CHAPTER 1
INTRODUCTION

1.1 Background and Rationale

Tsunami evacuation drills are a practice to assure the safe and orderly dismissal of residents and visitors from expected danger areas in the event of tsunami. The drill can provide authorities with a good opportunity to recognize and remedy shortcomings in the evacuation plan (Aswarangkul, 2005), but alone may be insufficient to derive a well-tested plan for tsunami evacuation. Too little has been learned from previous drills because frequent drills are impractical due to four limitations:

First, insights from each tsunami evacuation drill are spatially specific. Running drills in a given locations, authorities may recognize and remedy shortcomings in their evacuation plans, but are not sure whether the plans, after remediation, would be effective elsewhere. To overcome this limitation, they may want to conduct a number of drills in all tsunami hazard zones. In practice, however, this will rarely happen. Authorities have to allocate people and resources for other important purposes. In Thailand, planning through drills has been restricted to the most risky areas first (Samabuddhi *et al*., 2005).

Second, tsunami evacuation drills conducted in populous regions are a labor intensive excercise, because they require all inhabitants to leave the evacuation zones once the warning sirens have been sounded. Recent drills, conducted in Phuket, involves between 3,000 and 6,000 participants (MONRE, 2005; Xinhua, 2005). Therefore, the government has planned to conduct only two drills each year (Xinhua, 2005), which are actually not enough (Samabuddhi *et al*., 2005).

Third, realistic tsunami evacuation drills are difficult for witnesses to test the performance of evacuations under various scenarios. In Phang Nga, for example, drill participants had to move, on foot, about 600 m within 20 minutes, from their designed positions to the evacuation shelter (Sammabuddhi and Ngamkham, 2005); it is not flexible to repeat the exercise. Drills can be boring when participants become tired of a series of exercises. To be sure, in many places, the tsunami waves have reached up to 2 km inland (Duerrast and Meekeaw, 2005; Pearce and Holmes, 2005); therefore, the hazard and the safe zones are a long way apart.

Finally, the Andaman region of Thailand has been designed to attract tourists, whose essential purpose is to relax or to enjoy the beach resort (Mill, 1990; MOF, 2005). Most visitors are vacation and leisure travelers, essentially buying an experience they hope will be pleasurable (Howell, 1993). They may be unwilling to participate tsunami evacuation drills. Drill participation is neither a pleasurable nor a non-risk experience. Drill accidents, such as road accident, have been reported at times (Ruangrassamee, 2005). In addition, evacuation involves personnel becoming engaged in non-routine activities, and there should be no expectation that staff can handle evacuation activities with the skill level associated with their everyday responsibilities (Taaffe *et al*., 2005). Fear of drill accidents may cause drill avoidance.

Despite these limitations, greater understanding is still required of how effective the tsunami evacuation plan is likely to be. Learning through evacuation modeling is potentially an excellent complement to learning through drills. To date, many modeling methodologies have been used in predicting the performance of evacuations under various emergency events (*e.g.* Pidd *et al*., 1996; Gwynne *et al*., 1999; Shen, 2005; Simonovic and Ahmad, 2005). Some of the methodologies are sufficiently general to be applied to different disasters (*e.g.* Simonovic and Ahmad, 2005), including tsunamis.

The objective of this thesis is to apply a simulation modeling technique, called system dynamics (SD), for evaluating the effectiveness of a tsunami evacuation plan for Patong Beach, Phuket, Thailand. The primary outcome is a set of computer models which provides insights into the key factors to which the beach users' capability to reach safety is sensitive. This research effort offers a pragmatic tool for building confidence in the tsunami warning system and evacuation plan for Patong municipality.

1.2 Review of Literatures

This section describes the nature of tsunami waves, tsunami propagation models, an approach to tsunami hazard mitigation, rooms for improvement in the field of tsunami, and a brief introduction to system dynamics modeling. The review proceeds as follows. Topic 1.2.1 provides an overview of the general characteristics of tsunamis and presents some selected equations to represent the structures of tsunami waves. Topic 1.2.2 describes the limitations of classic models of tsunami propagation. Topic 1.2.3 discusses the advantages of tsunami evacuation simulation and provides a review of all previous works on tsunami evacuation modeling. Topic 1.2.4 reveals the rooms for improvement in tsunami hazard mitigation, particularly in tsunami and evacuation modeling. Topic 1.2.5 introduces the concepts of system dynamics, the simulation modeling framework used in this study.

1.2.1 General Characteristics of Tsunamis

Tsunamis are a series of dispersive gravity sea waves generated by a major disturbance of the seafloor and overlying water (Coch, 1998; Hayir, 2006). They are regarded as long waves or shallow water waves if the water depth is less than 5% of the wavelength (Dean and Dalrymple, 1991). Tsunamis can be triggered by faulting associated with earthquakes (Hammack, 1973), volcanic eruption or caldera collapes, submarine landslide (Gutenberg, 1939), or meteorite impact with the ocean (Coch, 1998; Abbott, 2003). The most common cause of major tsunamis seems to be earthquake (Table 1).

