

# Numerical simulation of dispersive shallow water waves with Rosenau-KdV equation

Research Article

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**Abstract:** In this paper, the Rosenau-KdV equation that is one of the significant equations in physics was discussed. The collocation finite element method is implemented to find the numerical simulation of the dispersive shallow water waves with Rosenau-KdV equation using the quintic B-spline basis functions. A linear stability analysis based on von Neumann approximation theory of the numerical scheme is investigated. To demonstrate the precise and efficiency of the proposed method, the motion of solitary wave is studied by calculating the error norms  $L_2$  and  $L_\infty$ . The invariants  $I_1$ ,  $I_2$  and their relative changes have been computed to define the conservation properties of the simulation. As a result, the obtained results are found better than some recent results.

**MSC:** 35Q51 • 35Q53 • 35Q58

**Keywords:** Rosenau-KdV equation • Solitons • Shallow water • Collocation

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## 1. Introduction

Many physical phenomena can be defined by the Korteweg–de Vries (KdV) equation which was discovered by Korteweg and de Vries as the following [1–8]:

$$U_t + UU_x + U_{xxx} = 0. \quad (1)$$

Eq. (1) plays a important role in the study of nonlinear dispersive shallow water waves. These types of equations have been significant class of nonlinear equations with numerical simulations in physical phenomena. The case of wave-wave and wave-wall interactions can not be defined using the well-known KdV equation in the study of the dynamics of dense discrete systems. To accomplish this deficiency of the KdV equation, Rosenau equation was derived [9, 10]:

$$U_t + U_{xxxxt} + U_x + UU_x = 0. \quad (2)$$

The theoretical results on existence, uniqueness and regularity of the solution for Eq. (2) was proved [11]. On the numerical solutions of the Eq. (2), many studies have been performed by the scholars [12–17]. Then, for the further consideration of the nonlinear wave, Jin-Ming Zuo developed the Rosenau-KdV equation and discussed the solitary wave solutions and its periodic solutions in Ref.[18]

$$U_t + U_{xxxxt} + U_x + UU_x + U_{xxx} = 0, \quad (3)$$

where  $U_{xxx}$  is the viscous term and the independent variables  $x$  and  $t$  indicate the spatial and temporal variables, respectively. Recently, the solitary solutions for the generalized Rosenau-KdV equation with consuetudinary power law

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nonlinearity were examined [19–21]. Two invariants were given for the equation in [19, 20]. Especially, in [20] both the singular single soliton solution was derived with the ansatz method and the perturbation theory was used. The ansatz method is implemented to obtain the topological soliton (shock) solution of the generalized Rosenau-KdV equation [21]. The  $G'/G$  expansion, ansatz and the exp-function methods are implemented to achieve several solutions to the equation [22]. Singular solitons, solitary waves and shock waves with conservation laws of the Rosenau-KdV-RLW equation are obtained [23]. The conservation laws of the Rosenau-KdV-RLW equation are computed with power law nonlinearity by the aid of multiplier approach in Lie symmetry analysis [24]. Solutions of the perturbed Rosenau-KdV-RLW equation are obtained [25]. A conservative three-level linear finite difference scheme for the numerical solution of the initial-boundary value problem of the Rosenau-KdV equation is suggested [26]. This is the only method applied to obtain the numerical solution of the Rosenau-KdV equation in the literature.

In this paper, Rosenau-KdV equation is solved numerically by using collocation method with the quintic B-spline basis functions.

## 2. Numerical scheme using quintic B-Spline basis functions

Let us take into consideration the Rosenau-KdV Eq. (3) by the following boundary conditions:

$$\begin{aligned} U(a, t) = 0, \quad U(b, t) = 0, \\ U_x(a, t) = 0, \quad U_x(b, t) = 0, \quad t > 0. \end{aligned} \tag{4}$$

and the initial condition.

$$U(x, 0) = f(x) \quad a \leq x \leq b, \tag{5}$$

To able to apply the numerical method, the solution region of the problem is restricted over an interval  $a \leq x \leq b$ . The interval is partitioned into uniformly sized finite elements of length  $h$  by the knots  $x_m$  such that  $a = x_0 < x_1 < \dots < x_N = b$  and  $h = \frac{b-a}{N}$ . The set of quintic B-spline functions  $\{\phi_{-2}(x), \phi_{-1}(x), \dots, \phi_{N+1}(x), \phi_{N+2}(x)\}$  forms a basis over the solution interval  $[a, b]$ . The numerical solution  $U_N(x, t)$  is represented in terms of the quintic B-spline basis functions

$$U_N(x, t) = \sum_{j=-2}^{N+2} \phi_j(x) \delta_j(t) \tag{6}$$

where  $\delta_j(t)$  are time dependent parameters to be defined from the boundary and collocation conditions.

