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INTERACTION BETWEEN TIDE AND STORM SURGE USING MIKE21 NUMERICAL MODEL

ĐÁNH GIÁ TƯƠNG TÁC PHI TUYẾN GIỮA THỦY TRIỀU VÀ NƯỚC DÂNG DO BÃO BẰNG MÔ HÌNH MIKE21

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Abstract

The study of the relationship between tides and storm surges is important for forecasting sea level rise during storms to support flood prevention and response in coastal areas. The paper focuses on assessing the existence of nonlinear tide-surge interactions. Observational water level data measured at the hydrographic station are used to calibrate the MIKE21 model. Boundary conditions are changed under different scenarios in order to simulate water level variations including pure tidal level fluctuations, wind-pressure-induced surge levels and the total water levels with various wind fields during Typhoon Washi occurring both earlier and later than in reality. Statistical results show that in Hon Dau with a tidal magnitude of about 3.6m, the storm surge peak tends not to coincide with high tide but occurs near low tide with increasing height, reaching its highest point within about 1 hour around low tide and its lowest point within about 3-4 hours after high tide. These results again confirm the existence of the nonlinear interaction between tides and storm surges. The maximum total water level is mainly influenced by tides and occurs near high tides, while the storm surge component caused by the wind pressure field varies in the opposite direction.

Keywords: *Total water level, storm surge, tide, numerical model.*

Tóm tắt

Việc nghiên cứu mối liên hệ giữa thuỷ triều và nước dâng do bão có ý nghĩa quan trọng đối với công tác dự báo mực nước biển dâng trong bão nhằm phục vụ phòng chống và đối phó với ngập lụt tại các vùng ven biển. Bài báo tập trung nghiên cứu đánh giá sự tồn tại của tương tác phi tuyến giữa thuỷ triều và nước dâng do bão. Số liệu mực nước thực đo tại trạm hải văn được sử dụng để hiệu chỉnh mô hình MIKE21. Các điều kiện biên thay đổi với các kịch bản khác nhau nhằm mô phỏng biến trình mực nước bao gồm mực dao động triều thuần tuý, mực dâng rút do gió áp và mực nước tổng hợp với các trường gió trong bão WASHI diễn biến sớm hơn và muộn hơn thực tế. Kết quả thống kê cho thấy tại khu vực Hòn Dấu với độ lớn thuỷ triều khoảng 3,6m, đỉnh nước dâng do bão có xu hướng không trùng với đỉnh triều mà tập trung gần chân triều. Độ cao của đỉnh nước dâng tăng dần khi tiến gần đến chân triều, đạt cao nhất trong khoảng 1 giờ quanh chân triều và thấp nhất trong khoảng 3-4 giờ sau đỉnh triều. Các phân tích này một lần nữa khẳng định sự tồn tại của tương tác phi tuyến giữa thuỷ triều và nước dâng do bão. Trong khi mực nước tổng hợp cực đại chịu sự chi phối chủ yếu của thuỷ triều và tập trung gần đỉnh triều, thành phần nước dâng do trường gió áp trong bão gây ra lại biến đổi theo xu hướng ngược lại.

Từ khóa: *Mực nước tổng hợp, nước dâng do bão, thủy triều, mô hình số trị.*

1. Introduction

The interaction between tides and storm surges is a nonlinear phenomenon that plays an important role in accurately determining extreme water levels in coastal areas during severe typhoons. While tides are a periodic process with high forecast reliability, storm surges depend on short-term fluctuations such as strong winds and low pressure, leading to

