The 2004 Indian Ocean tsunami caused enormous loss of lives and damage to property in Sri Lanka and in several other countries bordering the Indian Ocean. One way of mitigating potential loss of lives from a similar event in the future is through early warning and quick evacuation of vulnerable coastal communities to safer areas, and such evacuation planning is usually carried out based on inundation maps. Accordingly, the present paper outlines the numerical modelling carried out to develop tsunami inundation maps on a grid of 10 m resolution for three cities on the south coast of Sri Lanka. The results give the tsunami arrival time contours and the spatial distribution of the extent of inundation, the maximum flow velocities as well as the hydrodynamic force in these three cities due to an event similar to the 2004 tsunami.

Keywords: Tsunami; inundation; numerical modeling.

1. Introduction

The mega-tsunami of 26th December 2004 unleashed by the earthquake of $M_w = 9.1–9.3$ in the Sumatra-Andaman subduction zone caused enormous loss of lives and damage to property in Sri Lanka and in several other countries bordering the Indian Ocean. In Sri Lanka, 13 of the 14 districts lying along the coastal belt were affected: the death toll was nearly 40 000 with 15 000 injured and about 89 000 housing units either completely or partially damaged leaving one million people homeless and causing massive disruption to livelihoods. The unprecedented tragedy clearly underscored the need to have a proper system in place for tsunami early warning as well as for quick evacuation of vulnerable coastal communities to safer areas. One essential pre-requisite in planning such evacuation is the development of inundation maps which provide a graphical presentation of damage-prone areas with expected depth of flooding and flow velocities in case of a similar tsunami attack. Accordingly, the present paper outlines the numerical modeling of tsunami propagation and inundation carried out to develop detailed inundation maps for three cities, namely, Galle, Matara and Hambantota on the south coast of Sri Lanka.
2. Fault Model

The megathrust earthquake that initiated at around longitude 95.80° E and latitude 3.40° N off the west coast of northern Sumatra on 26th December 2004 at 00:59 UTC proceeded northward rupturing 1200 km–1300 km of the Andaman-Sunda trench in about 8 min–10 min [Ammon et al., 2005].

Given the comparatively longer duration of the rupture process as well as its larger spatial extent, transient fault plane models too have been employed in the literature to describe the Sumatra-Andaman earthquake in addition to the more commonly used impulsive models. The impulsive fault plane models assume that the seafloor deforms instantaneously, rupturing the entire fault line simultaneously; such models further assume that the sea surface follows the seafloor deformation instantaneously. On the other hand, the seafloor deformation and the rupture along the fault line are both represented as transient processes in the transient models.

Wang and Liu [2006a] showed that transient seafloor displacement computed by Ji [2005] (also reported in Ammon et al., 2005) and its corresponding impulsive version, which simply used the final stage value of the transient deformation as the seafloor deformation, do not give significant quantitative differences in determining the deep water wave profile of the 2004 tsunami far from the source region in comparison with satellite altimetry measurements. Moreover, Wang and Liu [2006b] also showed that the above impulsive model and the transient model give almost similar onshore inundation distributions on a grid of resolution 45.9 m in the horizontal direction around the bay of Trincomalee on the east coast of Sri Lanka. This is not entirely surprising because the rupture speed of the fault plane was at least one order of magnitude larger than the celerity of tsunami propagation [Wang and Liu, 2007].

Accordingly, the seafloor deformation for the present simulations was, at first, obtained from that recommended in Wang and Liu [2006a], i.e. the impulsive version of the transient model of Ji [2005]. However, tsunami model simulations carried out with these sea floor deformations were found to underestimate the measured nearshore tsunami water surface elevations by about 40 percent in all three cities under consideration. Wang and Liu [2006a] too found that the simulations with the above fault model underestimated the amplitude of the leading wave by about 45 percent when compared with the tide gauge records of the 2004 tsunami at Male and Gan in the Maldives.

Therefore, the original sea floor deformation was increased uniformly by 75 percent so as to give better agreement with field measurements of tsunami heights in one of the cities, namely, Galle. Subsequent model runs with the increased displacement for the other two cities too showed better agreement of model results with the field measurements (further details are given in Sec. 5.3). The initial sea-surface displacement corresponding to this optimized fault model is shown in Fig. 1.

3. Grid Set-Up

A dynamically coupled system of nested grids was employed to simulate the tsunami propagation from Andaman-Sumatra subduction zone towards Sri Lanka and the subsequent inundation of the three cities under consideration. Table 1 gives the spatial extent and the resolution of each grid as well as the coordinate system employed and the type of shallow water equations (SWE) used, i.e. linear or non-linear. The bathymetric data for the largest
grid employed in the simulations, i.e. Layer 1 shown in Fig. 2, was obtained by interpolating ETOPO2 data with a resolution of 2' to a grid of 0.6765' (~1250 m) spacing. Layer 2, which is embedded in Layer 1, is also outlined in Fig. 2.

