ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 31 **Number 1** **2012**

A STUDY OF THE EFFECT OF PERMEABILITY OF ROCKS IN TSUNAMI GENERATION AND PROPAGATION BY SEISMIC FAULTING USING LINEARIZED SHALLOW –WATER WAVE THEORY

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ABSTRACT

The effect of permeability of rocks inside the ocean on Tsunami generation and Propagation is investigated. We study the nature of Tsunami build up and propagation using realistic curvilinear source models. The models are used to study the effect of permeability on tsunami amplitude amplification as a function on spreading velocity and rise time. Effect of permeability on Tsunami waveforms within the frame of the linearized shallow water wave theory for constant water depth are analyzed analytically using Transform methods. It is observed that in the region of highly permeable rocks the tsunami wave run is fast in comparison to low permeable rocks. The amplitude as a function of the propagated uplift length and width are analyzed. The cases of Tsunami-2011 (Japan), Tsunami-2006 (Srilanka), and Tsunami-2006 (Madras) have been demonstrated in the study.

Keywords: Tsunami Modeling, Water wave, permeability, Laplace and Fourier Transforms

1. INTRODUCTION

The generation of Tsunamis by a seafloor deformation is an example for the case where the waves are created by a given motion of the bottom. There are different natural phenomena that can lead to a Tsunami e.g. one can mention submarine slumps, volcanic explosions, earthquakes. (Tinti and Bortolucci 2000) investigated analytically the generation of tsunamis by submarine slides. They specialized the general solution of the 1D Cauchy linear problems for longer water waves to deal with rigid body to explore the characteristics of the generated waves. (Kervella et al. 2007) performed a comparison between three-dimensional linear and nonlinear tsunami generation models.

They observed very good agreement from the superposition of the wave profiles computed with the linear and fully nonlinear models. (Abou - Dina and Hassan 2006) have adopted a nonlinear theory and constructed a numerical model of tsunami generation and propagation which permits a variable bed displacement with an arbitrary water depth to be included in the model. The body motion in terms of Froude number, wave pattern, wave amplitude and wave energy have been studied by many authors (Takahasi and Hatori 1962), (Okada 1985), (Kajiura 1963), (Villeneuve 1993), (Nakamura 1953), (Tuck and Hwang 1972). All the previous studies mention above neglected the details of wave generation in fluid during the source time. One of the reasons is that it is commonly assumed that the source details are not important. (Trifunac and Todorovska 2002) mentioned the source parameters for submarine slides and earthquakes including source duration, displacement amplitude areas and volumes of selected past earthquakes that have or may have generated a tsunami.

(Dutykh and Dias 2007) generated waves theoretically by multiplying the static deformations caused by slip along a fault by various time laws: instantaneous, exponential, trigonometric and linear. (Harbitz et al. 2006) have investigated the characteristics of a tsunami generated by a submarine landslide. It is observed that tsunamis generated by submarine landslides have very large run up heights close to the surface area, but have more limited field effects than earthquake tsunamis. (Marghany and Hashim 2011) have studied 3D tsunami wave reconstruction using fuzzy B-spline. They used 2DDFT and presented a model to reconstruct of coastal successive tsunami waves of the test site in Srilanka.

In all the previous approaches, authors have not included the under ground water conditions, such as the nature of rocks inside the ocean. The most important feature of rocks which affect wave run up is permeability. Our approach is to study the effect of permeability in Tsunami generation and propagation. We have taken the model demonstrated by (Hassan et al. 2010) and considered that the ocean floor is porous. We have improved the model by taking the approach that the floor below the ocean is made up of rocks which are porous and differ in permeability. We studied the effect of permeability on tsunami generation and propagation. It is observed that under the ocean region where the permeability of rocks is high, tsunami waverunup is faster in comparison to those regions where the permeability of rocks is low. The cases of Tsunamis at Japan, Srilanka and Madras have been discussed.

2. MATHEMATICAL FORMULATION OF THE PROBLEM

Consider a three dimensional fluid domain Ω as shown in Figure 1. It is supposed to represent the ocean above the fault area. It is bounded above by the free surface of the ocean $z = \eta(x, y, t)$ and below by the porous ocean floor $z = -h(x, y) + \zeta(x, y, t)$, where $\eta(x, y, t)$ is the surface elevation, $h(x, y)$ is the water depth and $\zeta(x, y, t)$ is the sea floor displacement function. The domain is unbounded in the horizontal directions x and y, and can be written as $\Omega = R^2 \times [-h(x, y) + \zeta(x, y, t), \eta(x, y, t)]$. For simplicity, $h(x, y)$ is assumed to be a constant. Before the earthquake, the fluid is assumed to be at rest, thus the free surface and the porous boundary are defined by $z = 0$ and $z = -h$, respectively.

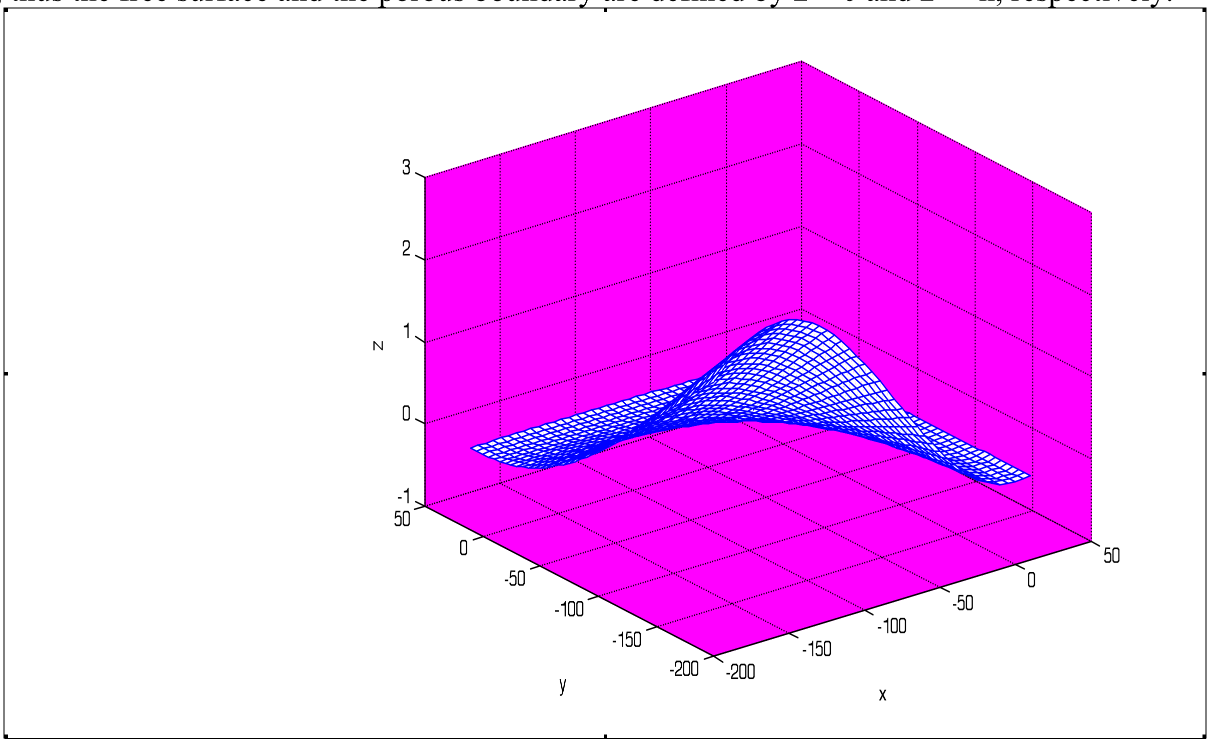


Figure 1. Definition of the fluid domain and coordinate system for a very rapid movement of the assumed source model.

