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Hydrodynamic Assessment of a Proposed FSRU Development in the Visakhapatnam Outer Harbour

M. Phani Kumar[1,*], Kapil Walke[2], Prabhat Chandra[3]

Abstract

This study presents a detailed hydrodynamic assessment of a proposed Floating Storage and Regasification Unit (FSRU) in the Visakhapatnam Outer Harbour. A depth-integrated, two-dimensional hydrodynamic model was developed using MIKE-21 Flexible Mesh (FM) to quantify the influence of the terminal layout, dredged pocket configuration, and vessel presence on tidal circulation, freshet-driven flows, and extreme-event conditions. Baseline simulations were performed using existing bathymetry and operational geometries, followed by proposed configurations that included the FSRU jetty, moored vessel, and a dredged pocket to −15 m. Additional sensitivity cases—sand-trap infill, deepening of the southern shallow patch, and dredging to −21.5 m—were included to examine localized hydrodynamic responses. An extreme-event simulation based on the Hudhud cyclone (2014) was carried out on an expanded domain incorporating tide, wind, and wave forcing. Results indicate no significant modification in tidal prisms at the outer entrance, inner entrance, and sand-trap gap. However, localized redistribution of tidal flux is evident, with the flow split across the north–south sections shifting from approximately 100–100 cumecs (existing) to 50–150 cumecs (proposed). Under cyclone forcing, the FSRU yields a marked reduction in current magnitudes at the jetty—decreasing from 1.4 m/s in the existing configuration to approximately 0.2 m/s—demonstrating beneficial sheltering effects. Dredging alternatives beyond −15 m provides limited additional benefits and do not significantly influence large-scale circulation. The study confirms the hydrodynamic suitability and operational safety of the proposed FSRU alignment.

Keywords: FSRU, hydrodynamic modelling, MIKE-21 FM, Visakhapatnam Port, tidal circulation, cyclone Hudhud, dredging impacts, coastal dynamics, numerical modelling, port hydrodynamics

***Author for Correspondence**
M. Phani Kumar
E-mail: mpkumar@cwprs.gov.in

[1]Scientist and HoD, Central Water and Power Research Station (CWPRS), Ministry of Jal Shakti, Government of India, Pune, India
[2]Assistant Research Officer, Central Water and Power Research Station (CWPRS), Ministry of Jal Shakti, Government of India, Pune, India
[3]Director, Central Water and Power Research Station (CWPRS), Ministry of Jal Shakti, Government of India, Pune, India

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INTRODUCTION

Background and Motivation

Liquefied natural gas (LNG) import terminals are increasingly relying on floating storage and regasification units (FSRUs), owing to their modularity, reduced capital costs, and lower installation time relative to onshore terminals [1–4]. The strategic placement of FSRUs within sheltered basins, however, demands a comprehensive evaluation of local hydrodynamic conditions, especially in regions exposed to monsoons, wave-driven littoral transport, and extreme cyclonic storms [1, 2]. Visakhapatnam Port, located on the east coast of India in the Bay of Bengal, contains a breakwater-protected outer harbor and a lagoon-type inner harbor [3, 4–6]. The proposed FSRU site lies in the southern section of the outer basin, bounded by the Shore-Detached South Breakwater (SBW) and the sand trap, and adjacent to the Off-Shore Tanker Terminal (OSTT). This configuration presents a unique set of hydrodynamic considerations:

- The sand trap intercepts a significant northward littoral drift (~0.6 million m^3/year).
- The region receives monsoon-driven freshet flows from Meghadrigedda and Kondagedda streams.
- Cyclonic storms (notably Hudhud 2014) can impose severe waves and current loads.

Thus, any modification to bathymetry or structural layout, including the introduction of an FSRU and associated dredging, must be evaluated to ensure safety, navigability, and long-term stability [7, 8–10].

Scope and Contributions

This work reformulates a detailed technical study. Contributions include,

- A validated hydrodynamic model for Visakhapatnam Outer Harbour using MIKE-21 FM.
- Quantification of tidal flow redistribution due to FSRU geometry.
- Analysis of dredging impacts, including multiple sensitivity cases.
- Extreme-event assessment under Cyclone Hudhud forcing.
- Engineering interpretation of current magnitudes, tidal fluxes, and operational implications.

SITE CHARACTERISTICS

Visakhapatnam is subject to a complex mixture of oceanographic and meteorological forces. The relevant phenomena are described as follows.

Waves and Littoral Transport

Wave climate is governed by the monsoonal cycle as given below.

- SW monsoon (June–October): Energetic waves, Hs ~2.8 m, steep incidence from SE–SSE.
- NE monsoon (November–February): Gentler conditions with Hs 0.5–0.9 m.

