

CHAPTER 3 RESULTS AND DISCUSSION

1. MONTE model

This section describes the logic behind the governing equations of the MONTE model, and discusses the results of validity testing.

1.1. 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,

$$S = R \arccos (\sin \theta_0 \sin \theta_1 + \cos \theta_0 \cos \theta_1 \cos(\lambda_0 - \lambda_1)) \quad (17)$$

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

$$s(t) = s(t_0) + \int_{t_0}^t c(\tau) d\tau \quad (18)$$

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

$$s_t = s_{t-\Delta t} + \Delta t \cdot c_t \quad (19)$$

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 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

$$c_t = \sqrt{gd_{t-\Delta t}} \quad (20)$$

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 $d_{t-\Delta t}$:

$$d_{t-\Delta t} = d_a + (d_b - d_a)(s_{t-\Delta t} - s_a)/(s_b - s_a) \quad (21)$$

$$d_a = d_{La} + (d_{Ua} - d_{La})(\theta_a - \theta_{La})/(\theta_{Ua} - \theta_{La}) \quad (22)$$

$$d_b = d_{Lb} + (d_{Ub} - d_{Lb})(\theta_b - \theta_{Lb})/(\theta_{Ub} - \theta_{Lb}) \quad (23)$$

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 (Figure 6).

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

$$\theta_a = \arctan \left(\frac{(\sin \theta_0 \cos \theta_1 \sin(\lambda_a - \lambda_1) - \sin \theta_1 \cos \theta_0 \sin(\lambda_a - \lambda_0))}{(\cos \theta_0 \cos \theta_1 \sin(\lambda_0 - \lambda_1))} \right) \quad (24)$$

$$\theta_b = \arctan \left(\frac{(\sin \theta_0 \cos \theta_1 \sin(\lambda_b - \lambda_1) - \sin \theta_1 \cos \theta_0 \sin(\lambda_b - \lambda_0))}{(\cos \theta_0 \cos \theta_1 \sin(\lambda_0 - \lambda_1))} \right) \quad (25)$$

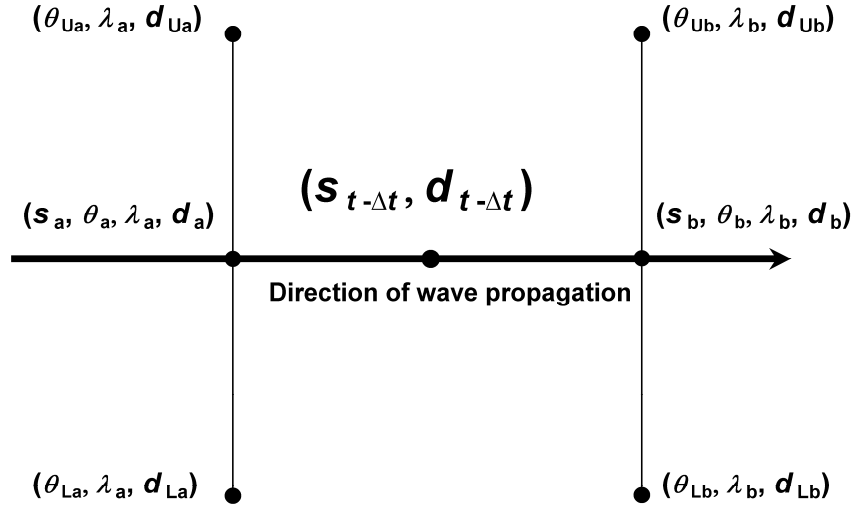


Figure 6. Symbols used in the paper to express the bilinear interpolation of local water

depth

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 heights at time $t - \Delta t$, $H(t - \Delta t)$, can be predicted by Green's law (Green, 1838; Muraleedharan *et al.*, 2006a, 2006b):

$$H_{t-\Delta t} = H_0 (d_0 / d_{t-\Delta t})^{1/4} \quad (26)$$

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. (20) is adapted to

$$c_t = \sqrt{g(d_{t-\Delta t} + H_{t-\Delta t})} \quad (27)$$

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 (Murty, 2007). 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:

$$H_{t-\Delta t} = \begin{cases} H_0 (d_0/d_{t-\Delta t})^{1/4} & \text{if } H_{t-\Delta t} < H_{\max} \\ H_{\max} & \text{if } H_{t-\Delta t} \geq H_{\max} \end{cases} \quad (28)$$

1.2 Model Validity

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) behavioral test (Forrester and Senge, 1980; Balas, 1996; Sterman, 2000).

1.2.1 Structural Confirmation

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 4). However, some components are uncommon.

