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APPLICATION OF KDV EQUATIONS IN POLICY-MAKING FOR EXTREME WAVE AND TSUNAMI PREDICTIONS IN VULNERABLE SOCIETIES

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Abstract

This study aims to examine the possibility of implementing the KdV equations for policymaking in vulnerable communities. It is crucial as Indonesia is located between two continents and two large oceans, significantly influencing marine phenomena, such as the frequent occurrence of extreme waves. Additionally, seismic activity can cause earthquakes with the potential to trigger tsunamis. Therefore, continuous research on extreme waves and tsunamis is required. This research provides a semi-analytical solution to the KdV equation using disturbance parameters, carried out from the first to the seventh order, to generate maximum waves. In this study, the modified KdV equation considers the bichromatic wave input η_1*, 2 wavenumber expansion equations using perturbation theory and Taylor series, and* η *expansion using perturbation theory to produce a seventh-order solution. This solution differs from third-order and fifth-order solutions in the context of higher-order influences, with the peak distance found to be closer than the initial point. It may indicate that the higher-order effects of the solution influence the maximum peak of the wave. The results of this research contribute to a progressive step in helping communities vulnerable to extreme waves and tsunamis.*

Keywords: *KdV Equation; Interference Parameters; Extreme Waves.*

A. Introduction

Indonesia is an archipelagic country located between the Indian Ocean and the Pacific Ocean, as well as between the Asian and Australian continents. Most of its territory consists of oceans. Due to this geographical location, Indonesia's climate is very dynamic, influencing marine phenomena such as the frequent occurrence of extreme waves in Indonesian seas. Extreme waves can significantly impact people's social lives in areas vulnerable to these threats, including tsunamis. In connection with this phenomenon and its impact, extreme waves are also called *freak waves* or *giant waves*. Wind, tides, currents, and tectonic activity are identified as the causes of extreme waves. In particular, the occurrence of giant waves is often caused by tectonic plate activity, which leads to earthquakes and tsunami waves (Lange et al., 2018; Meltzner et al., 2006; Weller et al., 2012).

In addition, Indonesia, which lies along the "Pacific Ring of Fire," has great potential for earthquakes and tsunamis due to tectonic plate movements and volcanic eruptions. Earthquakes in the sea can trigger the formation of tsunami waves, as seen on December 26, 2004, in Aceh. Therefore, a study to characterize and assess the variations of waves in Indonesian waters, particularly those related to extreme waves and tsunamis, is essential. This research can serve as a reference for coastal communities and the government in disaster preparedness efforts. (Lindell et al., 2019; Azhari et al., 2024). Furthermore, studies of extreme waves are also useful for shipping, trade, and fishing activities, and can provide information on efforts to prevent disasters and marine accidents involving ships.

Extreme waves in Indonesia often occur randomly, both in terms of location and time. These waves have very strong destructive power, especially for ships and offshore structures in their vicinity (Divinsky et al., 2004; Earle, 1975; Mori & Liu, 2002; Smith, 1976; Trulsen & Dysthe, 1997).

Waves can be identified as extreme if their height exceeds 2.2 times the height of significant waves (Dean, 1990; Kjeldsen, 1984). Surface wave behavior can be explained using partial differential equations such as the Korteweg de Vries (KdV) equation, Boussinesq, Kadomtsev-Petviashvili (KP), Benjamin Bona Mahony (BBM), and others, all of which are nonlinear. These nonlinear partial differential equations are challenging to solve. To address this, linearization is used to find solutions that closely approximate real natural phenomena. For example, simplification is achieved by unidirectionalizing the KdV equation (Cahyono, 2002; Azhari et al., 2024). This process reduces the equation to a nonlinear partial differential equation with a lower derivative order than the original, making it easier to determine the solution when linearization is applied to the KdV equation.

The KdV equation is a wave equation that describes wave propagation in one direction on the surface of shallow water with small wave amplitudes and large wavelengths (Ablowitz, 2011). Solving methods for nonlinear equations is very rare, prompting scientists to seek solution approaches that often culminate in numerical, analytical, or a combination of both methods. One such solving method is the asymptotic method. According to Mashuri and Marwan (2011), the asymptotic method can be applied to determine the approximate solution to the KdV equation, where the amplitude can be expanded using a power series up to the third order.

Marwan (2006) also applied the asymptotic expansion method to determine the solution of the Boussinesq equation for extreme waves. Additionally, Mashuri and Marwan (2011) applied this method to determine the solution of the Kadomsevt-Petviashvili equation, which describes the two-dimensional version of the KdV equation. In the KdV equation, higher-order terms increase the wave amplitude values, but these values cannot match the amplitudes produced by the complete Laplace equation. The KdV equation is a simpler derivation approximating the full Laplace equation.

Many mathematical techniques are often applied to facilitate the solving of differential equations, such as linearization, transformation, expansion into the Taylor and Mac Laurin series, numerical methods, asymptotic expansions, and more. These techniques make problem-solving easier while maintaining an acceptable level of error. The choice of technique depends on the type of problem and the ease with which it can be simplified. For surface wave problems, the mathematical technique often used is linearization combined with asymptotic expansion (Cahyono, 2002; Ramli, 2010). This technique allows us to construct solutions from the nonlinear surface wave equations to the desired order of approximation.