Mathematically these conditions can be written in the form of initial conditions:

$\eta(x, y, 0) = \zeta(x, y, 0) = 0.$

At time $t > 0$ the bottom boundary moves in a prescribed manner which is given by
$z = -h + \zeta(x, y, t).$

The deformation of the sea bottom is assumed to have all the necessary properties needed to compute its Fourier transform in x, y and its Laplace tansform in t. The resulting deformation of the free surface $z = \eta(x, y, t)$ is to be found as part of the solution. It is assumed that the fluid is incompressible and the flow is irrotational. The former implies the existence of the velocity potential $\varphi(x, y, z, t)$ which fully describes the flow and the physical process. Since the ocean floor is made up of rocks which are porous, $\varphi(x, y, z, t)$ must satisfy the Brinkman equation of motion

$$\mu \nabla^2 \varphi(x, y, z, t) - \frac{\mu}{k} \varphi(x, y, z, t) = 0 \qquad \text{where } (x, y, z) \in \Omega \tag{2.1}$$

The potential $\varphi(x, y, z, t)$ must satisfy the following kinematic and dynamic boundary conditions on the free surface and porous boundary, respectively:

$$\varphi_z = \eta_t + \varphi_x \eta_x + \varphi_y \eta_y \quad \text{on } z = \eta(x, y, t), \tag{2.2}$$

$$\varphi_z = \zeta_t + \varphi_x \zeta_x + \varphi_y \zeta_y \quad \text{on } z = -h + \zeta(x, y, t), \tag{2.3}$$

$$\varphi_t + \frac{1}{2}(\nabla \varphi)^2 + g\eta = 0 \quad \text{on } z = \eta(x, y, t) \tag{2.4}$$

where g is the acceleration due to gravity. As described above, the initial conditions are given by

$$\varphi(x, y, z, 0) = \eta(x, y, z, 0) = \zeta(x, y, z, 0) = 0. \tag{2.5}$$

In the case of tsunamis propagating on the surface of deep oceans, one can consider that Shallow-water theory is appropriate because the water depth (typically several kilometers) is much smaller than the wave length (typically several hundred kilometers), which is reasonable and usually true for most tsunamis triggered by submarine earthquakes, slumps and slides. Hence the problem can be linearized by neglecting the nonlinear terms in the boundary conditions (2-4) and if the boundary conditions are applied on the nondeformed instead of the deformed boundary surfaces (i.e. on $z = -h$ and $z = 0$ instead of $z = -h + \zeta(x, y, t)$ and $z = \eta(x, y, t)$). The linearized problem in dimensionless variables can be written as

$$(\nabla^2 - \sigma^2)\, \varphi(x, y, z, t) = 0 \qquad \text{where } (x, y, z) \in R^2 \times [-(h + h_s), 0], \tag{2.6}$$

Subjected to the following boundary conditions

$$\varphi_z = \eta_t \qquad \text{on } z = 0 \tag{2.7}$$

$$\varphi_z = \zeta_t \qquad \text{on } z = -h \tag{2.8}$$

$$\varphi_t + g\eta = 0 \quad \text{on } z = 0 \quad . \tag{2.9}$$

The linearized shallow water solution of the equation "(2.6)" can be obtained by Fourier-Laplace transform.

3. SOLUTION OF THE PROBLEM

Our interest is to study the effect of porous parameter in the resulting uplift of free surface elevation $\eta(x, y, t)$. An analytical analysis is examine to illustrate the generation and propagation of a tsunami with effect of permeability of rocks for a given bed profile ζ (x, y, t). Fourier-Laplace transform of the Brinkman equation has been used to study the effect of permeability of rocks in tsunami development. All our studies were taken into account constant depths for which the Laplace and Fast Fourier Transform (FFT) methods could be applied. The equations "(2.6)-(2.9)" can be solved by using the method of integral transforms. We apply the Fourier transform in (x, y).

$$\Im[f] = \hat{f}(k_1, k_2) = \int_{R_2} f(x,y)e^{-i(k_1x+k_2y)}dxdy$$

with its inverse transform

$$\Im^{-1}[\hat{f}] = f(x,y) = \frac{1}{(2\pi)^2}\int_{R_2}\hat{f}(k_1,k_2)e^{i(k_1x+k_2y)}dk_1\,dk_2$$

and the Laplace transform in time t,

$$L[g] = G(s) = \int_0^\infty g(t)e^{-st}dt$$

For the combined Fourier and Laplace transforms, the following notation is introduced:

$$\Im(\,L(\,f(x, y, t))) = \overline{F}(k_1,k_2,s) = \int_{R_2} e^{-i(k_1x+k_2y)}\,dxdy\int_0^\infty f(x, y, t)e^{-st}dt$$

Combining "(2.7)" and "(2.9)" yields the single free –surface condition

$$\varphi_{tt}(x, y, 0, t) + g\varphi_z(x, y, 0, t) = 0. \tag{3.1}$$

After applying the transforms and using the property $\Im[\frac{d^n f}{dx^n}] = (ik)^n\,\overline{F}(k)$ and the initial conditions "(2.5)", equations "(2.6)", "(2.8)" and "(3.1)" become

$$\overline{\varphi}_{zz}(k_1,k_2,z,s) - (k_1^{\,2} + k_2^{\,2} + \sigma^2)\,\overline{\varphi}(k_1,k_2,z,s) = 0 \tag{3.2}$$

$$\overline{\varphi}_z(k_1,k_2,-h,s) = s\overline{\zeta}(k_1,k_2,s) \tag{3.3}$$

$$s^2\overline{\varphi}(k_1,k_2,0,s) + g\overline{\varphi}_z(k_1,k_2,0,s) = 0 \tag{3.4}$$

The transformed free-surface elevation can be obtained from "(2.9)" as

$$\overline{\eta}(k_1, k_2, s) = -\frac{s}{g}\overline{\varphi}(k_1, k_2, 0, s) \tag{3.5}$$

The general solution of "(3.2)" will be given by

$$\overline{\varphi}(k_1, k_2, z, s) = A(k_1, k_2, s)\cosh(kz) + B(k_1, k_2, s)\sinh(kz) \tag{3.6}$$

where $k = \sqrt{k_1{}^2 + k_2{}^2 + \sigma^2}$. The functions A ($k_1$, k_2, s) and B (k_1, k_2, s) can be easily found from the boundary conditions "(3.3)" and "(3.4)",

$$A\ (k_1, k_2, s) = \frac{g\,s\,\overline{\xi}\,(k_1, k_2, s)}{\cosh(kh)[s^2 + g\,k\tanh(kh)]}$$

$$B\ (k_1, k_2, s) = \frac{s^3\overline{\zeta}(k_1, k_2, s)}{k\cosh(kh)[s^2 + g\,k\tanh(kh)]}$$