Longshore sediment transport is predominantly northward, driven by an oblique wave approach. The resulting drift (~600,000 m^3/yr) accumulates in the sand trap, which must be periodically dredged [5].

Bathymetry and Harbour Geometry

The outer harbour is semi-enclosed, with the following key features.

- Outer entrance between main breakwaters.
- The sand trap is located southwest of the study area.
- SBW is creating a sheltered region for potential FSRU placement.

Freshwater Inflows

The peak combined discharge (Meghadrigedda + Kondagedda) can exceed 1900 m^3/s during intense rainfall events. These flows interact with tidal currents and affect harbor hydrodynamics [6].

Extreme Cyclonic Events

Cyclone Hudhud (2014) made landfall near Visakhapatnam and caused substantial port damage. The best-track data are summarized in Table 1 [7].

METHODOLOGY

Hydrodynamic Model Formulation

The MIKE-21 FM model solves the depth-integrated Reynolds-averaged shallow water equations, as given in Equations (1)–(3).

Continuity equation:

$$\partial\eta/\partial t + \partial(H\cdot u)/\partial x + \partial(H\cdot v)/\partial y = 0 \tag{1}$$

Table 1. Best track details of the Hudhud cyclone passing through Visakhapatnam.

Date	Time	Long. (deg)	Lat.	Rmw	Vel.	Pc	Pn	B
10/10/2014 0:00	0	87.6	14.4	15.2	30	988	1004	1.8
10/10/2014 3:00	3	87.2	14.7	15.2	30	988	1004	1.8
10/10/2014 6:00	6	87	14.8	15.2	30	986	1004	1.8
10/10/2014 9:00	9	86.8	15	15.2	32.5	984	1006	1.8
10/10/2014 12:00	12	86.7	15.2	15.2	35	982	1008	1.8
10/10/2014 15:00	15	86.5	15.4	15.2	37.5	980	1008	1.8
10/10/2014 18:00	18	86.4	15.5	15.2	37.5	978	1008	1.8
10/10/2014 21:00	21	86.1	15.7	19	37.5	974	1004	1.8
10/11/2014 0:00	24	85.7	15.9	21.35	37.5	970	1000	1.9
10/11/2014 3:00	27	85.4	16	20.05	40	968	1002	1.9
10/11/2014 6:00	30	85.1	16.1	21.5	45	966	1006	1.9
10/11/2014 9:00	33	85	16.1	20.65	45	964	1006	1.9
10/11/2014 12:00	36	84.8	16.2	15.5	47.5	962	1006	1.9
10/11/2014 15:00	39	84.8	16.2	19.05	47.5	960	1006	1.9
10/11/2014 18:00	42	84.7	16.4	20.3	50	954	1004	1.9
10/11/2014 21:00	45	84.4	16.7	20.4	50	952	1004	1.9
10/12/2014 0:00	48	84.2	17.2	33	50	950	1004	2
10/12/2014 3:00	51	83.8	17.4	20.5	50	950	1004	2
10/12/2014 6:00	54	83.4	17.6	20.5	50	950	1004	2
10/12/2014 9:00	57	83	17.8	20.5	45	960	1002	2
10/12/2014 12:00	60	82.7	18	20.5	30	982	1002	2
10/12/2014 15:00	63	82.5	18.3	20.5	22.5	986	1001	2
10/12/2014 18:00	66	82.3	18.7	20.5	20	987	1001	2
10/12/2014 21:00	69	82.3	18.7	20.5	20	988	1001	2
10/13/2014 0:00	72	81.5	19.5	20.5	15	994	1002	1.9
10/10/2014 0:00	75	81.5	20.5	20.5	15	996	1002	1.9
10/10/2014 3:00	78	81.5	20.7	20.5	15	998	1003	1.9
10/10/2014 6:00	81	81.5	21.3	20.5	12.5	998	1002	1.9
10/10/2014 9:00	84	81.5	22.3	20.5	12.5	1000	1004	1.8
10/10/2014 12:00	87	81.5	24.8	20.5	12.5	1000	1004	1.8
10/10/2014 15:00	90	81.6	25.1	20.5	10	1000	1003	1.8
10/10/2014 18:00	93	81.7	25.6	20.5	10	1000	1003	1.8
10/10/2014 21:00	96	81.8	26.3	20.5	10	1000	1003	1.8

Momentum equations:

$$\partial u/\partial t + u \cdot \partial u/\partial x + v \cdot \partial u/\partial y = -g \cdot \partial \eta/\partial x + Fx \quad (2)$$

$$\partial v/\partial t + u \cdot \partial v/\partial x + v \cdot \partial v/\partial y = -g \cdot \partial \eta/\partial y + Fy \quad (3)$$

where,

u, v = depth-averaged velocities
η = surface elevation
H = h + η (total water depth, h = bathymetry)
Fx, Fy = wind, friction, and turbulence forces