Table 1. Some Notable Tsunamis in Recent Times

Date	Cause	Height	Site	Deaths
1 Nov. 1775	Earthquake	10 m	Lisbon, Portugal	30,000
27 Aug. 1883	Volcanic eruption	35 m	Indonesia	36,000
15 Jun. 1896	Earthquake	29 m	Japan	27,000
2 Mar. 1933	Earthquake	20 m	Japan	3,000
1 Apr. 1946	Earthquake	15 m	Alaska	175
22 May 1960	Earthquake	10 m	Chile	>1,250
27 Mar. 1964	Earthquake	6 m	Alaska	125
1 Sept.1992	Earthquake	10 m	Nicaragua	170
12 Dec. 1992	Earthquake	26 m	Indonesia	>1,000
12 Jul. 1993	Earthquake	31 m	Japan	239
2 Jun. 1994	Earthquake	15 m	Indonesia	238
17 Jul. 1998	Landslide	14 m	Papua New Guinea	>2,200
26 Dec. 2004	Earthquake	35 m	Banda Aceh, Indonesia	300,000

Source: Adapted from Abbott (2003).

Earthquakes almost invariably occur on faults, fractures in the earth on which one side moves with respect to the other (Stein and Wysession, 2003). According to the elastic rebound theory, materials at distance on opporsite sides of the fault move relative to each other, but friction on the fault locks it and prevents the sides from slipping. Eventually the strain accumulated in the rock is more than the rocks on the fault can withstand, and the fault slips, resulting in earthquakes.

Dip-slip faulting, either reverse (thrust) or normal one, can cause a sudden vertical motion of the seafloor, which vertically shifts the whole column of water above the active fault area. This focal mechanism sets the water into motion, generating tsunamis with wavelength roughly equal to the length of rupture width. Lautrup (2005) and Halif and Sabki (2005) use this model to describe the process of tsunami generation.

For a megatrust earthquake, the rupture width can be greater than 150 km (Bryant, 2001). However, different studies have provided different conclusions about this and other aspects of the rupture. Consider the focal mechanim that generated the tsunami on 26 December 2004. Different values of the rupture length, rupture width, velocity of rupture propagation have been reported (Bilham, 2005; Vigny *et al.*, 2005). Hence, data on the source parameters of next tsunamis would be subjected to uncertainty.

Wave periods and wavelengths of tsunamis are possitively related to the size of rupture width, which are extremely long, compared to water depth. Scientists agree that tsunamis are shallow water waves, $d/\lambda < 0.07$, even in the deep ocean (Dean and Dalymple, 1992).

Once generated, a tsunami propagates outward in all directions. The speed at which the waveform propagates, wave celerity (C) or phase speed, can be calculated using shallow water aproximation (Kunda, 1990). Based on the wave theory developed by Airy (1845), the expression for phase speed of water (sinusoidal) wave is given by

$$C = \sqrt{\frac{g\lambda}{2\pi}\tanh\frac{2\pi d}{\lambda}} \qquad (1)$$

where g is the gravitational acceleration; λ is the horizontal distance between corresponding points on two successive waves (wavelength); and d is the distance from the seabed to the still water level (water depth).

Notice that $\tanh x \approx x$ as $x \longrightarrow 0$. For tsunamis propagating in the open sea, with $d/\lambda \ll 1$, we have $\tanh\frac{2\pi d}{\lambda} \approx \frac{2\pi d}{\lambda}$. So, the phase speed, Eq. (1), simplifies to

$$C = \sqrt{gd} \qquad (2)$$

The approximation gives better than 3% accuracy if $d < 0.07\lambda$ (Kunda 1990). The wave speed is independent of wavelength and increases with the water depth. Many reserachers (Holloway et al. 1985; Shokin et al. 1987; Satake 1988; Tinti and Gavagni 1995; Ortiz et al. 2000; Choi et al. 2003; Annunziato and Best 2005; Halif and Sabki 2005; Lautrup 2005; Dalrymple et al. 2006; Larsen 2007; Wessel 2007) use Eq. (2) as a governing equation to calculate the speed of the leading tsunami wave.

While Eq. (2) indicates that full range of tsunami periods in a tsunami wave train travels as shallow water waves, not all of individual waves travel at the same speed (Bryant, 2001). Longer-period waves outrun the very short ones; a tsunami wave train after traveling across an ocean tends to reach shore with regular long-period waves followed by shorter ones (Bryant, 2001). This phenomenon is known as dispersion.

Tsunamis have such long wavelengths that they are always dragging across the ocean bottom, no matter how deep the water (Abbott, 2003). The wavelength of a tsunami is a simple function of wave speed C and period T, as follows:

$$L = CT \qquad (3)$$

which holds for linear, sinusoidal waves and is not appropriate for calculating the wavelength of a tsunami as it moves into shallow water (Bryant, 2001).