Fig. 1. The initial sea-surface displacement from the optimized fault model.

Table 1. Model parameters of the nested grids employed in the numerical simulations.

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>Extent of grid (Geographic, WGS84)</th>
<th>No. of Grids</th>
<th>Grid Spacing</th>
<th>Coordinate System</th>
<th>Type of SWE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>from 78.4000 to 98.2950, 0.0000 to 14.8987</td>
<td>1765 x 1320</td>
<td>0.6765 min. (~1250 m)</td>
<td>Spherical</td>
<td>Linear</td>
</tr>
<tr>
<td>2</td>
<td>from 79.2301 to 82.4061, 5.0143 to 6.4896</td>
<td>1385 x 640</td>
<td>0.1353 min. (~250 m)</td>
<td>Spherical</td>
<td>Linear</td>
</tr>
<tr>
<td>3</td>
<td>from 80.1179 to 81.1954, 5.7804 to 6.1790</td>
<td>2355 x 870</td>
<td>50 m</td>
<td>Cartesian</td>
<td>Linear</td>
</tr>
<tr>
<td>41</td>
<td>from 80.1883 to 80.2419, 5.9980 to 6.0511</td>
<td>595 x 590</td>
<td>10 m</td>
<td>Cartesian</td>
<td>Non-Linear</td>
</tr>
<tr>
<td>42</td>
<td>from 80.5176 to 80.5676, 5.8967 to 5.9611</td>
<td>555 x 715</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>from 81.1031 to 81.1503, 6.0890 to 6.1589</td>
<td>525 x 775</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2. Layer 1 of the computational domain; location of layer 2 is also shown.

The bathymetric data for Layer 2 with a grid resolution of 0.1353’ (~250 m) shown in Fig. 3 as well as for Layer 3 (grid spacing 50 m) shown in Fig. 4 was at first interpolated from ETOPO2 data and was then updated with data from the available navigation charts. These navigation charts typically covered depths down to about 3000 m–4000 m at scales 1:150 000 or 1:300 000. Further high resolution bathymetric data available for nearshore areas of Galle (Admiralty Chart No. 819 covering 80.1880°E~80.2461E, 5.9992°N~6.0408°N) and Hambantota (Inset in Admiralty Chart No. 3265 covering 81.1222°E ~81.1472°E, 6.1097°N~6.1400°N) at scales of 1:10 000 and 1:15 000, respectively, were also used.

Three fourth level grids, denoted by Layers 41, 42 and 43 with a grid spacing of 10 m are used to cover the three cities, Galle, Matara and Hambantota, respectively (see Fig. 4 for locations of these grids with respect to Layer 3). The topographic data for the three cities were obtained from high resolution LIDAR (Light Detection and Ranging) survey data (The precise digital earth model of the coastal areas of Sri Lanka, Project Director: Prof. Fabrizio Ferrucci, Italy) made available to the first author by the Ministry of Disaster Management and Human Rights of the Government of Sri Lanka. These LIDAR data have been acquired at a horizontal resolution of 1 m and a vertical resolution of not more than 0.3 m and were originally projected on to the UTM WGS84–Zone 44N coordinate system.

Two sets of LIDAR data are available: one DGM (Digital Ground Model) giving elevation of bare earth with 90–95 percent of vegetation and man-made elevated features removed, and the other, DSM (Digital Surface Model) giving surface elevation without removing vegetation or other man-made features. For the present model simulations only DGM data were used.
4. Model Formulation