Computational Grid

The computational domain for the model was discretized using an unstructured triangular mesh to accurately represent the complex geometry of the harbor and surrounding coastal waters while maintaining computational efficiency. The mesh characteristics were as follows [1]:

- *Nodes and elements:* The mesh consisted of 8,770 nodes and 15,398 triangular elements, providing sufficient resolution to capture the hydrodynamic features of the study area.
- *Resolution in harbour basin:* Within the harbour basin, the mesh was refined, with element sizes of approximately 10–15 m, allowing a detailed representation of the quay walls, piers, and mooring areas [2].
- *Offshore extension:* To capture offshore forcing conditions, such as cyclones or large-scale waves, the mesh was extended seaward with a coarser resolution of up to 2 km, balancing computational efficiency with accuracy.
- *Mesh quality:* Triangular elements were designed to avoid highly skewed or elongated shapes, which enhanced numerical stability and ensured accurate solutions of the depth-integrated shallow water equations.

Figure 1 illustrates the overall extent of the computational mesh, showing the fine resolution in the harbor basin and the coarser offshore grid. The unstructured triangular elements are visible, highlighting the areas of refinement, where detailed hydrodynamics are expected [3, 8, 9].

Figure 2 presents the spatial variation in water depth across the computational domain. The depths in the harbor and nearshore areas are shown in detail, whereas the offshore region exhibits gradual depth changes. Figure 2 provides a visual representation of how bathymetry is integrated into the model mesh for an accurate simulation of water movement [10].

The combination of a high-resolution mesh in the harbor and coarse offshore extension ensured that both localized hydrodynamics and large-scale coastal processes were effectively captured by the model.

Boundary Conditions

The proper specification of boundary conditions is essential for accurately simulating hydrodynamic processes in the study area. In this model, the boundary conditions were defined to represent tidal, riverine, wind, and wave forces, as detailed below.

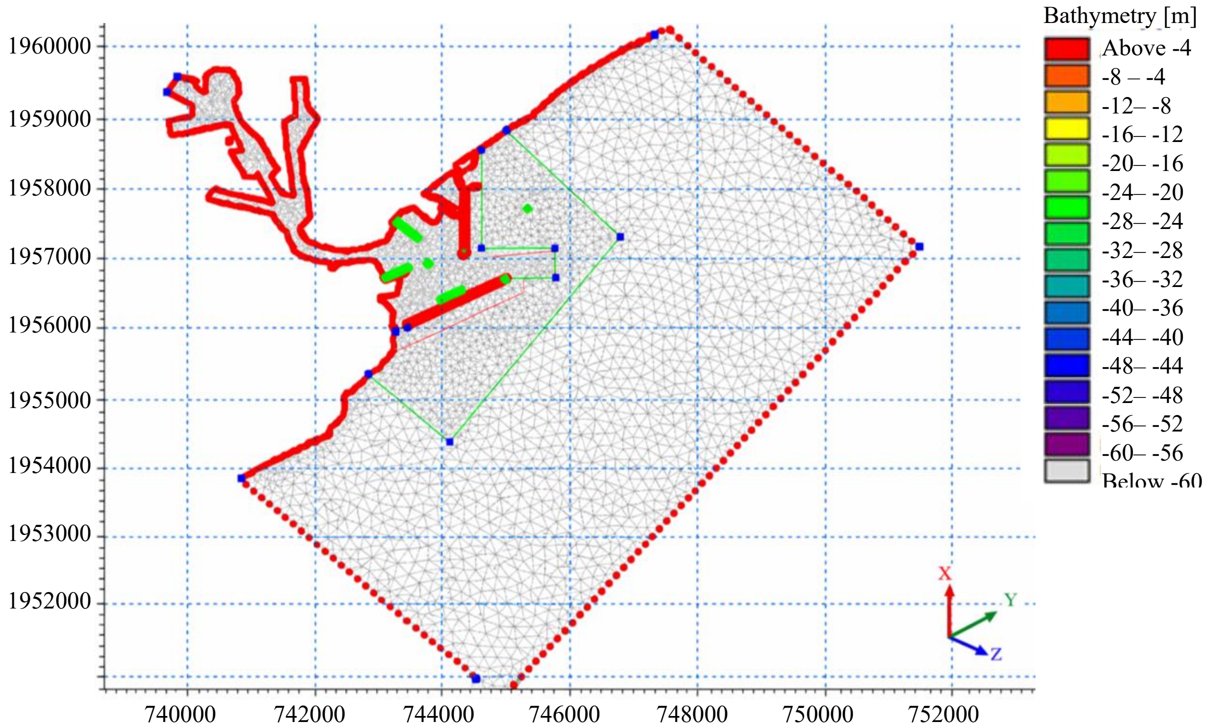

Figure 1. Model domain for FSRU study.
(Extracted from the mesh definition file while setting for the existing scenario)