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complications when these two processes occur simultaneously. Many studies have shown that the total water level during a storm cannot be determined simply by the linear sum of tides and storm surges but must consider the nonlinear interaction between them. In Vietnam, some initial studies have clarified the influence of tide-surge interactions on extreme water levels in areas such as the Gulf of Tonkin. According to [1], there is a clear non-linear interaction between tides and storm surges. When the storm making landfall at high tide, the total water level decreases compared to the linear sum; this value increases in case of low tide. The largest deviation occurs when the water level is high and strongly out of phase with the tide. The non-linear interaction between tides and storm surges in the North Sea of Vietnam is very noticeable. It increases or decreases the total water level compared to the linear sum of the two quantities depending on the phase of the tide [1]. Typical international studies have clearly described the surge-tide interaction mechanism in the North Sea, showing the strong influence of tidal phase on the timing and intensity of storm surge. Statistical analysis of sea level observed at stations shows that the highest residual surge tended not to coincide with the tidal peak and mainly occurred in the period of 3-5 hours earlier [2]. In [3], the POM model was adopted in order to determine the storm surges with tidal influence; the model was calibrated and verified by means of the data collected from Typhoon Damrey in 2005 in the Gulf of Tonkin. The timing of the peak surge may be affected under the impact of semi-diurnal tides [4]. Tides have a significant influence on storm surge; storm surge reaches higher values when storms make landfall at low tide and lower values when storms make landfall at high tide. When storms make landfall at rising or falling tides, tidal amplitude has little influence on the magnitude of storm surge. The strongest influence of tidal amplitude on storm surge occurs when storms make landfall at the time of highest water level [5]. Calculation results of storm surge in coastal areas from Quang Binh to Quang Nam in the period 1951-2014, showed that storm surges in the study area had a magnitude of over 2.0m occurred along the coast from Da Nang to Quang Binh, and 3.0m along the coast of Quang Tri and Hue [6]. The 2D ROMS model was tested to simulate 3 cases: Typhoon Xangsane in September 2006, post-storm circulation in combination with the southwest monsoon after Typhoon Kalmeagi in September 2014 making landfall in Quang Ninh and surges during a record high tide in Ho Chi Minh City. The results showed that the model simulated storm surges as well as monsoons relatively well, the surge caused by the monsoon during the high tide on October 20, 2013 at the Saigon River mouth could reach up to 0.4m [7]. The tidal impacts on storm surge was negligible when Typhoon Frankie making landfall at low tide, but was significant in the case of Typhoon Washi at high tide, with a 13% difference between storm surge levels with and without tides [8]. Applying the SuWat (Surge Wave and Tide) model to simulate storm surge with the wind pressure field from the analytical model (according to storm parameters) and the WRF numerical forecast model showed that in the situation of Typhoon Kalmaegi, storm surge occurred after the landfall with a height of more than one meter, and the duration was 12 hours [9]. The influence of storm parameters (wind field, pressure and speed) on storm surge in the Northern coastal area, especially the storm surge after the landfall, by means of simulation using the integrated numerical model SuWAT with Typhoon Kalmaegi-14. The post-storm strong wind field was identified as the main cause of the storm surge after the landfall in the Northern coastal area [10]. The TSIM11 numerical model built by the Institute of Mechanics, Vietnam Academy of Science and Technology, was applied to simulate the waves, tides and storm surge. When a typhoon makes landfall, the maximum storm surge height is inversely proportional to the amplitude of corresponding tidal fluctuations at a time when the water level is greater than the mean value [11]. Integrating the interaction between waves, tides and storm surge in forecasting models is essential for the purpose of improving forecast accuracy, thereby better supporting the mitigation of storm-induced damage in the coastal area of northern Vietnam [12].

Studies on surge-tide-wave interactions are simulated through hydrodynamic models that consider wind, pressure and tide fields, such as SuWAT, ADCIRC, POM, ROMS, MIKE21 or FVCOM. Some studies also apply nonlinear error analysis methods by comparing the total water level from the full model with the separate sum of tide and surge to quantify the level of interaction. These studies have initially detected and evaluated the interaction phenomenon between tide and storm surge. However, there are still shortcomings in research in this topic including insufficiency of observed water level data, low resolution of wind fields, and asynchrony in setting up tide-storm models. In addition, in some studies, the wind field used is still in the form of theoretical parameters, causing errors in simulating the time and amplitude of surge. Specifically, wind formulas such as those introduced by Holland (1980) [13] and Young & Sobey (1981) [14], assuming that the wind has a circular symmetric distribution around the storm center [1,3-6,8-9,11-12]. The major limitation of this formulaic wind input is the determination of maximum wind speed radius, which requires many measuring stations in order to calibrate the cyclonic wind field. Employing formulaic wind also means that the wind field before and after the storm is both zero. In reality, the storm structure is often distorted due to the influence of terrain, upper-level winds, and interactions with the ground. The above symmetrical formulas are even more unsuitable for complex terrain (bays, estuaries, straits) such as the Gulf of Tonkin or mountainous coastal areas with wind fields that change strongly due to terrain. In addition, using these storm wind formulas leads to the inability to simulate the surge before and after the storm peak. Therefore, using the wind field calculated from the formulae for water level simulation (with tides) will lead to inaccurate results when compared with the measured water level data at the stations. Studies on storm surges in the coastal areas of Vietnam mainly use the wind formulae, or just compare the surge model results with the residual component (after separating the tidal components) which lacks of physical meaning as the derived residual levels are the sum of all non-tidal component and their interactions [1, 3, 5, 6, 7-10, 12]. This practice also contains large errors since the tide component derived from observed data with insufficient length, such as in [10, 11], is inaccurate. In fact, there have also been no study that fully evaluates the interaction process between storm surge and tide at different times in a tidal phase (hourly). Consequently, in order to determine the highest and lowest water levels at a specific time when interacting with the tide, the integration of a full hydrodynamic model, using re-analysis wind-pressure data (ERA5, CFSR, etc) instead of formulaic wind-pressure field generated from storm track data by cyclone tools, and developing quantitative storm surge-tide interaction indices is a necessary direction to improve the quality of water level simulation under storm conditions in coastal areas of Vietnam and around the world.