Substituting the expressions for the functions A and B in the general solution "(3.6)" yields

$$\overline{\varphi}(k_1, k_2, z, s) = -\frac{g\,s\,\overline{\zeta}(k_1, k_2, s)}{\cosh(kh)[s^2 + \omega^2]}\left(\cosh(kh) - \frac{s^2}{gk}\sinh(kh)\right) \tag{3.7}$$

where $\omega = \sqrt{g\,k\tanh(kh)}$ is the circular frequency of wave motion. The free surface elevation $\overline{\eta}(k_1, k_2, s)$ can be obtained from "(3.5)" as

$$\overline{\eta}(k_1, k_2, s) = \frac{s^2\overline{\zeta}(k_1, k_2, s)}{\cosh(kh)(s^2 + \omega^2)} \tag{3.8}$$

A solution for η(x, y, t) can be evaluated for specified ζ(x, y, t) by computing approximately its transform $\overline{\zeta}(k_1, k_2, s)$ then substituting it into "(3.8)" and inverting $\overline{\eta}(k_1, k_2, s)$ to obtain $\overline{\eta}(k_1, k_2, t)$. We concern to evaluate η(x, y, t) by transforming analytically the assumed source model then inverting the Laplace transform of $\overline{\eta}(k_1, k_2, s)$ to obtain $\overline{\eta}(k_1, k_2, t)$ which is further converted to η(x, y, t) by using double inverse Fourier Transform.

The circular frequency ω describes the dispersion relation of tsunamis and implies phase velocity

$c = \dfrac{\omega}{k}$ and group velocity $U = \dfrac{d\omega}{dk}$. Hence $c = \sqrt{\dfrac{g\tanh(kh)}{k}}$ and $U = \dfrac{1}{2}c\left(1+\dfrac{2kh}{\sinh(2kh)}\right)$.

Since, $k = \dfrac{2\pi}{\lambda}$, hence as $kh \to 0$, both $c \to \sqrt{gh}$ and $U \to \sqrt{gh}$, which implies that the Tsunami velocity $\mathbf{v}_t = \sqrt{gh}$ for wavelengths λ long compared to the water depth h. The above linearized solution is known as the shallow water solution.

Now we consider a model for the sea floor displacement, namely a slowly curvilinear vertical faulting with rise time $0 \le t \le t_1$ and a variable single slip –fault, propagating unilaterally in the positive x-direction with time $t_1 \le t \le t^*$, both with finite velocity v. In the y-direction, the model propagate instantaneously. The set of physical parameters used in the problem are given in Table 1.

Table 1. Parameters used in the analytical solution of the problem.

Parameters	**Value for the uplift faulting**
Source width, W, km	100
Propagate length, L, km	100
Acceleration due to gravity, g, km/sec^2	0.0098
Water depth (uniform), h, km Tsunami velocity, $v_t = \sqrt{gh}$	
Rupture velocity, v, km/sec, to obtain maximum surface amplitude	0.14
Duration of the source process, t, min	$t_1 = \dfrac{50}{v} = 5.95$

For the source model,

$$\zeta(x,y,t) = \begin{cases} \zeta_0 \dfrac{vt}{2L}(1-\cos\dfrac{\pi}{50}x)(1-\cos\dfrac{\pi}{100}(y+150)), & 0 \le x \le 100, \quad -150 \le y \le -50 \\ \zeta_0 \dfrac{vt}{2L}(1-\cos\dfrac{\pi}{50}x), & 0 \le x \le 100, \quad -50 \le y \le 50 \\ \zeta_0 \dfrac{vt}{2L}(1-\cos\dfrac{\pi}{50}x)(1-\cos\dfrac{\pi}{100}(y-150)), & 0 \le x \le 100, \quad 50 \le y \le 150 \end{cases} \tag{3.9}$$

The free surface elevation takes initially the deformation of the bed shown in Figure 2 which remain at this elevation ζ_0 for $t \geq t_1$ and further propagate unilaterally in the positive x- direction with velocity v till it reaches t^*. Laplace and Fourier transform can now be applied to the bed motion described by (18) and we have

$$\Im(L(f(x, y, t)) = \bar{\zeta}(k_1, k_2, s) = \int_{R_2} e^{-i(k_1 x + k_2 y)}\, dxdy \int_0^\infty \zeta(x, y, t)\, e^{-st} dt \qquad (3.10$$

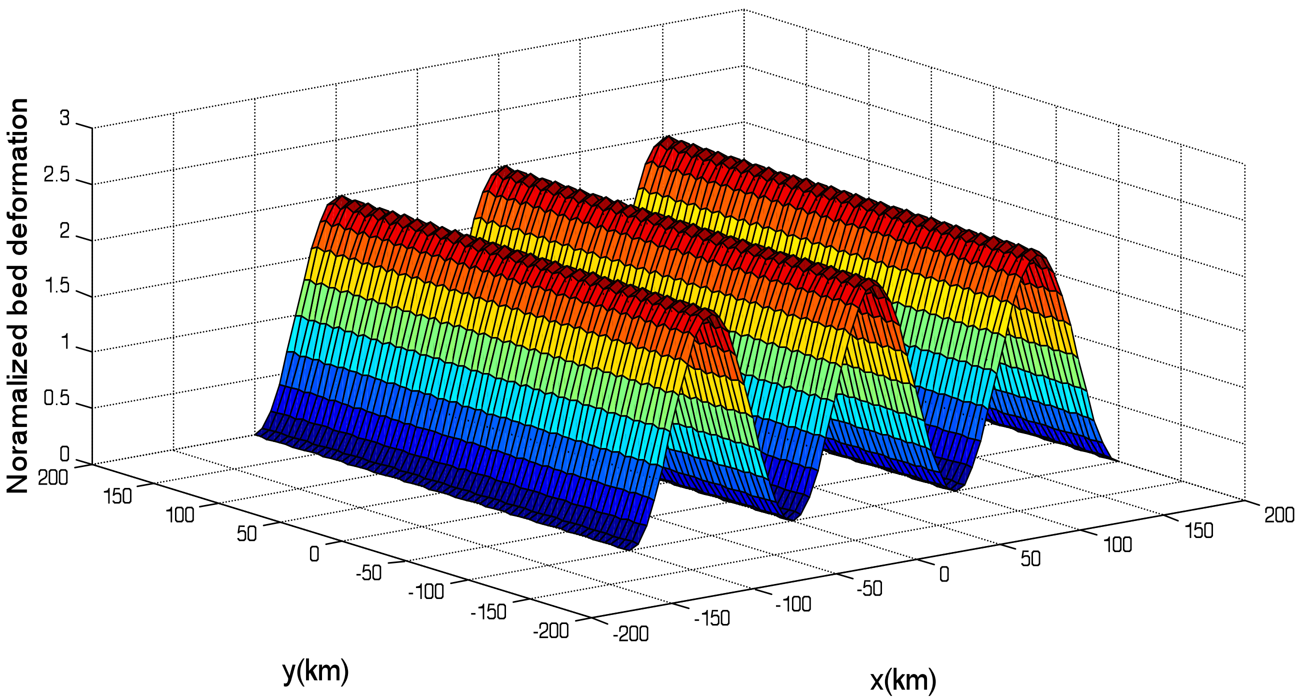


Figure 2. Three dimensional view of Normalized bed deformation representing by a slowly curvilinear uplift faulting at $t_1 = 50 / v$.

