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Full Length Research Paper

3D tsunami wave reconstruction from Quickbird data by using fuzzy B-spline

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This work reports on a study carried out for the generation of three-dimensional (3D) successive tsunami waves using high resolution satellite Quickbird data. The main objective of this study is to utilize fuzzy arithmetic to remodel real 3D tsunami wave propagation and runup from optical data such as Quickbird. In doing so, two-dimensional Fourier transform (2DFFT) was used to extract the successive tsunami wave characteristics which are frequency, wavelength, direction and energy. In this context, fuzzy B-spline was utilized to reconstruct a global topographic structure between the data points, were used to support an approximation to the real successive tsunami wave propagation and run-up. The best reconstruction of coastal successive tsunami waves of the test site in Kalutara, Sri-Lanka, was acquired with Quickbird visible band data.

Key words: Tsunami, Quickbird satellite data, two-dimensional Fourier transform (2DFFT), fuzzy B-spline, three-dimensional (3D).

INTRODUCTION

In satellite remote sensing images, the dynamic interaction between successive tsunami wave propagations and coastal geomorphology, biodiversities and urban infrastructures are clearly shown. At present, there are few studies have quantified the damages and rate changes along coastal regions (Cheng et al., 2005; Chia et al., 2005; Marghany et al., 2006). Yet, the dynamic of successive tsunami wave characteristics has not been accounted. Salinas et al. (2005) studied the fundamental properties of the tsunami wave propagations from SPOT-4 imagery which was acquired 20 min after the first wave arrival to the port of Phuket, Thailand. They used two scan lines layered over the selected wave pattern and plotted as a function of distance to retrieve the tsunami wavelength. Nevertheless, scientists and researchers have agreed that prior to map wave spectra extracted from satellite data, 2DFFT must be used to convert the satellite data into frequency domain (Populous et al., 1991; Vachon et al., 1994; Marghany, 2004). In this context, both linear and nonlinear algorithms have used to retrieve wave characteristics from satellite imagery. Further, for SPOT-4, there are several parameters which could influence the image qualities: (1) Angular dispersion, wavelength, and wave height; (2) Weather conditions which involve cloud cover and visibility; and (3) The sum of the sun elevation angle and the viewing incidence (populous et al., 1991). Salinas et al. (2006) have attempted to model the runup from SPOT-5 by involving beach slope and physical wave spectra properties from SPOT-5 imagery which were retrieved by method of Salinas et al. (2005). Indeed, the tsunami wave properties that are frequency, wavelength, and wave height are required to be fit in runup model. Moreover, the beach slope surveying after the event must not be taken into account due to the rapid dynamic changes of coastal geomorphology in short period due to the rapid changes in coastal water dynamic movements. In addition, runup model is required for accurate digital elevation model (DEM) of coastal zones. However, Salinas et al. (2006) stated that to approach the run-up and inundation problem, the non-linear shallow water equations must be solved with an appropriate treatment for breaking waves and moving shore lines. Likewise, they have reported that the complex geometry of the coastal line coupled with arbitrary beach and sea floor profiles, makes solving the shallow water equations a

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formidable task which can only be approached numerically (Salinas et al., 2006). Under this circumstance, the standard methods are required to acquire accurate successive tsunami wave propagations from satellite imagery and to avoid uncertainty which might be arisen due to absence of real time *in situ* measurements. In modeling dynamic pattern from the satellite imagery image processing, the uncertainty is major challenges. In this paper, we address the question of 3-D tsunami wave propagation and runup reconstructions using Quickbird imagery without needing any *in situ* wave measurements. This is demonstrated with using fuzzy B-spline. These hypothesis examined are: (1) The main algorithm of fuzzy B-spline is modified based on frequency domain analysis; (2) Reconstruction of 3D tsunami propagation from satellite Quickbird imagery is required to reconstruct impulse function from the known tsunami spectra, derived by 2-DFFT, (3) 3rd order B-spline interpolation can be used to invert 2D tsunami spectra into 3-D successive tsunami propagation and run-up.