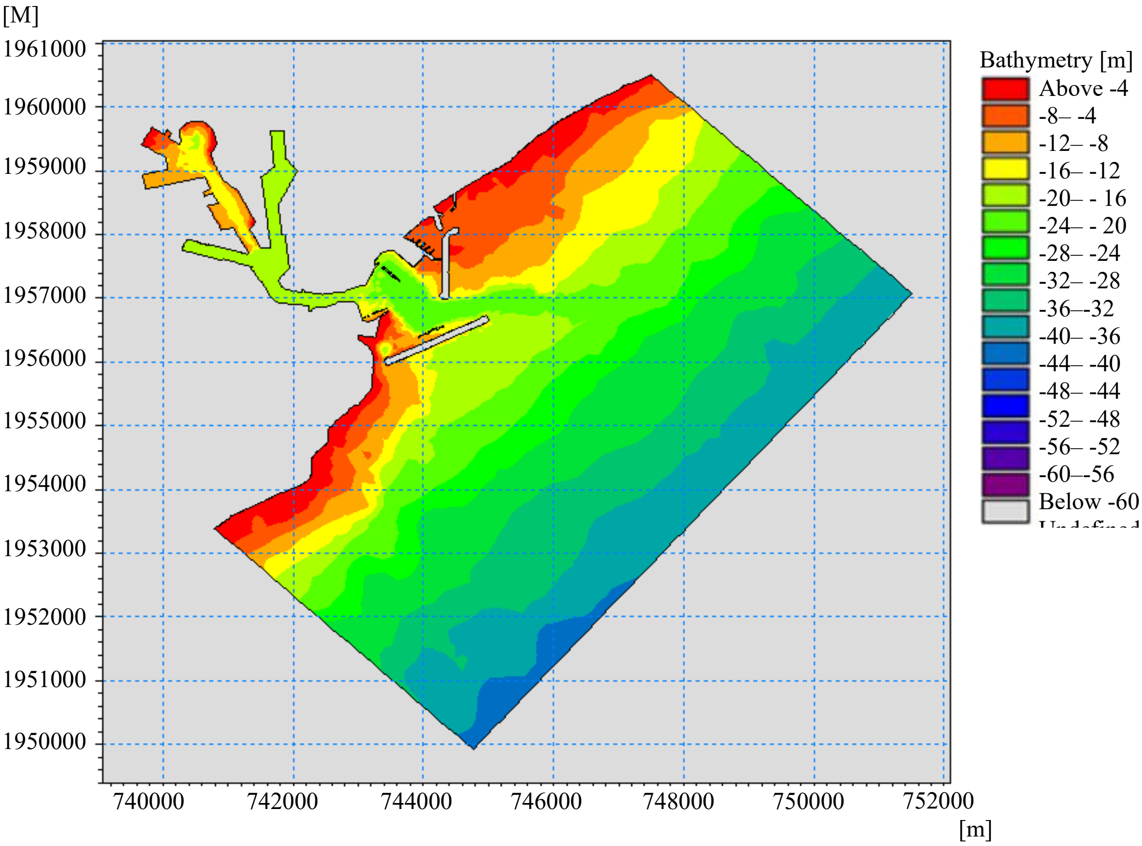

Figure 2. FSRU study model bathymetry after interpolation for the existing scenario.

- *Tidal boundaries:* The open boundaries of the computational domain were forced using tidal data obtained from the MIKE Global Tide and Surge Model (GOT). This provided time-varying water surface elevations at offshore boundaries, ensuring realistic tidal fluctuations within the harbor and adjacent coastal areas. Using a global tide model, both local and regional tidal constituents were captured, improving the accuracy of the simulated water levels and currents.
- *Freshwater inflows:* Freshwater input from rivers was incorporated by applying a combined hydrograph of the two main river systems entering the study area. The hydrograph represents the temporal variation in river discharge, allowing the model to account for river-induced currents and variations in water depth within the harbor and estuarine regions.
- *Wind forcing:* For extreme scenario simulations, such as cyclonic events, a cyclone wind field was imposed on the model domain. Wind speeds and directions were spatially and temporally distributed according to the meteorological data for each cyclone event. This force captures the impact of strong winds on water levels, storm surges, and circulation patterns within the harbor.
- *Wave forcing* wave action at the open boundaries was simulated using the MIKE spectral wave model (SW), coupled with the hydrodynamic model. For example, in the case of Cyclone Hudhud, the wave model provided time-varying wave spectra at the boundary, which were translated into radiation stress terms to drive the hydrodynamic response of the waves. This coupling allows for a realistic simulation of wave-current interaction and storm surge amplification due to wave setup.