The limits of integration are apparent from "(3.9)". Substituting the results of the integration "(3.10)" into "(3.8)", yields

$$\bar{\eta}(k_1,k_2,s) =$$

$$\frac{s}{\cosh(kh)(s^2+\omega^2)}\zeta_0\frac{v}{L}\frac{1}{2s}\left[\frac{(1-e^{-i100k_1})}{ik_1}-\frac{e^{-i100k_1}}{1-(\frac{50}{\pi}k_1)^2}[ik_1(\frac{50}{\pi})^2(e^{i100k_1}-1)\right]x$$

$$\left[\frac{(e^{i150k_2}-e^{i50k_2})}{ik_2}-\frac{1}{1-(\frac{100}{\pi}k_2)^2}[ik_2(\frac{100}{\pi})^2(e^{i50k_2}+e^{i150k_2})+\frac{4\sin(50k_2)}{k_2}+\left[\frac{e^{-i50k_2}-e^{-i150k_2}}{ik_2}+\frac{1}{1-(\frac{100}{\pi}k_2)^2}\right][ik_2(\frac{100}{\pi})^2(e^{i50k_2}+e^{i150k_2})]\right] \tag{3.11}$$

The free surface elevation $\bar{\eta}(k_1,k_2,t)$ can be evaluated using inverse Laplace transform of $\bar{\eta}(k_1,k_2,s)$ as follows:

First, recall that $L^{-1}(\frac{s}{s^2+\omega^2})=\cos\omega t$ and $L^{-1}(\frac{1}{s})=1$, and the inverse of a product of transforms of two functions is their convolution in time.

Hence

$\int_0^t \cos\tau\, d\tau = \frac{\sin\omega t}{\omega}$ and $\bar{\eta}(k_1,k_2,t)$ becomes

$$\bar{\eta}(k_1,k_2,t) =$$

$$\frac{s\,in\omega t}{\omega\cosh(kh)}\zeta_0\frac{v}{2L}\left[\frac{(1-e^{-i100k_1})}{ik_1}-\frac{e^{-i100k_1}}{1-(\frac{50}{\pi}k_1)^2}[ik_1(\frac{50}{\pi})^2(e^{i100k_1}-1)\right]x$$

$$\left[\frac{(e^{i150k_2}-e^{i50k_2})}{ik_2}-\frac{1}{1-(\frac{100}{\pi}k_2)^2}[ik_2(\frac{100}{\pi})^2(e^{i50k_2}+e^{i150k_2})+\frac{4\sin(50k_2)}{k_2}+\left[\frac{e^{-i50k_2}-e^{-i150k_2}}{ik_2}+\frac{1}{1-(\frac{100}{\pi}k_2)^2}\right][ik_2(\frac{100}{\pi})^2(e^{i50k_2}+e^{i150k_2})]\right] \tag{3.12}$$

Finally, $\eta(x, y, t)$ is evaluated using the double inverse Fourier transform of $\overline{\eta}(k_1, k_2, t)$

$$\eta(x, y, t) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty} e^{ik_2 y}[\int_{-\infty}^{\infty} e^{ik_1 x}\,\overline{\eta}(k_1, k_2, t)\,dk_1]\,dk_2 \quad . \tag{3.13}$$

This inversion is computed by using the FFT. The inverse FFT is a fast algorithm for efficient implementation of the Inverse Discrete Fourier Transform (IDFT) given by

$$f(m, n) = \frac{1}{MN}\sum_{p=0}^{M-1}\sum_{q=0}^{N-1} F(p.q)\,e^{i(\frac{2\pi}{M})pm}\,e^{i(\frac{2\pi}{N})}, p = 0,1,..., M-1; q = 0,1,..., N-1$$

where f (m, n) is the resulted function of the two spatial variables m and n, corresponding x and y, from the frequency domain function F(p, q) with frequency variables p and q, corresponding k_1 and k_2. This version is done efficiently by using the Matlab FFT algorithm.

The water wave motion in the near and far field by considering a model based on curvilinear uplifting has been discussed .The effect of permeability of rocks on the Tsunami wave generation and propagation have been investigated using the model.

4. DISCUSSION AND CONCLUSIONS

We are interested in investigating the effect of permeability of rocks near the ocean floor on the wave propagation in Tsunami based on the considered model. For $v/v_t = 0.8$, we have investigated the effect of porous ocean floor using Darcy number σ. Fig. 3, Fig .4 and Fig. 5 represent the wave propagation during Tsunamis with $\sigma = 5.0$, $\sigma = 10.0$ and $\sigma = 15.0$ respectively. In these figures three dimensional and two dimensional waves run up have been shown with the effect of σ. The closer view of wave run-up has been shown in Fig. 6, Fig. 7 and Fig. 8 for $\sigma = 5.0$, $\sigma = 10.0$ and $\sigma = 15.0$ respectively.

The case of Tsunami in Japan -2011 has been discussed by taking the approach of this model. It is observed that the amplitude of Tsunami wave run is extremely high in this case as can be seen in Fig. 10. (Vithanage 2008) has demonstrated the wave run during Tsunami in Srilanka -2006 and we modified it by taking the effect of permeability of ocean floor and shown in Fig. 11. (Kumar et al. 2008) have studied Tsunami hazard along Chennai coast and demonstrated Inundation map for it. We have used that map to explain the effect of permeability of ocean floor based on considered model. In Fig. 12, the affected regions of India near Chennai-2004 by Tsunami have been shown. We have investigated that the Tsunami wave propagation depend on the vulnerability of the region which is based on the permeability of rocks and sediments inside the coastal zone. It is observed that in the region of less vulnerability the amplitude of Tsunami wave run was low in comparison to high vulnerable region.

It is observed that near the source the wave has large amplitude and as the permeability of the ocean floor increases the amplitude of wave increases. The present analysis suggests that some abnormally large tsunamis could be explained in part by considering the effect of permeability of rocks near the ocean floor. Our results should help to improve Tsunami forecasts and warnings based on recoverable seismic data.