Table 4. Model structure with real system equivalents

Model components/equations	Real system equivalents	Sources
Distance Propagated	Distance traveled $s(t)$	Shokin <i>et al.</i> (1987)
effect of distance on depth	Relationship between s and d	†
potential wave height	Wave height H_2	Dean and Dalrymple (1991)
relative distance	Nondimensional distance $s'(t)$	(1991)
still water depth	Still water level d	*
wave celerity	Wave celerity or phase velocity C	CERC (1984)
wave height	Wave height H	CERC (1984)
DEPTH CORRECTION FACTOR	Errors in bathymetry data \mathcal{E}	CERC (1984)
FINAL TIME	Final time of simulation t_n	*
GRAVITATIONAL ACCELERATION	Normal gravity γ	Moritz (2000)
INITIAL DISTANCE PROPAGATED	Distance propagated at time 0 $x(t_0)$	†
INITIAL TIME	Tsunami generation time t_0	*
INITIAL WAVE HEIGHT	Initial wave height H_0	*
MAXIMUM WAVE HEIGHT	Maximum stable wave height H_{\max}	*
SOURCE DEPTH	Still water level at tsunami source	*
TIME CONVERSION FACTOR	d_0	Grilli <i>et al.</i> (1997)
TIME STEP	60 seconds of a minute	†
TOTAL DISTANCE VELOCITY CORRECTION FACTOR	Temporal step Δt	Shokin <i>et al.</i> (1987)
	Geodetic distance $R\phi$	Banerjee (2005)
	Correction terms to the speed of the wave	†
Eq. (48)	Eq. (19)	*
Eq. 49)	$d'_t = d_0 \cdot d'_t = d_0(d_t/d_0)$	†
Eq. (50)	$s' = s/S$	†

Eq. (51)	Eq. (26)	Green (1838)
Eq. (52)	Eq. (31)	CERC (1984); Grilli
Eq. (53)	Eq. (28)	(1997)
Eq. (54)	Eq. (30)	Yeh <i>et al.</i> (1994)
		†

*Easily recognized component. †Component that is not common and needs to be explained.

Effect of distance on depth, E_d (Eq. 54), 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. 21) is used for values between the specified points:

$$E_d = \left(\frac{s_{t_0}}{S}, \frac{d_{t_0}}{d_0} \right), \left(\frac{s_{t_0+\Delta t}}{S}, \frac{d_{t_0+\Delta t}}{d_0} \right), \left(\frac{s_{t_0+2\Delta t}}{S}, \frac{d_{t_0+2\Delta t}}{d_0} \right), \dots, \left(\frac{s_{t_0+n\Delta t}}{S}, \frac{d_{t_0+n\Delta t}}{d_0} \right) \quad (29)$$

which is equivalent to the spatial expression:

$$E_d = \left(\frac{s_{\lambda_0}}{S}, \frac{d_{\lambda_0}}{d_0} \right), \left(\frac{s_{\lambda_0+2}}{S}, \frac{d_{\lambda_0+4}}{d_0} \right), \left(\frac{s_{\lambda_0+6}}{S}, \frac{d_{\lambda_0+6}}{d_0} \right), \dots, \left(\frac{s_{\lambda_1}}{S}, \frac{d_{\lambda_1}}{d_0} \right) \quad (30)$$

where $n = T/\Delta t$; 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. 51), the expression returns $d'_t = d_t/d_0$. The value of d' at any relative distance s' is precomputed with linear interpolation (Eqs. 22 and 23) from ETOPO2v2.

DEPTH CORRECTION FACTOR F_d (Eq. 36) 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. 44) converts the unit of wave celerity from m/s to m/min.

VELOCITY CORRECTION FACTOR F_v (Eq. 47) 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% ($F_v = 1.6$).

1.2.2 Parameter Confirmation

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 5).

1.2.3 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.

Table 5. 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	*
F_v (Dmnl)	1.5	(1, 2]	Grilli (1997)
g (m/s ²)	9.8	[9.78, 9.83]	Moritz (2000)

H_0 (m)	1.6	[1.5, 10]	Bilham (2005); Halif and Sabki (2005)
H_{\max} (m)	6	[5, 6]	Kawata <i>et al.</i> (2005)
R (m)	6371000	(6371000, 6371000.8]	Moritz (2000)
$s(t_0)$ (min)	0	0	*
S (m)	544710	≈ 544710	Banerjee (2005)
t_0 (min)	0	0	*
t_n (min)	120	> 115	Papadopoulos (2006)
Δt (min)	0.03125	0	Bryant (2001)
λ_0 (radians)	1.6406095	[1.627, 1.650]	Grilli <i>et al.</i> (2007)
λ_1 (radians)	1.715239776	1.715239776	Grilli <i>et al.</i> (2007)
θ_0 (radians)	0.0953	[0.0668, 0.1293]	Grilli <i>et al.</i> (2007)
θ_1 (radians)	0.13788	0.13788	Grilli <i>et al.</i> (2007)

*Easily assigned value.