MODEL

Wave spectra estimation from Quickbird satellite data

Since the wave changes its direction and wavelength as it propagates, the two dimensional discrete Fourier transforms (DFT) was used to derive the wave number spectra from QuickBird data. First, choose a window kernel size of 512 × 512 with the pixel size equal to ΔX (Populus et al., 1990). Following Marghany (2001), let $X(m_1, m_2)$ represent the digital count of the pixel at (m_1, m_2) which is used to perform DFT, which is given as

$$F(kx, ky) = N^{-2} \sum_{m_2=0}^{N-1} \left[\sum_{m_i=0}^{N-1} X(m_1, m_2).e^{-ikx.m_1.\Delta X} \right].e^{-iky.m_2.\Delta X} \qquad (1)$$

where, $m_1 \text{ and } m_2 = 1,2,3,......., N$ and *kx* and *ky* are the wave numbers in the *x* and *y* directions, respectively.

Following Goto and Ogawa (1992), the run-up is estimated by

$$R = \left[J_0{}^2 (\frac{4\pi l}{L}) + J_1{}^2 (\frac{4\pi l}{L}) \right]^{-1} 4[\int\int E(k_x, k_y) dk_x dk_y]^{0.5} \qquad (2)$$

where $E(k_x, k_y)$ is spectra energy , L wavelength are derived from 2DFFT according to Populus et al. (1990), J_0, J_1 are the Bessel functions of the first kind of order 0 and 1, and l is the horizontal distance between toe of the slope and the shoreline.

Fuzzy B-spline method

Frequency domain of B-spline

The analysis of B-splines in frequency domain is required to determine the impulse response of B-spline interpolation which denotes any function in a continuous domain (or more correctly: Distribution) that has a form of the Dirac's ∂ distribution wave trains with the varying discrete sequence of tsunami wave amplitudes. The basic step in the reconstruction process is the construction of the continuous function from discrete frequency sample values. In further analysis, the impulse function is created from the known samples. The B-spline weight functions are continuous functions and sampling β_n of these functions can be applied. According to Mihajlovic et al. (1999), the frequency domain analysis of B-spline F_n is given by

$$F_n = \hat{f}(\omega) \frac{\sin c^{n+1}(\frac{\omega}{2\pi})}{\beta_n(0) + 2\sum_{k=1}^{0.5n} \beta_n(k)\cos(k\omega)} \qquad (3)$$

where $\beta_n(k)$, the discrete Fourier is transform of sequence samples from selected kernel windows in Quickbird imagery, $\hat{f}(\omega)$ is Fourier frequency domain which is obtained from Equation 1. Equation 3 is considered as correction to the B-spline, so its frequency response is wider. Increasing order *n* leads to frequency response which is getting closer to the ideal lowpass filter.

Fuzzy B-spline method

The fuzzy B-splines (FBS) are introduced allowing fuzzy numbers instead of intervals in the definition of the frequency domain of B-spline. According to Marghany and Mazlan (2011), a fuzzy number is defined using interval analysis. There are two basic notions that we combined together: Confidence interval and presumption level. A confidence interval is a real values interval which provides the sharpest enclosing range for tsunami wave spectra propagation in spatial domain. Following Marghany et al. (2010), an assumption level, μ -level is an estimated truth value in the (0, 1) interval on our knowledge level of the tsunami wave spectra (Anile, 1997). The 0 value corresponds to minimum knowledge of tsunami frequency spectra, and 1 to the maximum variation in tsunami frequency spectra was retrieved from Quickbird imagery. A fuzzy number is then prearranged in the confidence interval set, each one related to an assumption level $\mu \in (0, 1)$. Moreover, the following must hold for each pair of confidence intervals which define a number: $\mu \succ \mu' \Rightarrow \omega \succ \omega'$. Let us consider a function $f : \omega \rightarrow \omega'$, of *N* fuzzy variables of $\omega_1, \omega_2, ..., \omega_n$. Where ω_n are the global minimum and maximum values of the function on the tsunami frequency spectra. Based on the spatial variation of the tsunami spectra propagation, the fuzzy B-spline algorithm is used to compute the function *f.* Following Anile (1997), a fuzzy B-spline f_{BS} relative to crisp knot sequences ($\beta_1, \beta_2, ..., \beta_m$), and *m = q + 2(n - 1)* is function from the real curve to the set of real fuzzy numbers:

$$f_{\beta S} = \sum_{i=0}^{q+2(n-1)} f_i F_{n_{i,p}}(\beta_n) \qquad (4)$$

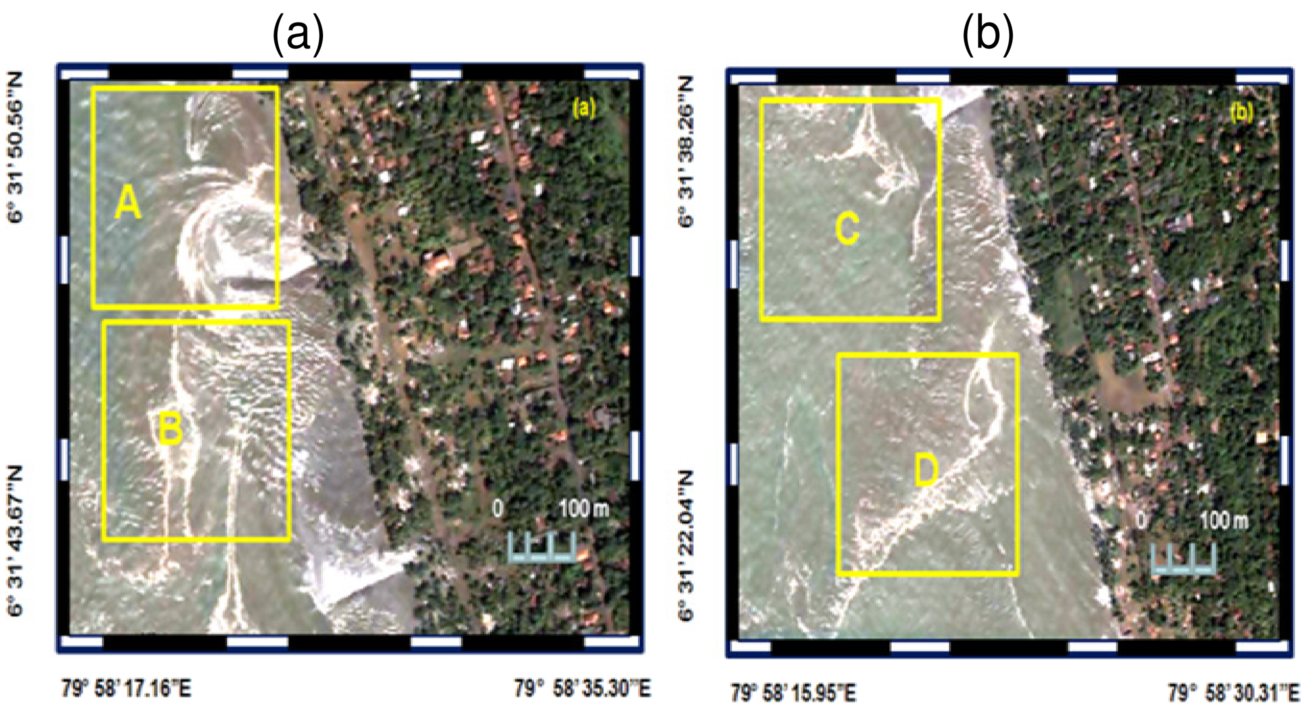

Figure 1. Quickbird imagery in (a) North of Kalutra, and (b) South of Kalutra.

where f_i is the control coefficient, and $F_{n_{i,p}}(\beta_n)$ are the crisp frequency domain of B-spline function of order of *n*.

RESULTS AND DISCUSSION

Figure 1 show images were acquired by the Digital Globe Quickbird satellite. It shows a portion of the southwest coast of Sri Lanka, by the town of Kalutara (Figure 1). The images were acquired on Sunday December 26, 2004, at 10:20 am local time, slightly less than four hours after the 6:28 am (local Sri Lanka time) earthquake and shortly after the moment of tsunami impact. The tsunami first impacted the eastern coastline of Sri Lanka shortly after 8:00 am and then swept along the southern and south-western shores over the following 90 min or so. Its effects were inconsistent from place to place, but in general, the eastern, north-eastern and south eastern coastline was particularly hard hit, while the waves refracted around the island to devastate the southern and south-western coast in a patchy manner.

