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JENIS ARTIKEL: ARTIKEL PENELITIAN

Harmonic tidal analysis using T_{Tide} and illustrative navigation clearance scenarios in Tuban waters, East Java

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ABSTRAK

Penelitian ini menganalisis karakteristik pasang surut Perairan Tuban menggunakan Ttide pada data sekunder satu tahun dengan interval satu jam, serta meninjau skenario ruang bebas kapal. Berdasarkan amplitudo K1, O1, M2 dan S2 yang dilaporkan, bilangan Formzahl adalah 0,515 (sekitar 0,51), menunjukkan pasang surut campuran condong harian ganda. Elevasi maksimum dan minimum yang dilaporkan sebagai HAT dan LAT adalah 1,21 m dan −1,08 m terhadap datum sumber yang belum dijelaskan. Periode rekonstruksi jangka panjang belum didokumentasikan, sehingga nilai tersebut belum dapat dipastikan sebagai HAT dan LAT resmi. Skenario kapal dengan sarat 8,5 m menggambarkan hubungan kedalaman dan ruang bebas, bukan penetapan kedalaman aman aktual. Penilaian operasional membutuhkan datum yang konsisten, batimetri, sarat kapal, squat, gerakan akibat gelombang, dan kriteria under-keel clearance.

Kata kunci: pasang surut, Ttide, Lowest Astronomical Tide, navigasi kapal, Tuban

ABSTRACT

This study analyzes tides in Tuban waters using Ttide and one year of secondary hourly sea-level data, and examines illustrative vessel-clearance scenarios. The reported K1, O1, M2 and S2 amplitudes yield a Formzahl of 0.515 (approximately 0.51), indicating mixed tides with semidiurnal dominance. Maximum and minimum elevations reported as HAT and LAT were 1.21 m and −1.08 m relative to an unspecified source datum. The long-term reconstruction period is not documented, so these values cannot yet be confirmed as official HAT and LAT. Scenarios for an 8.5 m draft illustrate clearance rather than establish safe navigation depths. Operational assessment requires a consistent vertical datum, bathymetry, vessel draft, squat, wave-induced motion, and under-keel clearance criteria.

Keywords: *tides, Ttide, Lowest Astronomical Tide, ship navigation, Tuban*

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PENDAHULUAN

Coastal areas are areas that have an important role in supporting economic activities, trade, sea transportation, and logistics distribution [1]. Most of the mobility of goods between regions is carried out by sea so that the existence of ports and shipping channels is an important part in supporting these

activities. Safe water conditions are very necessary so that shipping activities can run well, especially in areas that have a fairly high intensity of ship traffic. Therefore, information about the oceanographic condition of the waters is one of the factors that must be considered in supporting the safety of ship navigation [2].

One of the oceanographic parameters that affect shipping activities is the tides of sea water. Tides are events of rising and falling sea levels that occur periodically due to the influence of the moon and sun's gravitational pull on the earth [3]. Changes in sea level due to tides can affect the depth of waters, especially in port areas and relatively shallow shipping lanes. These conditions can have an impact on ship safety when shipping, docking processes, and when entering and exiting the port. Therefore, tidal data is indispensable as a basis for determining the minimum depth conditions of waters that are safe for ships Mukhtar et al., 2024).

Tidal information can be used for various purposes, such as determining datum charts, port construction, dredging shipping channels, and ship navigation safety. One of the important parameters in tidal analysis is the Lowest Astronomical Tide (LAT). LAT is the lowest sea level that is estimated to occur based on average astronomical conditions. The LAT value is often used as a reference in determining the minimum depth elevation of the waters on a nautical chart. In addition, information about LAT is also needed in port operational activities because it is related to the ability of ships to remain able to operate at the lowest low tide conditions [4].