Quintic B-splines  $\phi_m(x)$ , ( $m = -2(1)N + 2$ ), at the knots  $x_m$  are determined over the interval  $[a, b]$  by Ref.[27]

$$\phi_m(x) = \frac{1}{h^5} \begin{cases} (x - x_{m-3})^5, & [x_{m-3}, x_{m-2}] \\ (x - x_{m-3})^5 - 6(x - x_{m-2})^5, & [x_{m-2}, x_{m-1}] \\ (x - x_{m-3})^5 - 6(x - x_{m-2})^5 + 15(x - x_{m-1})^5, & [x_{m-1}, x_m] \\ (x - x_{m-3})^5 - 6(x - x_{m-2})^5 + 15(x - x_{m-1})^5 - 20(x - x_m)^5, & [x_m, x_{m+1}] \\ (x - x_{m-3})^5 - 6(x - x_{m-2})^5 + 15(x - x_{m-1})^5 - 20(x - x_m)^5 + 15(x - x_{m+1})^5, & [x_{m+1}, x_{m+2}] \\ (x - x_{m-3})^5 - 6(x - x_{m-2})^5 + 15(x - x_{m-1})^5 - 20(x - x_m)^5 + 15(x - x_{m+1})^5 - 6(x - x_{m+2})^5, & [x_{m+2}, x_{m+3}] \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Each quintic B-spline covers six elements so that each element  $[x_m, x_{m+1}]$  is covered by six B-splines. A typical finite interval  $[x_m, x_{m+1}]$  is mapped to the interval  $[0, 1]$  by a local coordinate transformation described by  $h\xi = x - x_m$ ,  $0 \leq \xi \leq 1$ . Thus, quintic B-splines (7) in terms of  $\xi$  over  $[0, 1]$  can be given as the following:

$$\begin{aligned} \phi_{m-2} &= 1 - 5\xi + 10\xi^2 - 10\xi^3 + 5\xi^4 - \xi^5, \\ \phi_{m-1} &= 26 - 50\xi + 20\xi^2 + 20\xi^3 - 20\xi^4 + 5\xi^5, \\ \phi_m &= 66 - 60\xi^2 + 30\xi^4 - 10\xi^5, \\ \phi_{m+1} &= 26 + 50\xi + 20\xi^2 - 20\xi^3 - 20\xi^4 + 10\xi^5, \\ \phi_{m+2} &= 1 + 5\xi + 10\xi^2 + 10\xi^3 + 5\xi^4 - 5\xi^5, \\ \phi_{m+3} &= \xi^5. \end{aligned} \tag{8}$$

Using the nodal values of  $U, U', U'', U'''$  and  $U^{iv}$  at the knots  $x_m$  are given in terms of the element parameters  $\delta_m$  by

$$\begin{aligned} U_N(x_m, t) &= U_m = \delta_{m-2} + 26\delta_{m-1} + 66\delta_m + 26\delta_{m+1} + \delta_{m+2} \\ U'_m &= \frac{5}{h}(-\delta_{m-2} - 10\delta_{m-1} + 10\delta_{m+1} + \delta_{m+2}), \\ U''_m &= \frac{20}{h^2}(\delta_{m-2} + 2\delta_{m-1} - 6\delta_m + 2\delta_{m+1} + \delta_{m+2}), \\ U'''_m &= \frac{60}{h^3}(-\delta_{m-2} + 2\delta_{m-1} - 2\delta_{m+1} + \delta_{m+2}), \\ U^{iv}_m &= \frac{120}{h^4}(\delta_{m-2} - 4\delta_{m-1} + 6\delta_m - 4\delta_{m+1} + \delta_{m+2}), \end{aligned} \tag{9}$$

where the symbols  $'$ ,  $''$ ,  $'''$  and  ${}^{iv}$  symbolize differentiation according to  $x$ , respectively. The splines  $\phi_m(x)$  and its four principle derivatives vanish outside the interval  $[x_{m-3}, x_{m+3}]$ . Now we identify the collocation points with the knots and use Eq. (9) to evaluate  $U_m$ , its space derivatives and substitute into Eq. (3) to obtain the set of the coupled ordinary differential equations. For the linearization technique we get the following equation:

$$\begin{aligned} & \dot{\delta}_{m-2} + 26\dot{\delta}_{m-1} + 66\dot{\delta}_m + 26\dot{\delta}_{m+1} + 2\dot{\delta}_{m+2} \\ & + \frac{120}{h^4}(\delta_{m-2} - 4\delta_{m-1} + 6\delta_m - 4\delta_{m+1} + \delta_{m+2}) \\ & + \frac{5}{h}(-\delta_{m-2} - 10\delta_{m-1} + 10\delta_{m+1} + \delta_{m+2}) \\ & + \frac{5Z_m}{h}(-\delta_{m-2} - 10\delta_{m-1} + 10\delta_{m+1} + \delta_{m+2}) \\ & + \frac{60}{h^3}(-\delta_{m-2} + 2\delta_{m-1} - 2\delta_{m+1} + \delta_{m+2}) = 0 \end{aligned} \quad (10)$$

where

$$Z_m = U_m = \delta_{m-2} + 26\delta_{m-1} + 66\delta_m + 26\delta_{m+1} + \delta_{m+2}$$

and indicates derivative with respect to  $t$ . If time parameters  $\delta_i$ 's and its time derivatives  $\dot{\delta}_i$ 's in Eq. (10) are discretized by the Crank-Nicolson formula and usual finite difference approximation, respectively:

$$\delta_i = \frac{1}{2}(\delta^n + \delta^{n+1}), \quad \dot{\delta}_i = \frac{\delta^{n+1} - \delta^n}{\Delta t} \quad (11)$$

we obtain a recurrence relationship between two time levels  $n$  and  $n+1$  relating two unknown parameters  $\delta_i^{n+1}$ ,  $\delta_i^n$  for  $i = m-2, m-1, \dots, m+1, m+2$

$$\begin{aligned} & \gamma_1 \delta_{m-2}^{n+1} + \gamma_2 \delta_{m-1}^{n+1} + \gamma_3 \delta_m^{n+1} + \gamma_4 \delta_{m+1}^{n+1} + \gamma_5 \delta_{m+2}^{n+1} \\ & = \gamma_5 \delta_{m-2}^n + \gamma_4 \delta_{m-1}^n + \gamma_3 \delta_m^n + \gamma_2 \delta_{m+1}^n + \gamma_1 \delta_{m+2}^n \end{aligned} \quad (12)$$

where

$$\begin{aligned} \gamma_1 &= [1 - E(1 + Z_m) - M + K], \\ \gamma_2 &= [26 - 10E(1 + Z_m) + 2M - 4K], \\ \gamma_3 &= [66 + 6K], \\ \gamma_4 &= [26 + 10E(1 + Z_m) - 2M - 4K], \\ \gamma_5 &= [1 + E(1 + Z_m) + M + K], \\ m &= 0, 1, \dots, N, \quad E = \frac{5}{2h} \Delta t, \quad M = \frac{30}{h^3} \Delta t, \quad K = \frac{120}{h^4}. \end{aligned} \quad (13)$$

For the linearization technique, the term  $U$  in non-linear term  $UU_x$  is taken as

$$Z_m = U_m = \delta_{m-2} + 26\delta_{m-1} + 66\delta_m + 26\delta_{m+1} + \delta_{m+2}. \quad (14)$$

The system (12) consists of  $(N+1)$  linear equations including  $(N+5)$  unknown parameters  $(\delta_{-2}, \delta_{-1}, \dots, \delta_{N+1}, \delta_{N+2})^T$ . To obtain a unique solution to this system, we need four additional constraints. These are got from the boundary conditions and can be used to eliminate  $\delta_{-2}, \delta_{-1}$  and  $\delta_{N+1}, \delta_{N+2}$  from the system (12) which becomes later a matrix equation for the  $N+1$  unknowns  $d = (\delta_0, \delta_1, \dots, \delta_N)^T$  of the form

$$Ad^{n+1} = Bd^n. \quad (15)$$

The matrices  $A$  and  $B$  are pentagonal  $(N+1) \times (N+1)$  matrices and this matrix can be solved by using the pentagonal algorithm. However, two or three inner iterations are implemented to the term  $\delta^{n*} = \delta^n + \frac{1}{2}(\delta^n - \delta^{n-1})$  at each time step to cope with the non-linearity caused by  $Z_m$ . Before the solution process begins iteratively, the initial vector  $d^0 = (\delta_0, \delta_1, \dots, \delta_{N-1}, \delta_N)$  must be determined by using the initial condition and the following derivatives at the boundary conditions:

$$\begin{aligned} U_N(x, 0) &= U(x_m, 0), & m &= 0, 1, 2, \dots, N \\ (U_N)_x(a, 0) &= 0, & (U_N)_x(b, 0) &= 0, \\ (U_N)_{xx}(a, 0) &= 0, & (U_N)_{xx}(b, 0) &= 0, \end{aligned} \quad (16)$$