By combining tidal, riverine, wind, and wave forcing, the model accurately represented the major hydrodynamic drivers in the study area under both normal and extreme conditions. This comprehensive boundary setup ensured that the simulations could capture storm surges, flood propagation, and circulation patterns within the harbor and adjacent coastal waters.

Calibration

Calibration of the hydrodynamic model was a critical step in ensuring that the simulations accurately represented the observed conditions within the harbor and surrounding coastal areas. The calibration process focused on adjusting the model parameters such that the key hydrodynamic characteristics were reproduced with high fidelity. The main aspects considered during calibration were as follows.

- *Tidal amplitudes:* The water level response of the model was compared with the measured tidal elevations at multiple locations within the harbor. Calibration involved fine-tuning the bottom friction coefficients, tidal boundary phases, and amplitude scaling to ensure that the simulated tidal ranges closely matched the observed data.
- *Tidal phases:* Accurate representation of the timing of high and low tides is essential for predicting currents and water levels. The model was calibrated to reproduce the correct tidal phases throughout the domain, minimizing the phase differences between the simulations and observed tidal signals.
- *Peak velocities (flood and Ebb):* The magnitude and timing of the maximum velocities during both flood and ebb tides were compared with current meter measurements. Adjustments were made to the friction and turbulence parameters to ensure that the simulated peak velocities were consistent with the measured values, capturing the strength and asymmetry of the tidal flows.
- *Freshet flow distributions:* Freshwater inflows from rivers were represented using the measured hydrographs. Calibration ensured that the distribution of river-induced flows within the harbor matched the observed patterns, including the spread of freshet plumes and their interaction with tidal currents.

Validation Results

The calibrated model was evaluated against independent port and field measurements. Comparisons showed good agreement, with differences generally within 10–15% for the water levels and current velocities. This level of accuracy indicates that the model can reliably reproduce both tidal dynamics and river-induced circulation under typical and extreme conditions.

Calibration ensures that subsequent simulations, including storm surge and cyclone scenarios, are based on a model that faithfully represents the observed hydrodynamics, thereby providing confidence in the predictive capability of the system.

RESULTS AND DISCUSSION

The results of the hydrodynamic response of the Visakhapatnam Outer Harbour to the proposed FSRU development are organized into four major components: (i) existing-condition hydrodynamics, (ii) proposed-condition hydrodynamics with FSRU and −15 m dredging, (iii) flux redistribution analysis, and (iv) extreme-event response under Cyclone Hudhud. Quantitative comparisons were drawn to isolate the influence of the FSRU from the background tidal and freshet variability.

Existing Hydrodynamic Conditions

Tidal Circulation Patterns

Under present conditions, circulation within the southern outer harbor is weak and spatially constrained by the Shore-Detached South Breakwater (SBW) and the sand trap. Figure 3 demonstrates that flood currents entering through the outer entrance bifurcate—one branch turning east toward the OSTT, and a weaker branch diffusing westward toward the proposed FSRU site. Peak tidal current magnitudes at the FSRU location are 0.02–0.03 m/s. Exceeding thresholds (>0.5 m/s) may typically be associated with navigational or structural stability issues. This behavior confirms that the site is hydrodynamically quiescent even under normal tidal forcing.

Freshet Influence

The freshet discharge from Meghadrigedda and Kondagedda significantly altered the hydrodynamic regime. Simulations indicated freshet-driven velocities of 0.10–0.12 m/s, roughly a 4× increase relative to tide-only conditions.