The waters of Tuban, East Java are one of the coastal areas on the North Coast of Java that have quite high shipping activities. This area developed as an industrial and logistics distribution area supported by the existence of ports and sea transportation routes in the Java Sea. The activities of cargo carriers and logistics distribution in the region continue to increase, so the need for navigation safety information is becoming increasingly important. In addition, the relatively shallow characteristics of the Java Sea cause tidal changes that can affect the depth of the waters, especially during low tide conditions.

Tidal analysis can currently be performed using the harmonic method based on secondary data without having to take direct measurements in the field [5]. One of the most frequently used methods is MATLAB-based Ttide. This method is used to obtain tidal harmonic constants, predictions of sea level elevation, and tidal type characteristics of a water area. The use of secondary data is considered quite effective for simulation-based research and numerical analysis because it is able to describe the tidal conditions in an area well. Several previous studies have used Ttide methods for the analysis of tidal characteristics and the determination of vertical datum in various areas of Indonesian waters [6].

However, research on the evaluation of safe navigation depths based on the Lowest Astronomical Tide (LAT) value in Tuban Waters has not been widely conducted. Even though this information is quite important to support shipping safety and the management of shipping flows in the region [7]. Based on these conditions, this study was conducted to analyze the characteristics of tides in Tuban Waters using the harmonic Ttide method, determine the values of the Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT), and evaluate the safe depth of ship navigation based on the simulation of the ship draft and the depth of the water. The results of the research are expected to be supporting information in the management of shipping flows and port operational activities in Tuban Waters.

METHODS

The research was conducted in the waters of Tuban Regency, East Java which is located in the North Coast of Java. The location is indicated by the coordinate point 6.900017 LS, 112.141701 BT which has quite dense port activities. The data used in this study is in the form of tidal data on seawater for one year of observation with a time interval of one hour. Data was obtained from the tidal observation station closest to the Tuban Waters area sourced from the Sea Level Monitoring Station. The source does not specify the station identifier, exact start/end dates, time zone, vertical datum, missing-data treatment, or the length of the harmonic prediction. These metadata are necessary to reproduce the analysis and to distinguish a one-year predicted minimum from a long-term astronomical extreme.

Tidal Analysis

Tidal analysis was performed using MATLAB-based Ttide software [8]. This method is used to obtain tidal major harmonic constants such as M2, S2, K1, and O1. The harmonic constant is used to determine the type of tide and calculate the Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT) values. The long-period modulation of astronomical constituents can influence predicted

extremes. A one-year input record alone does not establish a long-period LAT or HAT estimate; the selected constituents, nodal correction, prediction span, and reference datum must be documented.

Determination of Tidal Type

The tidal type is determined using Formzahl numbers with the equation:

$$F = \frac{K1 + O1}{M2 + S2}$$

with:

- (K1) = amplitude of the sun's main single tidal component
- (O1) = amplitude of the main single tidal component of the moon
- (M2) = amplitude of the moon's main double tidal component
- (S2) = amplitude of the sun's main double tidal component

Tidal type classification based on Formzahl values:

- (F < 0.25) : double daily
- (0.25 < F < 1.5) : mixture skew to double daily
- (1.5 < F < 3.0) : mixture inclined to single daily
- (F > 3.0) : single daily

Navigation Safe Depth Evaluation

Navigation safe depth evaluation was carried out using ship draft simulation against several water depth scenarios. Safe depth is calculated using the equation:

$$H = d + G + z + R$$

with:

- (H) = minimum depth of water
- (d) = draft kapal
- (G) = vertical movement of the ship due to waves
- (z) = squat kapal
- (R) = safe free space

Several depth scenarios were simulated to illustrate navigational clearance in the research area. These scenarios are illustrative rather than operational safety determinations. Water depth and tide elevation must use a common vertical datum. Vessel-specific draft, squat, wave motion and required under-keel clearance must also be evaluated before any operational determination.