As soon as tsunamis reach a continental slope and interact with the seafloor, various energy dissipation processes occur. The dissipative processes due to wave-seafloor interaction are small on a steep continental slope, but they cannot be neglected on long slopes (Le Mehaute and Wang, 1996). For gentle slope, the increase in wave height by shoaling is overcome by the decrease of wave height by energy dissipation (Le Mehaute and Wang, 1996). On the continental shelf, tsunamis further lose energy through frictional dissipation with the seabed (Bryant, 2001). The frictional coefficient used to determine the dissipation is a function of the grain size on the seabed and the amplitude of water motions under tsunami wave at the bottom (Bryant, 2001). In hydraulics, two coefficients are often used: the De Chezy friction coefficient, C_f, and Manning's roughness coefficient, n. The first can be related to either wave celerity or to Manning's n using the following equations (Bryant, 2001):

$$C_f = \frac{\sqrt{g}}{C} = \frac{g\eta^2}{\sqrt[3]{d+H_t}} \tag{4}$$

where C_f is the De Chezy frictional coefficient; η is the Manning's roughness coefficient (0.03 for typical coastal waters); and H_t is the tsunami wave height above mean sea level (m).

When tsunamis cross the shelf, frictional dissipation of wave energy becomes a function of the shelf width. As shelves become shallower, frictional attenuation becomes more significant. Thus, the coasts most prone to the full impact of tsunamis are coastlines with narrow shelves (Bryant, 2001).

Tsunamis arrive as a series of waves separated by periods typically in 10-to-60-minute range; the waves are typically a meter or so in height in the open ocean and 6-to-15-m high on reaching shallow water, except where topography, such as bays and harbors, forces the energy to create much taller waves (Abbott, 2003). The highest known tsunami wave occurred on 9 July 1958, when a massive rockfall dropped into Lituya Bay, Alaska (Miller, 1960; Abbott, 2003). The wave is documented to have toppled trees growing 524 meters above the water level (Miller, 1960).

Linear theory are often used as a first approximation to calculate changes in tsunami wave height as the wave moves across a shelf and undergoes wave shoaling and refraction (Bryant, 2001). Both shoaling and refraction processes have been addressed in CERC (1984). The following formulae apply (Dean and Dalrymple, 1992):

$$H_2 = H_0 K_r K_s \tag{5}$$

$$K_r = \sqrt{\frac{b_0}{b_i}} = \sqrt{\frac{\cos\theta_0}{\cos\theta_i}} \tag{6}$$

$$K_s = \sqrt{\frac{C_0}{C_i}} = \sqrt[4]{\frac{d_0}{d_i}} \tag{7}$$

where H is the crest-to-trough wave height (m); K_r is the refraction coefficient (dimensionless, dmnl); K_s is the shoaling coefficient (dmnl); b_i is the distance between wave rays at any shoreward point (m); b_0 is the distance between wave rays at a source point(m); C_i is the wave celerity at any shoreward point (m/s); and C_0 is the wave celerity at a source point (m/s).

As tsunamis are shallow water waves, they feel the ocean bottom at any depth and their crests undergo reflaction or bending around higher seabed topography (Bryant, 2001). The refraction is measured by the ratio b_o:b_1. In water with straight and parallel offshore contour, it is possible to determine the refraction coefficient, $(b_0/b_2)^{1/2}$, directly (Dean and Dalrymple, 1992). Simple geometry indicates that the ratio b_o:b_1 is equivalent to the ratio $\cos\theta_0$: $\cos\theta_i$, where θ is the angle that the tsunami wave crest makes to the bottom contours as the wave travel shoreward (Dean and Dalrymple, 1992; Bryant, 2001).

For the special case of $b_0 = b_1$, the wave height can be predicted by Green's law (Green, 1838): as a tsunami moves into shallower water near the coast, it slows down, and wave height increases via conservation of energy flux:

$$H_1 = H_0 (d_0 / d_1)^{1/4} \tag{8}$$

where H_1 is the wave height in the shoaling region; H_0 is the wave height at tsunami source; d_1 is the water depth in the shoaling region; and d_0 is the water depth at the source. The expression assumes that the bathymetric changes are so gradual as to not cause refraction (Dean and Dalrymple, 1991). Eq. (8) has been used by Satake (1988), Synolakis (1990), and Tadepalli and Synolakis (1996) for modeling of the leading waves of tsunamis.

In a large ocean, bathymetric obstacles such as island, chains, rises, and seamounts can refract a tsunami wave such that its energy is concentrated or focused upon a distance shoreline (Bryant, 2001). On the other hands, bottom topography can spread tsunami wave crests, dispersing wave energy over a larger area. This process is called defocusing (Bryant, 2001).

Refraction of tsunamis generated by linear faults close to shore tends to focus the tsunami wave energy onto a narrow stretch of coastline (Bryant, 2001). Within the last 5 m depth of water, the crest of the tsunami waves will tend to refract at an angle of less than 10° and rush directly onto coasts rather than run alongshore (Bryant, 2001). CERC (1984) suggests that refraction effects may be significant in the region where the water depth is less than one-twenty-fifth the wavelength.

When a tsunami approaches the shore, its wave height increases by converting kinetic energy to potential energy because the kinetic energy of a tsunami is evenly distributed throughout its entire depth (Yeh *et al.*, 1994). When the beach slope is steep, the conversion is especially efficient with little dissipation, meaning that more energy is available during run-up onto the beach (Yeh *et al.*, 1994).