The numerical model — COMCOT (Cornell Multi-grid Coupled Tsunami Model) — is used to simulate transoceanic tsunami propagation and subsequent inundation in coastal areas. COMCOT uses a modified leap-frog finite difference scheme to solve (both linear and nonlinear) shallow water equations in a staggered finite-difference nested grid system. The model has been validated by experimental data [Liu et al. 1995] and has been successfully used to investigate several historical tsunami events, such as the 1960 Chilean tsunami, the 1992 Flores Islands (Indonesia) tsunami [Liu, et al., 1994; Liu, et al., 1995], and more recently, the 2004 Indian Ocean tsunami [Wang and Liu, 2006a, 2006b, 2007].
Using a nested grid system, COMCOT is capable of simultaneously calculating the tsunami propagation in ocean and the inundation in the targeted coastal zones. In the nested grid system, the inner (finer grid) regions adopt a smaller grid size and time step and are nested inside an outer (larger grid) region. At the beginning of each time step, along the interface of two different regions, the volume flux, which is product of water depth and depth-averaged velocity, is interpolated from the outer (larger grids) region into inner (finer grids) region. The water surface elevations and the volume fluxes in the inner (finer grids) region are calculated and the resulting free-surface elevations are averaged to update those values in the larger grids, which overlaps the inner region. The volume fluxes in the outer (larger grids) region can also be updated. With this algorithm, we can capture nearshore features of tsunami dynamics with a high spatial and temporal resolution, and at the same time, we can still maintain a high computational efficiency. To simulate onshore flooding, a moving boundary scheme described by Cho [1995] was employed, in which the “shoreline” is defined as the interface between a wet grid and its adjacent dry grids. Along the “shoreline”, the volume flux is assigned to be zero. Once the water surface elevation at the wet grid is higher than the land elevation in its adjacent dry grids, the “shoreline” is moved one grid toward the dry grid and the volume flux is no longer zero and needs to be calculated by the governing equations.

The amplitude of the 2004 Indian Ocean tsunami during its propagation in the ocean basin and continental shelf was in the order of magnitude of 1 m–2 m, whilst the typical water depth is around 3 km–4 km in ocean basin and is in the order of magnitude of 100 m on the shelf. Therefore, the nonlinearity is relatively small and can be ignored. In addition, the wavelength of the leading wave was in the order of magnitude of 100 km in ocean basin and 10 km nearshore, about two orders of magnitude larger than water depth, indicating that the dispersive effect is not of importance. Thus, linear shallow water equations are adequate to solve tsunami propagation in Layers 1, 2 and 3.

On the other hand, in the inundation areas in Layer 4, the water depth becomes very small and approaches zero at the tip of the surging bore. Thus, the nonlinearity, i.e. the wave amplitude to depth ratio, could become significant. However, owing to the shallowness of the water, the frequency dispersion effects, which are represented by the water depth to wave length ratio, can still be negligible. Therefore, tsunami overland flow can be adequately described by the non-linear shallow water equations with bottom frictional terms included [Wang and Liu, 2007].

As the spatial extent is comparatively larger in Layers-1 and -2, we adopt the linear shallow water equations on the spherical coordinate system as given in the following:

\[
\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left[ \frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \phi} \left( \cos \phi Q \right) \right] = 0
\]

\[
\frac{\partial P}{\partial t} + \frac{gh}{R \cos \phi} \frac{\partial \zeta}{\partial \psi} - fQ = 0
\]

\[
\frac{\partial Q}{\partial t} + \frac{gh}{R} \frac{\partial \zeta}{\partial \phi} + fP = 0
\]

where, \(\zeta\) is free surface elevation; \((\psi, \phi)\) denote the longitude and latitude of the Earth; \(R\) is the Earth radius; \(P\) and \(Q\) stand for the volume fluxes \((P = hu \text{ and } Q = hv), \text{ with } u \text{ and } v \text{ being the depth-averaged velocities in longitudinal and latitudinal directions, respectively); \(h\) is the still water depth; and \(f\) represents Coriolis force coefficient.
However, given the comparatively smaller spatial extent of Layer-3 and -4, we solve the governing equations in Cartesian coordinate system in this region. The non-linear shallow-water equations in Cartesian coordinate system can be expressed as:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0
\]

\[
\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{H} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{H} \right) + gH \frac{\partial \zeta}{\partial x} + \tau_x H = 0
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{PQ}{H} \right) + \frac{\partial}{\partial y} \left( \frac{Q^2}{H} \right) + gH \frac{\partial \zeta}{\partial y} + \tau_y H = 0
\]

where, \(\zeta\) is the free surface elevation; \((x, y)\) denote the horizontal coordinates in Cartesian coordinate system; \(\tau_x\) and \(\tau_y\) are the bottom shear stress in \(x-\) (pointing to the east) and \(y-\) (pointing to the north) directions, respectively; and \(H\) is the total water depth.

The bottom shear stress terms are modelled by using the Manning’s formula as:

\[
\tau_x = \frac{\rho g n^2}{h^{5/3}} \left( \frac{P^2 + Q^2}{H} \right)^{1/2}
\]

\[
\tau_y = \frac{\rho g n^2}{h^{5/3}} \left( \frac{P^2 + Q^2}{H} \right)^{1/2}
\]

where \(n\) is the Manning’s relative roughness coefficient, which parameterizes the land surface conditions. A discussion of the different types of bottom friction terms used in tsunami inundation modeling, and their uncertainties, is given by Titov and Synolakis [1998]. In the present work, we use a Manning’s roughness coefficient of \(n = 0.02\) over dry land and \(n = 0\) over lakes and waterways onshore. The presence of buildings and other structures, if sufficiently strong, too retard the tsunami flood flow and help dissipate energy although such effects have not been parameterized in the present model formulation.