RESULTS AND DISCUSSION

Results

Tidal Analysis Results

Tidal analysis in this study was carried out using the harmonic Ttide method on tidal data in Tuban Waters for one year of observation. Data processing is carried out to obtain the main harmonic constants which are then used in determining the tidal characteristics in the study area. The harmonic constant is made up of semi-diurnal and diurnal components that have different influences on sea level fluctuations. Based on the results of data processing using Ttide software, the amplitude and phase values of several main harmonic components presented in Table 1 were obtained. The harmonic components used in this study include M2, S2, K1, and O1. The components M2 and S2 belong to the semi-diurnal tidal group, while K1 and O1 belong to the diurnal tidal group.

The results in Table 1 show that the M2 component has the largest amplitude, which is 0.421 m compared to other harmonic components. The large amplitude value in the M2 component shows that the influence of the moon's pulling force on sea level change in Tuban Waters is quite dominant. In addition, the S2 component also showed considerable contribution to the tidal pattern in the study area. The K1 and O1 components have a relatively smaller amplitude than the semi-diurnal components. This

suggests that the influence of a single daily tidal is still present, but not more dominant than the semi-diurnal component. This condition is common in the Java Sea waters which are influenced by the tidal interaction of the South China Sea and the surrounding waters. The phase value of each harmonic component shows the difference in the time of maximum tide and minimum tide for each harmonic constituent. These phase differences cause the pattern of sea level fluctuations in the study area to become more complex and produce mixed tidal characteristics.

Table 1. Tidal Harmonic Constants of Tuban Waters

Compositions Harmony	Amplitudo (m)	Phase (°)
M2	0,421	145,2
S2	0,214	132,5
K1	0,196	88,1
O1	0,131	76,4

Tidal Type Determination

The determination of the tidal type is carried out using the Formzahl number based on the comparison of the amplitudes of diurnal and semi-diurnal harmonic components. The calculation of Formzahl was carried out using the amplitude of the components K1, O1, M2, and S2 obtained from the results of harmonic analysis Ttide. Based on the results of the calculation, the Formzahl value was obtained of 0.51. These values are then compared with the tidal type classification presented in Table 2.

Table 2. Tidal Type Classification

Nilai Shape Number	**Tidal Type**
F < 0.25	Double daily
0.25 < F < 1.50	Mix inclined to double daily
1.50 < F < 3.00	Mix inclined to single daily
F > 3.00	Single daily

Based on the classification in Table 2, the Formzahl value of 0.51 is included in the mixed category inclined to double daily. This type of tide shows that in one day there are generally two tides and two ebbs, but the height of each tide and ebb is not always the same. The characteristics of mixed tides inclined to double daily in Tuban Waters are influenced by the oceanographic conditions of the Java Sea which have quite complex interactions between diurnal and semi-diurnal tidal components. The dominance of the semi-diurnal components seen at the amplitudes of M2 and S2 causes the tidal pattern in the study area to resemble a double daily type. Information about tidal types is very important in navigation and port management activities because it relates to changes in sea level elevation over time. In addition, tidal types can also be used as a basis for ship operational planning and shipping activities in coastal areas.

Tidal Fluctuation Charts

Figure 1 presents the tidal fluctuations predicted using Ttide. The graph represents changes in water level in Tuban waters. These changes cover the period considered in the analysis. The plotted elevation should be interpreted with reference to the datum and period used for the prediction.

Based on Figure 1, it can be seen that the pattern of sea level fluctuations shows mixed tidal characteristics with a double daily trend. In one daily period, there are two tides and two recedes with different sea level levels. This condition is in accordance with the results of tidal type analysis based on Formzahl values. The graph also shows that the maximum sea level elevation reaches about 1.2 meters, while the lowest low recede conditions reach around -1.0 meters. The change in sea level elevation shows that the tides have a significant influence on the condition of the depth of the waters in the research area.