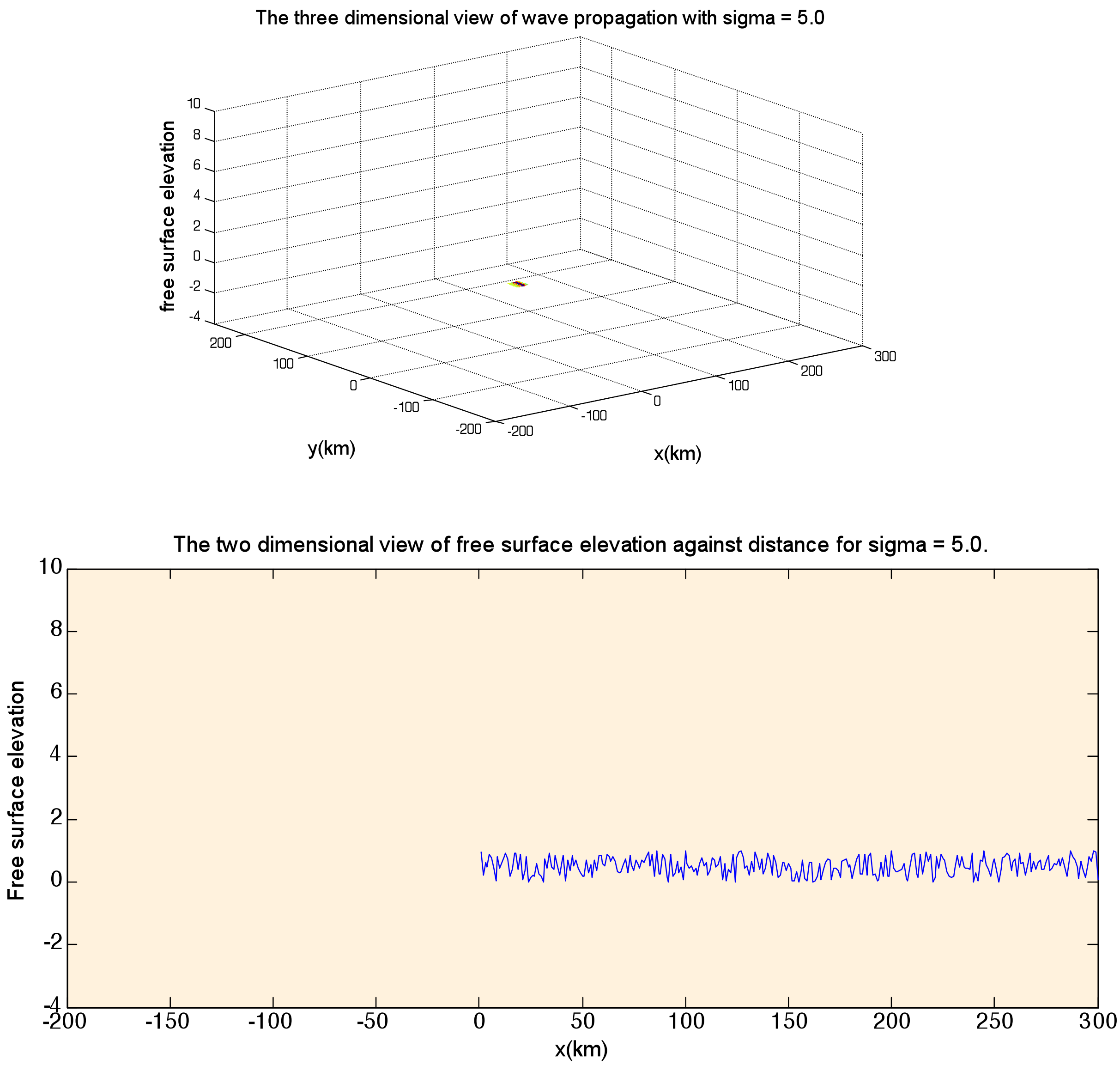
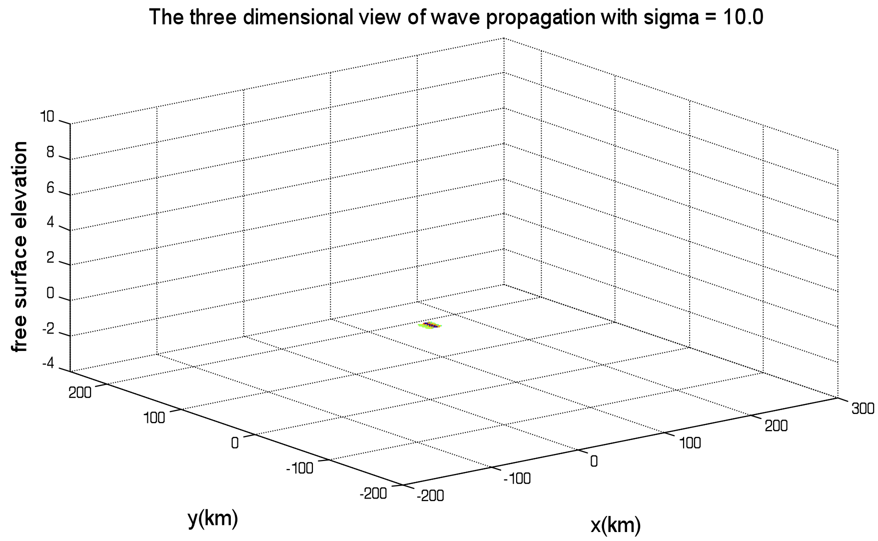


Figure 3. Dimensionless free surface deformation $\eta(x, y, t^*)/\zeta_0$ for $v/v_t < 1$ at h = 2 km, L = 150 km, W = 100 km, v_t = 0.14 km/sec and t^* = 50/v sec.



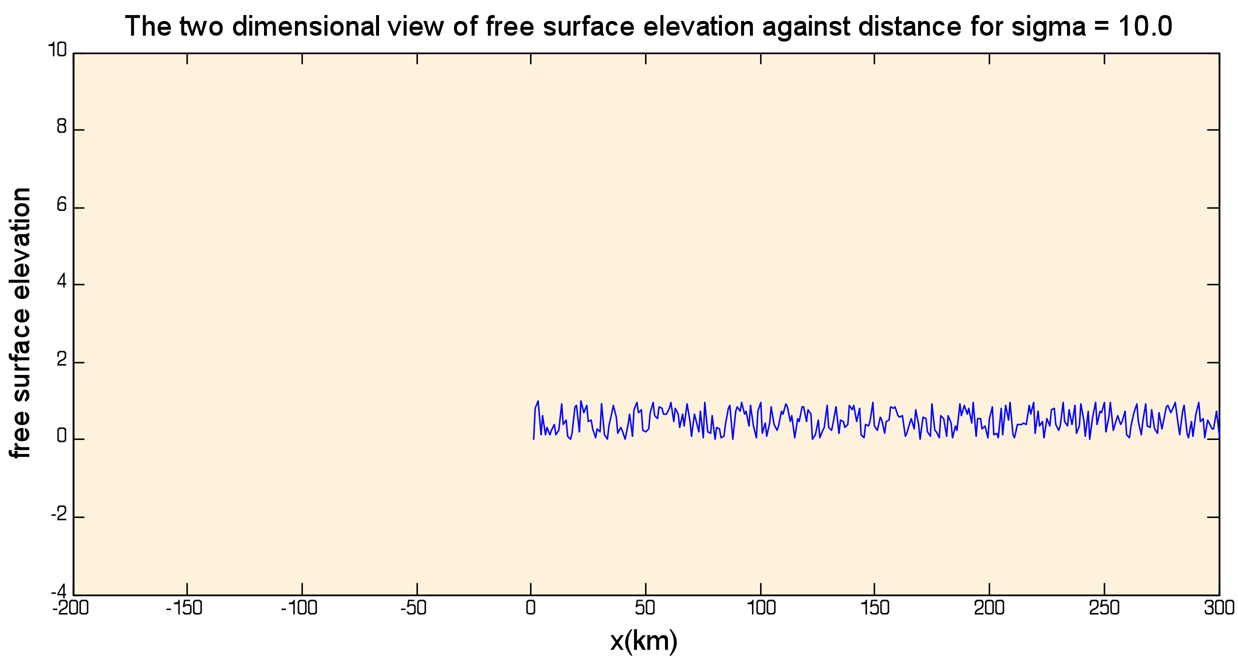


Figure 4. Dimensionless free surface deformation $\eta(x,y,t^*)/\zeta_0$ for $v/v_t < 1$ at h = 2 km, L = 150 km, W = 100 km, v_t = 0.14 km/sec and t^* = 50/v sec.