Because of the smaller spatial extents of Layers 2, 3 and 4, Coriolis force effect is not considered for these regions.

5. Results and Discussion

5.1. Introduction

The model results were processed to obtain the spatial distributions of the maximum values of the depth of inundation, the flow velocity and the hydrodynamic force as well as their temporal variations in the three cities under consideration due to an event similar to the 2004 Indian Ocean tsunami. Moreover, tsunami arrival time contours were also computed based on the first 1 cm rise of the mean water level.

5.2. Tsunami arrival times

The computed arrival time contours for the 2004 tsunami are shown in Fig. 5 for the three cities under consideration: (a) Galle, (b) Matara, and (c) Hambantota. The topography and the bathymetry of the fourth level grids used in the numerical simulations are also shown in these figures.
Fig. 5. Computed tsunami arrival time contours in minutes after the start of the earthquake for the city of: (a) Galle, (b) Matara, and (c) Hambantota. The color scale gives the topography and the bathymetry of each grid.
We see that, according to the numerical results, the tsunami reaches the central area of Galle city (located ~80.216°E, 6.032°N) about 135 min after the earthquake. This agrees well with the numerical simulations of Tomita et al. [2007] who reported an arrival time of 135 min–139 min and with the eyewitness accounts of an arrival time of 140 min reported by the Geological Survey and Mines Bureau (GSMB) of Sri Lanka. An article in the Gulf Today newspaper of 13th January 2005 showed a picture of a clock in a damaged house near the harbour that had stopped at 9:25 AM local time, i.e. 146 min after the earthquake. Moreover, Inoue et al. [2007] give a tsunami arrival time in Galle city of between 120 min–150 min based on eyewitness accounts.

The eyewitness accounts reported by the GSMB and Inoue et al. [2007] indicate tsunami arrival times of 135 min–140 min and 135 min, respectively, for the city of Matara (Fig. 5(b)), although the numerical simulations suggest an arrival time of about 123 min.

For the city of Hambantota (Fig. 5(c)), the numerical simulations suggest an arrival time of around 130 min whilst GSMB report tsunami arriving the main bus terminal, which is located about 100 m from the shore, 135 min–140 min after the earthquake. Moreover, Inoue et al. [2007] report that the clock that was on the clock tower located close to the bus terminal had stopped at 9:22 AM local time, i.e. 143 min after the earthquake, probably corresponding to the arrival of the maximum wave which according to some eyewitnesses was the first wave. However, another eyewitness account reported in Inoue et al. suggests an arrival time of 130 min for the first wave.

It must be noted that, although the earthquake started at 00:59 UTC off northern Sumattra, and propagated towards Andaman-Nicobar islands over a duration of about 8 min–10 min, the numerical simulation assumes an instantaneous rupture at 00:59 UTC. However, it is likely
that, considering the inclination of the longitudinal axis of the rupture zone, the primary forcing for the tsunami that arrived in the south coast of Sri Lanka was from Nicobar area and the rupture in that area may have occurred about 5 min–7 min later. Secondly, the computed arrival times correspond to the first 1 cm rise of water level, although the crest of the wave, which most people may have noted, would have arrived about 5 min–10 min later depending on the period of the wave. Thirdly, as mentioned by Inoue et al. [2007], some of the eyewitnesses may not have been wearing watches during the tsunami, so they depended only on their sense of time; furthermore, some eyewitnesses may not have seen the first wave because they were not near the ocean at that time, so the first wave of an eyewitness does not necessarily correspond to the actual first wave.

5.3. Computed and measured tsunami heights

We compare in Fig. 6 the computed maximum water elevations with those measured by post-tsunami survey teams at several locations close to the shoreline in the modeled areas of the three cities, Galle, Matara, and Hambantota. The coordinates of the locations of field measurements of water levels are given in Table 2. Note that these measurements of water elevation have been made at distances ranging from 12 m to 425 m inland from the shoreline. We see in Fig. 6 that the simulated water levels agree reasonably well with the field measurements. We also note that the computed values are consistently lower than the measured elevations (with a mean deviation of 20 percent over a range of 2–28 percent) at all locations except at M1 in Matara, where the computed elevation is 26 percent higher than the measured value. However, it must be noted that the present numerical simulations of onshore inundation have been carried out over bare land whilst in reality the urban landscape adjacent to the shoreline in the three cities is congested with buildings and other structures. So, it is not entirely surprising that the typical surface waviness of a fast moving turbulent flow often carrying large amounts of debris and sometimes getting channelled through narrow spaces constrained by buildings and other obstructions could result in a higher water mark under field conditions than over the bare terrain simulated in the numerical computations.