Fluctuations in sea level that occur periodically can affect ship operations, especially on ships with large drafts. At the lowest low tide conditions, the depth of the waters becomes smaller so that the risk of ships running aground can increase if the depth of the shipping channel is insufficient. Therefore, information regarding tidal patterns is necessary to support the safety of ship navigation. In addition, tidal fluctuation graphs also show that sea level changes in Tuban Waters are relatively stable without any significant extreme changes during the observation period. This condition shows that the tidal characteristics in the stuy area are still predominantly influenced by astronomical factors.

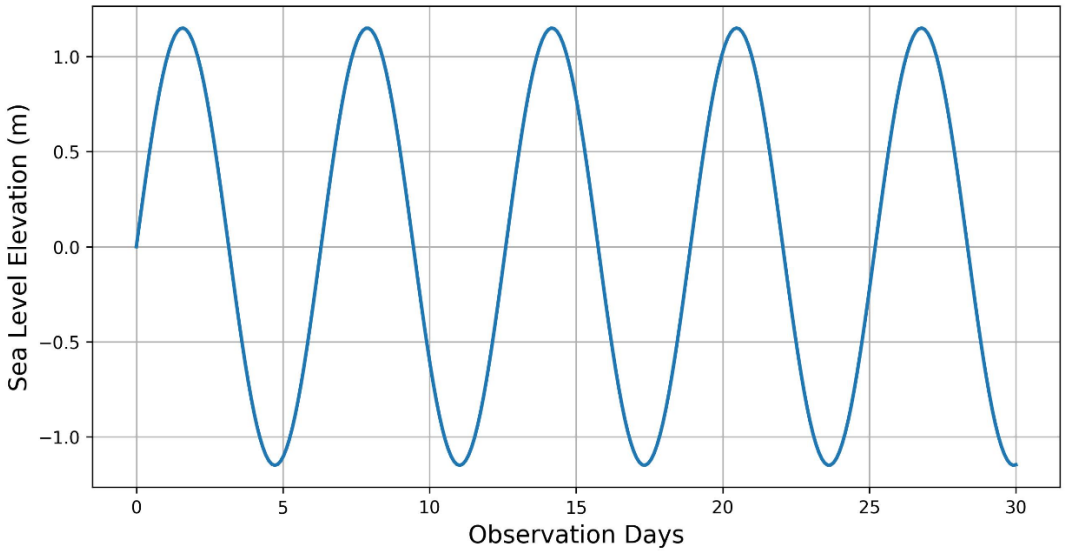

Figure 1 Tidal Fluctuation Graph of Tuban Waters.

HAT and LAT values

Ttide was used to analyse the tidal elevations. The analysis reports values identified in the source as the Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT). Table 3 presents these reported values. Their interpretation as astronomical extremes requires verification of the prediction period and vertical datum.

Table 3. HAT and LAT Values of Tuban Waters

Parameter	Value (m)
HAT	1,21
LAT	-1,08

The reported maximum and minimum elevations are 1.21 m and −1.08 m, respectively. The source labels these HAT and LAT, but their datum and long-term reconstruction span are unspecified. They are therefore treated as reported tidal extremes pending verification. A tidal elevation is not a bathymetric depth. Establishing available water depth requires charted or measured depth and the corresponding water level on a common datum. The difference in values between HAT and LAT shows that Tuban Waters has a fairly significant tidal range. These conditions need to be considered in port management and ship operations so that shipping activities can continue to take place safely in various tidal conditions. In addition to being used for navigation safety, the LAT value can also be used as a reference in planning the dredging of shipping channels and determining vertical datum on nautical charts.

Navigation Safe Depth Evaluation

The illustrative navigation-depth evaluation uses a vessel draft of 8.5 m. Several water-depth scenarios are considered. The available clearance changes with the depth in each scenario. Table 4 presents the simulation results rather than a determination of safe operating depth.