1.2.4 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. 20) and solitary wave theory (Eq. 27) 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 increases the speed of the crest in the shallow water region:

$$c_t = \begin{cases} \sqrt{g(d_{t-\Delta t} + H_{t-\Delta t})} & \text{if } d_{t-\Delta t} > 50 \text{ m} \\ F_v \sqrt{g(d_{t-\Delta t} + H_{t-\Delta t})} & \text{if } d_{t-\Delta t} \leq 50 \text{ m} \end{cases} \quad (31)$$

The corrected model provides better predictions for all the considered targets (see Section 1.2.6).

1.2.5 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.

1.2.6 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 6). 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 6), 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.

Table 6. Tsunami travel times and time differences for some targets of the 26 December 2004 tsunami

No.	Target	Coordinates	Tsunami travel time		TD†
			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). †Time 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.

1.2.7 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 7). 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.

Table 7. 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 h 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 8. Sensitivity to some parameters of tsunami travel times predicted to Patong Beach

Parameters	Assigned values	TD†
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]

† Time 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.

1.2.8 Sensitivity Tests

The sensitivity tests 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 to 10 min), and bathymetry errors (1 to 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 8). The Euler and RK4 methods did not give significantly different results. In all cases, the time differences were well below 2 min/h; the model can generate 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).

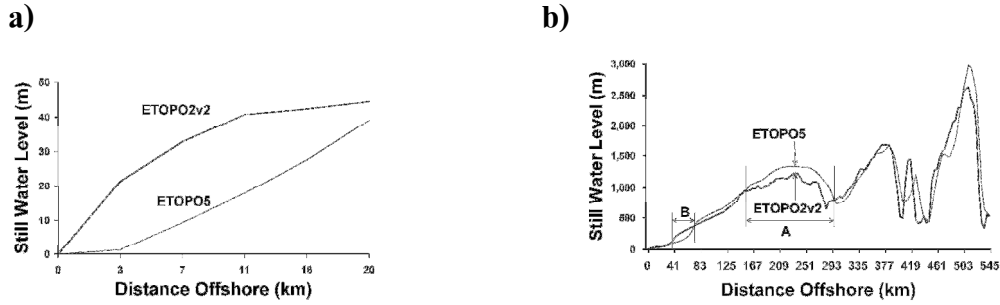


Figure 7. Two bathymetry profiles along the ray trajectory to Patong Beach, based on the ETOPO5 and ETOPO2v2 data sets. a) ETOPO5 error in nearshore region. b) Major regions (A and B) of ETOPO5 error in offshore region

Table 9. Time differences for some levels of bathymetry resolution and error in nearshore regions

Bathymetry data	TD (min/h)									
	Targets†									
	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, $|TD| \geq 2$ min/h. † 1 = Chennai; 2 = Jason-1; 3 = Khao Lak; 4 = Koh Lanta; 5 = Koh Lanta; 6 = Koh Phra Thong; 7 = Koh Similan; 8 = Patong Beach; 9 = Topex/Poseidon.

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 (Figure 7a). Smaller time errors (2.5 and -3.56 min) were found in regions A and B (Figure

7b), where the average ETOPO5 errors in water along the ray trajectories were about 14.1% and -30.7% , respectively (Table 9).

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' to 10'). Tsunami travel times based on those datasets showed negligible time differences (Table 9). 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' to 10'), would provide better predictions than ETOPO5 (Table 9). Bathymetry data accurate to 94% (error $\leq 6\%$) 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 10). 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.

Table 10. Time differences under some degrees of resolution and accuracy of nearshore bathymetry

Bathymetry error (%)	TD [†] (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	
	*									

[†] Time 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, $|TD| \geq 2$ min/h.

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

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

Hence, we believe that the MONTE 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).

2. SPEED model

2.1 Theoretical Formulation

An evacuation plan is defined here as a plan to develop the ability of coastal inhabitants, particularly pedestrians on the beach, to reach the nearest designated safe area before the arrival of the first tsunami crest. To evaluate the effectiveness of such a plan, we relied on the theoretical concepts described below.