![Fig. 6. Comparison of computed and measured values of the maximum water elevation in Galle (G1–G4), Matara (M1 and M2), and Hambantota (H1–H5). See Table 2 for coordinates of the locations of field measurements.](image-url)
Table 2. The coordinates of the locations of field measurements of maximum water levels shown in Fig. 6.

<table>
<thead>
<tr>
<th>City</th>
<th>Location</th>
<th>Geographical Coordinates on WGS84 (deg.)</th>
<th>Distance from the shoreline (m)</th>
<th>Source of field measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Longitude (°E)</td>
<td>Latitude (°N)</td>
<td></td>
</tr>
<tr>
<td>Galle</td>
<td>G1</td>
<td>80.2373</td>
<td>6.0340</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>G2</td>
<td>80.2328</td>
<td>6.0327</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>G3</td>
<td>80.2244</td>
<td>6.0374</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>G4</td>
<td>80.2150</td>
<td>6.0338</td>
<td>425</td>
</tr>
<tr>
<td>Matara</td>
<td>M1</td>
<td>80.5264</td>
<td>5.9359</td>
<td>389</td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>80.5500</td>
<td>5.9432</td>
<td>51</td>
</tr>
<tr>
<td>Hambantota</td>
<td>H1</td>
<td>81.1286</td>
<td>6.1312</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>81.1280</td>
<td>6.1315</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>81.1279</td>
<td>6.1315</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>H4</td>
<td>81.1273</td>
<td>6.1318</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>H5</td>
<td>81.1272</td>
<td>6.1235</td>
<td>88</td>
</tr>
</tbody>
</table>

5.4. Spatial distribution of inundation and flow velocities

The model results of the spatial distribution of the maximum depth of inundation that would be caused by an event similar to the tsunami in December 2004 in the cities of (a) Galle, (b) Matara, and (c) Hambantota are shown in Fig. 7. The arrows indicate the primary flow paths of onshore flooding. Following Walsh et al. [2003], the computed tsunami inundation is shown on these maps in three color-coded depth ranges: 0–0.5 m, 0.5 m–2 m, and greater than 2 m. These depth ranges have been chosen because they are approximately knee-high or less, knee-high to head-high, and more than head-high. The probable limit of tsunami inundation is the landward edge of the light grey zone. On these maps, lakes, lagoons, streams and canals present in the area as well as the sea are also shown.

The solid circles indicate the furthest extent of inundation from the extensive field measurements that were carried out by the first author in the immediate aftermath of the tsunami [Wijetunge, 2006]. We see that, on the whole, the extent of inundation obtained from the model simulations shows good agreement with the same from the field measurements. It must, however, be added that the points of furthest penetration of inundation from the field measurements do not necessarily correspond to locations where the depth of flooding had been zero; instead, it is likely that the field measurements indicate the locations where the water depth had been very low, probably up to around 30 cm–50 cm. On the other hand, the model simulated furthest limit of inundation in the present results corresponds to a threshold water depth of 5 cm.

The corresponding maps of the magnitude of the computed maximum flow velocities for the three cities are shown in Fig. 8 using three color bands corresponding to velocities less than 1.5 m/s, between 1.5 m/s and 3.0 m/s, and greater than 3.0 m/s. The arrows giving the direction of the maximum flow velocities are not shown on these figures for reasons of clarity.
Sea/ Lakes/ Waterways: ● Field measurements of extent of inundation

(a)

Sea/ Waterways: ● Field measurements of extent of inundation

(b)

Fig. 7. Modelled tsunami inundation in the city of: (a) Galle, (b) Matara, and (c) Hambantota. The arrows indicate the primary flow paths of onshore inundation.
Let us first consider the main features of tsunami flow and inundation in the city of Galle (see Fig. 7(a)). The model simulations indicate that a comparatively weaker surge of water due to the tsunami first entered the central area of the city (main bus terminal, location $B$ in Fig. 7(a)) from south-west along the canal (see Fig. 9(a) for a view of this canal, looking towards the sea), and then about 3 min later, stronger flooding from the eastern side. A video record made by the Independent Television Network of Sri Lanka during the tsunami attack at the bus terminal as well as eyewitness observations further confirm this; a snapshot taken from this video depicting the inundated main bus terminal and the surrounding area is shown in Fig. 9(b). Then the flow from both sides, the stronger flow being from the east of location $B$, the elongated hilly areas on either side, further aided by the canal running in the same direction. The results of the inundation simulations also indicate that, at a location around (80.214'E, 6.039'N), part of the surge of water running between the two hills veers towards south-west and travels along the branch of the canal going that way.
Fig. 8. Computed magnitude of maximum flow velocities in the city of: (a) Galle, (b) Matara, and (c) Hambantota.
Meantime, tsunami surge enters that part of the coastline to the west and east of the Galle Port (location C) as well with greater momentum. Numerical simulations also appear to indicate that the two breakwaters of the port have at least partially reduced the momentum of the tsunami waves approaching the inner harbour from the west and the south, and the port infrastructure appears to have been more affected by the flow entering from the eastern side of the port whilst to a lesser extent from the south as a result of overtopping of the breakwater.

