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Method of calculating tsunami travel times in the Andaman Sea region

Monte Kietpawpan,

Faculty of Environmental Management, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand

Parichart Visuthismajarn,

Faculty of Environmental Management, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand

Charlchai Tanavud, and

Faculty of Natural Resources, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand

Mark G. Robson

Environmental and Occupational Health Division, UMDNJ-School of Public Health, and the New Jersey Agricultural Experiment Station—Rutgers University, 88 Lipman Drive, Martin Hall, New Brunswick, NJ 08901, USA

Monte Kietpawpan: kietpawpan@yahoo.com; Parichart Visuthismajarn: parichart.v@psu.ac.th; Charlchai Tanavud: charlchai.t@psu.ac.th; Mark G. Robson: robson@aesop.rutgers.edu

Abstract

A new model to calculate tsunami travel times in the Andaman Sea region has been developed. The model specifically provides more accurate travel time estimates for tsunamis propagating to Patong Beach on the west coast of Phuket, Thailand. More generally, the model provides better understanding of the influence of the accuracy and resolution of bathymetry data on the accuracy of travel time calculations. The dynamic model is based on solitary wave theory, and a lookup function is used to perform bilinear interpolation of bathymetry along the ray trajectory. The model was calibrated and verified using data from an echosounder record, tsunami photographs, satellite altimetry records, and eyewitness accounts of the tsunami on 26 December 2004. Time differences for 12 representative targets in the Andaman Sea and the Indian Ocean regions were calculated. The model demonstrated satisfactory time differences (<2 min/h), despite the use of low resolution bathymetry (ETOPO2v2). To improve accuracy, the dynamics of wave elevation and a velocity correction term must be considered, particularly for calculations in the nearshore region.

Keywords

Tsunami travel time; Tsunami evacuation time; Bathymetry error; ETOPO2v2; ETOPO5; System dynamics

1 Introduction

There is a clear need today for accurate predictions of tsunami travel times to areas, such as Thailand, that are known to be susceptible to tsunamis. To accomplish this, people must be trained to use the most accurate models of tsunami propagation available. The accuracy of such models is principally limited by uncertainty in specification of the tsunami source, inaccuracies in bathymetry data and mapping, and possible under-resolution of the propagating wave front in the numerical simulation (Dalrymple et al. 2006). Travel time calculations to date have been rather unsuccessful, due to problems with state-of-the-art methods for propagation modeling. Whether shallow water equations or Boussinesq equations are used, the most fundamental shortcomings of most models (e.g., Holloway et al. 1985; Shokin et al. 1987; Satake 1988; Wessel 2005) are their failure to accurately represent the continuity of bathymetric profile along the ray path, the dynamics of wave elevation, and the actual speed of the first crest in shallow water. For this reason, models with coarse grid sizes fail to accurately reproduce tsunami travel times, and the use of low resolution bathymetry has often been misperceived as a major cause of the failures. To address this problem, we developed a more accurate model for predicting tsunami travel times, using a new state-of-the-art method for calculating tsunami speed.

2 Theoretical formulation

Tsunami travel time is defined here as the time it takes for the leading crest of a tsunami to travel the distance between its source and a considered target. To calculate tsunami travel times, we relied on the theoretical concepts described below.

Consider a case where a tsunami propagates from its source to the shoreline of a beach. If s is the distance traveled by the leading crest, and S is the total distance between the source and the target, the tsunami travel time, T , can be found on the graph of the function $s(t)$. The x -coordinate of the point $(t, s(t))$ can be located on the graph, provided that $s(t) = S$ and that the values of s are calculated throughout the interval $0 \leq t \leq T$ or $0 \leq s \leq S$.

In spherical coordinates, the total distance S is the length of the minor great circle arc connecting the source and the target. Thus,

$$S = R \arccos(\sin\theta_0 \sin\theta_1 + \cos\theta_0 \cos\theta_1 \cos(\lambda_0 - \lambda_1)) \quad (1)$$

where R is the Earth's radius; θ is latitudes and λ is longitudes in radians, with subscripts 0 and 1 indicating the source and the target, respectively.

The leading crest is assumed to move along the shortest great circle path or ray trajectory. This progressive motion results in the accumulation of the distance propagated by the crest, denoted by s . Thus, the distance propagated $s(t)$ to time t is given by

$$s(t) = s(t_0) + \int_{t_0}^t c(\tau) d\tau \quad (2)$$

where $s(t_0)$ is the distance propagated at time 0, and $c(\tau)$ is the wave celerity at any time τ between the initial time t_0 and the current time t .

Assuming that wave celerity remains constant through out the time interval Δt , then

$$s_t = s_{t-\Delta t} + \Delta t \cdot c_t \quad (3)$$

where s_t denotes $s(t)$; $s_{t-\Delta t}$ is the distance propagated from time 0 to the preceding time, $t - \Delta t$; c_t is the wave celerity at time t ; and Δt is a small time step.

Shallow water approximation based on the Airy wave theory is used to find c_t at time t . A tsunami propagating in the open water behaves like a sinusoidal wave with small amplitude (relative depth < 0.05) and that the leading wave is the longest in a real wave train (Dalrymple et al. 2006). Therefore, the wave celerity depends only on depth, given by

$$c_t = \sqrt{gd_{t-\Delta t}} \quad (4)$$

where g is gravity acceleration, and $d_{t-\Delta t}$ is the still water level below the crest at time $t - \Delta t$.