Marwan (2010) researched the KdV equation up to the third-order sideband term to determine the maximum height of the amplitude generated by solutions up to the third order. It was found that the third-order term produces a sideband term with an amplitude exceeding that of the second-order term. The third-order sideband is close to the first-order frequency, allowing it to dominate the influence of the other second and third-order terms. Furthermore, Afriadi et al., (2018) extended the asymptotic expansion up to the fifth order for the same purpose.

After obtaining the position of the wave crest from the third-order KdV solution approach, it was found to be lower than the experimental results using the HUBRIS software. This discrepancy is presumably due to inadequate expansion. Therefore, Afriadi et al., (2018) researched the KdV equation to find solutions up to the fifth order using asymptotic expansions, comparing the amplitude heights of the third-order solutions with those of the fifth-order solutions.

Therefore, this study aims to develop a solution to the KdV equation using an asymptotic expansion based on disturbance parameter theory up to the seventh order with a semi-analytical analysis approach. Obtaining a KdV solution up to the seventh order is expected to provide insights into how extreme waves can be generated in a test pond. Additionally, the KdV equation is expected to predict the height of tsunami waves in vulnerable areas indirectly.

Furthermore, the outcomes of this study represent a significant social contribution toward aiding people susceptible to extreme waves and tsunamis. Research that helps mitigate the impact of extreme waves and tsunamis is crucial for the safety and well-being of communities in vulnerable areas. Understanding the behavior of these natural disasters and developing effective strategies for early detection, warning systems, and evacuation plans can save lives and minimize damage.

B. Method

The main idea of this research is to find a solution to the surface wave mathematical model, namely the KdV equation. This solution is obtained using the disturbance parameter in the form of an asymptotic expansion. Based on this objective, the tools and materials used include computers, Matlab software, HUBRIS data, comparative journals (Marwan, 2010), and the books listed in the bibliography.

This research involves the third- and fifth-order semi-analytic solutions for the asymptotic expansion of a mathematical model, namely the modified KdV equation. Considering that the KdV equation describes wave propagation in one direction on the shallow water surface, the initial stage of this study primarily focused on finding solutions for extreme wave propagation. A specific study on tsunami waves, which have their own wave dynamics, will be conducted in the subsequent phases of this research, considering the initial phase's limitations.

Regarding operational variables, this study employs the disturbance parameter equation, utilizing the fifth-order asymptotic expansion for wave elevation in the form.

$$\eta = \varepsilon\eta_1 + \varepsilon^2\eta_2 + \varepsilon^3\eta_3 + \varepsilon^4\eta_4 + \varepsilon^5\eta_5 + \varepsilon^6\eta_6 + \varepsilon^7\eta_7 \quad (1)$$

$\eta_1 = a[e^{i\alpha} + e^{i\beta}] + cc,$ Where a is the amplitude of the bichromatic wave, cc is the complex conjugate, and $\alpha = (k_+x - \omega_1 t)$ and $\beta = (k_-x - \omega_2 t)$ while ε expresses the ratio of the amplitude of the waves in the first order to the depth of the pool. In this research, changes in the wave profile during propagation will be examined using the modified KdV equation, expressed as follows:

$$\partial_t\eta + i\Omega(-i\partial_x)\eta + \mu\eta\partial_x\eta = 0 \quad (2)$$

Equation (2) is derived by applying the unidirectionalization method and represents the nonlinear dispersion coefficient of the aqueous medium.

It takes the form of a linear dispersion relation $\Omega(k) = k\sqrt{tgh\ k/k}$. When equation (1) is substituted into equation (2) and the terms are grouped up to the fifth order, it can be expressed as.

$$\varepsilon\,(\partial_t\eta_1 + i\Omega(-i\partial_x)\eta_1 + \ \varepsilon^2(\partial_t\eta_2 + i\Omega(-i\partial_x)\eta_2 + \ \mu\eta_1\partial_x\eta_1) + \varepsilon^3(\partial_t\eta_3 + i\Omega(-i\partial_x)\eta_3 + \mu[\eta_1\partial_x\eta_2 + \ \eta_2\partial_x\eta_1]) + \ \varepsilon^4(\partial_t\eta_4 + i\Omega(-i\partial_x)\eta_4 + \mu[\eta_1\partial_x\eta_3 + \ \eta_2\partial_x\eta_2 + \ \eta_3\partial_x\eta_1\ ]) + \ \varepsilon^5(\partial_t\eta_5 + i\Omega(-i\partial_x)\eta_5 + \mu[\eta_1\partial_x\eta_4 + \ \eta_2\partial_x\eta_3 + \ \eta_3\partial_x\eta_2 + \ \eta_4\partial_x\eta_1]) + \ O(\varepsilon^6) = 0 \quad (3)$$

The parameter μ is a nonlinear coefficient set to 1.5. The technique used above unexpectedly generates resonance at an odd high order. To address this, a correction was applied to the wave number using the Linstead-Poincare development technique (Whitham, 1974) formulated as.