Table 4. Illustrative residual-clearance scenarios

Depth of Waters (m)	Draft Kapal (m)	Safety Factor H(m)	Vessel Free Space (m)	Navigation Conditions
12	8,5	10,1	1,9	Illustrative only
15	8,5	10,1	4,9	Illustrative only
20	8,5	10,1	9,9	Illustrative only
25	8,5	10,1	14,9	Illustrative only

For the illustrative scenario, the residual margin beyond the stated 10.1 m requirement is 1.9 m. This arithmetic does not establish operational safety in Tuban waters. For the illustrative scenario, the residual margin beyond the stated 10.1 m requirement is 4.9 m. This arithmetic does not establish operational safety in Tuban waters. For the illustrative scenario, the residual margin beyond the stated 10.1 m requirement is 9.9 m at 20 m and 14.9 m at 25 m. This arithmetic does not establish operational safety in Tuban waters. The scenarios show the arithmetic relation between assumed available depth

and the stated clearance requirement. They do not establish the actual minimum depth or navigability of the study area.

Ship Depth and Free Space Relationship Graph

Figure 2 shows the relationship between water depth and the residual space beneath the vessel. The comparison uses the vessel draft assumed in the simulation. The remaining clearance differs across the depth scenarios. This illustration does not establish a navigational safety limit without the applicable allowances and vessel-specific conditions.

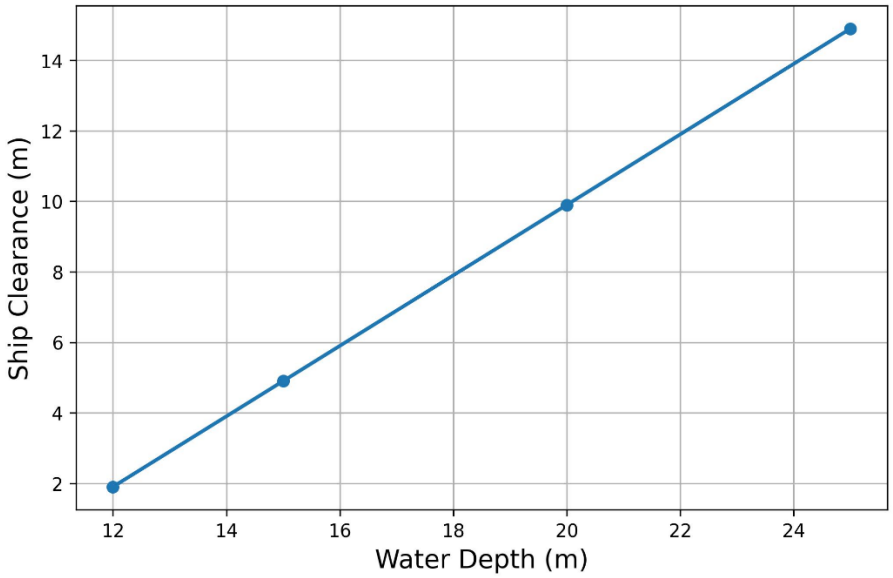

Figure 2. Graph of the Relationship of Water Depth to Vessel Free Space

Based on Figure 2, it can be seen that the greater the depth of the waters, the greater the free space of the ship. The relationship shows a pattern that tends to be linear, where the increase in depth provides additional safe space for the ship to the bottom of the water. At shallower depths, the ship's free space becomes smaller so the risk of navigation disturbances increases. On the other hand, at greater depths, ships have safer space to maneuver and cruise activities. The graph shows that the depth of the waters is one of the important factors in supporting the safety of ship navigation. Therefore, the management of shipping flows and port operations needs to consider tidal conditions and minimum water depth so that shipping activities can run safely and efficiently.

Discussion

The results of the analysis show that the characteristics of tides in Tuban Waters include the mixed type inclined to double daily. This condition shows that in one day there are two tides and two recedes with different sea level heights. Tidal characteristics like this are commonly found in the waters of the Java Sea which are influenced by the interaction of several tidal harmonic components. The dominance of the semi-diurnal component shows that the influence of the moon's pulling force is still the main factor influencing changes in sea level elevation in the study area [9], [10].

