sediment transport along the Odisha coast due to Phailin cyclone showed a predominant alongshore south-westerly transport for majority of the cyclone simulation period. The total load transport and the transport vector for the period when it peaked at Gopalpur and Paradip respectively are shown in Fig 10(a) and 10(b). The variation of total sediment transport off Paradip and Gopalpur in about 30 m water depth (Fig. 11) during the cyclone showed that the peak total sediment transport at Gopalpur was about $0.00015 \text{ m}^3/\text{s}/\text{m}$ ($4730 \text{ m}^3/\text{yr}/\text{m}$) and it is observed to be about four times greater than that at Paradip. Unlike the tsunami induced total sediment transport which was more of a cross shore sediment transport, the Phailin storm induced total sediment transport is predominantly along the coast moving from northeast to southwest along the Odisha coast.

CONCLUSIONS

The effects of tsunami and a cyclonic storm on the coastal morphology and nearshore sediment transport along two coastal regions of India viz., Odisha coast and north Tamil Nadu coast are considered. Numerical modelling of the hydrodynamics and sediment transport due to cyclonic storm Phailin and the 2004 December Indian Ocean tsunami are carried out. The morphology changes observed due to tsunami and storm on the inlet mouths showed similar breaching pattern which is predominantly induced by the wave activity. The tsunami induced sediment transport was primarily cross-shore whereas the cyclonic storm induced sediment transport was alongshore. Compared to the tsunami induced sediment transport in vicinity of submarine canyons which was mostly in offshore direction, the sediment transport along the north-Tamil Nadu coast was onshore closer to the coast and towards offshore in the nearshore waters. The cyclonic storm induced sediment transport at

the landfall point near Gopalpur was observed to be about 4 times that at Paradip which is about 200 km north.

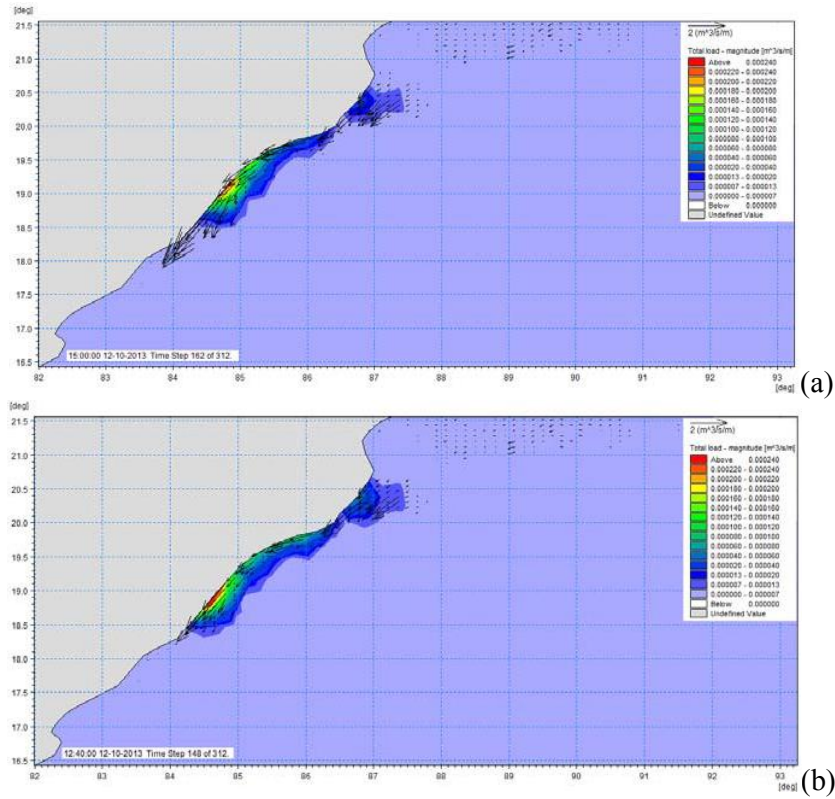


Fig. 10. Variation of total sediment transport during (a) peak sediment transport at Gopalpur and (b) peak sediment transport at Gopalpur Paradip.