$$k_+ = \ k_{+0} + \ \varepsilon k_{+1} + \ \varepsilon^2 k_{+2} + \ \varepsilon^3 k_{+3} + \ \varepsilon^4 k_{+4} \quad (4)$$

Moreover, $\Omega(k_+)$ itself can be expressed in a Taylor series as follows.

$$\Omega(k_{\pm}) = \ \Omega(k_{\pm 0}) + (\ \varepsilon k_{\pm 1} + \varepsilon^2 k_{\pm 2} + \cdots)\ \Omega'(k_{\pm 0}) + (\ \varepsilon k_{\pm 1} + \varepsilon^2 k_{\pm 2} + \cdots)^2 \Omega''(k_{\pm 0}) + \quad (5)$$

Integrating η_1, equations (4) and (5) into equation (3) and solving each order formed above will produce a semi-analytical solution of exact KdV.

This research was conducted following the ethical standards of scientific research and institutional guidelines of Universitas Islam Negeri Ar-Raniry Banda Aceh. No human or animal subjects were directly involved in this study. All data used were obtained from secondary sources and publicly available materials such as simulation datasets, journals, and mathematical modeling software. The study ensures academic integrity, originality, and appropriate acknowledgment of all referenced works.

C. Results and Discussion

The results of this study present the semi-analytical solution obtained through the application of the modified KdV equation. This section elaborates on the mathematical processes involved in deriving the higher-order wave solutions, followed by the interpretation of the seventh-order results. The explanation begins with the equation integration techniques used to obtain partial derivatives and continues with the presentation of solutions up to the seventh order. The outcomes of these calculations provide the foundation for understanding the behavior of extreme waves and their implications for predicting tsunami phenomena.

1. **Results**

   a. Equation integration techniques

This section will demonstrate the partial derivatives for t and x. Equations (4) and (5) are substituted into equation (3). The results of these substitutions, which have been separated into orders, yield a form that can be expressed as follows. In order to obtain a clearer understanding of the mathematical structure of the seventh-order KdV solution, this section begins by presenting the process of deriving partial derivatives with respect to time (t) and position (x). The substitution of equations (4) and (5) into equation (3) allows the derivation of successive terms that represent the nonlinear interactions between wave amplitude, dispersion, and propagation velocity. Through this substitution, each order of approximation can be systematically separated to reveal the hierarchical influence of higher-order terms on wave formation.

At this stage, the differentiation of each variable produces several coupled nonlinear expressions, which describe the evolution of wave profiles as they propagate in shallow water. The application of asymptotic expansion enables the simplification of these complex relationships into a form that maintains both analytical clarity and physical relevance. The resulting formulation captures how small perturbations in the initial wave parameters develop into significant variations in wave height and phase over time.

The mathematical expression derived from these operations, as presented below, provides the foundation for determining the seventh-order wave characteristics. It illustrates how nonlinear and dispersive terms interact to produce extreme or solitary wave patterns, offering a theoretical framework that aligns closely with observed phenomena in real marine environments.