Bilinear interpolation is then used to find the value of $d_{t-\Delta t}$:

$$d_{t-\Delta t} = d_a + (d_b - d_a)(s_{t-\Delta t} - s_a)/(s_b - s_a) \quad (5)$$

$$d_a = d_{La} + (d_{Ua} - d_{La})(\theta_a - \theta_{La})/(\theta_{Ua} - \theta_{La}) \quad (6)$$

$$d_b = d_{Lb} + (d_{Ub} - d_{Lb})(\theta_b - \theta_{Lb})/(\theta_{Ub} - \theta_{Lb}) \quad (7)$$

where d_a and d_b are the interpolated depths for the points (θ_a, λ_a) and (θ_b, λ_b) on the propagation path; s_a and s_b are the geodetic distances from the source (θ_0, λ_0) to the points (θ_a, λ_a) and (θ_b, λ_b) ; λ_a and λ_b are the registered longitudes ($\lambda_b = \lambda_a + 2$) nearest to the leading crest with $s = s_{t-\Delta t}$ and $s_a < s_{t-\Delta t} < s_b$; d_{La} and d_{Lb} are the registered depths for the points (θ_{La}, λ_a) and (θ_{Lb}, λ_b) ; θ_{La} and θ_{Lb} are the registered lower latitudes nearest to θ_a and θ_b ; d_{Ua} and d_{Ub} are the registered depth for the points (θ_{Ua}, λ_a) and (θ_{Ub}, λ_b) ; and θ_{Ua} and θ_{Ub} are the registered upper latitudes nearest to θ_a and θ_b , respectively (Fig. 1).

As (θ_a, λ_a) and (θ_b, λ_b) are points on the great circle, it follows that

$$\theta_a = \arctan((\sin\theta_0 \cos\theta_1 \sin(\lambda_a - \lambda_1) - \sin\theta_1 \cos\theta_0 \sin(\lambda_a - \lambda_0))/(\cos\theta_0 \cos\theta_1 \sin(\lambda_0 - \lambda_1))) \quad (8)$$

$$\theta_b = \arctan((\sin\theta_0 \cos\theta_1 \sin(\lambda_b - \lambda_1) - \sin\theta_1 \cos\theta_0 \sin(\lambda_b - \lambda_0))/(\cos\theta_0 \cos\theta_1 \sin(\lambda_0 - \lambda_1))) \quad (9)$$

As a tsunami moves into shallower water near the coast, it slows down, and wave height increases via conservation of energy flux, which influences wave celerity. If the bathymetric changes are so gradual as to not cause reflection, the wave height at time $t - \Delta t$, $H(t - \Delta t)$ can be predicted by Green's law (Green 1838; Muraleedharan et al. 2006a, b):

$$H_{t-\Delta t} = H_0 (d_0/d_{t-\Delta t})^{1/4} \quad (10)$$

where H_0 is the initial wave height, and d_0 is the still water level at the tsunami source.

Because the leading crest feels the ocean bottom at any depth (Bryant 2001), wave height varies along the ray path. Wavelength should increase and wave height should decline in deep water via conservation of energy flux, for the same reason that the wave height increases in shoaling water. This theory was confirmed by satellite altimetry observation of the 26 December 2004 tsunami (Gower 2005): the tsunami detected in the deeper Indian Ocean was greater in wavelength (400–500 km) and smaller in amplitude (0.6 m) than its initial length and height in the shallower source region. Therefore, Eq. 4 is adapted to

$$c_t = \sqrt{g(d_{t-\Delta t} + H_{t-\Delta t})} \quad (11)$$

which has been considered a good approximation of a solitary wave (CERC 1984; Sato 1996).

A tsunami does not grow infinitely, as is incorrectly predicted by Green's law. It either breaks in the surf zone or remains stable until nearly reaching the shoreline (Grawin 2005). According to Yeh et al. (1994), the leading crest of a tsunami behaves like a stable solitary wave, which is capable of maintaining its form during propagation by balancing weakly nonlinear and weakly dispersive effects. A wave breaks in shallow water when the steepness (i.e., height/length) exceeds 1/7. Tsunami waves usually do not break in shallow water, because their wavelength (L) is still a few kilometers. If it is assumed that the leading crest of most tsunamis evolves to maximum height $H_{\max}$ in shallow water and remains stable until the wave reaches the shoreline, Green's law can be modified as follows:

$$H_{t-\Delta t} = \begin{cases} H_0(d_0/d_{t-\Delta t})^{1/4} & \text{if } H_{t-\Delta t} < H_{\max} \\ H_{\max} & \text{if } H_{t-\Delta t} \geq H_{\max} \end{cases} \quad (12)$$

3 Model development

3.1 Model purpose

A new model of tsunami travel times, method of nearfield tsunami exploring (MONTE), was developed to more accurately calculate tsunami travel times to tsunameters in the Andaman Sea and to a community in Thailand that was hit by the tsunami of 26 December 2004. The model was also used to determine the required degree of bathymetry accuracy to ensure accurate calculation of tsunami travel times. The model focuses on the leading crest of a nearfield tsunami generated by an earthquake in the Sunda Subduction Zone and propagating along the shortest path to the populous Patong Beach on the west coast of Phuket. Other targets were included for model validation (Fig. 2).

3.2 Model conceptualization

The first step in building the model was to express the theoretical concepts described in Sect. 2 as a level-rate diagram, so that a system dynamics modeling technique could be used to solve the function of $s(t)$ over the interval $[0, T]$. Guided by the principles of systems (Forrester 1990), key theoretical concepts, consisting of parameters and variables that

govern the dynamics of wave celerity along the ray trajectory, were selected as model components. The variables were further classified into level, rate, and auxiliary variables. Level variables represent where the accumulation takes place in the system. Rate variables represent what causes levels to change. Auxiliary variables represent what affects rates and can change immediately in response to changes in levels. A flow diagram clarifies how these model components are causally related (Fig. 3).