Consider a case where a tsunami warning and response system includes: (i) a tsunameter on the seafloor, (ii) an acoustic link to a surface buoy equipped with a satellite telecommunications capability (Gonzalez *et al.*, 2005), (iii) a national tsunami warning center with scientists responsible for analyzing waveform data and disseminating warning to sirens in a target community, (iv) pedestrians on the beach in the target community, (v) a recommended evacuation route, and (vi) the nearest designated safe area. The ability of the pedestrians to reach the safe area can be expressed as hazard quotient, HQ, that indicates the level of potential risk to pedestrians under a tsunami event. Pedestrians were treated as evacuees at risk if they cannot reach the safe area before the arrival of the leading tsunami crest. Hence

$$HQ = RSET/ASET \quad (32)$$

where the required safe evacuation time, RSET, is the calculated time necessary between the siren sounding and the time at which all evacuees can reach the safe area. The available safe evacuation time, ASET, is the calculated time available between sounding of the sirens and the time at which the leading crest of a major tsunami arrives. Evacuation plans can be considered effective if $HQ \leq 1$, or ineffective if $HQ > 1$, a case where evacuees could be exposed to tsunami inundation, and the risk cannot be considered negligible (Sugimoto *et al.*, 2003).

Once the sirens are sounded, the pedestrians take time for trip preparation (*e.g.*, seeking further information, observing others, finding family members, and gathering items) before evacuating on foot along the evacuation route toward the safe area. Travel time of the last evacuee is a function of his or her walking speed and the distance of the evacuation route. During walking, the evacuee slows down or even stops when traffic friction occurs, causing a delay in moving toward the destination. Thus

$$RSET = T_p + T_D + (L + S)/V \quad (33)$$

where T_p is the time (measured in min) the last evacuee takes for trip preparation after the sirens have been sounded; T_D is the delay (min) in the evacuee's movement because of traffic friction; L is the length of the minor evacuation route (m), measured from the start point on the beach to the entrance of the major evacuation route; S is the length of the major evacuation route (m) that leads to the designated safe area; V is the last evacuee's average walking speed (m/min).

If a major tsunami is generated by a 'tsunami earthquake' (Okal, 1993), and the Deep-ocean Assessment and Reporting Tsunami (DART) system (Gonzalez *et al.*, 2005) is used to detect the tsunami and to transmit the waveform data to the tsunami warning center, the available safe evacuation time (Kietpawpan *et al.*, 2008) is given by

$$ASET = T_C - (T_M + T/4 + T_w) \quad (34)$$

where T_C is the tsunami travel time to the target community; T_M is the tsunami travel time to the closest tsunameter; T is the period of the first tsunami wave; T_w is the delay in analyzing waveform data and disseminating a warning to the target community, all measured in minute. The term 'T/4' denotes the detecting delay of tsunameters (Titov *et al.*, 2001).

For tsunamis propagating in the Andaman Sea, both T_C and T_M can be accurately calculated using the method of Kietpawpan *et al.* (2008), whereas T_W can be estimated by officials responsible for issuing tsunami warning to the target community.

To evaluate the effectiveness of a tsunami evacuation plan, a set of criteria and benchmarks was developed (Table 2), and a set of HQ values calculated under three basic scenarios: the most optimistic, normal, and most pessimistic conditions.

2.2 Model Validity

The structural soundness and accuracy of the SPEED model in generating plausible conclusions on the effectiveness of the tsunami evacuation plan for Soi Bangla 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).

2.2.1 Structural Confirmation

To confirm that the model structure is found in the real system, we compared the components and equations of the model with the relevant descriptive knowledge of the national tsunami warning system and the evacuation plan for Soi Bangla. Most of the components and equations are easily recognized and have equivalent concepts found in relevant literature (Table 11). However, some equations are uncommon.

Table 11. Model structure with real system equivalents

Model structure	Real system equivalents	Sources
<i>Components</i>		
Available safe evacuation time	Available safe evacuation time, ASET	Kietpawpan <i>et al.</i> (2008)
Reporting delay of surface buoy	Report delay of DART II, t_R	Meinig <i>et al.</i> (2005)
Walking speed	Walking speed of evacuee, V	Wong and Cheung (2006)
Hazard quotient	Hazard quotient, HQ	Hill <i>et al.</i> (2000)
Length of major evacuation route	Distance of Soi Bangla, S	PMO (2007b)
Length of minor evacuation	Distance from beach area to Soi	

route	Bangla, L	*
Preparation time	Preparation time, t_p	Charnkul and Tanaboriboon (2006)
Required safe evacuation time	Required safe evacuation time, RSET	Kietpawpan <i>et al.</i> (2007)
Traffic delay	Pedestrian delay, D	Virkler (1998)
Tsunami travel time to community	Tsunami travel time to target community, t_C	Titov <i>et al.</i> (2001)
Tsunami travel time to tsunameter	Tsunami travel time to tsunameter, t_M	Titov <i>et al.</i> (2001)