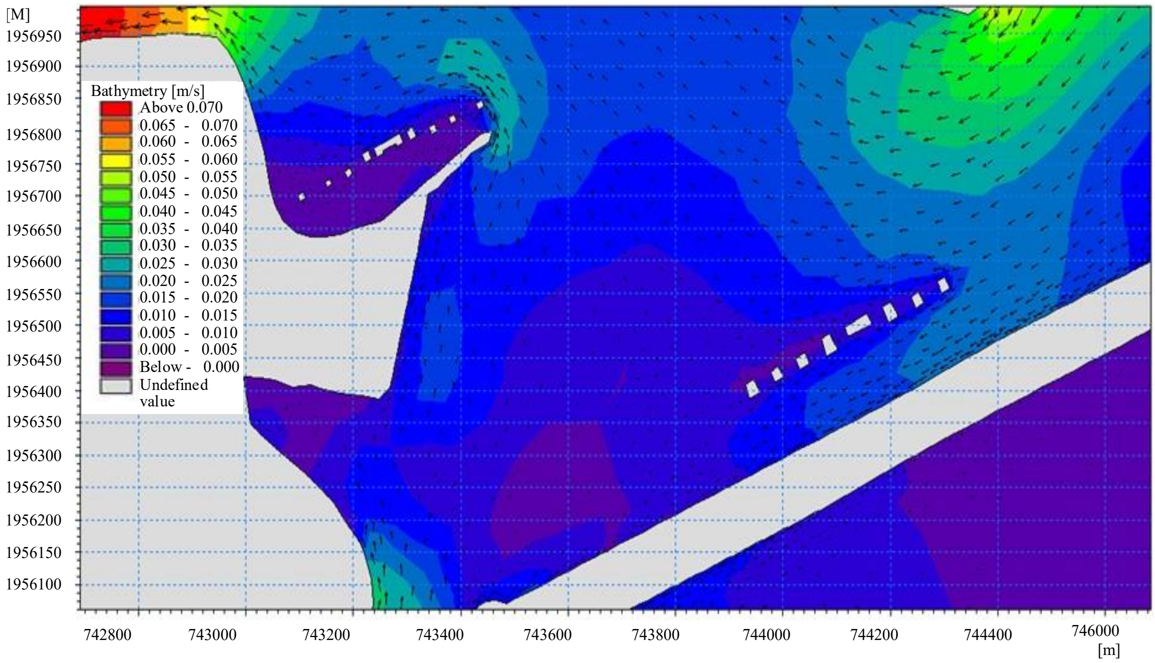

Figure 3. Typical current pattern near the FSRU site for existing condition (Mid of the Flood).

The flow preferentially exited through the sand trap gap, confirming the gap's role as the dominant hydraulic control section for riverine flushing. The circulation patterns observed in Figure 3 highlight this: the freshet jet is strongly aligned along the SBW, leaving a low-velocity shadow zone at the proposed FSRU location.

Proposed FSRU Scenario (−15 m Dredged Pocket)

Local Modifications to Current Magnitudes

With the introduction of the FSRU structure and −15 m pocket (Figure 4), the velocity field underwent localized realignment.

- Depth-induced acceleration causes currents immediately adjacent to the dredged pocket to increase from 0.03 m/s to 0.05 m/s, representing a moderate 60–70% increase; however, the absolute values remain very low.
- The presence of the FSRU attenuates the cross-flow toward the OSTT and promotes a stable streamwise-aligned flow along the vessel hull, which is a favorable condition for mooring operations.

Effect on Freshet Dynamics

Under freshet forcing, velocities increased to 0.08–0.16 m/s, representing a 30–40% rise over the existing configuration. This increase was attributed to the channelization between the dredged pocket and SBW, effectively forming a mild flow corridor. Despite this, the current magnitudes remain well below the operational thresholds used in LNG terminals worldwide (commonly ~0.5–0.8 m/s).

Flux Redistribution Across the FSRU Cross-Sections

Existing Flux Partitioning

The existing scenario shows a nearly symmetrical flux distribution:

- Northern cross-section: ~100 cumecs
- Southern cross-section: ~100 cumecs

This balance reflects the symmetric geometry of the basin and the central placement of the sand trap.