Figure 2 shows the wave spectra have extracted by 2-DFFT which is applied with kernel window size of 512 × 512 pixels in two different areas in the Quickbird data (Figure 1). Figures 2a and b show different pattern of tsunami wave spectra along the coastal water. Figure 2a depicts tsunami wave spectra direction of 150° towards the coastline while Figure 2b shows wave propagation towards 70°.

It is interesting to find that the dominant wave length was between 50 and 140 m. The change of direction pattern from area A to B was due to diffraction impact. This could be contributed to tsunami waves been diffracted around Sri-Lanka Island and then moved perpendicular to the Kalutara coast and spread inland, causing widespread flooding. Figure 1a shows that the water drained back into the ocean; it built two barriers along Kalutara coastline. As successive tsunami passed the large barrier; the wave spread along the crest behind the barrier. It was diffracted so that the barrier stopped part of the wave crest and passed rest by to generate a large eddy with the radius of 150 m behind the barrier. This indicates that the successive tsunami waves hitting the Kalutara coastline have changed the coastal zone morphology patterns (Marghany et al., 2006). A few minutes later, new series of tsunami wave spectra struck the coastline with wavelength ranged between 50 to 100 m and dominant direction of 60° towards the shoreline (Figures 2c and d).

Figure 3 shows the 3D tsunami wave propagations constructed by using fuzzy B-spline. It is interested to find the clear structure of tsunami wave heights which are between 3 and 6 m. The maximum wave height of 6 m was due to the wave breaking. The maximum wave height is shown across an eddy movement while the waves have spread inland was between 4 and 6 m height. Figure 3a shows 3-D dimensions for wave diffraction along Kalutara coastline. This indicates turbulent water movement due to combination of wave

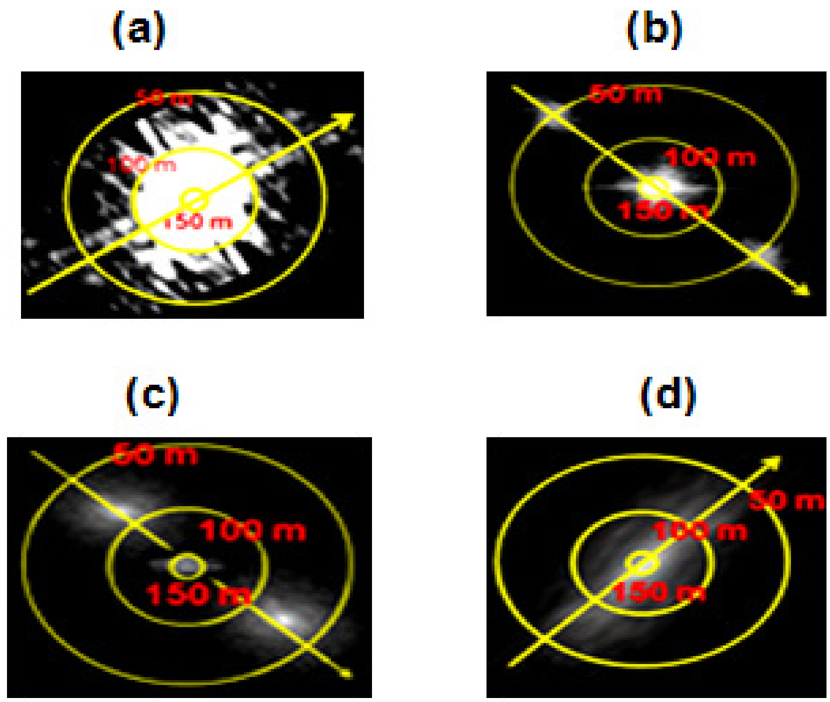

Figure 2. Tsunami wave spectra were derived from Figure 1 at (a) window A, (b), window B, (c) window C, and (d) window D.