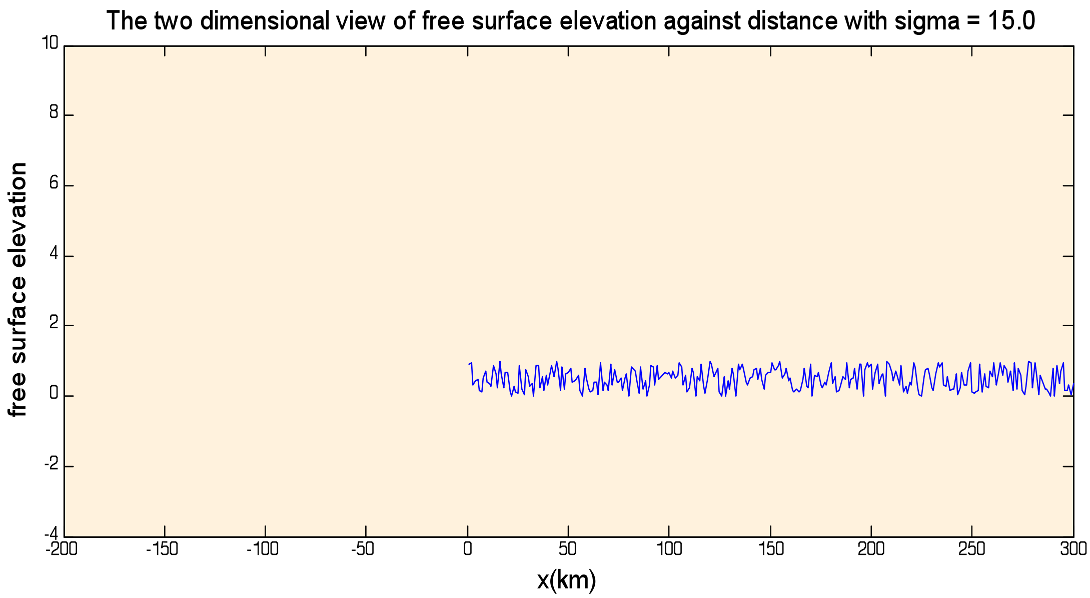


Figure 5. Dimensionless free surface deformation $\eta(x, y, t^*)/\zeta_0$ for $v/v_t < 1$ at h = 2 km, L = 150 km, W = 100 km, v_t = 0.14 km/sec and t^* = 50/v sec.

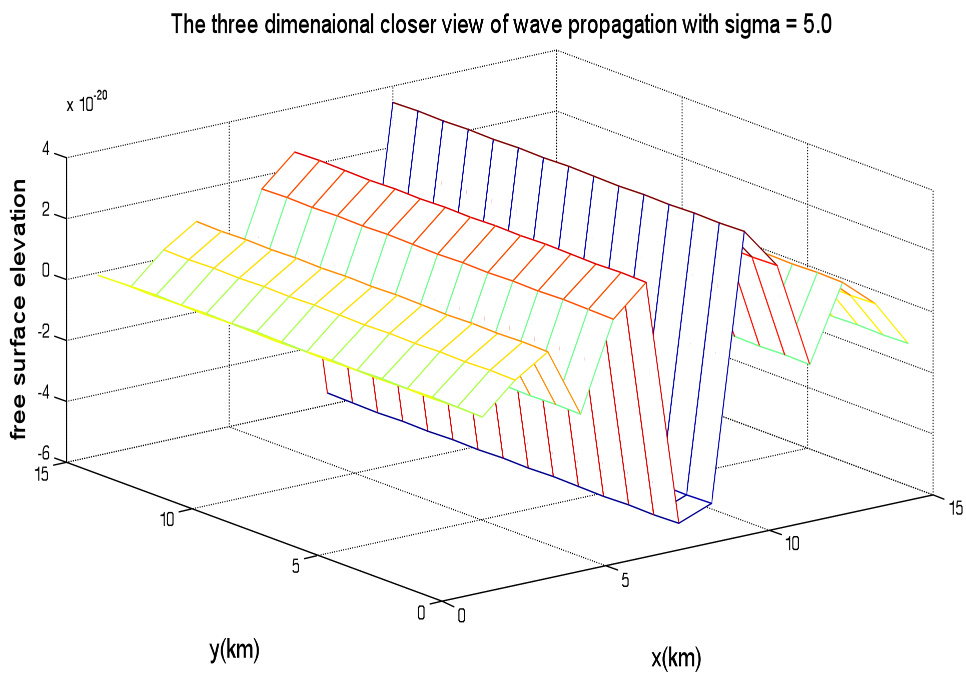


Figure 6. Dimensionless closer view of wave propagation for h = 2 km, L = 150 km, W = 100 km, v_t = 0.14 km/sec and t^* = 50/v sec.

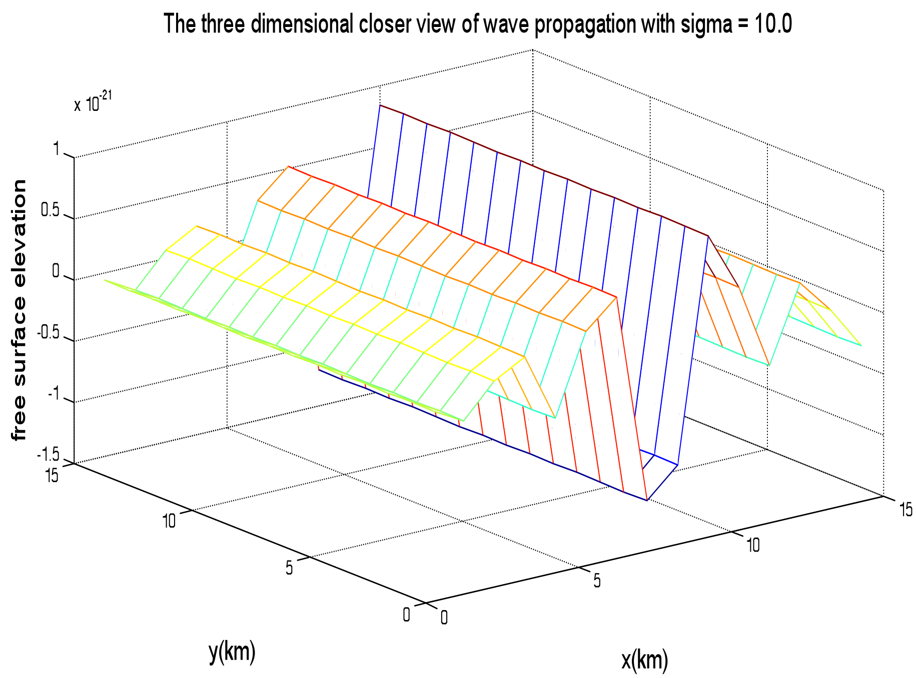


Figure 7. Dimensionless closer view of wave propagation for h = 2 km, L = 150 km, W = 100 km, v_t = 0.14 km/sec and t^* = 50/v sec.