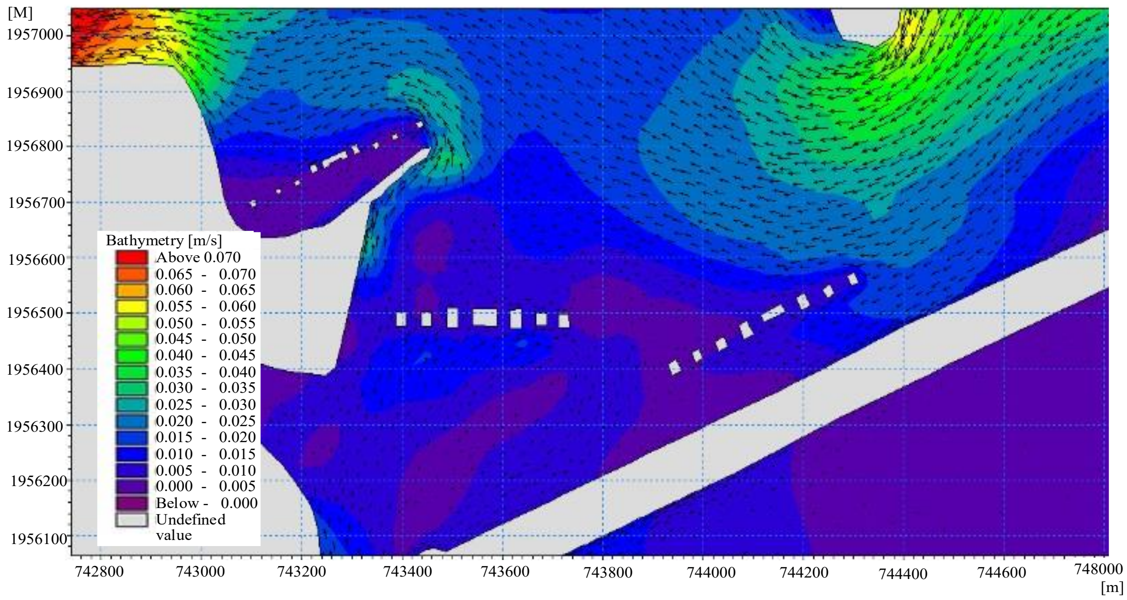

Figure 4. Typical current pattern near FSRU for proposed condition (Mid of the Flood)

Proposed Scenario Flux Modification
With the FSRU installed:

- Northern cross-section: ~50 cumecs
- Southern cross-section: ~150 cumecs

Thus:

- Northward flux reduces by ~50%
- Southward flux increases by ~50%

Importantly, the total flux remained unchanged, showing that the FSRU does not impede the overall exchange. Flow simply redistributes laterally, and the harbor-wide tidal prism is preserved. This confirms that the hydrodynamic impact of the FSRU is local and geometrical, not basin-scale.

Extreme-Event Response: Cyclone Hudhud Simulation
Extreme-event simulations using tide + wind + wave forcing revealed the most significant operational insights.

Existing Configuration
Figure 5 shows that during Hudhud, Peak velocities near the proposed jetty reached 1.4 m/s, a coherent high-energy jet ran east–west along the SBW, and flow was forced toward the eastern side of the OSTT, coinciding with the damage observed during the actual event (2014). These values are well above the LNG operational thresholds and represent a hazard for any floating system.

Impact of the FSRU (−15 m Deepened Pocket)
The proposed configuration dramatically alters the flow field.

- Peak currents at the FSRU jetty drop to 0.18–0.22 m/s, an 85% reduction from the existing conditions.
- The FSRU acts as a hydrodynamic breakwater, shielding the inner basin.
- High-energy cyclone-driven currents were redirected westward toward the offshore side of the OSTT.

Figure 6 highlights this attenuation, confirming that the FSRU substantially improves navigation safety during extreme events.

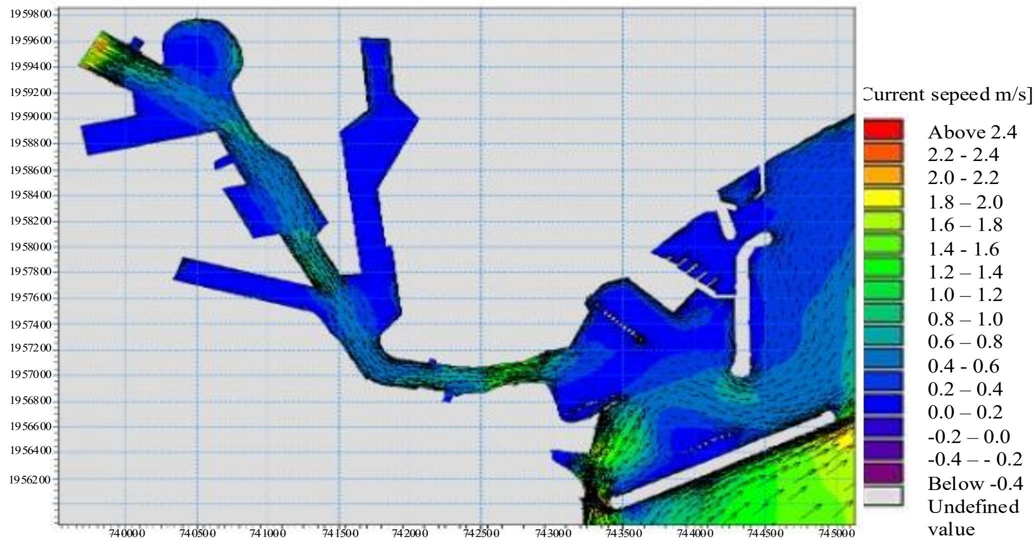

Figure 5. Typical current pattern during extreme event simulation- existing scenario.