Close to shore and around islands, tsunamis follow classic diffraction theory (Bryant, 2001). Diffraction, together with refraction and geometric spreading, decreases wave energy and reduces the amplitude of a tsunami (Bryant, 2001). Even so, tsunamis are capable of penetrating into sheltered coastal areas without significantly losing their energy (Yeh *et al.*, 1994). Little energy is dissipated, especially on steep coasts, because the kinetic energy of the tsunami is evenly distributed throughout the water column (Bryant, 2001).

Usually, tsunamis do not break, but surge onto shore at speeds of 5-8 m/s (Bryant, 2001). Murty (2007) suggests that a wave breaks in shallow water when the steepness (wave height/wavelength) exceeds 1/7; tsunamis usually do not break in shallow water, because their wavelength is still a few kilometers. If a tsunami in shallow water maintains its form as a solitary wave, the phase speed can be empirically approximated using the following expression (CERC, 1984):

$$C = \sqrt{g(d+H)} \qquad (9)$$

This expression, instead of Eq. (2), has been used by many tsunami researchers (*e.g.* Sato, 1996; Titov and Gonzalez, 1997; Pelinovsky *et al.*, 2001; Jr-Hung *et al.*, 2005; Dalrymple, 2007).

Synolakis (1995) points out that existing transoceanic codes stop the wave propagation calculation far from the shoreline, usually at the 10 m depth contours, to avoid either numerical artifacts associated with wave breaking or uncertainties in the available nearshore bathymetry and topography data. The wave height at that location is then taken as the tsunami height. This practice, still used in some recent studies (*e.g.* Choi *et al.*, 2003; Liu, 2005), has been considered inappropriate by some experts (*e.g.* Xie, 2007; Murty, 2007).

Destructive power of tsunamis varies from case to case, dependent on both physical and social factors. There is a tendency to view the destructive power of tsunamis as being due to the great height of their waves, but the height of tsunamis are not as important as the momentum of their large masses separated by ultra-long wavelengths (Abbott, 2003). Another key factor is community preparedness. A massive tsunami can be much less lethal in well-prepared communities. In Japan, for example, only 239 people died when a 30 m high tsunami smashed into Hokkaido in

1993 (Chung, 1995). By contrast, the lack of preparedness of the coastal inhabitants in the Indian Ocean region resulted in about 300,000 casualties in 2004 (Bird and Lubkowski, 2005; Hollings, 2005; Voute, 2005).

1.2.2 Tsunami Propagation Models

Seven simulation models of tsunami propagation are critically reviewed below. General characteristics and inherent limitations of the models are discussed.

1.2.2.1 FUNWAVE

The FUNWAVE model is perhaps the most advanced propagation model today. It was initially developed for modeling ocean wave transformation from deep water to the coast, including breaking and runup (Wei and Kirby, 1995). The equations implemented in the model are based on the work of Wei *et al*. (2007), with extensions to cover bottom friction, breaking and shoreline runup effects developed by Chen *et al*. (2000). The model is used for predicting both tsunami arrival time and runup height at the shoreline of a considered target community. It can reasonably be used *in lieu* of field data in locations where post-tsunami surveys have not been conducted. But, the model may not be needed for locations where tsunami inundation zones can be defined using empirical data from field observations instead. Some limitations of FUNWAVE are as follows:

- The model involves highly complex mathematical algorithms, which are hard to be understood or evaluated for their validity by emergency planners with no solid background in wave mechanics and mathematics.
- It contains needless model components. This is true, for example, in the case of the eastward propagation of the tsunami toward Thailand. The wave only exhibits weak dispersive effects, thus somewhat lessening the need for a model such as FUNWAVE.
- The model is implemented over a Cartesian coordinate grid, but the propagation medium on the Earth surface is more properly treated as spherical.
- Computations have to be stopped when breaking first occurs and this limitation may reduce the utility of the model.
- The ETOPO2 bathymetry is used, but this dataset contains systematic errors because of data mis-registeration.
- The model requires intensive data on tsunami source processes that must be obtained by using the TOPICS (Tsunami Open and Progressive Initial Conditions) software to provide the needed data.

- The model gives inaccurate results. The predicted tsunami amplitude (2.8 m) at the shore for Patong Beach is much smaller than the post-tsunami observations (4.8—5.5 m) made by a survey team from Japan (Kawata *et al*., 2005).

1.2.2.2 GEOWARE

Geoware was developed by Paul Wessel (http://www.geoware-online.com), and is used by the NOAA Pacific Tsunami Warning Center for its operations calculations. The software calculates first-arrival travel times on a grid for a tsunami generated at a given location (s), such as an earthquake epicenter (s). The package contains two programs (TTT and TTT_pick) which calculates tsunami travel times and samples the grid at given locations, respectively. The TTT program applies the Hygens principle which states that all points on a wave front are point sources for secondary spherical waves. From the starting point, times are computed to all surrounding points. The grid point with minimum time is taken as the next starting point and times are computed from there to all surrounding points. The starting point is continually moved to the point with minimum total travel time until all grid points have been evaluated. Limitations of this model are as follows:

- Spatial representation by Hygens principle requires very small grid size for improving calculation accuracy.
- GEOWARE is a DOS system based model, which is not a user friendly model.
- The wave speed equation used in this model, $C = \sqrt{gH}$, starts to break down when the water depth is very shallow. The real wave moves faster than the simulated waves.
- The model is suffered from coarse bathymetry resolution, making it meaningless to compare the simulated results with individual field observations. The discrepancies could be caused by the large grid size and uncertainties in the fault-plan mechanism.
- The wave is propagated along the specified grids, not along the shortest path (minor great circle arc), so the model tends to overpredict the tsunami travel times.