$$
\begin{aligned}
&\mathcal{E}(-ia[\omega_1 e^{i\alpha} + \omega_2 e^{i\beta}] + ia[\Omega(k_{+0})e^{i\alpha} + \Omega(k_{-0})e^{i\beta}] + cc') + \\
&\mathcal{E}^2(\partial_t\eta_2 + i\Omega(-i\partial_x)\eta_2 + \mu\eta_1\partial_x\eta_1 + ia[k_{+1}\Omega'(k_{+0})e^{i\alpha} + \\
&k_{-1}\Omega'(k_{-0})e^{i\beta}]) + \mathcal{E}^3(\partial_t\eta_3 + i\Omega(-i\partial_x)\eta_3 + \mu[\eta_1\partial_x\eta_2 + \eta_2\partial_x\eta_1] + \\
&ia[k_{+1}^2\Omega''(k_{+0}) + k_{+2}\Omega'(k_{+0})]e^{i\alpha} + ia[k_{-1}^2\Omega''(k_{-0}) + \\
&k_{-2}\Omega'(k_{-0})]e^{i\beta}) + \mathcal{E}^4(\partial_t\eta_4 + i\Omega(-i\partial_x)\eta_4 + \mu[\eta_1\partial_x\eta_3 + \eta_2\partial_x\eta_2 + \\
&\eta_3\partial_x\eta_1] + ia[k_{+1}^3\Omega'''(k_{+0}) + 2k_{+1}k_{+2}\Omega''(k_{+0}) + k_{+3}\Omega'(k_{+0})]e^{i\alpha} + \\
&[k_{-1}^3\Omega'''(k_{-0}) + 2k_{-1}k_{-2}\Omega''(k_{-0}) + k_{-3}\Omega'(k_{-0})]e^{i\beta}) + \mathcal{E}^5(\partial_t\eta_5 + \\
&i\Omega(-i\partial_x)\eta_5 + \mu[\eta_1\partial_x\eta_4 + \eta_2\partial_x\eta_3 + \eta_3\partial_x\eta_2 + \eta_4\partial_x\eta_1] + \\
&ia[k_{+1}^4\Omega''''(k_{+0}) + 3k_{+1}^2k_{+2}\Omega'''(k_{+0}) + (k_{+2}^2 + k_{+1}k_{+3})\Omega''(k_{+0}) + \\
&k_{+4}\Omega'(k_{+0})]e^{i\alpha} + ia[k_{-1}^4\Omega''''(k_{-0}) + 3k_{-1}^2k_{-2}\Omega'''(k_{-0}) + (k_{-2}^2 + \\
&k_{-1}k_{-3})\Omega''(k_{-0}) + k_{-4}\Omega'(k_{-0})]e^{i\beta}) + \varepsilon^6(\partial_t\eta_6 + i\Omega(-i\partial_x)\eta_6 + \\
&\mu(\eta_1\partial_x\eta_5 + \eta_2\partial_x\eta_4 + \eta_3\partial_x\eta_3 + \eta_4\partial_x\eta_2 + \eta_5\partial_x\eta_1) + \\
&ia\{[k_{+1}^5\Omega'''''(k_{+0}) + 4k_{+1}^3k_{+2}\Omega''''(k_{+0}) + (3k_{+1}k_{+2}^2 + \\
&3k_{+1}^2k_{+3})\Omega'''(k_{+0}) + (2k_{+2}k_{+3} + 2k_{+1}k_{+4})\Omega''(k_{+0}) + \\
&k_{+5}\Omega'(k_{+0})]e^{i\alpha} + [k_{-1}^5\Omega'''''(k_{-0}) + 4k_{-1}^3k_{-2}\Omega''''(k_{-0}) + \\
&(3k_{-1}k_{-2}^2 + 3k_{-1}^2k_{-3})\Omega'''(k_{-0}) + (2k_{-2}k_{-3} + 2k_{-1}k_{-4})\Omega''(k_{-0}) + \\
&k_{-5}\Omega'(k_{-0})]e^{i\beta}\}) + \varepsilon^7(\partial_t\eta_7 + i\Omega(-i\partial_x)\eta_7 + \mu(\eta_1\partial_x\eta_6 + \eta_2\partial_x\eta_5 + \\
&\eta_3\partial_x\eta_4 + \eta_4\partial_x\eta_3 + \eta_5\partial_x\eta_2 + \eta_6\partial_x\eta_1) + ia\{[k_{+1}^6\Omega''''''(k_{+0}) + \\
&5k_{+1}^4k_{+2}\Omega'''''(k_{+0}) + [6k_{+1}^2k_{+2}^2 + 4k_{+1}^3k_{+3}]\Omega''''(k_{+0}) + \\
&[k_{+2}^3 + 6k_{+1}k_{+2}k_{+3} + 3k_{+1}^2k_{+4}]\Omega'''(k_{+0}) + [k_{+3}^2 + 2k_{+2}k_{+4} + \\
&2k_{+1}k_{+5}]\Omega''(k_{+0}) + k_{+6}\Omega'(k_{+0})]e^{i\alpha} + [k_{-1}^6\Omega''''''(k_{-0}) + \\
&5k_{-1}^4k_{-2}\Omega'''''(k_{-0}) + [6k_{-1}^2k_{-2}^2 + 4k_{-1}^3k_{-3}]\Omega''''(k_{-0}) + \\
&[k_{-2}^3 + 6k_{-1}k_{-2}k_{-3} + 3k_{-1}^2k_{-4}]\Omega'''(k_{+0}) + [k_{-3}^2 + 2k_{-2}k_{-4} + \\
&2k_{-1}k_{-5}]\Omega''(k_{-0}) + k_{-6}\Omega'(k_{-0})]e^{i\beta}\}) + O(\varepsilon^8) = 0 \qquad (5)
\end{aligned}
$$

The accent mark Ω indicates the derivative of Ω with respect to the wave number k, where the order of derivatives corresponds to the number of accent marks. Meanwhile, cc' represents partial derivatives of cc with respect to x and t, respectively, where i has a value of $\sqrt{-1}$.

b. Solutions of order of seven

The seventh-order solution is obtained from the term contained $\mathcal{E}^7$ in equation (5). Exponential forms of η_1, η_2, η_3, η_4 and η_5 , which have been obtained in the previous orders, will be substituted into equation (5). Combining elements with the same exponential power produces a fifth-order exponential solution (η_5). Equation (5), which contains ε^5, can be written in the following form.

$$\varepsilon^7(\partial_t\eta_7 + i\Omega(-i\partial_x)\eta_7 + \mu\,(\eta_1\partial_x\eta_6 + \eta_2\partial_x\eta_5 + \eta_3\partial_x\eta_4 + \eta_4\partial_x\eta_3 + \eta_5\partial_x\eta_2 + \eta_6\partial_x\eta_1) + ia\{[k_{+1}^6\Omega''''''(k_{+0}) + 5k_{+1}^4k_{+2}\Omega'''''(k_{+0}) + [6k_{+1}^2k_{+2}^2 + 4k_{+1}^3\,k_{+3}]\Omega''''(k_{+0}) + [k_{+2}^3 + 6k_{+1}k_{+2}k_{+3} + 3k_{+1}^2k_{+4}]\Omega'''(k_{+0}) + [k_{+3}^2 + 2k_{+2}k_{+4} + 2k_{+1}k_{+5}]\Omega''(k_{+0}) + k_{+6}\Omega'\,(k_{+0})]e^{i\alpha} + [k_{-1}^6\Omega''''''(k_{-0}) + 5k_{-1}^4k_{-2}\Omega'''''(k_{-0}) + [6k_{-1}^2k_{-2}^2 + 4k_{-1}^3\,k_{-3}]\Omega''''(k_{-0}) + [k_{-2}^3 + 6k_{-1}k_{-2}k_{-3} + 3k_{-1}^2k_{-4}]\Omega'''(k_{+0}) + [k_{-3}^2 + 2k_{-2}k_{-4} + 2k_{-1}k_{-5}]\Omega''(k_{-0}) + k_{-6}\Omega'\,(k_{-0})]e^{i\beta}\}) = 0 \quad (6)$$