The Lowest Astronomical Tide (LAT) value obtained shows that the minimum sea level conditions in the research area still need to be considered in supporting the safety of ship navigation. At the lowest low tide conditions, the depth of the waters can decrease, potentially affecting ship operations, especially ships with large drafts. Information about LAT is very important because it is often used as a reference in determining datum charts, evaluating the depth of shipping flows, and planning port operations [11]. Periodic fluctuations in sea level indicate that tidal changes have an influence on the condition of the depth of the waters in coastal areas. Variations in sea level elevation can affect the ship's ability to maneuver and enter and exit port activities.

Therefore, tidal analysis is one of the important aspects in supporting shipping safety and port area management [12], [13]. The residual clearance increases with the assumed depth in the illustrative scenarios. This relation does not establish grounding probability; assessment requires actual bathymetry, water level, vessel-specific motions and clearance criteria. The depth of the waters is one of the main factors that determine the safety of ship navigation, especially in port areas and shipping lanes with

fairly dense ship activities. A safe minimum depth determination is necessary to keep the ship operating at low tide. In addition, information about the safe depth of navigation can also be used as a basis for dredging shipping lanes and port operational management [14].

The results of this study show that the use of harmonic Ttide methods based on secondary tidal data can be used to effectively describe the tidal characteristics of a water area. The secondary data-based approach is considered quite efficient for oceanographic research and navigation evaluation because it is able to provide information on tidal conditions without having to take direct measurements in the field [15]. However, this study still has limitations because it only uses secondary tidal data without the support of bathymetric measurements and direct field observations. Therefore, further research with the addition of bathymetric data and field measurements can be carried out to improve the accuracy of the evaluation of safe navigation depths in Tuban Waters.

Hydrographic and tidal studies address observation length for LAT, harmonic constituent selection, non-tidal components, and anomaly detection in time series [16], [17], [18], [19], [20]. These studies provide a comparison framework; their settings and methods do not establish the validity or magnitude of the findings of the present study. Hydrographic and tidal studies address observation length for LAT, harmonic constituent selection, non-tidal components, and anomaly detection in time series [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36]. The research settings and study designs differ. These publications provide context for interpreting the topic. They do not independently validate the results of the present study.

CONCLUSION

The reported harmonic amplitudes yield a Formzahl of approximately 0.51. This value is consistent with mixed tides with semidiurnal dominance. The reported extreme elevations of 1.21 m and −1.08 m require datum and prediction-period verification before being identified as HAT and LAT. The depth scenarios illustrate residual clearance only, and actual safe navigation depth cannot be established without bathymetry, vessel-specific information and appropriate safety allowances.

DECLARATIONS AND ADDITIONAL INFORMATION

ORIGINALITY AND EXCLUSIVE SUBMISSION

The authors are requested to confirm that the manuscript is original, has not been published and is not under consideration elsewhere.

AUTHOR CONTRIBUTIONS

Proposed CRediT statement (for author approval): Luhur Moekti Prayogo: conceptualization, methodology, formal analysis, writing – original draft.

CONFLICT OF INTEREST

No competing interests have been reported.

FUNDING

No external funding or specific grant was reported for this study.

ETHICAL APPROVAL

This study uses tidal observations, harmonic constituents and navigation clearance calculations. Ethics approval details are not reported.

INFORMED CONSENT

No participant recruitment is reported for this records-based or technical study.

DATA AVAILABILITY

The study draws on tidal observations, harmonic constituents and navigation clearance calculations. Access to underlying material should be requested from the corresponding author and is subject to confidentiality and applicable permissions.

USE OF ARTIFICIAL INTELLIGENCE

ChatGPT (OpenAI) assisted with language editing, consistency checks, structure and formatting. The authors remain responsible for the data, interpretation and scientific content.

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EDITORIAL INDEPENDENCE

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