So we have the following matrix form of the initial vector  $d^0$ :

$$Wd^0 = B \quad (17)$$

$$\text{where } W = \begin{bmatrix} 54 & 60 & 6 & & & & \\ 25.25 & 67.50 & 26.25 & 1 & & & \\ 1 & 26 & 66 & 26 & 1 & & \\ & 1 & 26 & 66 & 26 & 1 & \\ & & & & \ddots & & \\ & & & & & 1 & 26 & 66 & 26 & 1 \\ & & & & & & 1 & 26.25 & 67.50 & 25.25 \\ & & & & & & & 6 & 60 & 54 \end{bmatrix}$$

$$d^0 = (\delta_0, \delta_1, \dots, \delta_{N-1}, \delta_N) \text{ and } B = [U(x_0, 0), U(x_1, 0), \dots, U(x_{N-1}, 0), U(x_N, 0)]^T.$$

This matrix system can be solved efficiently by using a variant of Thomas algorithm.

### 3. Stability analysis

In order to apply the von Neumann stability analysis, the Rosenau-KdV equation can be linearized by supposing that the quantity  $U$  in the nonlinear term  $UUx$  is locally constant. Replacing Fourier mode

$$\delta_j^n = \hat{\delta}^n e^{ijkh} \quad (18)$$

where  $k$  is the mode number and  $h$  is the element size, into Eq. (12) gives the growth factor  $g$  of the form

$$g = \frac{a - ib}{a + ib}, \quad (19)$$

where

$$\begin{aligned} a &= \gamma_3 + (\gamma_2 + \gamma_4) \cos[hk] + (\gamma_1 + \gamma_5) \cos[2hk], \\ b &= (\gamma_4 - \gamma_2) \sin[hk] + (\gamma_5 - \gamma_1) \sin[2hk]. \end{aligned} \quad (20)$$

The modulus of  $|g|$  is 1, for this reason the linearized scheme is unconditionally stable.

### 4. Numerical experiments and discussion

In this section, to show the accuracy of the numerical simulation of dispersive shallow water waves with Rosenau-KdV equation and to compare obtained results with both exact values and other results given in the literature, the  $L_2$  and  $L_\infty$  error norms are calculated by using the analytical solution in Eq. (21). We take into consideration the motion of single solitary wave solution for three test problems. Accuracy and efficiency of the method is reckoned by the error norm  $L_2$

$$L_2 = \|U^{exact} - U_N\|_2 \approx \sqrt{h \sum_{j=1}^N |U_j^{exact} - (U_N)_j|^2}, \quad (21)$$

and the error norm  $L_\infty$

$$L_\infty = \|U^{exact} - U_N\|_\infty \approx \max_j |U_j^{exact} - (U_N)_j|, \quad j = 1, 2, \dots, N-1. \quad (22)$$

Rosenau-KdV equation satisfies only two conservation laws given by Ref.[16]

$$\begin{aligned} I_1 &= \int_a^b U dx \approx h \sum_{j=1}^N U_j^n, \\ I_2 &= \int_a^b [U^2 + (U_{xx})^2] dx \approx h \sum_{j=1}^N [(U_j^n)^2 + (U_{xx})_j^n]. \end{aligned} \quad (23)$$

In the simulation of solitary wave motion, the invariants  $I_1$  and  $I_2$  are observed to check the conversation of the numerical algorithm.

#### 4.1. The motion of single solitary wave

For this problem, the Rosenau-KdV Eq. (3) is considered for the boundary conditions  $U \rightarrow 0$  as  $x \rightarrow \pm\infty$  and the initial condition

$$U(x, 0) = \left(-\frac{35}{24} + \frac{35}{312} \sqrt{313}\right) \sec h^4 \left(\frac{1}{24} \sqrt{-26 + 2\sqrt{313}x}\right). \quad (24)$$

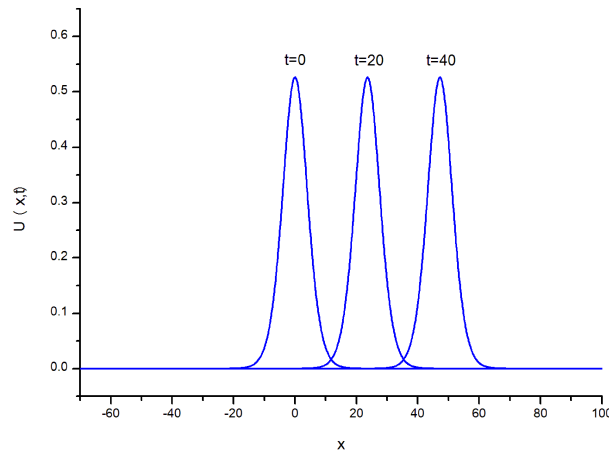
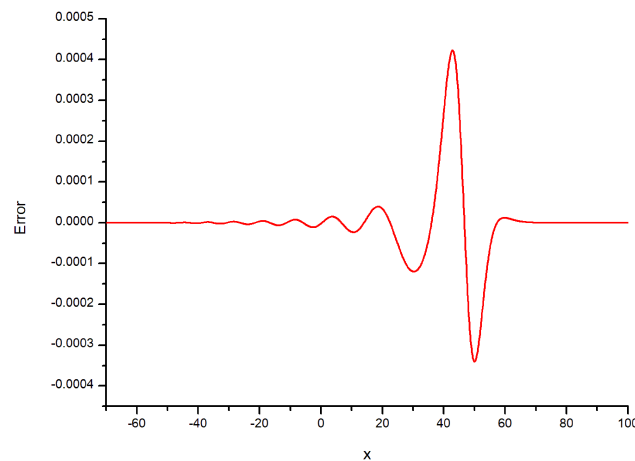
Note that the analytical solution of the equation can be written as