To obtain a solution of order 7, you first substitute each term and wave number from the solutions of the previous orders into equation (6). To determine the value of the fifth-order wave number, identify terms with powers of $e^{i\alpha}$ and $e^{i\beta}$ equate the left and right sides. Then, substitute the wave number values from the previous order into terms containing wave number elements. The values $k_{\pm1} = 0$ and $k_{\pm3} = 0$ obtained from the previous order solution, when substituted into the equation above, will yield $(k_{+2}^2 + k_{+1}k_{+3})\Omega''(k_{+0})e^{i\alpha}$ and $(k_{-2}^2 + k_{-1}k_{-3})\Omega''(k_{-0})e^{i\beta}$ in the wave number correction element. Similar to previous odd orders, namely order 3 and order 5, the seventh order also experiences resonance. A correction to the wave numbers in this order can produce $k_{\pm6}$ in the form.

$$k_{+6} = F_7k_{+0} + F_8k_{+2}^3 + F_9k_{+2}k_{+4} \quad (7)$$

With values F_7, F_8, and F_9 and can be seen below.

$$F_8 = -a^6\mu\frac{\left[\frac{A_2D_{16}+A_5D_2+A_6D_{10}+A_78+A_8D_{14}+B_1C_4+B_2C_{11}+B_3C_{20}+B_4C_{16}+B_5C_{24}+B_6C_4+B_7C_1+B_8C_7+B}{E_3+E_{15}+E_{24}}\right.}{\Omega\prime(K_{+0})},$$

$$F_8 = -a^6\mu\frac{[\Omega'''(k_{+0})]}{\Omega'(k_{+0})},\ \text{dan}\ F_9 = -a^6\mu\frac{2[\Omega''(k_{+0})]}{\Omega'(k_{+0})}\,k_{-6}$$

The value k_{-6} is as follows.

$$k_{-6} = F_{10}k_{-0} + F_{11}k_{-2}^3 + F_{12}k_{-2}k_{-4} \quad (8)$$

With the values F_{10}, F_{11}, and F_{12} can be seen below

$$F_{10} = -a^6\mu\frac{\left[\begin{gathered}A_1D_{30}+A_4D_{32}+A_5D_8+A_6D_4+A_7D_{10}+B_1C_{21}+B_2C_{16}+B_3C_{14}+B_4C_{20}+B_5C_{22}+B_6C_{23}+B_7C_5+B_8C_3\\+E_6+E_{15}+E_{48}\end{gathered}\right.}{\Omega\prime(K_{-0})},$$

$$F_{11} = -a^6\mu\frac{[\Omega'''(k_{-0})]}{\Omega'(k_{-0})}, \text{ dan } F_{12} = -a^6\mu\frac{2[\Omega''(k_{-0})]}{\Omega'(k_{-0})}.$$

The values of F_7, F_8, F_9 F_{10}, F_{11}, and F_{12} above are obtained by simplifying the terms containing the elements $e^{i\alpha}$ and $e^{i\beta}$. These elements contained in F_7, F_8, F_9 F_{10}, F_{11}, and F_{12} are elements derived from solutions of previous orders.

After obtaining the value of the wave number for order 7, terms that have been partially derived with respect to x are combined with terms having the same power. By consolidating elements of each term with the same rank and substituting them into equation (6), followed by simplification, a seventh-order solution can be derived, which can be written as follows:

$$\begin{aligned}\eta_7 = {} & a^7V_1e^{7i\alpha} + a^7V_2e^{5i\alpha} + a^7V_3e^{3i\alpha} + a^7V_4e^{7i\beta} + a^7V_5e^{5i\beta} + a^7V_6e^{3i\beta} + \\ & a^7V_7e^{i(6\alpha+\beta)} + a^7V_8e^{i(5\alpha+2\beta)} + a^7V_9e^{i(4\alpha+3\beta)} + a^7V_{10}e^{i(4\alpha+\beta)} + \\ & a^7V_{11}e^{i(3\alpha+4\beta)} + a^7V_{12}e^{i(3\alpha+2\beta)} + a^7V_{13}e^{i(2\alpha+5\beta)} + a^7V_{14}e^{i(2\alpha+3\beta)} + \\ & a^7V_{15}e^{i(2\alpha+\beta)} + a^7V_{15}e^{i(2\alpha+\beta)} + a^7V_{16}e^{i(\alpha+6\beta)} + a^7V_{17}e^{i(\alpha+4\beta)} + \\ & a^7V_{18}e^{i(\alpha+2\beta)} + a^7V_{19}e^{i(6\alpha-\beta)} + a^7V_{20}e^{i(5\alpha-2\beta)} + a^7V_{21}e^{i(4\alpha-3\beta)} + \\ & a^7V_{22}e^{i(4\alpha-\beta)} + a^7V_{23}e^{i(3\alpha-4\beta)} + a^7V_{24}e^{i(3\alpha-2\beta)} + a^7V_{25}e^{i(2\alpha-5\beta)} + \\ & a^7V_{26}e^{i(2\alpha-3\beta)} + a^7V_{27}e^{i(2\alpha-\beta)} + a^7V_{28}e^{i(\alpha-6\beta)} + a^7V_{29}e^{i(\alpha-4\beta)} + \\ & a^7V_{30}e^{i(\alpha-\beta)} \\ & + cc \end{aligned} \tag{9}$$

Simplifying equation (9) using Euler's formula yields the trigonometric form as follows.

η_7 =

$$2a^7[V_1 cos7\alpha + V_2 cos5\alpha + V_3 cos3\alpha + V_4 cos7\beta + V_5 cos5\beta + V_6 cos3\beta + V_7\cos(6\alpha+\beta) + V_8\cos(5\alpha+2\beta) + V_9\cos(4\alpha+3\beta) + V_{10}\cos(4\alpha+\beta) + V_{11}\cos(3\alpha+4\beta) + V_{12}\cos(3\alpha+2\beta) + V_{13}\cos(2\alpha+5\beta) + V_{14}\cos(2\alpha+3\beta) + V_{15}\cos(2\alpha+\beta) + V_{16}\cos(\alpha+6\beta) + V_{17}\cos(\alpha+4\beta)$$

$$+V_{18}\cos(\alpha+2\beta) + V_{19}\cos(6\alpha-\beta) + V_{20}\cos(5\alpha-2\beta) + V_{21}\cos(4\alpha-3\beta) + V_{22}\cos(4\alpha-\beta)$$

$$+V_{23}\cos(3\alpha-4\beta) + V_{24}\cos(3\alpha-2\beta) + V_{25}\cos(2\alpha-5\beta) + V_{26}\cos(2\alpha-3\beta) + V_{27}\cos(2\alpha-\beta) + V_{28}\cos(\alpha-6\beta) + V_{29}\cos(\alpha-4\beta) + V_{30}\cos(\alpha-2\beta)].\quad(10)$$

The free wave equation of equation (9) is obtained in the same manner as the free waves in the previous orders and can be written as follows.

$$\eta_{7f} = 2a^7\{V_1\cos(k_{63}x-7\omega_1 t) + V_2\cos(k_{64}x-5\omega_1 t) + V_3\cos(k_{65}x-3\omega_1 t) + V_4\cos(k_{66}x-7\omega_2 t) + V_5\cos(k_{67}x-5\omega_2 t) + V_6\cos(k_{68}x-3\omega_2 t) + V_7\cos(k_{69}x-[6\omega_1+\omega_2]t) + V_8\cos(k_{70}x-[5\omega_1+2\omega_2]t) + V_9\cos(k_{71}x-[4\omega_1+3\omega_2]t) + V_{10}\cos(k_{72}x-[4\omega_1+\omega_2]t) + V_{11}\cos(k_{73}x-[3\omega_1+4\omega_2]t) + V_{12}\cos(k_{74}x-[3\omega_1+2\omega_2]t) + V_{13}\cos(k_{75}x-[2\omega_1+5\omega_2]t)\} + V_{14}\cos(k_{76}x-[2\omega_1+3\omega_2]t) + V_{15}\cos(k_{77}x-[2\omega_1+\omega_2]t) + V_{16}\cos(k_{78}x-[\omega_1+6\omega_2]t) + V_{17}\cos(k_{79}x-[\omega_1+4\omega_2]t) + V_{18}\cos(k_{80}x-[\omega_1+2\omega_2]t) + V_{19}\cos(k_{81}x-[6\omega_1-\omega_2]t) + V_{20}\cos(k_{82}x-[5\omega_1-2\omega_2]t) + V_{21}\cos(k_{83}x-[4\omega_1-3\omega_2]t) + V_{22}\cos(k_{84}x-[4\omega_1-\omega_2]t) + V_{23}\cos(k_{85}x-[3\omega_1-4\omega_2]t) + V_{24}\cos(k_{86}x-[3\omega_1-2\omega_2]t) + V_{25}\cos(k_{87}x-[2\omega_1-5\omega_2]t) + V_{26}\cos(k_{88}x-[2\omega_1-3\omega_2]t) + V_{27}\cos(k_{89}x-[2\omega_1-\omega_2]t) + V_{28}\cos(k_{90}x-[\omega_1-6\omega_2]t) + V_{29}\cos(k_{91}x-[\omega_1-4\omega_2]t) + V_{30}\cos(k_{92}x-[\omega_1-2\omega_2]t)].\quad(11)$$