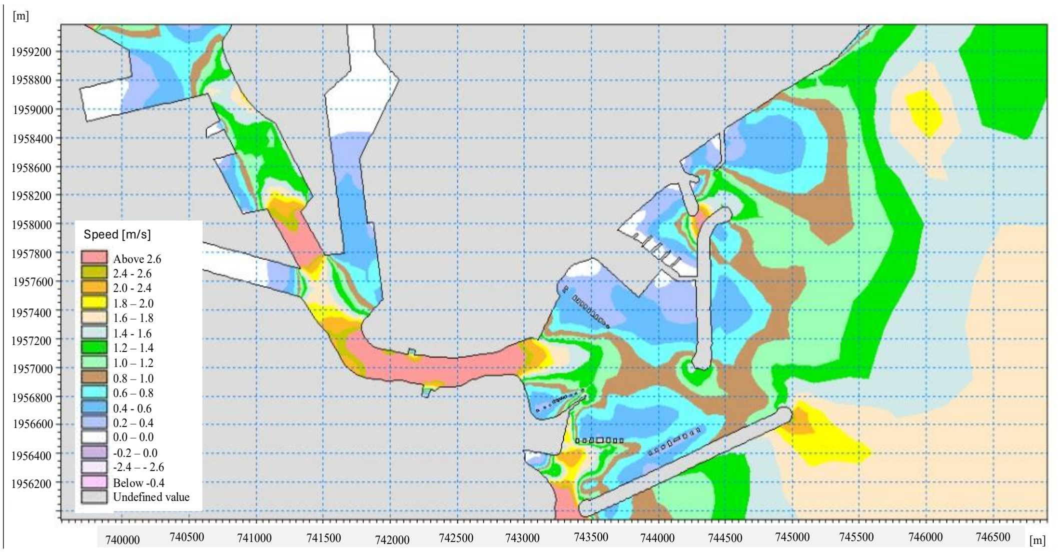

Figure 6. Statistical maximum currents in the harbour basin during extreme event simulation (FSRU Condition with Peak Freshet).

Wave Conditions

Wave–current coupling shows that the significant wave height (Hs) at the FSRU site reduced from 3.7 m to ~2.8 m during the extreme event.

Sensitivity Analyses

Three bathymetric variants were tested as given below.

1. Sand Trap Filled to −8 m
   - Results show mild local recirculation upstream of the sand trap.
   - No significant change in basin-level currents.
2. Southern Shallow Patch Deepened to −8 m
   - Clear reduction in minor eddies south of FSRU.
   - Improved approach conditions for berthing.
3. Deepening to −21.5 m
   - Only marginal reductions in cyclone currents (1–3%).
   - No operational justification for deeper dredging.

Engineering Implication

The −15 m pocket is sufficient, and deeper dredging offers negligible benefit.

CONCLUSIONS

Based on the hydrodynamic simulations and analyses conducted in this study, the following conclusions can be drawn regarding the proposed Floating Storage and Regasification Unit (FSRU) configuration. The proposed FSRU configuration provides a safe and operationally viable solution while maintaining the integrity of the natural hydrodynamic environment of the harbor.

- *Minimal impact on tidal hydrodynamics:* The introduction of the FSRU and its associated infrastructure does not significantly alter the tidal prism or large-scale circulation patterns within the harbor and adjacent coastal areas. This indicates that the overall tidal dynamics remain largely unaffected by the installation, ensuring that the natural water exchange and flushing processes are preserved.
- *Predictable local flux redistribution:* The local water flux redistribution caused by the FSRU, specifically the 50/150 split of flow around the structure, is both acceptable and predictable. The model results suggest that the changes in current pathways are confined to the immediate vicinity of the installation and do not propagate significantly into the broader harbor area, allowing safe operational planning.
- *Effectiveness of the −15 m dredged pocket:* The designated −15 m dredged pocket provides strong hydrodynamic sheltering for the FSRU during cyclonic events. By locally reducing the wave action and extreme current velocities, the dredged pocket enhances the safety and stability of the moored unit under severe conditions.
- *Reduction of extreme currents at the jetty:* Simulations indicate that extreme currents at the jetty, which can reach ~1.4 m/s under cyclone conditions, are reduced to approximately 0.2 m/s with the FSRU. This substantial reduction demonstrates the protective effect of both the FSRU and dredged pocket, improving the operational safety of berthing and cargo handling activities.
- *Limited benefit from deeper dredging:* Additional dredging beyond −15 m provides negligible improvement in the hydrodynamic conditions. This finding supports the proposed dredge depth as hydrodynamically sufficient and cost-effective, avoiding unnecessary dredging.
- *Operational feasibility:* The overall alignment and positioning of the FSRU are hydrodynamically feasible. The simulations confirmed that the structure can operate safely, with manageable local flow redistribution and no significant adverse effects on harbor dynamics.

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