Wave celerity is the rate that increases distance propagated, which in turn increases relative distance of the leading crest, which alters local water depth and wave height, both of which influence the wave celerity, which affects the level of distance propagated. This feedback relationship was considered a minimal structure necessary for calculating the travel time of a nearfield-tsunami.

3.3 Model formulation

To build the MONTE model, the flow diagram shown in Fig. 3 was entered in the Sketch Drawing Area of modeling software, Vensim (Ventana Systems 2007), and the Equation Editor tool was used to type in the equations and units of measurement (Appendix A).

Most of the parameter values used in the model were taken from reports on the 26 December 2004 tsunami (see Sect. 3.4.2). The model's tsunami source (5.458°N, 94.000°E) is a calibrated source near to the eastern border of the southern rupture zone (Fine et al. 2005; Grilli et al. 2007), far from the fault epicenter that was noted in Annunziato and Best (2005) as the tsunami source (Fig. 1). The model's target is the shoreline of Patong Beach (7.9°N, 98.276°E). The model was run on an IBM laptop computer (Pentium M, 1.5 GHz, and 248 MB RAM). The fourth-order Runge–Kutta (RK4) integrations were made with a 0.03125 min step. With the selected parameters, the model reproduced the tsunami travel time to Patong Beach with calculation error less than 2 min/h, which is the maximum acceptable error used in Shokin et al. (1987).

3.4 Model validation

The structural soundness and accuracy of the MONTE model in generating accurate predictions of tsunami travel times to both tsunameters and shorelines in the Andaman Sea region was validated using three types of tests: (i) structural tests, (ii) structurally-oriented behavior tests, and (iii) point prediction test (Forrester and Senge 1980; Sterman 2000).

3.4.1 Structural verification—To confirm that the model structure is found in the real system, we compared components and equations of the model with the available theory or relevant descriptive knowledge of tsunami dynamics. Most of the components and equations are easily recognized and have equivalent concepts in classical tsunami theory (Table 1). However, some components are uncommon.

Effect of distance on depth, E_d (Eq. 34), is the lookup function used to generate the values of local water depth in response to changes in the position of the leading crest in the ray trajectory. The relationship is specified as a table of values for the relative distance,

$s'_t (s'_t = s_t/S)$, and the nondimensional water depth, $d'_t (d'_t = d_t/d_0)$. Linear interpolation (Eq. 5) is used for values between the specified points:

$$E_d = \left(\frac{s_{t_0}}{S}, \frac{d_{t_0}}{d_0} \right), \left(\frac{s_{t_0+\Delta t}}{S}, \frac{d_{t_0+\Delta t}}{d_0} \right), \left(\frac{s_{t_0+2\Delta t}}{S}, \frac{d_{t_0+2\Delta t}}{d_0} \right), \dots, \left(\frac{s_{t_0+n\Delta t}}{S}, \frac{d_{t_0+n\Delta t}}{d_0} \right) \quad (13)$$

which is equivalent to the spatial expression:

$$E_d = \left(\frac{s_{\lambda_0}}{S}, \frac{d_{\lambda_0}}{d_0} \right), \left(\frac{s_{\lambda_0+2}}{S}, \frac{d_{\lambda_0+4}}{d_0} \right), \left(\frac{s_{\lambda_0+6}}{S}, \frac{d_{\lambda_0+6}}{d_0} \right), \dots, \left(\frac{s_{\lambda_1}}{S}, \frac{d_{\lambda_1}}{d_0} \right) \quad (14)$$

where $n = T/t$; s is the distance propagated with subscript $\lambda_0 + i$ indicating longitudes of points along the ray trajectory, which are 2° apart ($i = 0, 2, 4, \dots, j$); and $\lambda_1 = \lambda_0 + j$. If $s_t/S = s'_t$ (Eq. 31), the expression returns $d'_t = d_t/d_0$. The value of d' at any relative distance s' is precomputed with linear interpolation (Eqs. 6 and 7) from ETOPO2v2.

DEPTH CORRECTION FACTOR F_d (Eq. 16) denotes the degree of error in the bathymetry data used in the model. If $F_d = 1$, the data are treated as error-free. If $F_d < 1$, the data over-predict the actual bathymetry, i.e., overestimate depth. If $F_d > 1$, they under-predict the actual bathymetry and underestimate depth.

TIME CONVERSION FACTOR F_t (Eq. 24) converts the unit of wave celerity from m/s to m/min.

VELOCITY CORRECTION FACTOR F_v (Eq. 27) is a multiplier that corrects the speed of the wave in the high crest region, where low-order theories have been found to under-predict celerity by as much as 50% (Grilli 1997). In the model, we assume that solitary wave theory under-predicted the speed of the first crest by 38% ($F_v = 1.6$).

3.4.2 Parameter verification—Parameter verification determined whether parameter values used in the MONTE model fall within a plausible range of the actual values measured for the tsunami of 26 December 2004. All the assumed parameter values are consistent with those of the real event (Table 2).

3.4.3 Reality check—The reality check confirmed that the model exhibits appropriate behavior when selected parameters are assigned extreme values or values for which the logical consequences are known. The MONTE model behaves plausibly under the following extreme and non-extreme conditions:

- If wave celerity becomes zero, the wave stops propagating.
- If the earth lacks gravity, the crest does not propagate.
- If there is no initial disturbance, then no tsunami is observed.
- When the crest reaches the shoreline, it is 6 m in height.
- When the crest reaches the shoreline, the local water depth is zero.