1.2.2.3 JRC

The JRC model was developed with funding from the Joint Research Center (Annunziato and Best, 2005). The model was intended to be used for reproducing the tsunami travel times to different targets of the 2004 tsunami event. Some limitations of the model are as follows:

- It is not a heuristic device for better understanding the effects of bathymetry error and resolution on tsunami travel times.
- The governing equation of wave speed is based on the shallow water approximation, which is violated in shallow water region, where wave elevation and velocity correction term affect wave speed substantially.
- The bathymetry data called ETOPO5 was used, which has lower degree of accuracy and resolution than a more detailed dataset such as ETOPO2v2; therefore, the model results are not so reliable.
- The tsunami source was proposed to be located at the fault epicenter, which are inconsistent with recent findings of tsunami source region (*e.g.* Fine *et al*, 2005).
- The model was validated using no reliable observed data on tsunami travel times in the Andaman Sea region, such as the echco sounder record from yacht Mercator (Siffer, 2005), photographs from digital camera (Thomson, 2005), and satellite altimetry records (Fine *et al*., 2005).
- The model is extremely sensitive to the bathymetry, which therefore has to be specified very carefully.
- The model was written in Visual Basic and C, so it is hard to validate the model structure.

1.2.2.4 MONTE

The MONTE (Method of Near-field Tsunami Exploring) model was developed with funding from the World Vision Foundation of Thailand (Kietpawpan *et al*., 2006). The model was intended for serving as a tool for calculating the safe available tsunami evacuation time in Patong Beach, Phuket. The latest version of this model has been developed, with funding from the Graduate School, Prince of Songkla University, to address the following limitations:

- The ETOPO5 bathymetry was used, while more precise ETOPO2v2 is freely and easily accessible. The model should be re-run with the ETOPO2v2 data.
- The method of model construction is not clearly explained. It is necessary to provide more details about theoretical formulation and the steps taken in the development of the model.
- Sensitivity test and analysis is considered as being much too brief. These aspects are extremely important in the evaluation of the quality of the model documentation and its originality. More compelling data and more comparisons should be provided.

- The equation for tsunami wave speed, which states that wave celerity is equal to the square root of the acceleration due to gravity times the water depth, only holds in deep water conditions. For the shallow water area, the equation is no longer valid. That is, the real tsunami will arrive earlier than the calculated tsunami wave for locations which put well inland. A velocity correction term and wave elevation should be included in the model boundary for achieving a better agreement between the observed and computed travel times.

1.2.2.5 MOST

The MOST (Method of Splitting Tsunami) model was developed by NOAA (Titov and Gonzalez, 1997). It is capable of simulating three processes of wave evolution: generation by an earthquake, transoceanic propagation, and inundation of dry land. The initial condition for this model is the sea floor deformation computed using elastic deformation model. The model sees all the displacement field and, as a result, small disturbance is propagating before the main tsunami wave. It is a big question, if these smaller waves are real or not, as they are not easily detectable by any instruments. The tsunami arrival time is gauged by the main wave arrival. Limitations of this models are as follows:

- It is not easily to derive the timings from the simulated animation because the problem time is not indicated. The model user has to guess these times considering the still image above declared at 2:00 h and assuming a linear frame rate.
- The model has to be implemented on a particular supercomputer to allow computation of many scenarios and to perform multiple-run sensitivity analysis.
- As the model consumes many hours per a single run, it cannot be used in a real-time tsunami warning system.
- The model must be run on a Unix operating system for Apple computer with many necessary softwares not available in Thailand. According to Assoc. Prof. Absornsuda Siripong, adopting the MOST model costs more than a million baht and requires a long time to learn how to use it and to become an experienced user.
- The calculation errors are as much as 30 min for some sites in Thailand.

1.2.2.6 RAY TRACING

The ray tracing model was developed by Satake (1980). It was originally intended to be used for calculating tsunami travel times and wave amplitude in the Pacific Ocean and the Japan Sea. The calculation of wave amplitude makes use on the Green's law based on the energy flux conservation. The model has several limitations:

- The model encounters difficulties associated with the appearance of peculiarities of the solution, due to the strong heterogeneity of wave propagation medium (sharp change of the ocean depth gradient). This causes self-crossing of trajectories and/or a collapse of the ray tube (Shokin *et al.*, 1987). So, the model user has to distort all the bathymetry data by smoothing them; otherwise, rays will be unstable for less smoothed bathymetry data. This data distortion makes the model theoretically invalid.
- Computation is stopped when rays reach the 10-m depth contour to avoid the infinite grow of wave amplitude according to Green's law, which is obviously inconsistent with the natural process of wave elevation.
- The numerical codes of this model are highly complex and not publicly available.
- The model has been considered effective only to calculate the travel time, but not the wave amplitude, as pointed out by Choi *et al.* (2003).
- In shadow zones, it is impossible to evaluate the tsunami arrival time because no wave reflection is considered.
- The model was validated by propagating the wave in a uniform ocean, which allows no chance to see the impact of bathymetry resolution on the accuracy of the simulated tsunami travel times.
- The model construction was poorly documented, making it difficult for other researchers to reproduce and validate the model structure.