The wall of height around 7 m–9 m of the old Dutch Fort (location A in Fig. 7(a) and see Figs. 9(c) and 9(d) for views of part of the Fort) has prevented the tsunami surge from directly attacking the area inside the Fort. However, the flooding in the surrounding had made its way into the Fort, albeit with much lesser force and flow depths, through two horse-shoe shaped road entrances, about 5 m wide and 3.5 m high, and as a result of overtopping of a comparatively lower part of the perimeter wall on the eastern side. However, as would be expected, the minor flooding in some areas inside the Fort caused neither any loss of lives nor significant damage to property.

The surge of water due to the tsunami also found its way with greater force through the entrance to the Mahamodara lake (location D in Fig. 7(a)). The numerical results suggest that the lake and its waterways have facilitated the spreading of the flow of water further inland as indicated by the arrows shown on Fig. 7(a).
Figure 8(a) depicting the spatial distribution of the magnitude of the maximum flow velocities suggests flow speeds mostly between 1.5 m/s–3.0 m/s, at some points even exceeding 3 m/s, in the flooded areas within about 100 m from the shoreline, and below 1.5 m/s further inland. We also see velocities exceeding 3 m/s particularly in a stretch of coastline between longitude 80.190°E–80.195°E. It may be added here that, according to an experimental study reported in Takahashi [2005], people cannot, in general, remain standing in water depths larger than 0.5 m if the flow velocity exceeds 1.5 m/s. We see that, in the locality of the bus terminal (location B), the maximum flow speed is mostly 1.5 m/s–3 m/s whilst the flow depths are larger than 0.5 m indicating the difficulty in surviving against such currents, and the video record of the tsunami flow at this location confirms this. However, the maximum flow speed in the valley between the two elongated hills north of the bus terminal is largely below 1.5 m/s whilst the flow depths are mostly below 0.5 m, suggesting that most people in this area must have survived the tsunami.

Note that numerical results are not shown for that part of the city at the top right corners of Figs. 7(a) and 8(a) because LIDAR topographic data available for that area were found to be corrupt.

It must be added that the local flow velocities during the tsunami in December 2004 could have been somewhat different from those computed in the present study owing to, among other reasons, the fact that the model simulations have been done over bare land whereas various natural and man-made obstructions exist in reality. Such obstructions could, on one
hand, help dissipate energy thus retarding the flow on the whole, whilst on the other, could increase flow speeds locally due to the possibility of channelling of the flow.

We now consider in Figs. 7(b) and 8(b), respectively, the spatial distribution of inundation and flow velocities in the city of Matara. A large extent of the modelled area in Matara is fairly flat with an average elevation of about 2 m–3 m above MSL; however, there is a hilly area of peak elevation about 50 m to the east of longitude ~80.560°E. The other major feature of the topography is the river Nilwala meandering through the city as well as several streams connected to it, and as one would expect, the numerical results confirm that the river and its branch- ing streams have had a significant influence on the distribution of inundation in Matara.

The time sequence of model results suggest that the tsunami wave front first attacked the coastline to the west of longitude 80.535°E and then gradually reached the other parts of the city’s shoreline. As would be expected, the numerical results further indicate that a strong surge of water had entered the river through its mouth and travelled up whilst some flood water flowing overland across the area to the east of longitude 80.540°E also had fallen into the river.

Moreover, we see that the flow depths in the modeled area fall mostly between 0.5 m–2.0 m except at some stretches along a narrow band adjacent to the shoreline and also close to the limits of inundation. In this case too, the model results of the extent of inundation, on the whole, show good agreement with the field measurements (solid circles in black). There appears to be one outlier at (80.521°E, 5.948°N): the field records indicate that the tsunami surge has travelled up to this point along a narrow stream; however, it was found that the 10 m gridding of topographic data employed in the present simulations was too coarse to resolve such a narrow stream, and consequently, the inability of the model to simulate flow towards this point.