In order to gain a detailed assessment of the tide-surge interaction, the MIKE21FM model was applied for the coastal area of Hai Phong where Typhoon Washi made landfall from July 29 to July 31, 2005. The typhoon caused the highest observed total water level in the last 60 years (2.28m according to the State elevation system) with the maximum storm surge just 1 hour earlier than the tidal peak during spring tide period. The model was calibrated based on measured water level data at Hon Dau station and then applied under different scenarios. The computational scenarios were selected and established to provide evidence to answer the following questions, within the limit assumptions of the model and the specific case of Typhoon Washi in 2005: (1) Is the resulting water level exactly equal to the linear sum of the purely astronomical tide level component and the wind-pressure water level variation component? (2) Is the wind-pressure surge component completely independent or does it vary with the tide?

2. Model description

2.1. Introduction to MIKE 21FM HD Model

MIKE 21FM Flow model is a modelling system for depth-averaged flow provided, developed and supported by the Danish Hydraulic Institute (DHI). The model is used to simulate hydrodynamic processes and environments in areas such as: lakes, estuaries, bays, coastal areas and seas (ignoring stratification). The model can be used to simulate hydraulic phenomena and related issues including: tides, currents and storm surges. The hydrodynamic module (HD) is a basic module in the MIKE 21 flow model. The module simulates the variation of water levels and flows in response to various forces in lakes, estuaries and coastal areas.

Governing equations of the model

The general governing equations presented below are used for the Cartesian coordinate system.

Shallow water equation

The two-dimensional shallow water equations are obtained by assuming a hydrostatic pressure distribution and integrating the Navier-Stokes equations over the entire water depth. The two-dimensional shallow water equations in conservative form can be expressed as [15]:

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0$$

$$\frac{\partial hu}{\partial t}+\frac{\partial hu^2}{\partial x}+\frac{\partial huv}{\partial y}=fhv-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_A}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial p}{\partial x}-\frac{\tau_{fx}}{\rho_0}+\frac{\tau_{sx}}{\rho_0}-F_{vx}+\frac{\partial hT_{xx}}{\partial x}+\frac{\partial hT_{xy}}{\partial y}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial hvu}{\partial x}+\frac{\partial hv^2}{\partial y}=-fhu-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_A}{\partial y}-$$

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$$\frac{gh^2}{2\rho_0}\frac{\partial p}{\partial y} - \frac{\tau_{fy}}{\rho_0} + \frac{\tau_{sy}}{\rho_0} - F_{vy} + \frac{\partial hT_{xy}}{\partial x} + \frac{\partial hT_{yy}}{\partial y} \quad (1)$$

Where,

t:	Time;
x, y:	Cartesian coordinate system;
η:	Water level fluctuation;
d:	Mean water depth;
$h = \eta + d$:	Total depth;
u, v:	Average velocity in x and y directions;
$f = 2\omega\sin\phi$	Coriolis force parameter, (ω - angular velocity, ϕ - geographic latitude);
g:	Acceleration of gravity;
p_A:	Atmospheric pressure at the water surface;
ρ:	Water density;
ρ_0:	Reference density of water;
τ_{fx}, τ_{fy}:	x, y components of stress formed due to bottom friction, surface friction and flow resistance;
τ_{sx}, τ_{sy}:	x, y components of wind induced stress;
$F_v = (F_{vx}, F_{vy})$:	Resistance caused by plants;
T_{xx}, T_{xy}, T_{yy}:	Lateral stresses include viscous friction, turbulent friction, and other convection.

Lateral stresses are usually estimated by the eddy viscous equation based on the depth-averaged velocity:

$$T_{xx} = 2\nu\frac{\partial u}{\partial x} \qquad T_{xy} = \nu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \qquad T_{yy} = 2\nu\frac{\partial u}{\partial y}$$

Where ν is the eddy viscosity. The fluid is assumed to be incompressible.

2.2. Model setup

- Computational mesh (see Fig. 1): unstructured mesh (triangle) with resolution of 50m to 300m offshore.