Another ray tracing technique was used in Holloway *et al.* (1985). It has a drawback in estimation of bathymetry. The local water depth is simply computed as the average depth between two given points, resulting in substantial errors in tsunami travel time calculation: the predicted travel times are generally greater than the observed travel times.

1.2.2.7 SLOWMO

The Simple Long Ocean Wave Model (SLOWMO) was developed by Jesper Larsen, for calculating tsunami travel times only (Larsen, 2007). Some limitations of this model are listed below:

- The application assumes that the tsunami originates from a single point. In reality, a tsunami can be created along a rift in the ocean floor; therefore, the calculation will have an error due to misspecification of the tsunami source.
- The calculation nodes are situated at the center of the bathymetry grid boxes. The travel time is simply calculated as half the distance between two points divided by the wave phase speed in the box containing one point plus half the distance divided by the wave phase speed in the box containing the other point. The calculation should be changed to be more accurate by writing the wave speed as a function of where it is on the ray trajectory and use a bilinear interpolation based on all four surrounding grid points.
- The model uses ETOPO5 bathymetry, which is less accurate than a more detailed bathymetry dataset, such as ETOPO2v2 bathymetry.
- The wave speed equation is based on shallow water approximation, ignoring the significant effect of wave elevation and velocity correction term. The model tends to overpredict the tsunami travel times.
- The model was intended for calculating the travel times of far-field tsunamis, not of near-field tsunamis. So, it is hard to extract numerical results of tsunami travel times to a tsunameter and to a near-source target. The model output is a map showing when the tsunami will hit coastlines; the simulated travel times are expressed roughly in hour without decimal.

1.2.3 Tsunami Evacuation Simulation

Plan for evacuation is a basic strategy for saving lives immediately before tsunami waves arrive (National Tsunami Hazard Mitigation Program, 2001). To evaluate the performance of the plan, we need to rely on not only evacuation drills, but also evacuation models. Evacuation models allow the planner to experiment with a selection of alternative evacuation routes, destinations, and evacuee response rates as a means for determining effective evacuation strategies (Southworth, 1991; Vogt and Sorensen, 1992; Pidd *et al.*, 1996). The literature on disaster evacuations indicate that the modeling of tsunami evacuation is rarely attempted. The only serious modeling effort of tsunami evacuation was conducted in Japan (Sato *et al.*, 2003; Sugimoto *et al.*, 2003; Tetsushi, 2003; Katada *et al.*, 2004; Mokoto, 2004; Seiji *et al.*, 2005; Shigehiko, 2005).

Although evacuation research has been extensively conducted since the 1970s (Vogt and Sorensen, 1992), there is still the dearth of data on tsunami evacuation behavior. Tsunami are not frequent, and evacuation processes and behavior have not been well documented (Eisner *et al.*, 2003). Based on an initial literature search, only the few number of papers is available on tsunami evacuation modeling.

Virtually all are published in Japanese (Tetsushi, 2003; Makoto, 2004; Shigehiko, 2005; Nozawa *et al*., 2005). A handful of American researchers, including Harry Yeh and Irene Watts, have been working on tsunami evacuation since the early 2000s. However, their models are not yet widely accessible. None of previous works is based on the use of system dynamics (SD) in the simulation of tsunami evacuation.

Evacuation simulation problems are indeed well suited for application of SD modeling approach (Simonovic and Ahmad, 2005). The method has been used for modeling evacuations under several disasters, particularly fire and flood evacuations (Simonovic and Ahmad, 2001, 2005; Shen, 2005). Thus, there is a good opportunity for us to apply SD to tsunami evacuation modeling. When properly developed, the SD model of this type would be a useful tool for building confidence in the tsunami warning system and evacuation plan for Thai coastal communities, especially those along the Andaman seacoast.

1.2.4. Rooms for Improvement in Tsunami Hazard Mitigation

Potential rooms for improvement in mitigating tsunami hazards include the development of better methods to calculate tsunami travel times in the Andaman Sea region, and to evaluate the effectiveness of a tsunami evacuation plan. Justifications of such a development are described below.

1.2.4.1 Calculating of Tsunami Travel Times

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) is 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, it is necessary to develop a more accurate model for predicting tsunami travel times, using a new state-of-the-art method for calculating tsunami speed.