Table 11. Model structure with real system equivalents (Continued)

Model structure	Real system equivalents	Sources
<i>Components</i>		
Tsunami warning delay time	Delay in issuing an evacuation order, t_w	Johnstone (2005); Little <i>et al.</i> (2007)
Tsunami wave period	Tsunami wave period, T	Titov <i>et al.</i> (2001)
<i>Equations</i>		
Eq. (56)	Eq. (33)	*
Eq. (57)	Eq. (34)	Titov <i>et al.</i> (2001)
Eq. (58)	Eq. (32)	*
Eq. (59)	Evaluate safety based on HQ value	†
Eq. (60)	Draw a qualitative conclusion	†
Eq. (61)	Draw a quantitative conclusion	†
Eq. (62)	Eq. (33)	*
Eq. (63)	Eq. (34)	Titov <i>et al.</i> (2001)
Eq. (64)	Eq. (32)	*
Eq. (65)	Evaluate safety based on HQ value	†
Eq. (66)	Eq. (33)	*
Eq. (67)	Eq. (34)	Titov <i>et al.</i> (2001)
Eq. (68)	Eq. (32)	*
Eq. (69)	Evaluate safety based on HQ value	†

*Easily recognized component †Component that is not common and needs to be explained

Required safe evacuation time, $RSET$ (Eqs. 56, 62, and 66): The expression returns “Ma Error” if walking speed is zero, and Eq. (33) otherwise. The “Ma Error” refers to the mathematical error occurring when the expression violates one fundamental property of real numbers: no division by zero.

Hazard quotient, HQ (Eqs. 58, 64, 68): The expression returns “Ma Error” if the required safe evacuation time cannot be computed when the mathematical error occurs, and returns Eq. (32) otherwise.

Effective criteria, EC (Eqs. 59, 65, and 69): The expression returns “Ma Error” if HQ cannot be computed when the mathematical error occurs, and returns 1 if the value of HQ falls within the interval $[0, 1]$, meaning the plan is likely to be effective; evacuation of inhabitants is likely to be finished before inundation begins (Sugimoto *et al.*, 2003). If $HQ > 1$, the expression returns 0, meaning the plan is unlikely to be effective; inhabitants could be exposed to tsunami inundation. If $HQ < 0$, the expression returns “error,” suggesting that either $RSET$ or $ASET$ is incorrectly negative.

Effectiveness of tsunami warning system and evacuation plan, E (Eq. 60): The expression uses the criteria in Table 1 to draw a proper qualitative conclusion about the plan effectiveness, based on the values of HQ (Eqs. 59, 65, and 69).

Safety level, SL (Eq. 61): The expression translates the qualitative conclusion (Eq. 60) into the equivalent quantitative one (0, 33, 67, or 100%). However, if the qualitative conclusion becomes either ‘Ma error’ or ‘error,’ the expression returns “Please check the input,” to indicate the error source.

2.2.1 Parameter Confirmation

The parameter verification test determined whether parameter values used in the SPEED model fall within a plausible range of the actual values reported in relevant literature. All the assumed parameter values are consistent with those of the real system (Table 12).

Table 12. Model parameter values with a plausible range of actual values

Parameters (units)	Assigned values	Actual values	Sources
L (m)	50	[20, 100]	*
T (min)	20	[5, 45]	Titov <i>et al.</i> (2001)
T_C (min)	116	[114, 118]	Kietpawpan <i>et al.</i> (2007)
T_D (min)	6	[0, 10]	†

T_M (min)	40	[32, 52]	Kietpawpan <i>et al.</i> (2008)
T_P (min)	10	[5, 35]	Charnkul and Tanaboriboon (2006)
T_R (min)	1.5	[0, 3]	Meinig <i>et al.</i> (2005); Gonzalez <i>et al.</i> (2005)
T_W (min)	3	[2, 5]	Johnstone (2005); Smith (1998)
S (m)	600	[500, 700]	PMO (2007b)
V (m/min)	30	[20, 40]	Sato <i>et al.</i> (2003)

*Measured with a 50-m fiberglass measuring tape † Roughly estimated values

2.2.3 Boundary Adequacy

The boundary adequacy test confirmed that the model incorporates all of the major concepts and relationships for calculating the values of RSET and ASET. The concepts of RSET and ASET have long been used in the field of fire emergency (Gupta *et al.*, 2001), and recently applied to tsunami events (*e.g.* Kietpawpan *et al.*, 2008). The boundary of the RSET (Eq. 33) was extended from the *models* of tsunami evacuation time (Sato *et al.*, 2003; Charnkul and Tanaboriboon, 2006), by including the delay in pedestrian movement, T_D , as well as the length of the minor evacuation route, L . The term “ $S+L$ ” was considered adequate to represent the longest distance for evacuation. Delay in tsunami inundation, as is included in the model of Sato *et al.* (2003), was omitted, as there has been no seawall to slow down tsunamis in the west coast of Phuket.