- Input data:

+ Reanalysis wind and pressure data (see Fig. 3, Fig. 4) from ERA5 [16];

+ Tidal range from MIKE21 toolbox;

+ Bathymetric data from GEBCO (see Fig. 2);

+ Water level data at Hon Dau metoceanic station (Center for Meteorological and Hydrological Information and Data, Viet Nam Meteorological and Hydrological Administration).

- Simulation scenarios:

+ Tide only (baseline);

+ Storm surge only (wind + pressure);

+ Surge-tide combination (tide + wind + pressure).

+ Shifting the time of Typhoon Washi's landfall by the hour (1 to 13 hours both earlier and later) in order to simulate the situations where the typhoon causes the highest surge during high tide, low tide, flooding tide, or ebbing tide within a tidal day.

2.3. Model calibration and validation

Prior to the simulation of individual factors as well as hypothetical situations, the model is set up, then calibrated and validated to ensure reliability. Using the water level data measured at Hon Dau station as the reference series, the selected factor for calibration and validation is therefore the simulated total water level - in other words, the result of water level simulation with the input of all factors including tides at the liquid boundary and wind pressure field at the atmospheric boundary. This selection ensures that two factors equivalent in physical meaning (measured total water level with simulated total water level) are compared with each other, thereby considered as the basis for model calibration.

Statistical criteria for differences between the two measured and simulated series are calculated to fully evaluate the effectiveness of the model and the set of calibration parameters.

- Error assessment coefficients: Normalized mean square error (N-RMSE), normalized absolute error (N-MAE), Mean Bias;

- Volatility assessment coefficients: Nash-Sutcliffe coefficient (NSE), and correlation coefficient (R).

The simulation results of the total water level satisfy the criteria with N-RMSE and N-MAE accounting for approximately 5.4% and 4.3% of the variation range of the observational water level during the simulation period (see Fig. 5). The deviation between the average of the two series has a value of approximately 10cm. At the same time, the Nash coefficient of 0.94 shows that the model has good results and the correlation coefficient of 0.98 shows a high correlation between the two series. The model also managed to simulate the total water level rising during Typhoon Washi equivalent to the measured water level, and the time of the simulated water level peaking during the typhoon's influence is also close to the time of the peak water level observed.

For further model validation, the same model is employed to simulate total water level during the impact of Typhoon Doksuri (2017) which also shows satisfying outcome. Specifically, N-RMSE and N-MAE this time accounts for approximately 5.8% and 4.5% of the variation range of the observational water level. Nash coefficient of 0.92 and correlation coefficient of 0.97 together indicate a high correlation between simulated and measured result (Fig. 6).

The modified parameters during the calibrating and validating process includes: Bed resistance: Manning number, and Wind friction. Their final values acquired are, in order, 55 ($m^{1/3}/s$) and 0.0015. Following the succeeded calibration and validation, these model parameters as well as other parameters are kept unchanged, only the boundary conditions change through different simulation scenarios.

2.4. Simulation scenarios

The post-calibrated model was deployed to independently simulate two factors: (1) tide and meteorological surge and (2) water level with both tide and wind pressure. In which, the pure tidal level fluctuation was simulated by only allowing the tide to propagate from the boundary into the domain without setting the wind pressure field. In contrast, the meteorological surge fluctuation (not taking into account the effect of thermal expansion) was simulated by only setting the re-analysis wind pressure field at the height of 10m (U10) to vary in space and time without transmitting tide from the boundary. Besides, the total water level was also simulated with the temporal-offset wind pressure field from 1 to 13 hours earlier and later than the original.

3. Results and discussion

3.1. Simulation of total water level and separated components

The resulting water level fluctuation at Hon Dau is extracted in 3 calculation domains corresponding to 3 simulation scenarios: total water level (tidal boundary + wind pressure field) (see Fig. 7), pure tidal level (only tidal boundary, no wind pressure) and surge level by wind pressure (only wind pressure, no tidal boundary) (see Fig. 8). The pure tidal level is added linearly with the wind pressure surge, obtaining the "linear sum water level" and comparing it with the simulated total water level series (see Fig. 9).

The wind pressure level series shows the occurrence of regular up-and-down oscillations of the diurnal period, which may be the result of variations in air pressure and wind during the day (land-sea breeze). The simulated tide level alone shows a regular diurnal tidal regime, which has been confirmed at Hon Dau in previous documents. The highest tidal amplitude of about 4m during the spring tide period also shows the consistency between the simulation and existing knowledge of pure tides at Hon Dau.