$$U(x, t) = \left(-\frac{35}{24} + \frac{35}{312} \sqrt{313}\right) \sec h^4 \left[\frac{1}{24} \sqrt{-26 + 2\sqrt{313}} \left(x - \left(\frac{1}{2} + \frac{1}{26} \sqrt{313}\right) t\right)\right]. \quad (25)$$

In this section, to apply numerical method we have considered three sets of parameters. First of all, we have used the parameters  $h = 0.1$  and  $\Delta t = 0.1$  over the interval  $[-70, 100]$  to coincide with those of Ref.[26]. So, the solitary wave has an amplitude 0.52632 and the computations are done up to time  $t = 40$  to obtain the invariants and error norms  $L_2$  and  $L_\infty$  at various times. Error norms  $L_2$ ,  $L_\infty$  and two invariants of the Rosenau-KdV equation are listed in Table 1. It is seen from the table that the error norms are found to be small enough. The percentage of the relative error of the conserved quantities  $I_1$  and  $I_2$  are calculated with respect to the conserved quantities at  $t = 0$ . Percentage of relative changes of  $I_1$  and  $I_2$  are found to be  $1.177 \times 10^{-7} \%$ ,  $9.86 \times 10^{-8} \%$ , respectively. Fig. 1 shows the motion of solitary wave with  $h = 0.1$  and  $\Delta t = 0.1$  at various time levels. The distributions of the errors at time  $t = 40$  are illustrated for solitary waves amplitudes 0.52632 in Fig. 2.

**Table 1.** The invariants and the error norms for single solitary wave with amplitude= 0.52632,  $h = 0.1$ ,  $\Delta t = 0.1$ ,  $-70 \leq x \leq 100$ .

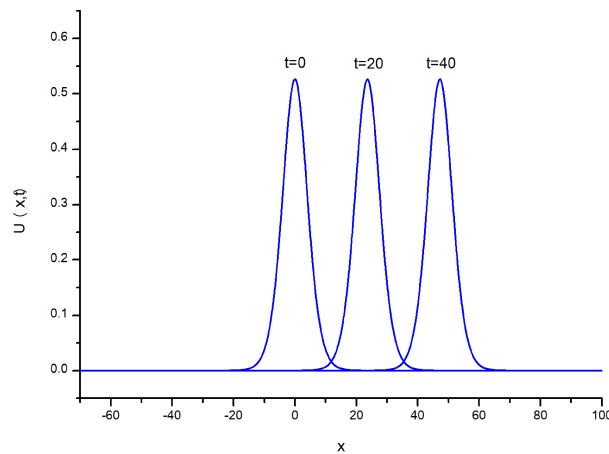
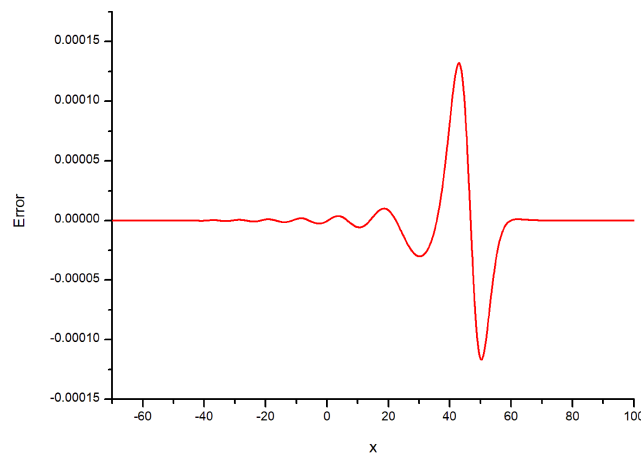
$t$		0	10	20	30	40
$I_1$	Present	5.4981750556	5.4981750556	5.4981750556	5.4981750555	5.4981750621
	[26]	5.4977225480	5.4977249365	5.4977287449	5.4977319638	5.4977342352
$I_2$	Present	1.9897841615	1.9897841624	1.9897841629	1.9897841633	1.9897841635
	[26]	1.9845533653	1.9845950759	1.9846459641	1.9846798272	1.9847015013
$L_2 \times 10^3$	Present	0.000000	0.370348	0.665684	0.924741	1.187411
	[26]	0.000000	1.641934	3.045414	4.241827	5.297873
$L_\infty \times 10^3$	Present	0.000000	0.149073	0.253418	0.336342	0.422656
	[26]	0.000000	0.631419	1.131442	1.533771	1.878952

