Method to Determine Locations of Tsunami Vertical Evacuation Shelters[1]

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Abstract

The 2004 Indian Ocean tsunami and the 2011 Great Tohoku Japan earthquake and tsunami focused a great deal of the world's attention on the effect of tsunamis on buildings and infrastructure. When a tsunami impacts structures in a coastal community, the structures are often not strong enough to withstand the forces and may collapse. Therefore, to maximize the survival probability, people evacuate to higher ground or move outside the inundation zone. However, this is not always possible because of short warning times for near-field tsunamis. Thus, sheltering-in-place or "sheltering-near-place" using vertical evacuation should be considered as an alternative approach to lateral evacuation from a tsunami inundation zone. This paper presents the method and results of a study to develop and demonstrate a methodology that applied genetic optimization to determine optimal tsunami shelter locations with the goal of reducing evacuation time thereby maximizing the probability of survival for the population in a coastal community. The City of Cannon Beach, Oregon, USA was used as an illustrative example. Several cases were investigated ranging from a single shelter to multiple shelters with

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locations of high elevation already in place near the city. The method can provide decision-support for determination of locations for tsunami vertical evacuation shelters. The optimum location of the shelter(s), which was found to vary depending on the number of shelters considered, can reduce the evacuation time significantly thereby reducing the number of fatalities and increasing the safety of a community.

Key Words: Tsunami; evacuation shelters; genetic algorithms; optimization; fragility; natural hazard mitigation; Cascadia Subduction Zone; vertical evacuation

Introduction

Recent tsunamis have focused the world's attention on large offshore earthquakes and the tsunamis they can generate. The most recent large event, the Great Tohoku Japan earthquake and tsunami, occurred off the east coast of Japan on March 11, 2011. A tsunami triggered by the M9.0 undersea earthquake, measured as one of the five most powerful earthquakes ever and the largest recorded in Japan, had an inundation depth at the shoreline of approximately 10 m with maximum runup heights in excess of 20 m in many areas (Mori et al. 2012). Officially, the tsunami struck between 23 minutes and one hour following the fault rupture depending on the site (Fukushima, Miyagi, and Iwate prefectures were close to the earthquake source) (JMA 2011). The water traveled as much as 10 kilometers (6 miles) inland because of flat land near the coast. Officially, there were over 15,500 deaths and more than 5,000 people are still missing with over 125,000 buildings damaged or destroyed (Japanese National Police Agency 2011).

When a tsunami impacts structures in a coastal community, they may not have sufficient lateral strength and may collapse. Therefore, people must evacuate to higher ground or move outside of the inundation zone, but this is not always possible because of the short warning times particularly in the case of near-field tsunamis. In these cases, sheltering-in-place or "sheltering-near-place" may be an alternative way to evacuate from the dangers of a tsunami (FEMA 2008).

The probability of survival for people in a community is related to: (1) the location of the shelter(s) or place(s) of high elevation; (2) the evacuation time available which is a function of the fault location; and (3) the actions of those evacuating such as how long it takes them to react, how fast they can move from their house to the shelter, and how well prepared they are (Afshar and Haghani 2008; Doerner et al. 2009; Salmerón and Apte 2010; Lindell et al. 2011). To determine this probability, a methodology that applies optimization techniques was employed to identify an optimal location for one or more shelters, with the study objective of providing assistance for vertical evacuation in a community. Genetic algorithms (GAs) were adopted in this study, which is essentially a heuristic search procedure based on the mechanics of natural selection and genetics. It has been employed broadly to generate useful solutions to optimization and search problems for over 40 years due to its simplicity and robustness (Holland 1975; Goldberg 1989; Yao and Sethares 1994; Hajela and Lee 1995; Rajan 1995; Doerner et al. 2009; Elsayed et al. 2011; Kumar and Parthasarathy 2011; Miandoabchi and Farahani 2011). In addition, GAs have been employed in many optimization problems to overcome the shortcoming of classical calculus-based optimization methods (Rajeev and Krishnamoorthy 1992; Hajela and Lee 1995; Hajirasouliha et al. 2011; Leng et al. 2011). Generally, calculus-based methods require the gradient of the objective function or the existence of derivatives to find local maxima by solving a set of nonlinear equations. This is a severe limitation even if the numerical approximation of the derivative is allowed. GAs do not require the presence of these derivatives nor the continuity of design variables which is initially assumed in calculus-based optimization methods (Goldberg 1989).