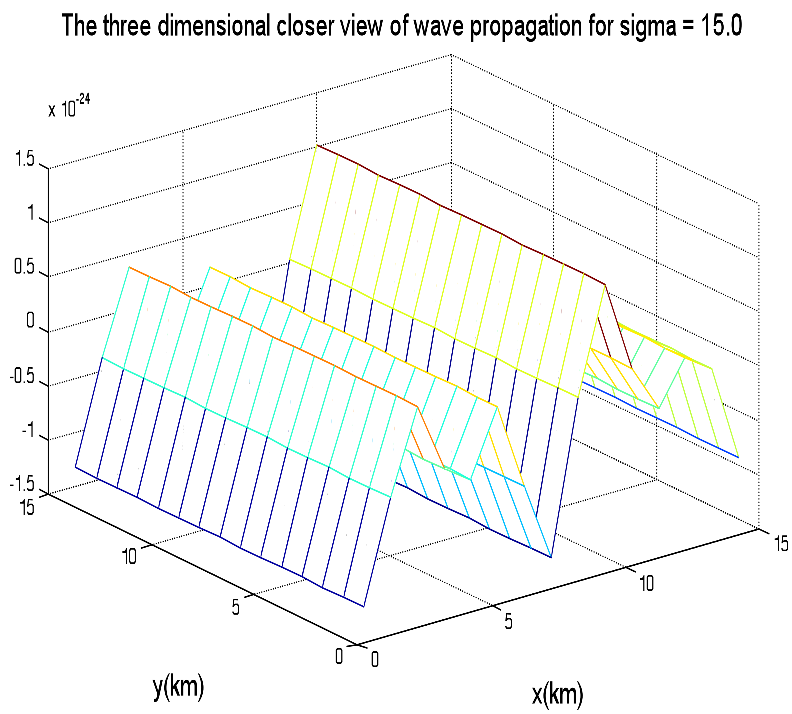


Figure 8. Dimensionless closer view of wave propagation for h = 2 km, L = 150 km, W = 100 km, v_t = 0.14 km/sec and t^* = 50/v sec.

Figure 9. The affected regions of Japan in Tsunami -2011.

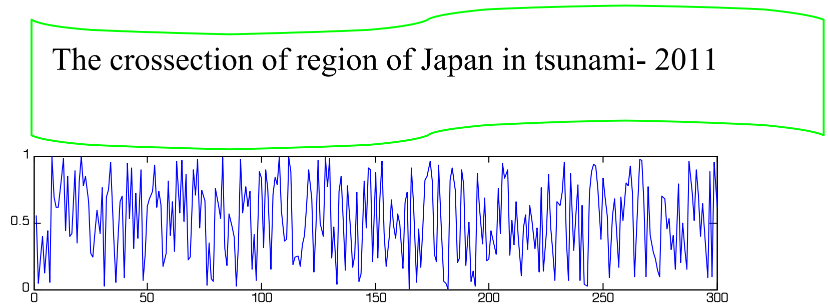
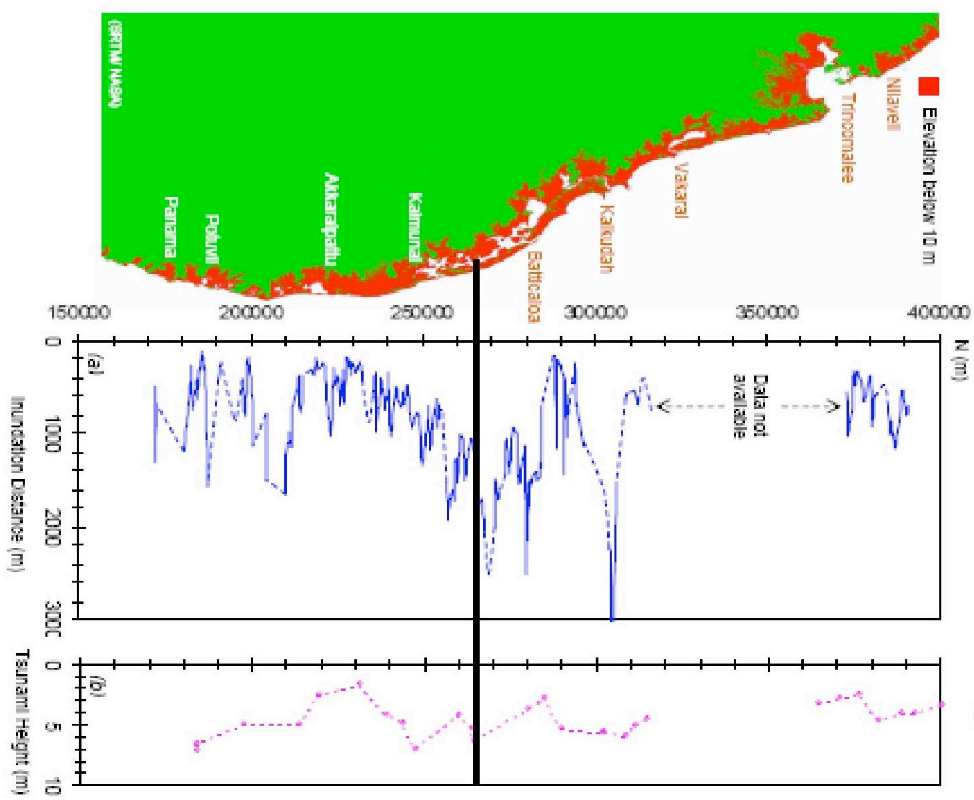


Figure 10. The wave propagation in Tsunami at Japan in 2011 based on the considered model.



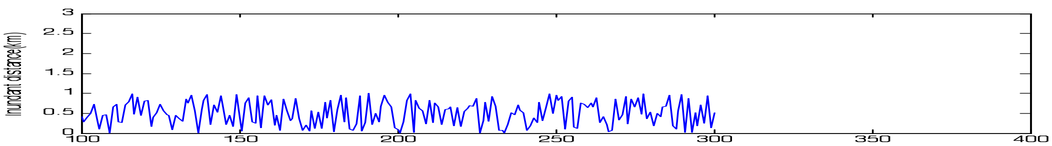


Figure 11. The wave propagation with the effect of permeability of rocks in Tsunami at Srilanka in 2006