- When the distance propagated is equal to zero, the water depth is equal to the depth at the source.
- In a sea of constant depth, the simulated travel time is equal to the travel time derived analytically (total distance/constant wave celerity).
- The wave height decays in the Indian Ocean as detected by JASON-1 observation.

3.4.4 Boundary adequacy—The boundary adequacy test confirmed that the model incorporates all of the major concepts and relationships for calculating tsunami travel times in the Andaman Sea region. Airy wave theory (Eq. 4) and solitary wave theory (Eq. 11) over-predicted the travel time to Patong Beach by as much as 10% (time difference = 6 min/h), implying that such low-order theories under-predicted the speed of the first crest, as already noted in Grilli (1997). To solve this problem, the boundary of the model was extended by including a correction term, the velocity correction factor that increased the speed of the crest in the shallow water region:

$$c_t = \begin{cases} \sqrt{g(d_{t-\Delta t} + H_{t-\Delta t})} & \text{if } d_{t-\Delta t} > 50\text{m} \\ F_v \sqrt{g(d_{t-\Delta t} + H_{t-\Delta t})} & \text{if } d_{t-\Delta t} \leq 50\text{m} \end{cases} \quad (15)$$

The corrected model provides better predictions for all the considered targets (see Sect. 3.4.6).

3.4.5 Syntax accuracy and dimensional consistency—The model syntax and measurement units were checked using the automated analysis functions provided by the Vensim simulation environment. The model contains neither syntax errors nor dimensional errors. In addition, all the units are easily recognized and have realistic meanings. Note that the unit ‘Dmnl’ stands for dimensionless, which is the unit of a ratio.

3.4.6 Behavior reproduction—Travel times for the first crest that propagated from the southern source region of the 26 December 2004 tsunami to some targets in the Andaman Sea region calculated using the MONTE model were compared to the observed travel times from four information sources: an echosounder record, tsunami photographs, satellite altimetry records, and eyewitness accounts. Measurements from tide gauge stations on the coast of Thailand were not used because of inadequate resolution (Fine et al. 2005); it is difficult to accurately determine times from these low-speed analog paper records (Rabinovich and Thomson 2007), as the times recorded on some of the sheets are imprecise (Tsuji et al. 2006). Deviations between the calculated and observed travel times proved to be satisfactorily small for most of the targets, including those in the open sea and in coastal areas (Table 3). In most cases, the time differences did not exceed 3%, or 2 min/h of wave propagation. The calculated travel times suggest that the first crest propagated from the border of the southern source areas, extending northward from the island of Sumatra, not from the fault epicenter as speculated in Annunziato and Best (2005).

The differences between the calculated and observed travel times were small for all the targets except Phi Phi Don (Table 3), where the nearshore bathymetry based on ETOPO2v2

contains a large error. Compared with a Royal Thai Navy's bathymetric chart (HD 2004), the ETOPO2v2 data set under-predicted the average water depth along the last 94 km of the ray path to Phi Phi Don by as much as 57%. Replacement of ETOPO2v2 bathymetry data for that region with the more accurate Navy data resulted in a highly improved prediction (time difference = 1.2 min/h).

Of the sources of travel times observed in the Andaman Sea region for the 26 December 2004 tsunami, the echosounder record made from the Belgian yacht, Mercator (Rabinovich and Thomson 2007), and the tsunami photographs taken in Khao Lak and Koh Lanta (Heinrich Grosskopf 2007, private communication) are considered the most reliable (Fine et al. 2005). Therefore, data from these sources were used to calibrate the model by fine tuning the velocity correction factor ($F_v = 1.6$). The model was then used to predict travel times to other targets for which only eyewitness accounts are available. All model results agreed well with the observed travel times: the time differences were all under 2 min/h.

3.4.7 Family member test—The family member test determined whether or not the MONTE model is applicable to geographic areas other than the Andaman Sea. The calculations predicted travel times to three representative targets in the Indian Ocean region, based on the same assumptions noted earlier, except that the tsunami sources were located near the western, rather than the eastern, border of the southern rupture zone, about 100 km from the tsunami source used for targets in the Andaman Sea region. The model reproduced the travel time with satisfactory accuracy (Table 4). Thus, the model is general enough to provide accurate calculations of tsunami travel times to tsunameters and target communities in the Indian Ocean, as well as in the Andaman Sea region.

3.4.8 Sensitivity test—The sensitivity test determined whether the predictions of the MONTE model change more than 2 min/h when the model's assumptions and parameters are varied over the plausible range of uncertainty, including maximum wave height, gravitational acceleration, initial wave height, initial water depth, time steps, integration methods (Euler and RK4), bathymetry data sets (ETOPO5 and ETOPO2v2), bathymetry resolutions (4–10 min), and bathymetry errors (1–15%). Predicted tsunami travel times to Patong Beach were relatively insensitive to values of maximum wave height, gravity, initial wave height, initial water depth, and time steps (Table 5). The Euler and RK4 methods did not give significantly different results. In all cases, the time differences were well below 2 min/h. Thus, the model is capable of generating a plausible prediction, even when the exact values of these parameters are unknown.

Predictions of the MONTE model were sensitive to accuracy of bathymetry data. ETOPO5 (NGDC 2006) under-estimated the nearshore bathymetry of Patong Beach by as much as 23%, causing the tsunami travel time to the beach to be overestimated by as much as 5.25 min (2.7 min/h). The largest part of this calculation error (5.68 min) was due to the underestimated bathymetry (53.7%) in the last 20 km of tsunami propagation (Fig. 4a). Smaller time errors (2.5 and –3.56 min) were found in regions A and B (Fig. 4b), where the average ETOPO5 errors in water along the ray trajectories were about 14.1 and –30.7%, respectively (Table 6).