Thus, the semi-analytical solution to the KdV equation for the seventh-order solution with$\varepsilon = 1$, can be expressed as follows.

$$\eta = \eta_1 + (\eta_2-\eta_{2f}) + (\eta_3-\eta_{3f}) + (\eta_4-\eta_{4f}) + (\eta_5-\eta_{5f}) + (\eta_6-\eta_{6f}) + (\eta_7-\eta_{7f})\quad(12)$$

2. Discussion

This section discusses the contribution of the KdV Equation to policy-making for vulnerable communities. Based on the results presented above, a solution to the seventh-order KdV equation was found through semi-analytical analysis of the higher-order Korteweg-de Vries (KdV) equation. This equation is anticipated to contribute to predicting extreme waves and giant waves such as tsunamis. Furthermore, it is expected that the results of this semi-analysis can be further developed to establish equations that can be used to simulate extreme waves. This, in turn, can aid in predicting the risk of extreme wave impacts.

Indonesia, particularly the Aceh region, has endured the harrowing impact of tsunami waves, resulting in widespread devastation to both infrastructure and communities (Amri & Giyarsih, 2022; Ismail et al., 2018, 2018b; Steinberg, 2007). Aceh, Indonesia, suffered a catastrophic event on December 26, 2004, when a powerful earthquake measuring 9.2 on the Richter scale struck off its coast. The ensuing tsunami wave ravaged the Aceh coastline and adjacent areas (Obura, 2006; Shearer & Bürgmann, 2010).

The impact of this tsunami was devastating for Aceh and its surroundings (Cas et al., 2014; Najar et al., 2020; Saatcioglu et al., 2005). Thousands of people lost their lives, and vast stretches of the coastal areas in Aceh suffered severe damage. Infrastructure, including houses, bridges, schools, and other public facilities, was either destroyed or extensively damaged (Ghobarah et al., 2006; Heger & Neumayer, 2019; Vidyattama et al., 2021). However, in the aftermath of the disaster, recovery and reconstruction efforts have been underway, supported by both domestic and international aid. Numerous humanitarian, governmental, and volunteer organizations have contributed to rebuilding infrastructure, providing humanitarian assistance, and offering psychosocial support to the victims (Athukorala, 2012; Brassard, 2010; Sukma, 2006; Telford & Cosgrave, 2007).

Over the years, Aceh has made significant progress in its post-tsunami recovery (Daly et al., 2020; Liew et al., 2010; Syamsidik et al., 2021; Tinning, 2011). New infrastructure has been constructed, such as houses, roads, schools, and health facilities. Furthermore, various economic and social development programs have been initiated to assist communities in restoring their livelihoods and enhancing their resilience to future disasters (Himaz, 2022).

Aceh's encounter with the tsunami has imparted a crucial lesson to the people of Indonesia and the world regarding the significance of preparedness in the event of similar natural disasters (Alles, 2012; Kurnio et al., 2021; Morin et al., 2008; Régnier et al., 2008; Spahn et al., 2010). Disaster mitigation measures and early warning systems have been reinforced in coastal areas, while efforts to educate individuals on evacuation procedures and safety measures have been intensified (Sakurai et al., 2018).

The 2004 Tsunami was not merely a catastrophic event in terms of infrastructure but also wrought profound social changes for the people of Aceh (Gaillard et al., 2008; Zikri, 2017). Following the tsunami, Acehnese society underwent significant transformations across various facets of life, including social relations, culture, and values (Ismail et al., 2018; Pelupessy & Bretherton, 2015). The calamity engendered a profound realization of the importance of solidarity and mutual assistance in confronting major tragedies. In response, the people of Aceh united and collaborated to rebuild their community. Both local and international aid poured in, and cooperation among communities, irrespective of religious or cultural differences, played a pivotal role in the recovery process (Aldrich, 2015; Hidayati, 2018; Schlehe, 2011; Wang, 2013).

Aceh is a region where the majority of the population adheres to Islam. The tsunami reinforced the significance of religion in the lives of the Acehnese people. Many individuals turned to their faith for solace, support, and guidance in coping with trauma and grief. Consequently, there has been a surge in religious activities and a deeper appreciation for religious values.

The tsunami also altered the social dynamics of Acehnese society (Birkmann et al., 2010; Liu-Lastres et al., 2020; Shah & Lopes Cardozo, 2014). Many families lost members, including parents, children, or siblings, leading to significant changes in family structure and relationships. Additionally, many children were orphaned or separated from their families, impacting societal values and social responsibilities towards these children.

The tsunami fostered a profound awareness of the importance of education and preparedness in dealing with natural disasters. Disaster education programs and awareness of tsunami risk have been enhanced both in schools and in society at large. The people of Aceh are now better trained in recognizing early warning signs and taking appropriate evacuation measures (Cerulli et al., 2020; Seneviratne et al., 2010; Syahputra, 2019).

After the tsunami, women in Aceh played a more significant role in recovery and reconstruction (Bell, 2011; Renuka & Srimulyani, 2015; Secretariat, 2012). Many women became the backbone of surviving families, taking on the responsibilities of rebuilding homes, earning a living, and educating children. This shift altered the traditional role of women in society and created opportunities for them to take a more active role in social and economic life.