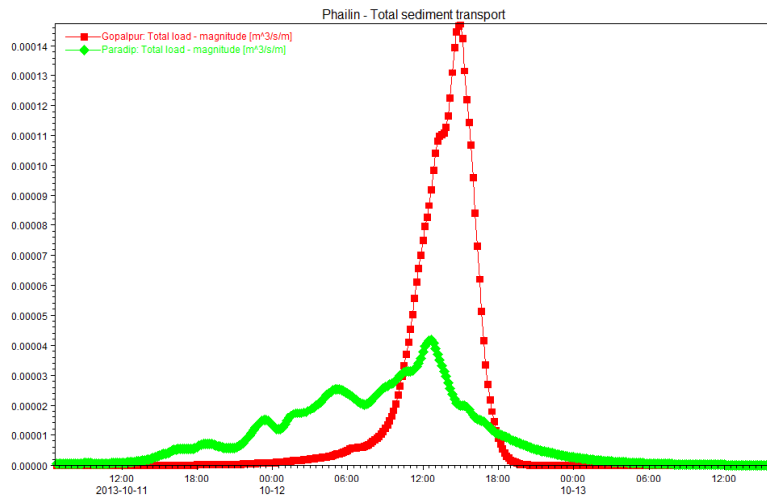


Fig. 11. Variation of total sediment transport off Paradip and Gopalpur for Phailin cyclone.



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REFERENCES

- Depperman, C. E. 1947. Notes on the origin and structure of Phillipine typhoons. Bull. Amer. Meteor. Soc. 28, 399-404.
- Desai, R.G.P., Joseph, A., Agarwadekar, □., Mehra, P., VijayKumar, K., Luis, R., Integrated Coastal Observation Network (ICON) for real-time monitoring of sea-level, sea-state, and surface-meteorological data, Oceans 10 MTS/IEEE Seattle, September 20-23, 2010, Seattle, □ ashington (□SA), 2010, 9 pp.
- Engelund, □ and E. Hansen, 1972. A Monograph on sediment transport in Alluvial Streams. Teknisk □orlag, Copenhagen.
- Gray, □.M. 1985. Technical document wmo/td no. 72, □ MO, Geneva, Swit□erland.
- Jaya Kumar, S., Ilangovan, D., Kirti A Naik., Gowthaman, R., Gurudas Tirodkar, Ganesh N. Naik, Ganeshan, P., Mani Murali, R., Michael, G. S., Ramana, M. V., and Bhattacharya, G. C., 2005. Run-up and inundation limits along southeast coast of India during the 26 December 2004 Indian Ocean tsunami. Current Science, 88(11): 1741-1743.
- Jaya Kumar, S., Ilangovan, D., Kirti A Naik., and Ramana Murthy, M.V., 2006. Tsunami height estimation in nearshore waters off Tamil Nadu coast using MIKE21 hydrodynamic model for the December 2004 Indian Ocean tsunami. 15th Congress of Asia and Pacific division of the International Association for Hydraulic Research (APD-IAHR) and International Symposium on □Maritime Hydraulics", IIT Madras Chennai, INDIA.
- Jaya Kumar Seelam, 2012, □A numerical study on tsunami induced sediment transport in vicinity of a submarine canyon off southeast coast of India. □ 4th International Conference on Estuaries and Coasts (ICEC2012), 8-11 October 2012, Hanoi, Vietnam.
- Mohanty, □.C. 1994. Tropical cyclone in the bay of bengal and deterministic methods for the prediction of their trajectories. Sadhana, 19(4): 567-582.
- Nair, T.M.B.; Remya, P.G.; Harikumar, R.; Sandhya, K.G.; Sirisha, P.; Srinivas, K.; Nagaraju, C.; Nherakkol, A.; Prasad, B.K.; Jeyakumar, C.; Kaviya □hahu, K.; Hithin, N.K.; RakhiKumari; SanilKumar, V.; RameshKumar, M.; Sheno, S.S.C.; Nayak, Shailesh, 2014, □ave forecasting and monitoring during very severe cyclone Phailin in the Bay of Bengal, Curr. Sci.: 106(8); 2014; 1121-1125.
- Niyas, N.T., A.K. Srivastava and H.R. Hatwar. 2009. Variability and trend in the cyclonic storms over north Indian Ocean., India Meteorology Department, Pune, India.
- Singh, O.P., T.M.A. Khan and M.S. Rahman. 2001. Has the frequency of intense tropical cyclones increased in the North Indian Ocean □Current Science, 80(4): 575-580.
- Synolakis, C.E. and Bernard, E.N., 2006. Tsunami science before and beyond boxing day 2004. Philosophical Transactions - A Math Physics Engineering Science, 364(1845): 2231-2265.
- Vinod Kumar, K., V.M. Aboobacker, P.P. Saheed and P. Vethamony. 2012. Coastal circulation along the central west coast of india during cyclone phyan: Measurements and numerical simulations. Natural Ha □ards, 64: 259-271.