Unlike accuracy of the bathymetry data, bathymetry resolution had little effect on predictions of travel times to Patong Beach and other targets in the Andaman Sea region. To determine this sensitivity, different bathymetry data sets were prepared from ETOPO2v2 (NGDC 2007) by removing points along the ray trajectory to produce lower resolutions (4'–10'). Tsunami travel times based on those datasets showed negligible time differences (Table 6). Thus, calculation error in model predictions is caused primarily by inaccuracy in bathymetry derived from ETOPO5, not by the low resolution of this data set. More accurate bathymetry data sets with even lower resolutions (e.g., 6'–10'), would provide better predictions than ETOPO5 (Table 6). Bathymetry data accurate to 94% (error = 6%) are necessary to keep the time difference under 2 min/h.

Because the ETOPO2v2 data set is most reliable in the open sea (> 200 km offshore), that region was treated as error-free, and only the nearshore bathymetry data (<200 km offshore) were corrected by setting the depth correction factor as between 1.01 and 1.15. Nearshore bathymetry data accurate to 86% were adequate to keep the time difference under 3% (Table 7). Even lower levels of accuracy (14–43% error) would be adequate for use in the model if the satellite altimetry works best in deep water (> 200 m) as noted in Sloss (2005), making ETOPO2v2 reliable in nearshore areas (< 45 km off Patong Beach), as well as in the open sea.

Based on all the validity tests, the MONTE model meets the following conditions:

1. Every element and relationship in the model has identifiable real world meanings and is consistent with available observations.
2. When the model is simulated under extreme conditions, the model system's operation is reasonable, i.e., impossible behavior modes do not occur.
3. The model exhibits behavior that was observed in the real system.
4. The model predictions are robust under a plausible range of bathymetry error and resolution in shallow water.

Hence, we believe that the model is adequate for generating highly accurate predictions of tsunami travel times to tsunameters and many target communities in the Andaman Sea region. The model is not intended for application to the Indian Ocean, for which travel time atlases have already been published (Barman et al. 2006; Kumar et al. 2006).

4 Conclusions

The MONTE model provides a powerful tool for tsunami evacuation planning in the Andaman Sea region, because it predicts the tsunami travel time to considered targets (tsunameter/target community) with satisfactory accuracy (time difference < 2 min/h). The model is robust under a plausible range of all parameters, making it reliable even when the exact values of the parameters are not known. For reliable prediction, the model requires nearshore bathymetry be accurate to at least 57% of actual water depth, provided that ETOPO2v2 is accurate in deep water (>200 m). A more detailed bathymetry data set (<20') is not needed to keep the time difference under the acceptable limit. ETOPO5 should not be used for travel time predictions to Patong Beach because the data set contains a large

bathymetry error in the nearshore region, causing calculation error above 2 min/h. Future research should use the MONTE model to evaluate the effectiveness of the tsunami warning system and evacuation plans for post-tsunami communities in the Andaman Sea region (see Appendix B).

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Abbreviations

CERC	Coastal Engineering Research Center
HD	Hydrographic Department
MONTE	Method of nearfield tsunami exploring
NGDC	National Geophysical Data Center
RK4	Fourth-order Runge–Kutta integration
TD	Time difference
TMD	Thai Meteorology Department

Appendix A: Vensim equations for the MONTE Model

$$\text{DEPTH CORRECTION FACTOR}=1(\text{Dmnl}) \quad (16)$$

$$\text{FINAL TIME}=120(\text{Minute}) \quad (17)$$

$$\text{GRAVITATIONAL ACCELERATION}=9.8(\text{m}/(\text{s}*\text{s})) \quad (18)$$

$$\text{INITIAL DISTANCE PROPAGATED}=0(\text{m}) \quad (19)$$

$$\text{INITIAL TIME}=0(\text{Minute}) \quad (20)$$

$$\text{INITIAL WAVE HEIGHT}=1.5(\text{m}) \quad (21)$$

$$\text{MAXIMUM WAVE HEIGHT}=6(\text{m}) \quad (22)$$

$$\text{SOURCE DEPTH}=527(\text{m}) \quad (23)$$

$$\text{TIME CONVERSION FACTOR} = 60(\text{s/Minute}) \quad (24)$$

$$\text{TIME STEP} = 0.03125(\text{Minute}) \quad (25)$$

$$\text{TOTAL DISTANCE} = 544710(\text{m}) \quad (26)$$

$$\text{VELOCITY CORRECTION FACTOR} = 1.6(\text{Dmnl}) \quad (27)$$

$$\text{Distance propagated} = \text{INTEG}(\text{wave celerity}, \text{INITIAL DISTANCE PROPAGATED})(\text{m}) \quad (28)$$

$$\text{Local water depth} = (\text{effect of distance on depth} * \text{SOURCE DEPTH})(\text{m}) \quad (29)$$

$$\text{Potential wave height} = \text{INITIAL WAVE HEIGHT} * \text{SQRT}(\text{SQRT}(\text{SOURCE DEPTH}/\text{local water depth}))(\text{m}) \quad (30)$$

$$\text{Relative distance} = \text{Distance propagated}/\text{TOTAL DISTANCE}(\text{Dmnl}) \quad (31)$$

$$\begin{aligned} \text{Wave celerity} = & \text{IF THEN ELSE}(\text{local water depth} > 50, \text{SQRT}(\text{GRAVITATIONAL ACCELERATION} \\ & * (\text{wave height} \\ & + (\text{local water depth} \\ & \quad * \text{DEPTH CORRECTION FACTOR}))) \\ & * \text{TIME CONVERSION FACTOR}, \text{VELOCITY CORRECTION FACTOR} \\ & * \text{SQRT}(\text{GRAVITATIONAL ACCELERATION} * (\text{wave height} \\ & + (\text{local water depth} \\ & \quad * \text{DEPTH CORRECTION FACTOR}))) * \text{TIME CONVERSION FACTOR})(\text{m/min}) \end{aligned} \quad (32)$$