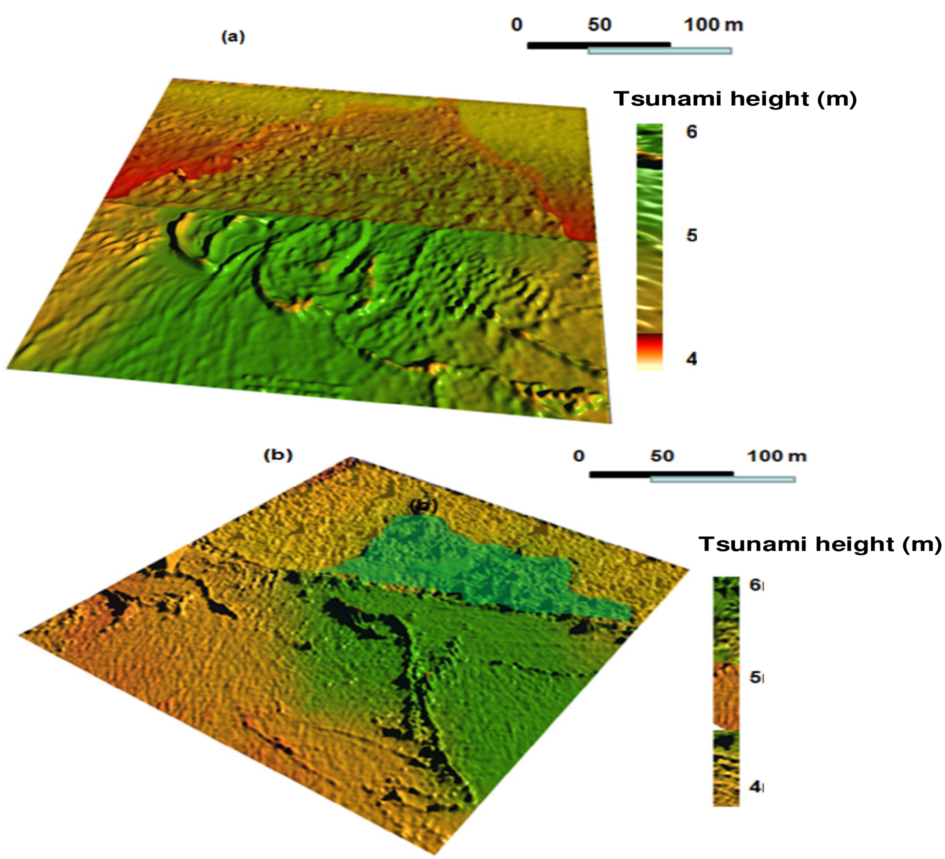

Figure 3. Fuzzy B-spline 3D Tsunami wave propagations and Runup in (a) North and (b) South of Kalutara coastline.

diffraction, refraction, reflection and longshore current movements between the two barriers. Taken together, these were able to cause a pattern which spelled out, approximately the pattern of the Arabic word for Allah and El-Gbar as shown Figures 3a and b, respectively. Figure 3a and b shows that the run-up ranged between 4 and 6 m. The minimum runup observed inland while the regions were closed to the coastline dominated by run-up of 6 m (Figure 3). It is obvious that the mechanism of run-up was accompanied by convergence zone (Figure 3).

This result confirms the study of Marghany and Sufian (2005). Fuzzy B-spline approximation of 3rd order provides 3D images which were virtually free of visible artifacts. This is contributed due to the fact that each operation on a fuzzy number becomes a sequence of corresponding operations on the respective μ-levels, and the multiple occurrences of the same fuzzy parameters is evaluated as a result of the function on fuzzy variables (Anile, 1997; Anile et al., 1997; Anile et al., 1995). It is very easy to distinguish between small and long waves. Typically, in computer graphics, two objective quality definitions for fuzzy B-spline were used: Triangle-based criteria and edge-based criteria. Triangle-based criteria follow the rule of maximization or minimization, respectively, of the angles of each triangle (Fuchs et al., 1997). The so-called max-min angle criterion prefers short triangles with obtuse angles. This finding confirms those of Keppel (1975) and Anile (1997).

CONCLUSIONS

This paper has demonstrated new method to reconstruct 3D image of tsunami wave propogations. The method was based on modification of the concept of fuzzy B-spline. Frequency domain analysis was implemented with B-spline. The basic step in the reconstruction process was the construction of the continuous function from discrete sample values of frequency spectra. These sample values were acquired from 2DFFT. The results show the 3D visualization of tsunami wave propagation which to be the most satisfactory. It can be concluded that the involving of frequency response analysis with fuzzy B-spline can be used as method for 3D reconstruction of coastal wave propagations from remotely sensed data.

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