1.2.4.2. Evaluating the Effectiveness of a Tsunami Evacuation Plan

Developing local evacuation plan is essential to protecting coastal inhabitants from tsunami events (Eisner, 2005). After authorities have developed the new evacuation plans for their communities, they must demonstrate in some manner that their communities are safe, and the inhabitants can have confidence in the performace of their plans. Traditionally, two techniques have been used to meet these needs: (1) full-scale tsunami evacuation demonstration, and (2) computer-based evacuation models. The full-scale evacuation demonstration involves staging an evacuation exercise using a representative target population within the community. Such an approach poses considerable ethical, practical, and financial problems (Gwynne *et al.*, 1999), and cannot prove that the evacuation plan is likely to be effective under a real emergency (Little *et al.*, 2007). Computer-based evacuation models (Inoue *et al.*, 1996; Kawata and Koike, 1996; Shimada *et al.*, 1999) offer the potential of overcoming all those shortfalls. However, these models take long time and much input data, because they use the techniques that require complex wave-runup calculations (Sato *et al.*, 2003). Consequently, such models are rarely applied by others. To address this problem, it is necessary to develope a more pragmatic method for testing the effectiveness of a given tsunami evacuation plan, using a new model to calculate the probability of successful evacuation.

1.2.5 System Dynamics

System dynamics is a modeling approach likely to be useful for simulation of tsunami propagation and evacuation under a tsunami emergency. Below is a summary of the system dynamics history and the general characteristics of system dynamics.

1.2.5.1 History of System Dynamics[1]

System dynamics is a simulation modeling approach developed by Jay W. Forrester at the Massachusetts Institute of Technology since 1956 (Forrester, 2007). The approach has been extended from the field of feedback control (Brown *et al.*, 1948; Weiner, 1948; Porter, 1950; MacMillan, 1951) to cope with the greater complexity of social systems (Forrester, 1971). Initially, the broad principles of

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[1] A detailed history of system dynamics has been provided in Forrester (1989, 2007) and Lane (2007). Umpleby and Dent (1999) addresses the history of system dynamics and other system traditions also.

feedback systems were first applied to industrial system (Forrester, 1961), subsequently applied to other social and economic system, and become known as the field of system dynamics since the 1980s (Nancy *et al.*, 1983), but the name ‘system dynamics’ first appeared in *World Dynamics* in 1971 (Forrester, 1971). System dynamics can be applied to any dynamic system (Sterman, 2000). In disaster management, system dynamics has only been applied to fire (Shen, 2005) and flood evacuations (Simonovic and Ahmad, 2005).

1.2.5.2 Characteristics of System Dynamics

One of the most basic concepts in system dynamics is the idea of feedback in systems (Meadows, 1980). The theory, principles, and behavior of feedback systems are fully described in Forrester (1968) and Goodman (1974). In brief, system dynamics assumes that systems are interlocking feedback loops (Meadows, 1980), which exist to drive everything that changes through time (Forrester, 1996). Every action, every change in nature, is set within a network of feedback loops (Forrester, 1996). Feedback loops are the structure within which all changes occur. All systems, everywhere, consist of these two kinds of concepts: levels and rates, and none other (Forrester, 1996). The level is an accumulation, or integration, or stock, or state variable. The rate is a flow that changes the amount in the level. Figure 1 shows a simple structure of feedback system, or a system dynamics model.

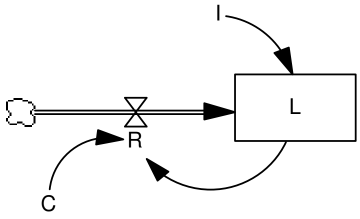

Figure 1. Flow diagram of a simple feedback system
Source: Adapted from Goodman (1974).

The double arrow in the diagram represents the physical flow; the curve arrows, known as information links, indicate causal influence in the direction shown by the arrows (Meadows, 1973). The cloud symbol represents the source or sink of flow, which is considered to lie outside the model boundary (Forrester, 1961). Drawn as valve is the rate of flow, which is controlled by the information links that point to it. The rectangle is the symbol of level, *i.e.* the results of accumulation of the flow. The rate *R* influnces the level *L*, which in turn influences *R*. The sequence of influence leads back to its own starting point and form a feedback loop, or technically termed a positive feedback structure.

As shown in the diagram, a one-way flow of material accumulates in the level *L*. In turn, information about the quantity in the level at any time controls the flow into *L* via the rate *R*. *R* is proportionately related to *L* by a constant *C*. The equations for the system with an arbitrary *C* value of 0.5 and an initial level value *I* of 1 are:

$$L = INTEG(+R, I) \tag{10}$$

$$R = CL \tag{11}$$

$$I = 1 \tag{12}$$

$$C = 0.5 \tag{13}$$

The notation used in Eq. (10) is exactly equivalent to the following traditional integral equation:

$$L(t) = \int_{t_0}^{t} R(s)ds + L(t_0) \tag{14}$$

where *R*(s) represents the value of rate (or inflow) at any time *s* between the initial time t_0 and the current time *t*.

The structure represented in Figure 1 also corresponds to the following differential equation:

$$\frac{dL}{dt} = R(t) = CL(t) \tag{15}$$

Hence, we can represent the system analytically by the following equation (Goodman, 1974):

$$L(t) = Ie^{(C*t)} \tag{16}$$

However, differential equations are difficult, confusing, weak, and unrealistic (Forrester, 1996). The traditional notation used in calculus is often confusing to many people (Sterman, 2000). For simplicity, then, this thesis represents the process of accumulation with the INTEG() function, following Sterman (2000), similar to Eq. (10).