The boundary of the ASET (Eq. 34) was extended from the forecasting model of Titov *et al.* (2001), by including the delay in sending a tsunami warning, T_W (Kietpawpan *et al.*, 2007). Even so, the model is not based on the DART II system used in the Andaman Sea region. The boundary of the ASET was further extended by incorporating the reporting delay of the DART II buoy, T_R , that can decrease the available safe evacuation time by as much as 3 min (Meinig *et al.*, 2005). Thus,

$$\text{ASET} = T_C - (T_M + T/4 + T_R + T_W) \quad (35)$$

The corrected model provides more conservative conclusions on the performance of the tsunami evacuation plan, although the inclusion of T_R does not change the conclusion of the model applied to Soi Bangla (see Section 3.7).

2.2.4 Syntax Accuracy and Dimensional Consistency

The model syntax and measurement units were checked by direct inspection of the equations. The model contains neither syntax errors nor dimensional errors. In addition, all the units are easily recognized and have realistic meanings.

3.5 Behavior Reproduction

Behavioral reproduction of ASET has been addressed in section 1.2.6; travel times of the leading tsunami crest can be successfully reproduced, with negligible errors (0.1–1.9 min/h of tsunami propagation). Only the value of RSET was reproduced in this section.

The reference value of RSET was measured during the full-scale tsunami evacuation demonstration conducted in Soi Bangla between 9:47 a.m. and 9:58 a.m. on 25 July 2007. Time variables were measured using a calibrated digital watch. The warning siren was sounded at 9:47 a.m., confirmed by the report of the National News Bureau (NNB, 2007a). Drill participants (>1,500 subjects) were asked to evacuate on foot, immediately after the siren was sounded. The last evacuee entered the entrance of the major evacuation route at 9:50 a.m., and reached the designated safe area at 9:58 a.m. Thus, the observed RSET was 11 min, well consistent with the calculated RSET (10.9 min). The assigned parameters were based on the actual drill conditions:

- About 5 min before the sirens were sounded, the polices established roadblocks, which eliminated the delay due to traffic congestion; $T_D = 0$ min.
- Before the sirens were sounded, all participants were standing on the beach, about 20 m away from the major evacuation route; $L = 20$ m.
- The last evacuee was the blind man assisted in walking by a rescue staff. The evacuee's average walking speed, measured over a 10-m distance using a stopwatch, was 54 m/min.
- The last evacuee's evacuation was terminated at 200 m away from the designated safe area; $S = 400$ m.

As deviation between calculated and observed evacuation times proved to be satisfactorily small (10 seconds), the model successfully reproduced the drill result, and confirmed that the drill was conducted under the optimistic conditions.

3.6 Family Member Test

With only limited time and budget availability, we could not demonstrate that the SPEED model is applicable to geographic areas other than Soi

Bangla. The full-scale evacuation drill on 25 July 2007 was conducted in only Soi Bangla; therefore, observed evacuation times for other evacuation areas were not available. In principle, nevertheless, the model would be applicable to areas where the warning systems and evacuation plans are characterized by the mechanism captured by this model.

Table 13. Sensitivity to each parameter of the SPEED model applied to Soi Bangla

Parameters	Assigned values	HQ [†]
L (m)	[20, 100]	0.6
T (min)	[5, 45]	0.6
T_C (min)	[114, 118]	[0.5, 0.6]
T_D (min)	[0, 10]	[0.5, 0.6]
T_M (min)	[32, 52]	[0.5, 0.7]
T_P (min)	[5, 35]	[0.5, 1.0]
T_R (min)	[0, 3]	0.6
T_W (min)	[2, 5]	0.6
S (m)	[500, 700]	[0.5, 0.6]
V (m/min)	[20, 40]	[0.5, 0.8]

[†] If HQ > 1.0, sensitivity to the parameter was considered significant

3.7 Sensitivity Tests

The sensitivity tests determine whether the conclusion of the SPEED model change from “Debatable (67%)” to another conclusion when the model’s parameters are varied over the plausible range of uncertainty. The model conclusion was robust under a plausible range of each parameter (Table 13), suggesting that the model is capable of generating a plausible conclusion, even when the exact values of these parameters are unknown.