The fact that the linear sum of the two individual simulation factors has a larger amplitude of oscillation than the simulated total water level and thus even larger than the observational series shows that a consequence of the interaction of tides with surges is to reduce the amplitude of oscillation of the total water level. This phenomenon is similar to the nonlinear interaction between tides and meteorology-induced surges in previous studies [1,11]. It can be seen that the tides and storm surges do not add linearly to each other but have interaction and thereby impacts on the total water level. In other words, the total water level is not simply the sum of tidal level and the storm surges (including wind pressure), but can be larger or smaller (see Fig. 10):

$$\eta_{TS} \neq \eta_T + \eta_S \qquad (2)$$

where,

η_{TS}: Total water level (tide + surge);

η_T: Tidal water level;

η_S: Storm surge.

3.2. Time-shifting scenarios of wind-pressure field in Typhoon Washi

In order to obtain a clearer view of the influence of tides on wind-pressure surges, specifically storm surges, Typhoon Washi is assumed to make landfall and induce storm surges at different times during a tidal day by setting the time of the entire re-analysis wind-pressure field from 1 to 13 hours both earlier and later. The simulation time domain of the scenarios together with the tidal boundary conditions and model parameters remain unchanged. The simulation results of the total water levels of the meteorological time-shifting scenarios will then be compared with the original situation (scenario "00"). In addition, the storm surges of each scenario will be extracted from the total water levels by subtracting the pure tidal level series resulted from the tide-only simulation (see section 3.1), from the simulated total water level series. The result of this subtraction is considered the total value series of wind-pressure surges and the interaction effects with the tides, hereinafter referred to as storm surges.

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The simulation results of the water level of 27 meteorological scenarios including the original scenario (see Fig. 11) show that: during the period of influence of Typhoon Washi, the peak of the total water level is always between 1 hour earlier and 2 hours later than the tidal peak, with the highest proportion of coincidental peaks. Specifically, the number of scenarios with coincidental peaks is 15 (accounting for 56%), the number of scenarios in which total water level peak is 1 hour earlier than the tidal peak is 6 (accounting for 22%), the number of scenarios in which total water level peak is 1 hour and 2 hours later than the tidal peak is 3 (accounting for 11%). Of which, the 6 scenarios show the coincidental peaks of highest water level and tidal level on July 31. These scenarios include the original situation and 5 scenarios with the typhoon making landfall from 1 to 5 hours later than the original one. Among the computational scenarios, there are 6 scenarios with peak water levels on August 1 and all coincide with the tidal peak. However, of these, only 3 scenarios have late landfalls (13, 12, and 11 hours later), the remaining 3 scenarios have early landfalls (13, 12, and 11 hour ealier) causing a rise in the total water level at the tidal slope and low tide on July 30 - 31, but the maximum water level does not exceed the high tide level on July 31 and August 1. From this, it can be seen that during the time of the impact of Typhoon Washi on Hon Dau area, the tidal level is a decisive factor in determining the occurrence of total water level peak.

Unlike the total water level, the storm surge peak under different simulation scenarios does not clearly occur near the tidal peak but changes over the storm duration. Notably, the 8 scenarios with the highest storm surge peak all belong to scenarios where the landfall is from 6 to 13 hours earlier than the actual time, accounting for 30%. These surge peaks all occur within 2 hours around the tidal trough on July 31. The scenario under which the landfall is 11 hours earlier shows the highest storm surge peak among the others, and coincides with the tidal trough. The lowest surge peak occurs under the scenario in which the landfall is about 3 to 4 hours later than the tidal peak. In the case of landfalls 5 to 13 hours later, the surge peak gradually increases towards the tidal trough of the next day (August 1). Thus, in general, the height of the storm surge peak tends to increase accordingly with an inverse phase change compared to the pure tidal level. The storm surge peak during the ebbing tide is lower than that during the flooding tide (see Fig. 12).

4. Conclusion and recommendations

The results of the MIKE21FM model simulating water level variations by reanalyses of wind-pressure field and tides over a period of one month in which a typhoon occurred confirms that there is a non-linear interaction between storm surges and tides. The total water level when a typhoon makes landfall is high during the tidal peak, whereas the storm surge is lowest during such time. The maximum storm surge level tends to increase gradually towards the tidal trough, and the total water level higher than the astronomical tidal level. It can be concluded that the maximum storm surge level caused by a typhoon tends to avoid the tidal peak. These results help provide additional guides for forecasting the total water level during storms, which can cause flooding in coastal areas. It is recommended that when simulating storm surges using numerical models, the meteorology-induced water level variations and tidal levels should be simulated together instead of being simulated separately.

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