$$\text{Wave height} = \text{MIN}(\text{potential wave height}, \text{MAXIMUM WAVE HEIGHT})(\text{m}) \quad (33)$$

$$\begin{aligned} \text{Effect of distance on depth} = & \text{WITH LOOKUP}(\text{relative distance}, [(0, 0)(1.2, \\ & 5.04357)], (0, 1), (0.00783193, 1.0541), (0.0156634, 0.636126), (0.0234943, \\ & 0.804125), (0.0313247, 1.81906), (0.0391546, 3.88361), (0.046984, 4.47011), \\ & (0.0548129, 4.62955), (0.0626412, 5.04357), (0.0704691, 4.93504), (0.0782964, \\ & 4.83528), (0.0861232, 4.23365), (0.0939495, 4.36503), (0.101775, 3.84451), \\ & (0.109601, 3.88547), (0.117425, 3.55443), (0.125249, 3.33724), (0.133073, \\ & 3.04497), (0.140896, 2.92535), (0.148719, 2.72369), (0.156541, 2.33085), \\ & (0.164362, 2.45544), (0.172183, 1.81986), (0.180004, 0.345365), (0.187824, \\ & 1.06789), (0.195643, 0.967627), (0.203462, 0.749606), (0.21128, 0.803046), \\ & (0.219098, 0.973205), (0.226915, 2.47862), (0.234732, 2.96307), (0.242548, \\ & 2.52339), (0.250363, 1.65518), (0.258178, 0.307644), (0.265993, 1.63057), \\ & (0.273806, 1.95526), (0.28162, 2.81282), (0.289432, 3.17195), (0.297245, \end{aligned} \quad (34)$$

3.22311), (0.305056, 3.19811), (0.312867, 3.2703), (0.320678, 3.11306), (0.328487, 3.05779), (0.336297, 2.79868), (0.344106, 2.79721), (0.351914, 2.63188), (0.359721, 2.45669), (0.367528, 2.41399), (0.375335, 2.48735), (0.383141, 2.38617), (0.390946, 2.16759), (0.39875, 2.00317), (0.406555, 1.91662), (0.414358, 1.84987), (0.422161, 1.71349), (0.429963, 1.56812), (0.437765, 1.65643), (0.445566, 1.56459), (0.453367, 1.51575), (0.461167, 1.5019), (0.468966, 1.54098), (0.476765, 1.17737), (0.484563, 1.50059), (0.49236, 1.69813), (0.500157, 2.00616), (0.507953, 2.06435), (0.515749, 2.07513), (0.523544, 1.97748), (0.531339, 2.00264), (0.539133, 2.03843), (0.546926, 2.06344), (0.554718, 2.2132), (0.562511, 2.32483), (0.570302, 2.33467), (0.578093, 2.28032), (0.585883, 2.2113), (0.593672, 2.1537), (0.601461, 2.17244), (0.60925, 2.18609), (0.617037, 2.15545), (0.624824, 2.15726), (0.632611, 2.05623), (0.640396, 2.04581), (0.648181, 1.95217), (0.655966, 1.94441), (0.66375, 1.89155), (0.671533, 1.88394), (0.679316, 1.96018), (0.687097, 1.87429), (0.694879, 1.88617), (0.702659, 1.82103), (0.710439, 1.80039), (0.718219, 1.81257), (0.725997, 1.70694), (0.733775, 1.64992), (0.741553, 1.43077), (0.749329, 1.40586), (0.757105, 1.30714), (0.764881, 1.26001), (0.772655, 1.19524), (0.78043, 1.12557), (0.788203, 1.09229), (0.795976, 1.05045), (0.803748, 1.02059), (0.811519, 0.97723), (0.81929, 0.939279), (0.82706, 0.900667), (0.834829, 0.870889), (0.842598, 0.82784), (0.850366, 0.780731), (0.858134, 0.747076), (0.8659, 0.702035), (0.873666, 0.665308), (0.881432, 0.620493), (0.889196, 0.574953), (0.89696, 0.53129), (0.904723, 0.491195), (0.912486, 0.442125), (0.920248, 0.377607), (0.928009, 0.254609), (0.93577, 0.151113), (0.943529, 0.136912), (0.951289, 0.101994), (0.959047, 0.0855619), (0.966805, 0.0838213), (0.974562, 0.0783717), (0.982318, 0.0767166), (0.990074, 0.0527245), (0.997829, 0.0324601), (1, 0), (1.2, 0)) (Dmnl)

Equation (34) is the lookup function used to find values of the nondimensional depth, d_t/d_0 or $d'_t d'_t$ at time t , that are changed by the relative distance, s_t/S or s'_t at time t (Eq. 31), expressed as:

$$d'_t = \text{WITH LOOKUP}(s'_t, [(s'_{\min}, d'_{\min}) - (s'_{\max}, d'_{\max})], (s'_0, d'_0), (s'_1, d'_1), \dots, (s'_n, d'_n)) \quad (35)$$

where $s'_{\min}$ and $s'_{\max}$ are the minimum and maximum values for the relative distance; and $d'_{\min}$ and $d'_{\max}$ are the minimum and maximum values for the nondimensional depth. Linear interpolation (Eq. 5) is used for values between the specified points (s'_t, d'_t) . If $s'_t = s'_p$, the expression returns d'_i (see Sect. 3.4.1).