In Fig. 8(b), we see several patches of high flow velocities, exceeding 3 m/s, most notably that between 80.545°E and 80.551°E (approximately), and extending right up to the river from the shoreline; this latter area includes the central part of the city with the main bus terminal also located there.

Let us now consider the spatial distribution of inundation and maximum flow speeds shown in Figs. 7(c) and 8(c), respectively, for the city of Hambantota. First of all, we see that the spatial distribution of inundation predicted by the model shows good agreement with the field measurements, i.e. solid circles in black, at most locations. The numerical simulation indicates that the tsunami first attacked the southern part of the city lying along latitude 6.120°N (approximately), although there is no significant onshore incursion of flood water in this area owing to the presence of sand dunes of height around 5 m–7 m with thick vegetation cover on top. Immediately thereafter, the tsunami wave front invades the shoreline encompassing the bay with a remarkably strong surge of water rushing through the neighbourhood of location E in Fig. 7(c); note flow depths and speeds exceeding 2 m (Fig. 7(c)) and 3 m/s (Fig. 8(c)), respectively. Also, note that the onshore lands in the lower southern part of the bay is quite steep and hilly whilst there is a sand dune of height about 5 m–10 m along the upper part of the bay to the north-east of location E. These topographical features of the
coastline of the bay must have been primarily responsible for making the tsunami surge across the locality of $E$, which is heavily populated with housing and other buildings including schools, so strong and devastating as has been reported by eyewitnesses too. Most of this strong surge travels towards Saltern-1 probably picking up further momentum as the land in the vicinity is gently sloping towards the saltern whilst the remaining part runs to Saltern-2 getting channelled through the sand dune on the right and the hilly area to the left of the main flow as indicated by the arrows. Meantime, flood water also rushes through location $F$, where the sand dune had been breached, towards both Saltern-2 and Saltern-3. It is clear that, on the whole, the comparatively vast extents of the salterns have also acted as sinks to absorb and spread water whilst the sand dunes, where present with sufficient elevation, have helped protect the settlements in their shadow from direct tsunami attack.

Clearly, the computed extent of inundation in all three cities showed good agreement with the respective points of furthest penetration of inundation from the field measurements. This appears to suggest that, despite some fundamental limitations, the non-linear shallow water models are capable of simulating tsunami inundation with an accuracy sufficient for most practical purposes such as tsunami hazard mapping for evacuation planning, provided that we use reliable topographic and bathymetric data together with an accurate representation of the seismic forcing.

Furthermore, the model results discussed above clearly indicate the dominant influence of the topographic features on the spatial distribution of tsunami inundation. Wang and Liu [2007] too made a similar conclusion based on their numerical simulations of inundation due to the 2004 tsunami in the north-east coast of Sri Lanka and in Banda Aceh, Indonesia.

### 5.5. Tsunami loading on structures

Given the seemingly low probability of destructive tsunami events affecting Sri Lanka, not all buildings and structures in the vulnerable areas of the coastal belt are expected to be designed to withstand tsunami loading. However, if it is necessary to locate critical infrastructure such as hospitals, sewage treatment facilities, fire stations and power substations in the inundation zone, such structures ought to be designed for tsunami loading to ensure their proper functioning in the event of a disaster. Moreover, information about the spatial distribution of the probable tsunami loading in the inundation zone will enable coastal planners to avoid high risk areas and locate new development in less vulnerable areas.

Accordingly, following Wang and Liu [2007], we provide an order of magnitude indicator of the potential tsunami force acting on a coastal structure. Since it is almost impossible and impractical to develop such an indicator for all types of buildings and infrastructure, as a first attempt, we shall only consider the building as a circular cylinder of unit diameter. During the tsunami run-up and run-down processes, the total horizontal force can be approximately calculated by the Morrison’s formula as:

$$ F = F_t + F_d = C_m \rho Ah \frac{\partial u}{\partial t} + C_d \frac{1}{2} \rho Dh |u| $$  \hspace{1cm} (4)
where, the first and the second terms represent the inertia and the drag forces, respectively; \( C_d \) and \( C_m \) denote the drag coefficient and the mass coefficient; \( A \) is the cross-sectional area of the cylinder; \( D \) is the diameter of the cylinder; \( h \) is the water depth; \( t \) is the time; \( u \) is the velocity; and \( \rho \) is the density of sea water.