Since being proposed by Holland (1975) and further developed by Goldberg (1983, 1989), GAs have been adopted for many engineering optimization problems. Rajeev and Krishnamoorthy (1992) presented a simple genetic algorithm for designing structural systems with discrete variables. Kongsomsaksakul et al. (2005) studied optimal shelter locations for flood evacuation planning using genetic algorithms. The shelter location was determined to minimize the evacuation time based on pre-defined locations. Doerner et al. (2009) proposed a heuristic approach based on GA to make location planning for public facilities in tsunami-prone coastal areas.

This study differs from the previous efforts (i.e. the research of Kongsomsaksakul et al. (2005) and Doerner et al. (2009)) in that no discrete number of locations is selected within the algorithms. This could easily be done but the approach in this paper is presented in its most general form. Once the location of the shelter(s) is determined, a fragility analysis is carried out to show the conditional survival probability under the given hazards level. It is felt to be a logical extension from earthquake engineering procedures. In earthquake engineering, probabilistic relationships between earthquake ground motion intensity (e.g. spectral acceleration) and structural damage (or another parameter, e.g. collapse, displacement) are the most typical fragilities. Ellingwood et al. (2004) and Rosowsky and Ellingwood (2002) developed a fragility analysis methodology for assessing the response of light-frame wood construction exposed to extreme windstorms and earthquakes. Park and van de Lindt (2009) developed a fragility formulation which provided a method to assess the seismic vulnerability of a structure using existing shake table test data.

In this study, a fragility analysis was performed to assess the survival probability subject to evacuation time. It should be noted that an evacuation time might not be reasonable enough to describe a tsunami hazard. The ability to accurately characterize tsunami hazard is somewhat lacking due to the rarity of these natural phenomena and, as mentioned above, the exact evacuation time (i.e. the time to tsunami wave arrival) is believed to vary significantly depending on numerous physical variables such as topography, bed bathymetry, wave velocity, wave height, etc. Therefore, this study focuses on determining the location of vertical evacuation shelters to secure a survival rate given a certain available evacuation time or to reduce the amount of time needed to provide a specific survival rate. Furthermore, the fragilities can provide information to make decisions related to positioning vertical evacuation shelters for tsunamis.

Mathematical Formulation

Optimization Techniques

Typically, a general constrained optimization problem can be expressed as:

$$\textit{Minimize} \quad f(x) \tag{1}$$

$$\text{Subject to} \begin{cases} g_i(x) \le 0 & : \quad i = 1, 2, \ldots q \\ h_j(x) = 0 & : \quad j = q+1, q+2, \ldots m \end{cases} \tag{2}$$

where $f(x)$ is a objective function which depends on the specifics of the problem, $g(x)$ are the inequality constraints, q is the number of inequality constrains, $h(x)$ are the equality constraints, and m-q provides the number of equality constraints.