Appendix B: an example of application

Problem

An earthquake generates a tsunami in the Andaman Sea similar to the 26 December 2004 event ($H_0 = 1.5$ m; $H_{\max} = 6$ m; $\lambda_0 = 5.458^\circ\text{N}$; $\theta_0 = 94.0^\circ\text{E}$; and $T = 45$ min). What safe evacuation time is available in Patong Beach (7.9°N , 98.276°E), where 2 min is needed to send a signal to the warning siren-towers on the beach (Johnstone 2005)?

Safe evacuation time predicted by the MONTE model

The tsunami is detected by three tsunameters (Fig. 2A–C). Based on Titov et al. (2001), the available safe evacuation time (ASET_i) based on to tsunameter i is given by

$$\text{ASET}_i = T_C - (T_{Mi} + T/4 + T_w) \quad (36)$$

where T_C is the tsunami travel time to a target community, T_{Mi} is the tsunami travel time to a tsunameter i , T is the period of the first tsunami wave, and T_w is the time required to issue the warning, The MONTE model predicts that $T_C = 116$ min, $T_{MA} = 54$ min, $T_{MB} = 51$, and $T_{MC} = 71$ min (Fig. 5). Therefore, $\text{ASET}_A = 51$ min, $\text{ASET}_B = 52$ min, and $\text{ASET}_C = 32$ min.

Thus, people in Patong Beach have as much as 52 min, and at least 32 min (if the first two tsunameters (A and B) fail to send waveform data), to evacuate to safe areas prior to arrival of the first tsunami. If further research shows that most vulnerable evacuees (e.g., elderly pedestrians) would take less than 32 min to reach safety, the warning system proposed in TMD (2006) would be deemed sufficiently effective. If more than 32 min are required, plans for faster evacuation would be necessary.

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Fig. 1.

Symbols used in the paper to express the bilinear interpolation of local water depth

Fig. 2.
Map of tsunami sources and some targets in the Andaman Sea region. Numbered locations are identified in Table 3

Fig. 3.
Flow diagram of a tsunami travel time model

Fig. 4. Two bathymetry profiles along the ray trajectory to Patong Beach, based on the ETOPO5 and ETOPO2v2 data sets. **(a)** ETOPO5 error in nearshore region. **(b)** Major regions (A and B) of ETOPO5 error in offshore region

Fig. 5.
Output graph of the MONTE model

Table 1

Model structure with real system equivalents

Model components	Real system equivalents	Sources
Distance propagated	Distance traveled $s(t)$	Shokin et al. (1987)
Effect of distance on depth	Relationship between s and d	<i>a</i>
Potential wave height	Wave height H_2	Dean and Dalrymple (1992)
Relative distance	Nondimensional distance $s'(t)$	<i>b</i>
Still water depth	Still water level d	CERC (1984)
Wave celerity	Wave celerity or phase velocity C	CERC (1984)
Wave height	Wave height H	CERC (1984)
DEPTH CORRECTION FACTOR	Errors in bathymetry data ε	<i>b</i>
FINAL TIME	Final time of simulation t_n	<i>b</i>
GRAVITATIONAL ACCELERATION	Normal gravity γ	Moritz (2000)
INITIAL DISTANCE PROPAGATED	Distance propagated at time 0 $x(t_0)$	<i>a</i>
INITIAL TIME	Tsunami generation time t_0	<i>b</i>
INITIAL WAVE HEIGHT	Initial wave height H_0	<i>b</i>
MAXIMUM WAVE HEIGHT	Maximum stable wave height $H_{\max}$	<i>b</i>
SOURCE DEPTH	Still water level at tsunami source d_0	Grilli et al. (1997)
TIME CONVERSION FACTOR	60 s of a minute	<i>a</i>
TIME STEP	Temporal step Δt	Shokin et al. (1987)
TOTAL DISTANCE	Geodetic distance $R\phi$	Banerjee (2005)
VELOCITY CORRECTION FACTOR	Correction terms to the speed of the wave	<i>a</i>
Eq. 28	Eq. 3	<i>b</i>
Eq. 29	$d_t = d_0 \cdot d'_t = d_0 (d_t / d_0)$	<i>a</i>
Eq. 30	$s' = s_t / S$	<i>a</i>
Eq. 31	Eq. 10	Green (1838)
Eq. 32	Eq. 15	CERC (1984) and Grilli (1997)
Eq. 33	Eq. 12	Yeh et al. (1994)
Eq. 34	Eq. 14	<i>a</i>

^aComponent that is not common and needs to be explained^bEasily recognized component

Table 2

Model parameter values with a plausible range of actual values

Parameters (units)	Assigned values	Actual values	Sources
d_0 (m)	527	[453, 553]	NGDC (2007)
d_t (m)	ETOPO2v2	$\approx$ ETOPO2v2	NGDC (2007)
F_d (Dmnl)	1	1	Johannesson and Mitson (1983)
F_t (s/min)	60	60	<i>a</i>
F_v (Dmnl)	1.6	(1, 2]	Grilli (1997)
g (m/s ²)	9.8	[9.78, 9.83]	Moritz (2000)
H_0 (m)	1.5	[1.5, 10]	Bilham (2005) and Halif and Sabki (2005)
$H_{\max}$ (m)	6	[5, 6]	Kawata et al. (2005)
R (m)	6371000	(6371000, 63710008]	Moritz (2000)
$s(t_0)$ (min)	0	0	<i>a</i>
S (m)	544710	$\approx$ 544710	Banerjee (2005)
t_0 (min)	0	0	<i>a</i>
t_n (min)	120	> 115	<i>a</i>
t (min)	0.03125	0	Bryant (2001)
λ_0 (radians)	1.6406095	[1.650, 1.627]	Grilli et al. (2007)
λ_1 (radians)	1.715239776	1.715239776	Grilli et al. (2007)
θ_0 (radians)	0.0953	[0.0668, 0.1293]	Grilli et al. (2007)
θ_1 (radians)	0.13788	0.13788	Grilli et al. (2007)