**Fig. 1.** Single solitary wave with  $h = 0.1$ ,  $\Delta t = 0.1$ ,  $-70 \leq x \leq 100$ ,  $t = 0, 20$  and  $40$ .**Fig. 2.** Error  $h = 0.1$ ,  $\Delta t = 0.1$ ,  $-70 \leq x \leq 100$ ,  $t = 40$ .

For the second case, the parameters  $h = 0.05$  and  $\Delta t = 0.05$  with interval  $[-70, 100]$  are taken. Hence, the solitary wave has amplitude 0.52632 and the simulations are run up to time  $t = 40$  to obtain the invariants and the error norms at several times. Error norms  $L_2$  and  $L_\infty$  and conserved quantities are reported in Table 2 together with the results obtained in Ref.[26]. It can be easily seen from the table that the obtained error norms are smaller than those given in Ref.[26]. The agreement between numerical and analytic solution is excellent. Percentage of relative changes

**Table 2.** The invariants and the error norms for single solitary wave with amplitude= 0.52632,  $h = 0.05$ ,  $\Delta t = 0.05$ ,  $-70 \leq x \leq 100$ .

$t$		0	10	20	30	40
$I_1$	Present	5.4981692134	5.4981692136	5.4981692136	5.4981692134	5.4981692116
	[26]	5.4980606845	5.4980608372	5.4980610805	5.4980612870	5.4980613985
$I_2$	Present	1.9897831853	1.9897831855	1.9897831855	1.9897831854	1.9897831852
	[26]	1.9843901753	1.9844010295	1.9844143675	1.9844232703	1.9844289740
$L_2 \times 10^4$	Present	0.000000	0.888297	1.823510	2.862236	3.842086
	[26]	0.000000	4.113510	7.631169	10.62971	13.27645
$L_\infty \times 10^4$	Present	0.000000	0.362314	0.649564	1.000742	1.320897
	[26]	0.000000	1.582641	2.835874	3.843906	4.709118

**Fig. 3.** Single solitary wave with  $h = 0.05$ ,  $\Delta t = 0.05$ ,  $-70 \leq x \leq 100$ ,  $t = 0, 20$  and  $40$ .**Fig. 4.** Error  $h = 0.05$ ,  $\Delta t = 0.05$ ,  $-70 \leq x \leq 100$ ,  $t = 40$ .

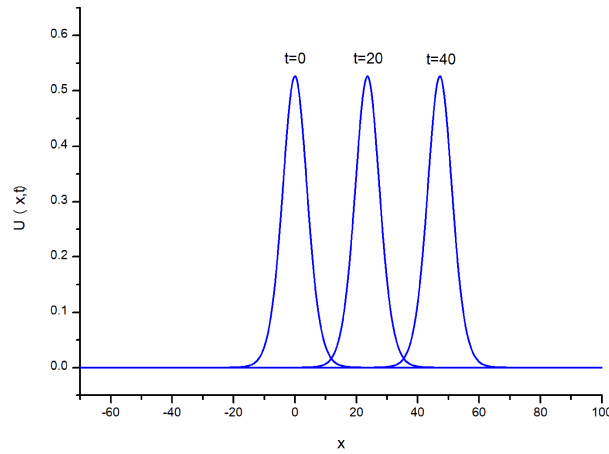
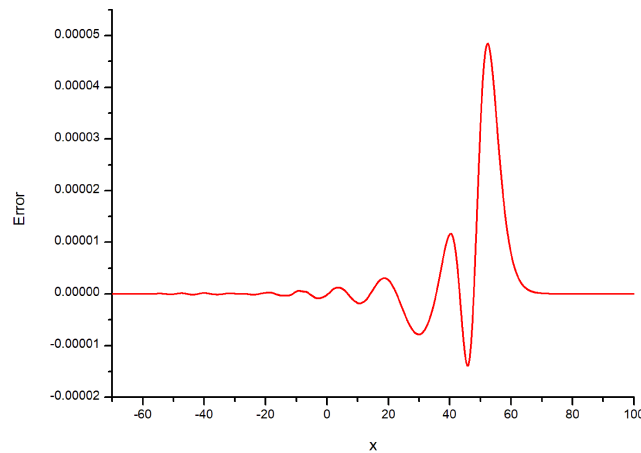
of  $I_1$  and  $I_2$  are found to be  $3.30 \times 10^{-8}$  %,  $6.7 \times 10^{-9}$  %, respectively. Perspective views of the traveling solitons are graphed at diverse time levels in Fig. 3. The distributions of the errors at time  $t = 40$  are drawn in Fig. 4.