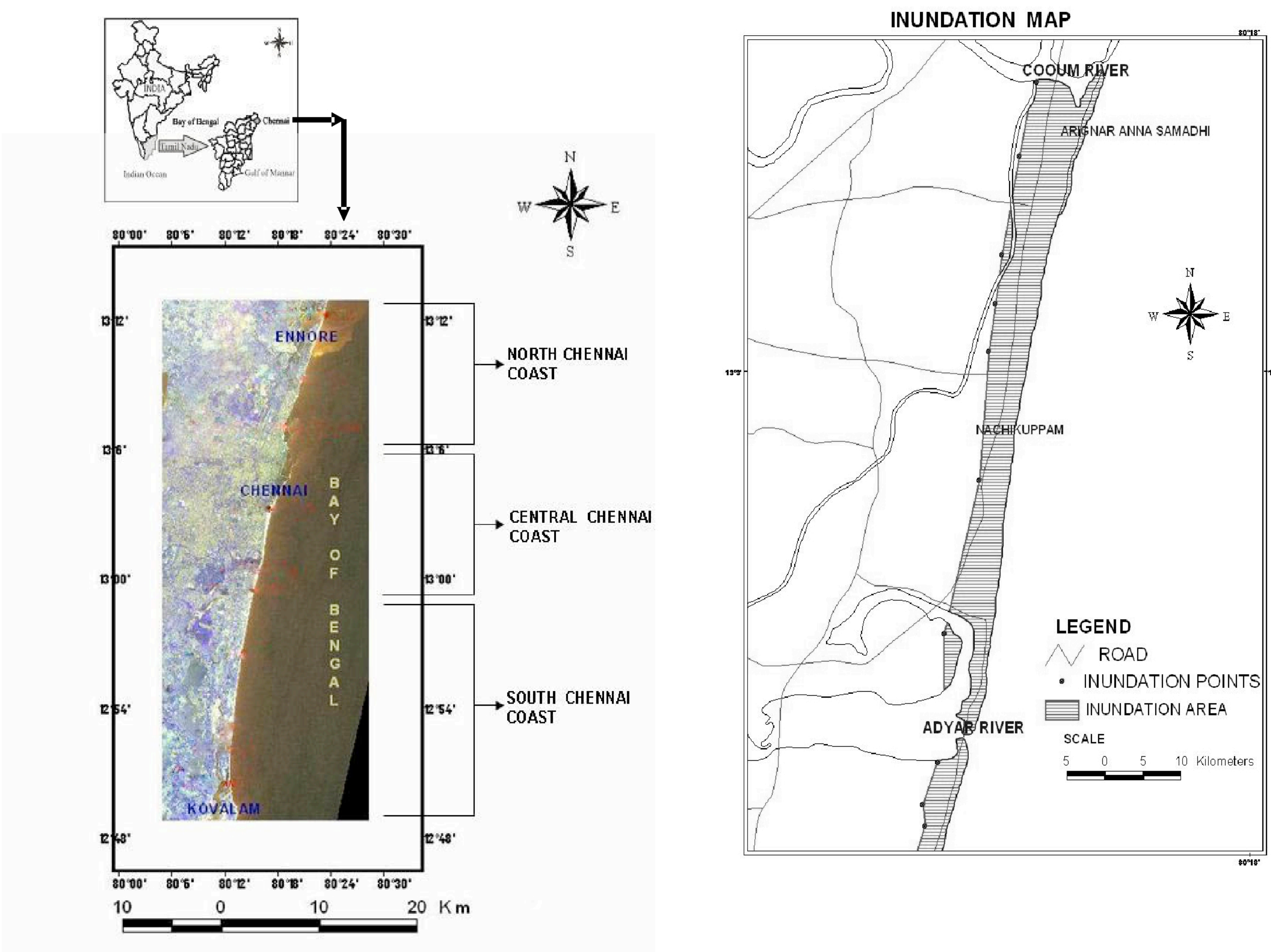


Figure 12. The affected regions of Chennai in Tsunami - 2004.

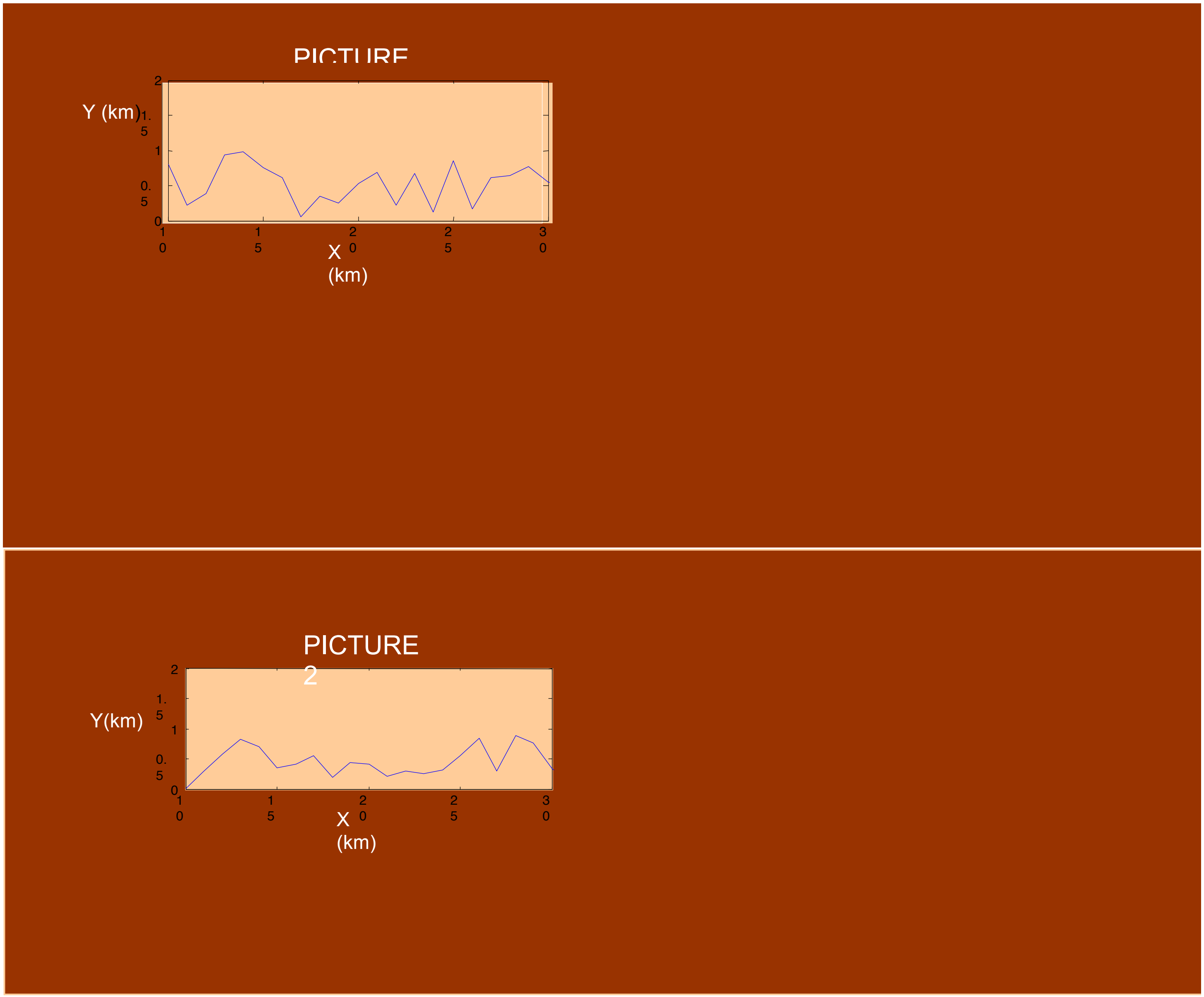


Figure 13. Picture 1 presents the wave propagation in less vulnerable region and Picture 2 presents it in high vulnerable region of Tsunami in Chennai 2004.

ACKNOWLEDGMENTS

The author, Parul Saxena is thankful to the Department of Atomic Energy, Government of India for the financial assistance and to the Department of Mathematics, Jaypee Institute of Information & Technology for research facilities during this work.

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