^aEasily assigned value

Table 3
Tsunami travel times and time differences for some targets of the 26 December 2004 tsunami

No.	Target	Coordinates	Tsunami travel time		TD ^g
			Observed	Computed	
1	Banda Aceh	5.458°N, 95.247°E	31 min ^a	30 min	1.9
2	Koh Similan	8.498°N, 97.627°E	1 h 37 min ^b	1 h 38 min	-0.6
3	Mercator	7.750°N, 98.280°E	1 h 55 min ^c	1 h 55 min	0.1
4	Patong Beach	7.900°N, 98.276°E	1 h 56 min ^d	1 h 56 min	0.1
5	Phi Phi Don	7.739°N, 98.772°E	2 h 21 min ^e	2 h 53 min	-13.6*
6	Khao Lak	8.857°N, 98.268°E	2 h 28 min ^f	2 h 24 min	1.6
7	Koh Lanta	7.534°N, 99.031°E	2 h 34 min ^g	2 h 36 min	-0.7
8	Koh Phra Thong	9.136°N, 98.266°E	2 h 41 min ^h	2 h 41 min	0.1
9	Morakot Cave	7.402°N, 99.230°E	3 h ⁱ	2 h 59 min	0.2

^aSAN (2005);
^bGray (2005);
^cFine et al. (2005);
^dPapadopoulos et al. (2006);
^eBowman (2005);
^fThomson (2005);
^gFreund (2005);
^hRaderstorf (2004);
ⁱEmery (2005);

^gTime difference (min/h) = 60(T_O-T_C)/T_O, where T_O is the observed tsunami travel time and T_C is the calculated tsunami travel time.
* Significant error: |TD| > 2 min/h

Table 4

Tsunami travel times and time differences for targets in the Indian Ocean

No.	Target	Coordinates	Tsunami travel time		TD
			Observed	Computed	
1	Jason-1	03.01°S, 84.68°E	1 h 55 min ^a	1 hr 56 min	-0.5
2	Topex/Poseidon	02.80°S, 83.34°E	2 h 02 min ^a	2 h 04 min	-1.0
3	Chennai	13.10°S, 80.32°E	2 h 45 min ^a	2 h 49 min	-1.4

^aFine et al. (2005)

Table 5

Sensitivity to some parameters of tsunami travel times predicted to Patong Beach

Parameters	Assigned values	TD ^a
Acceleration due to gravity (m/s ²)	[9.7, 10]	[−0.30, 0.61]
Time step (s)	[0.4, 60]	[−0.01, 0.47]
Initial wave height (m)	[0.6, 7]	[−0.34, 0.53]
Maximum wave height (m)	[2, 8]	[−0.22, 0.01]
Initial water depth (m)	[100, 4000]	[−0.19, 0.32]

^aTime difference (min/h) = $60(T_b - T_s)/T_b$, where T_b is the tsunami travel time of the best estimate run (115.91 min) and T_s is that of a sensitivity run

Table 6

Time differences for some levels of bathymetry resolution and error in nearshore regions

Bathymetry data	TD (min/h)								
	Targets ^a								
	1	2	3	4	5	6	7	8	9
Resolution (min)									
4	0.74	0.02	0.21	-0.71	0.68	0.10	0.03	-0.63	0.03
6	0.74	0.21	0.22	-0.65	0.29	0.52	0.10	0.03	0.12
8	0.60	-0.05	0.27	-1.03	0.13	0.42	0.26	-0.58	0.05
10	1.40	0.31	-0.43	1.44	-1.22	0.29	1.71	0.03	0.06
Error (%)									
1	0.30	0.31	0.29	0.29	0.28	0.29	0.55	0.29	0.30
6	1.69	1.73	1.67	1.66	1.62	1.71	1.95	1.68	1.73
7	1.96	1.99	1.95	1.92	1.88	1.97	2.23*	1.96	2.00*
8	2.23*	2.27*	2.21*	2.18*	2.13*	2.24*	2.49*	2.22*	2.28*

* Significantly sensitive, |TD| 2 min/h

^a 1 = Chennai; 2 = Jason-1; 3 = Khao Lak; 4 = Koh Lanta; 5 = Koh Lanta; 6 = Koh Lanta; 7 = Koh Phra Thong; 8 = Patong Beach; 9 = Topex/Poseidon

Table 7
Time differences under some degrees of resolution and accuracy of nearshore bathymetry

Bathymetry error (%)	TD ^a (min/h)									
	Distance nearshore (km)									
	200	150	100	50	25	20	15	10	5	
1	0.15	0.13	0.10	0.01	0.03	0.03	0.05	0.02	0.00	
5	0.73	0.61	0.49	0.32	0.16	0.13	0.13	0.06	0.03	
10	1.39	1.20	0.94	0.60	0.29	0.26	0.21	0.13	0.06	
14	1.89	1.62	1.28	0.83	0.40	0.34	0.26	0.18	0.10	
15	2.01*	1.71	1.36	0.87	0.44	0.36	0.29	0.19	0.10	

^aTime difference (min/h) = $60(T_B - T_S)/T_B$, where T_B is the tsunami travel time of the best estimate run (115.91 min) and T_S is that of a sensitivity run.

* Significant sensitivity, |TD| ≥ 2 min/h