Finally, for the third case, the parameters  $h = 0.025$  and  $\Delta t = 0.025$  with interval  $[-70, 100]$  are chosen. Therefore, the solitary wave has amplitude 0.52632 and the experiments are run from the time  $t = 0$  to the time  $t = 40$  to obtain the invariants and the error norms  $L_2$  and  $L_\infty$  at different times. Error norms  $L_2$  and  $L_\infty$  and conserved quantities are listed

**Table 3.** The invariants and the error norms for single solitary wave with amplitude= 0.52632,  $h = 0.025$ ,  $\Delta t = 0.025$ ,  $-70 \leq x \leq 100$ .

$t$		0	10	20	30	40
$I_1$	Present	5.4981698357	5.4981698365	5.4981698322	5.1981698290	5.4981698203
	[26]	5.4981454184	5.4981454791	5.4981455454	5.4981456095	5.4981456591
$I_2$	Present	1.9897809062	1.9897809077	1.9897809038	1.9897809019	1.9897808975
	[26]	1.9843493353	1.9843521098	1.9843555206	1.9843578113	1.9843592922
$L_2 \times 10^4$	Present	0.000000	0.357060	0.925408	1.057023	1.183710
	[26]	0.000000	1.028173	1.905450	2.650990	3.306738
$L_\infty \times 10^5$	Present	0.000000	1.421479	3.264848	4.742297	4.846861
	[26]	0.000000	3.965867	7.097948	9.610332	11.76011

in Table 3 together with the results obtained in Ref. [26]. The agreement between numerical and analytic solutions is perfect. Percentage of relative changes of  $I_1$  and  $I_2$  are found to be  $2.812 \times 10^{-7} \%$ ,  $4.369 \times 10^{-7} \%$ , respectively. The profiles of the solitary wave at different time levels are shown in Fig. 5. The distributions of the errors at time  $t = 40$  are depicted graphically for solitary waves amplitudes 0.52632 in Fig. 6.

**Fig. 5.** Single solitary wave with  $h = 0.025$ ,  $\Delta t = 0.025$ ,  $-70 \leq x \leq 100$ ,  $t = 0, 20$  and  $40$ .**Fig. 6.** Error  $h = 0.025$ ,  $\Delta t = 0.025$ ,  $-70 \leq x \leq 100$ ,  $t = 40$ .

Consequently, as seen from the three cases, the changes of the invariants are reasonable small and the quantity of obtained error norms are better than the ones in earlier numerical methods.

## 5. Conclusion

In this study, finite element method has been successfully applied to show numerical simulation of dispersive shallow water waves with Rosenau-KdV equation. Here, collocation method with quintic B-spline basis functions has been used. To show the accuracy of the method, we have calculated the error norms  $L_2$ ,  $L_\infty$  and the invariants  $I_1$ ,  $I_2$ . Since the error norms are satisfactorily small during the simulations, single solitary wave motion is well presented and conservation laws have been held satisfactorily constant in the course of the computer run. The obtained results show that the presented method is more precise than results in previous numerical method. Thus, numerical results demonstrate that presented method is a promising and powerful tool for solving the Rosenau-KdV equation. Main advantages of the present technique are: it is simple, effective and moreover easy to understand.