Monte Carlo simulations were also performed to determine whether the conclusions of the SPEED model change when all the parameters are simultaneously varied over the plausible range of uncertainty (Table 13). Equations (32)–(34) were translated to a causal diagram (Figure 8) within the Sketch Drawing Area of modeling software, Vensim Professional (Ventana Systems, 2007), and the Equation Editor tool was used to type in the equations and units of measurement (Appendix C), thereupon resulting in a new model, **Tsunami Evacuation Prototype (TOP)**.

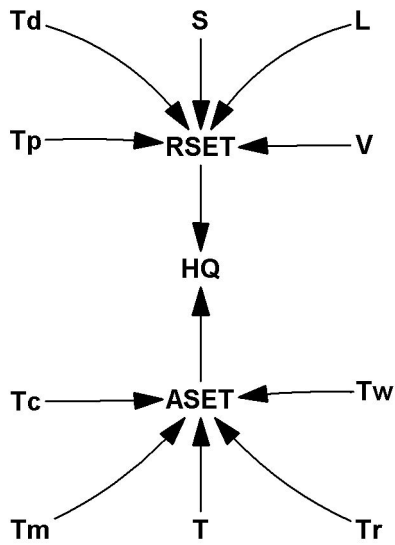


Figure 8. Causal diagram of the TOP model

The Monte Carlo simulations were carried out in the TOP model, using Latin hypercube sampling (Ford and Flynn, 2005) to generate parameter values that uniformly distributed over the plausible range (Table 13). For 2,000 simulations, $HQ = 1$ was at the point where 87% of all the simulations are under that HQ value. The probability that evacuees could fail to reach safety before the first tsunami strikes was relatively low, $\Pr\{HQ > 1\} = 0.13$. This finding contradicts the SPEED model's conclusion: the effectiveness of the plan was considered debatable, with only 67% safety level. The 67% conclusion seems to be rather conservative, as the values of HQ for the best, normal, and worst cases are equally weighted by the SPEED model. Actually, the best and worst cases are not the most likely outcomes (Serman, 2000), so the 20% gap between the TOP's and the SPEED's conclusions was not impressive. Besides, the use of TOP model needs to be implemented in a sophisticated Vensim software.

As a result, the second-version model, SPEED2, was developed by installing the Lumenaut Monte Carlo simulator, available free-of-charge from <http://www.lumenaut.com>. Cells I7 to I16 were selected as the input cells, and cell I21 as the output cell (Figure 5). The maximum and minimum values for each input variable (Table 13), the type of its distribution (uniformly random distribution), a noise seed (1234), and the number of simulations (2,000) were specified. For 2,000 simulations of the SPEED2 model, $HQ = 1$ was at the point between the 80th and the 90th percentiles, well consistent with the sophisticated TOP model's conclusion.

However, the output table of the SPEED2 model showed the percentiles at merely the multiple of ten (0th, 10th, 20th,..., and 100th percentiles), which would be problematic if another percentile (*e.g.* 85th) is selected as the safety criterion. Even so, if the safety criterion is deliberately set at either the 90th or 100th percentile, the SPEED2 model could be adequate.

3.8 Utility Test

The SPEED2 model is a cost-effective tool for understanding the implications of the evacuation plan. The model with 2,000 simulations represented 2,000 full-scale tsunami evacuation drills conducted in Soi Bangla. Hence, the model saved approximately US\$31.25 millions, as the local authorities must spend around US\$15,625 per drill (NNB, 2007b). In addition, the model provided insights that may otherwise be obtained after next 2,000 years of planning through drills, provided that the authorities continue to conduct only a single full-scale evacuation drill per year.

Based on all the validity tests, the SPEED2 model meets the following conditions:

- Every element and relationship in the model has identifiable real world meanings and is consistent with available observations.
- The model conclusions are robust under a plausible range of all parameter values.

Hence, we believe that the model is adequately useful for evaluating the effectiveness of the evacuation plan for Soi Bangla. The model provides conclusions that are more objective and credible than previous conclusions such as “*the drill is a very big success*” (Promyamyai, 2007), “*In Patong, they have a proper siren. It’s loud*” (Phuket Gazette, 2007) and “*We were satisfied with the overall drill*” (NNB, 2007a). Overall, the model would provide emergency managers with a pragmatic tool for building confidence in the effectiveness of their tsunami evacuation plans.