The findings of this study hold significant implications that extend well beyond the Indonesian context, particularly for nations located along tectonic subduction zones such as Japan, Chile, and New Zealand, which also face the recurring threat of tsunamis and extreme wave phenomena. The development of the seventh-order KdV equation through a semi-analytical approach contributes to advancing the precision of nonlinear wave modeling and supports the global scientific community's efforts in disaster prediction and risk mitigation. This approach aligns with the broader objectives of international frameworks that emphasize resilience, preparedness, and early warning systems in coastal areas (Sakurai et al., 2018; Spahn et al., 2010).

By enhancing the mathematical understanding of nonlinear wave propagation, the results of this study provide a valuable reference for the global application of the KdV model in predicting the behavior of extreme waves. In countries such as Japan and Chile—both of which have experienced catastrophic tsunami events—the adoption of accurate mathematical models like the KdV equation can improve the precision of early warning systems and disaster mitigation policies. The study also supports the view that mathematical modeling plays a vital role in transforming scientific insights into practical instruments for sustainable coastal management and community resilience (Morin et al., 2008; Kurnio et al., 2021).

Furthermore, this research provides essential input for the formulation of global and regional policy frameworks on marine disaster risk reduction. The semi-analytical solution of the KdV equation may be utilized by policymakers and engineers to strengthen coastal infrastructure design, improve hydrodynamic forecasting, and minimize human and economic losses associated with tsunamis and extreme waves (Heger & Neumayer, 2019; Daly et al., 2020). This integration between mathematical theory and practical policy underlines the interdisciplinary nature of the study, bridging the gap between physics-based modeling and social applications in disaster risk governance (Aldrich, 2015; Régnier et al., 2008).

On a global scale, the findings highlight the necessity for transnational collaboration in developing data-driven and model-based approaches to disaster preparedness. The applicability of the KdV framework in various marine and coastal contexts demonstrates that the behavior of nonlinear waves, when mathematically simulated, can serve as a universal analytical reference adaptable to different geographical and environmental conditions (Whitham, 1974; Ablowitz, 2011). By incorporating higher-order nonlinear effects and asymptotic expansions, the KdV model offers a valuable foundation for global tsunami research networks, paving the way for more reliable predictive systems that can contribute to safeguarding human lives and promoting sustainable coastal development worldwide (Syamsidik et al., 2021; Amri & Giyarsih, 2022).

Although this study provides valuable theoretical insights into nonlinear wave propagation, several limitations must be acknowledged. The model used in this research is based on one-dimensional wave propagation under simplified shallow-water conditions, which may not fully represent the complex and multidirectional nature of real ocean waves. In addition, the analysis relies on semi-analytical approximations without direct validation through experimental or numerical data. The assumption of uniform physical parameters, such as constant depth and stable wave amplitude, also limits the model's applicability in diverse and dynamic coastal environments. These constraints indicate that the findings should be interpreted within the scope of a theoretical framework rather than as direct empirical results.

D. Conclusion

The semi-analytical solution of the KdV equation up to the seventh order demonstrates that nonlinear wave dynamics can be effectively modeled through the integration of the modified KdV equation, bichromatic wave input, and wave number expansion derived from disturbance theory and the Taylor series. The synthesis of these analytical components reveals that higher-order effects have a significant influence on wave amplitude and crest distance. This finding shows that the complexity of wave behavior can be represented more precisely through expanded analytical modeling, providing a coherent theoretical response to the study's main objective—developing an advanced semi-analytical approach to explain and predict the formation of extreme waves that frequently occur in vulnerable coastal regions.

The importance of this study lies in both its theoretical and practical contributions. Theoretically, it deepens the understanding of nonlinear dispersive wave equations by extending the KdV solution to a higher order, thereby offering a more comprehensive analytical framework for future oceanographic and geophysical modeling. From a practical standpoint, the results of this research provide a foundation for enhancing early warning systems and formulating more accurate disaster mitigation policies related to tsunamis and extreme waves. By linking mathematical modeling with disaster management strategies, this study bridges the gap between abstract scientific theory and its real-world applications, especially for coastal societies exposed to high environmental risks.

In light of the limitations identified in the discussion, future studies are encouraged to develop the model further beyond the one-dimensional shallow-water framework. Expanding the KdV equation into multidimensional simulations would allow it to better represent the complex and multidirectional behavior of real ocean waves. Empirical validation through hydrodynamic laboratory experiments or field observations is also essential to strengthen the model's predictive accuracy and reliability. Moreover, incorporating variable bathymetry, analyzing wave–structure interactions, and conducting comparative studies across different tectonic zones would enhance the global applicability of this approach in tsunami and extreme wave prediction.

Ultimately, this research underscores that the integration of mathematical theory and practical disaster mitigation is a vital step toward building resilient coastal communities. The extended KdV model not only enriches academic discourse on nonlinear wave mechanics but also contributes to global initiatives aimed at minimizing the impacts of tsunamis and extreme waves. By continuously refining predictive models through theoretical innovation and empirical collaboration, this study reaffirms the crucial role of science in protecting human life and maintaining harmony between nature and society.

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