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## References

- [1] D. J. Korteweg and G. de Vries, On the change of form of long waves advancing in a rectangular canal, and on a new type of long stationary wave, *Phi-losophical Magazine* 39 (1895) 442–443.
- [2] D. Irk, I. Dağ and B. Saka, A small time solutions for the Korteweg-de Vries equation using spline approximation, *Applied Mathematics and Computation* 173(2) (2006) 834–846.
- [3] A. Biswas, Solitary wave solution for KdV equation with power-law nonlinearity and time-dependent coefficients, *Nonlinear Dynamics* 58(1-2) (2009) 345–348.
- [4] L. Wei, Exact soliton solutions for the general fifth Korteweg-de Vries equation, *Computational Mathematics and Mathematical Physics* 49(8) (2009) 1429–1434.
- [5] D. Dutykh, M. Chhay and F. Fedele, Geometric numerical schemes for the KdV equation, *Computational Mathematics and Mathematical Physics* 53(2) (2013) 221–236.
- [6] T. M. Rageh, G. Salem and F. A. El-Salam, Restrictive Taylor approximation for Gardner and KdV equations, *International Journal of Advances in Applied Mathematics and Mechanics* 1(3) (2014) 1–10.
- [7] N. J. Noon, Fully discrete formulation of Galerkin-Partial artificial diffusion finite element method for coupled Burgers' problem, *International Journal of Advances in Applied Mathematics and Mechanics* 1(3) (2014) 56–75.
- [8] M. F. El-Sayed, G. M. Moatimid, M. H. M. Moussa, R. M. El-Shiekh and M. A. Al-Khawlani, New exact solutions for coupled equal width wave equation and (2+1)-dimensional Nizhnik-Novikov-Veselov system using modified Kudryashov method, *International Journal of Advances in Applied Mathematics and Mechanics* 2 (1) (2014) 19–25.
- [9] P. Rosenau, A quasi-continuous description of a nonlinear transmission line, *Physica Scripta* 34 (1986) 827–829.
- [10] P. Rosenau, Dynamics of dense discrete systems, *Progress of Theoretical Physics* 79 (1988) 1028–1042.
- [11] M. A. Park, On the Rosenau equation, *Matematica Aplicada e Computacional* 9(2) (1990) 145–152.
- [12] S. K. Chung and S. N. Ha, Finite element Galerkin solutions for the Rosenau equation, *Applicable Analysis* 54(1-2) (1994) 39–56.
- [13] K. Omrani, F. Abidi, T. Achouri and N. Khiari, A new conservative finite difference scheme for the Rosenau equation, *Applied Mathematics and Computation* 201(1-2) (2008) 35–43.
- [14] S. K. Chung, Finite difference approximate solutions for the Rosenau equation, *Applicable Analysis* 69(1-2) (1998) 149–156.
- [15] S. K. Chung and A. K. Pani, Numerical methods for the Rosenau equation, *Applicable Analysis* 77(3-4) (2001) 351–369.
- [16] S. A. V. Manickam, A. K. Pani and S. K. Chung, A second-order splitting combined with orthogonal cubic spline collocation method for the Rosenau equation, *Numerical Methods for Partial Differential Equations* 14(6) (1998) 695–716.
- [17] Y. D. Kim and H. Y. Lee, The convergence of finite element Galerkin solution for the Rosenau equation, *The Korean Journal of Computational & Applied Mathematics* 5(1) (1998) 171–180.
- [18] J.-M. Zuo, Solitons and periodic solutions for the Rosenau-KdV and Rosenau-Kawahara equations, *Applied Mathematics and Computation* 2015(2) (2009) 835–840.
- [19] A. Esfahani, Solitary wave solutions for generalized Rosenau-KdV equation, *Communications in Theoretical Physics* 55(3) (2011) 396–398.



- [20] P. Razborova, H. Triki and A. Biswas, Perturbation of dispersive shallow water waves, *Ocean Engineering* 63 (2013) 1–7.
- [21] G. Ebadi, A. Mojaver, H. Triki, A. Yildirim and A. Biswas, Topological solitons and other solutions of the Rosenau-KdV equation with power law nonlinearity, *Romanian Journal of Physics* 58(1-2) (2013) 3–14.
- [22] A. Saha, Topological 1-soliton solutions for the generalized Rosenau-KdV equation, *Fundamental Journal of Mathematical Physics* 2(1) (2012) 19–23.
- [23] P. Razborova, B. Ahmed and A. Biswas, Solitons, shock waves and conservation laws of Rosenau-KdV-RLW equation with power law nonlinearity, *Applied Mathematics & Information Sciences* 8(2) (2014) 485–491.
- [24] P. Razborova, B. Ahmed and A. Biswas, Additional conservation laws for Rosenau-KdV-RLW equation with power law nonlinearity by Lie symmetry, *Nonlinear Dynamics* 79(1) (2015) 743–748.
- [25] P. Sanchez, G. Ebadi, A. Majover, M. Mirzazadeh, M. Eslami and A. Biswas, Solitons and other solutions to perturbed Rosenau-KdV-RLW equation with power law nonlinearity, *Acta Physica Polonica A* 127(6) (2015) 1577–1586.
- [26] J. Hu, Y. Xu and B. Hu, Conservative Linear Difference Scheme for Rosenau-KdV Equation, *Advances in Mathematical Physics* (2013) doi:10.1155/2013/423718.
- [27] P. M. Prenter, *Splines and Variational Methods*, John Wiley, New York, 1975.

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