The relative importance of the inertia force and the drag force can be estimated as:

\[
O\left( \frac{F_I}{F_D} \right) = O\left( \frac{C_m}{C_d} \frac{D}{L} \right)
\]

where \( L \) denotes the characteristic wavelength and \( a \) is the characteristic tsunami height. In the inundation zone, the tsunami height is of the same order of magnitude as the characteristic water depth, \( h \). For the 2004 tsunami, the wave period is typically between 20 min to 30 min, and hence, in a water depth of \( h = 1 \) m, the corresponding wavelength is roughly in the order of magnitude of \( L \approx 3.6 \) km, which is several orders of magnitude larger than the typical size of a building, \( D \). Consequently, the inertia force can be neglected in comparison with the drag force, i.e.

\[
F \approx F_d = C_d \frac{1}{2} \rho D h |u|.
\]

A reasonable value for the drag coefficient is 1.0–1.4 for a circular cylinder. For a tsunami front surging onshore, the Reynolds number is probably large enough for us to neglect the dependency of \( C_d \) on the Reynolds number in the present order of magnitude estimation of the drag force, so a constant value of \( C_d = 1.0 \) is adopted.

The order of magnitude of the maximum drag force that would be exerted on the unit pile \((D = 1 \) m\) is shown in Fig. 10 for the three cities, Galle, Matara and Hambantota.

In Matara (Fig. 10(b)), for example, the drag force acting on the unit pile in most of the flooded areas closer to the coast is in the order of magnitude of \( 10^4 \) Newton (about 1 metric ton) whilst in some localities the maximum force increases to \( 10^5 \) N (about 10 metric tons). Such large forces could and have caused severe damage especially to wooden and masonry buildings. In general, the maximum drag force decreases as we move inland from the coast owing to decreasing flow depths and velocities.

5.6. Limitations

Since the initial condition for the modeling is determined by the displacement of the ocean bottom along the fault line, the largest source of errors is the earthquake model. Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. Although, high resolution topographic data were available for the present study, the resolution of the bathymetric data used is much less.
Fig. 10. Spatial distribution of the magnitude of the maximum drag force index in: (a) Galle, (b) Matara, and (c) Hambantota. The grey scale gives the order of magnitude of the maximum drag force (Newton) in the logarithmic scale (base 10).
It must also be added that shallow water models assume a uniform velocity profile across the flow depth and neglect vertical accelerations. Moreover, the shallow water formulation employed in the present model does not explicitly account for all means of energy dissipation for a tsunami wave surging onshore over an urban landscape. For instance, although energy dissipation due to bottom friction is included in the present model, dissipation due to turbulence is not explicitly formulated. In this connection, it may be added that Choi et al. [2007] employed a three-dimensional RANS (Reynolds-averaged Navier-Stokes) model together with an RNG (Renormalization Group Theory) turbulent closure to simulate solitary wave run-up on a circular island. They compared their results with those from a shallow water model and found that the differences between the two models were less than 21 percent for run-up heights and less than 40 percent for horizontal velocities.

Nevertheless, these results are useful for local planners and emergency managers to identify areas that should be evacuated in the event of a major tsunamigenic earthquake in the Andaman-Sumatra subduction zone as well as in public education and awareness activities. Because of the uncertainties inherent in this type of modeling, these results are, however, not intended for land-use regulation.
6. Conclusions

The inundation caused by the 2004 Indian Ocean tsunami in three cities on the south coast of Sri Lanka have been numerically simulated by employing shallow water equations. The three cities, namely, Galle, Matara and Hambantota were all devastated by the 2004 tsunami. The model results have been processed to obtain the spatial distribution of the maximum values of the depth of inundation, the flow velocity and the hydrodynamic force as well as tsunami arrival time contours across the areas of interest for the three cities under consideration.

The model results of the extent of inundation showed good agreement with the field measurements of points of maximum penetration of flooding in the three cities.

These model simulations clearly indicate the dominant influence of the topographic features on the spatial distribution of tsunami inundation. It is also clear that waterways such as streams and canals that are open to the sea have provided an easy conduit for the tsunami surge to travel further inland like in Galle and Matara whilst natural barriers such as sand dunes, for example those in Hambantota, have prevented the tsunami from directly attacking the settlements in their shadow.

Acknowledgments

The work described in the present paper was carried out with financial support from National Science Foundation of Sri Lanka Grant No. RG/2005/DMM/02 and USAID/US Indian Ocean Tsunami Warning System (IOTWS) Project Grant No. 04-05-IOTWS-06, awarded to the first author. The first author also benefited from several discussions he had with Prof. F. Imamura, Director of the Tsunami Engineering Laboratory of the Tohoku University, Japan as well as with Dr. S. Takahashi, Executive Director of the Port & Airport Research Institute of Japan on the Japanese experience in developing tsunami hazard maps. The second and the third author would also like to acknowledge the grants from US National Science Foundation to Cornell University.

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