3. 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). The tsunami is detected by three tsunameters (Figure 3 — A, B, and C). What

is the probability that the existing evacuation plan (PMO, 2005a, 2007a, 2007b) is effective for Soi Bangla (7.9°N , 98.276°E) if the parameter values fall within the ranges given in Table 12? What mitigation measures are likely to significantly improve the performance of the plan?

Evacuation plan effectiveness predicted by the SPEED2 model: People in Soi Bangla 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. Of 2,000 simulations (Figure 9), more than 80% are the cases where evacuees could reach safety before the arrival of the first tsunami crest. Thus, the probability that the warning system proposed in TMD (2006) can be effective is relatively high, $\Pr(\{HQ \leq 1\}) > 0.8$. However, if the acceptable probability is greater than 0.8, plans for faster evacuation would be necessary.

Policy recommendations: If the acceptable probability is $\Pr\{HQ \leq 1\} = 1$, the following measures can be effective: vertical evacuation, immediate evacuation, and fast movement (Table 14). The evacuation shelter building, however, must be located near the beach (< 150 m). Otherwise, all pedestrians must follow closely the evacuation plan of the local authorities; they must evacuate immediately after the sirens are sounded. Alternatively, slow pedestrians must not stay in the evacuation area, and inhabitants who take 5–35 min for trip preparation must evacuate by running ($V \geq 1.75$ m/s). Other measures are unlikely to be helpful; their impacts are as low as that of the *status quo*. Even the adoption of advanced, real-time tsunami forecasting system would not much improve the performance of the evacuation plan for Bangla.

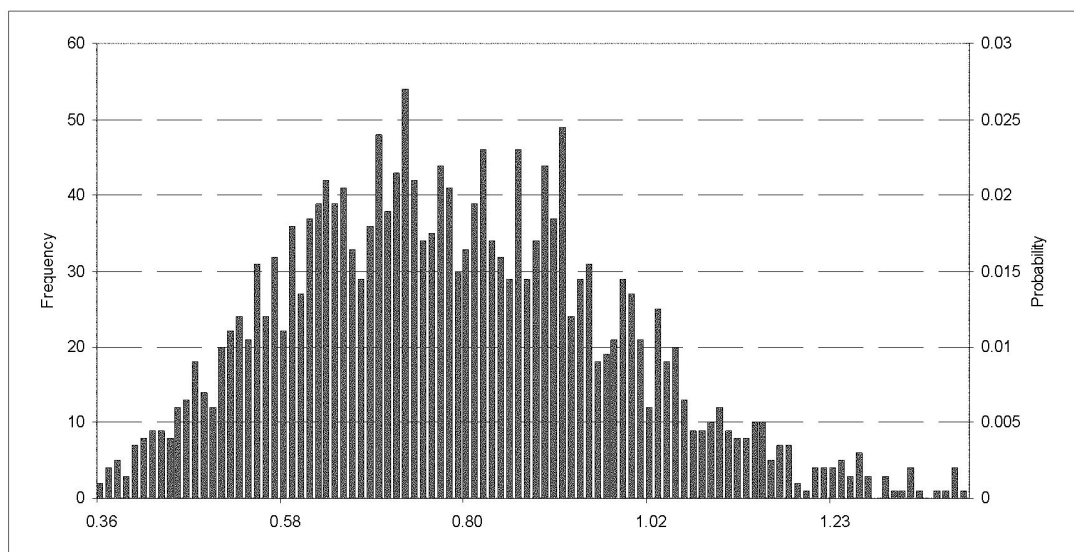


Figure 9. Frequency histogram of hazard quotients, constructed from 2,000 Monte Carlo simulations

Table 14. Tsunami hazard mitigation measures and their implications

Mitigation measures	Model equivalent	100th Percentile HQ
<i>Effective measures*</i>		
1. Evacuate immediately	$T_P = 0$ min	0.929
2. Forbid slow pedestrians	$V = 105$ m/min	0.994
3. Use vertical evacuation	$S = 150$ m	0.995
<i>Ineffective measures†</i>		
4. Keep the tsunameters functional	$T_M = 52$ min	1.148
5. Use real-time tsunami forecasting	$T_W = 0$ min	1.297
6. Stay away from the beach	$L = 0$ m	1.347
7. Eliminate traffic friction	$T_D = 0$ min	1.357
8. Improve DART buoy performance	$T_R = 0$ min	1.364
9. Take no action	See Table 12	1.387

*For 2,000 simulations, $\Pr\{HQ > 1\} = 0$: All evacuees are always safe, $\dagger\Pr\{HQ \geq 1\} > 0$: Some evacuees could be exposed to tsunami inundation.