To determine the behavior of the structure in Figure 1, system dynamicists use the numerical simulation procedure in calculating the values of all variables, and plot them as a function of time. Using rate and level equations, the computation is relatively simple (Goodman, 1974):

First, the first *R* value is computed with the aid of the initial *I* value of the level *L*. Second, *R* value is multiplied by *DT*, the time interval over which we compute the rate of flow. Third, the product of *R* and *DT* is added to the initial *I* value to produce a new *L* value. Finally, the initial *I* value is replaced, and with the new *L* value the process for a desired number of DT intervals is repeated in the time span of the simulation (time horizon). The computation can be done by hand but better by using a simulation environment, *e.g.* DYNAMO, POWERSIM, STELLA, or Vensim (for a good review, see Ford, 1999, appendix D-G).

Once calculated, the values of key variable are graphed over time to represent the system behaviors. Next, the modeler must test for building confidence in the model, by using a wide varity of tests (Forrester, 1961; Forrester and Senge, 1979; Richardson and Pugh, 1981; Balas, 1989, 1996; Sterman, 2000).

A detailed description of the system dynamics approach is available elashwere (Forrester, 1961, 1968; Goodman, 1974; Randers, 1980b; Richardson and Pugh, 1981; Roberts *et al*., 1983; Ford, 1999; Sterman, 2000). Suggested literatures in the field of system dynamics are listed in Roberts *et al*. (1983), Sastry and Sterman (1992), and Ventana Systems (2007). Additionally, the serious practitioner is recommended to have access to the MIT System Dynamics Group Literature Collection offered by the System Dynamics Society on DVD. The Collection includes D-memos, MIT doctoral and master's theses, instructional materials, and several papers published by members of the Group. D-memos are discussion memoranda prpared by professors, researchers, and students, representing about fifty years of work in system dynamics. They present a number of models, most of which consider the dynamics in complex systems. Most useful to novice modelers seems to be the instructional material called Road Maps. Although directed to younger audience with basic mathematical skills, Road Maps is a self study guide for learning system dynamics that provides basic technical knowledge needed for implementing any system dynamics project.

1.3 Objective

This study aims to develop a method to evaluate the effectiveness of a tsunami evacuation plan designed by the Patong Municipality, Phuket, Thailand (PMO, 2005a, 2005b). Its purpose is to provide a pragmatic tool for addressing the question most concerned by inhabitants in Patong municipality: "*Do you have confidence in the warning system and evacuation plan if there was another tsunami in Patong Beach?*" (SHIRE1, 2006; Wanderluster, 2006; Pongprayoon, 2006). The focus is on nearfield tsunamis generated in the Sunda Subduction Zone of the Andaman Sea, and propagating toward Patong Beach, with the populous Bangla Road as the considered evacuation area (Figure 2).

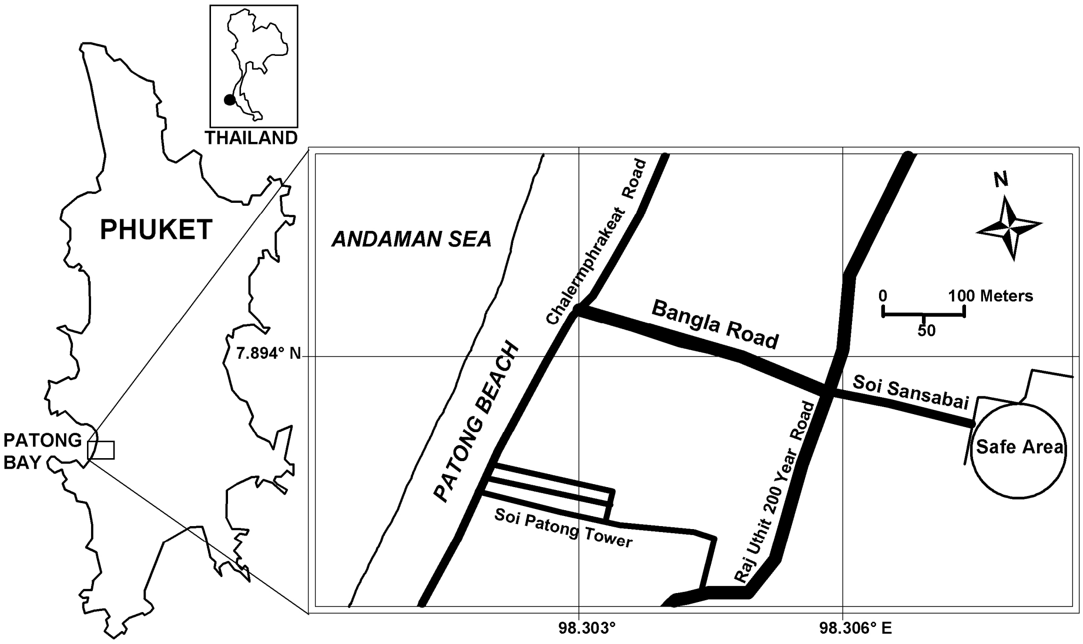

Figure 2. Map of Bangla Road in Patong municipality, Phuket