The general optimization problem is to find the solution subject to one or more inequality and equality constraints. There is no known method to determine the global maximum or minimum solution unless the objective function has one or more constraints. To do this, the penalty functions, which help eliminate impractical solutions during the procedure, are adopted and can be expressed as:

$$f_p(x) = f(x) + \sum_{i=1}^{m} C_i \left(P_i\right)^{\beta} \tag{3}$$

$$P_i^{\beta} = \begin{cases} \delta_i g_i(x) & : \quad i = 1, 2, \ldots\ldots, q \\ \left|h_i(x)\right| & : \quad j = q+1, \ldots, m \end{cases} \tag{4}$$

$$\delta_i = \begin{cases} 1 & : \quad \text{if } i\text{-th constraint is violated } (g_i(x) > 0) \\ 0 & : \quad \text{otherwise } (g_i(x) \le 0) \end{cases} \tag{5}$$

where $f_p(x)$ is a penalized objective function, $f(x)$ is the (unpenalized) objective function, C_i is a value imposed for violation of the i^{th} constraint with values equal to a relatively large number, β is a user-defined exponent with values of 1 or 2 typically used, δ_i is the Kronecker's delta function, and constraints 1 through q are inequality constraints. One can see that the penalty will only be activated when the constraint is violated, while constraints q+1 through m are equality constraints which will activate the penalty if there are any values (Arora 2004; Yeniay 2005).

Problem Statement

The aim of the study is to determine an optimal location for each of the shelters to minimize the tsunami evacuation time thereby maximizing the survival rate. Thus, the design variables of this problem are the location vector which can be expressed simply as:

$$X = \left\{ \left(x_1^s, y_1^s \right), \left(x_2^s, y_2^s \right), \cdots\cdots, \left(x_{N_{Shelter}}^s, y_{N_{Shelter}}^s \right) \right\} \tag{6}$$

where (x_1^s, y_1^s) is the location of the *1*st shelter, (x_2^s, y_2^s) is the location of the *2*nd shelter, and ($x_{N_{shelter}}^s$, $y_{N_{shelter}}^s$) is the location of the *N*th shelter. $N_{Shelter}$ is the number of shelters.

To do this, an objective function must be satisfied by minimizing a distance or elapsed time to evacuate from each structure to the shelters (i.e. minimizing the distance traveled for the community during an evacuation) and can be expressed as:

$$f(x) = \sum_{i=1}^{N_{House}} (L_i) \tag{7}$$

where $f(x)$ is the objective function, N_{House} is the number of residential structures in the community. Then, L_i, defined as the distance between the shelter and the *i*th structure in the community, can be calculated as:

$$L_i = \sqrt{(x_i - x_i^s)^2 + (y_i - y_i^s)^2} \tag{8}$$

where (x_i, y_i) is the location of the *i*th structure and (x_i^s, y_i^s) is the location of the shelter serving the *i*th structure (i.e. the nearest shelter for the target structure). It should be noted that the capacity of the shelters can change and was treated as one of the constraints which is shown in Equation (14) in the present study.

Equation (8) essentially gives the straight line distance from the shelter to a given location. This is a simplification knowing that evacuees would generally follow streets which may be laid out in a grid pattern, may not necessarily take the quickest route, or may be influenced by the actions of others. Nevertheless, this is felt to be a reasonable first approximation to relate the distances between the evacuees and the shelters. In general, three coordinates are needed to express the exact location of a structure or shelter and the objective function could be extended by adding a z coordinate (i.e. height or elevation). In that case, the height of the single structure and shelter should be included in the calculation for distance, but this is not examined here since it was felt to be insignificant for these elevations (i.e. less than 30 m (100 ft)).

Additionally, when people evacuate to the shelter(s), there is a possibility of a delayed reaction time. This reaction time can vary significantly and can depend on factors such as:

(1) recognition / information level (i.e. preparation or understanding of their evacuation plan or assigned shelter information);

(2) characteristics (i.e. taking immediate action for a near-field earthquake event);

(3) infrastructure to provide warning (e.g. immediate broadcast on TV and radio; reverse emergency calls and text messaging, sirens, etc);

(4) desire to collect items such as money, clothing or food.

These factors are certainly outside the direct scope of this study, but are relevant enough to the evacuation problem that some metric of inclusion is applied. It should be noted that the delay time was assumed by the authors. The value does not reflect all possible reactions, but is intended to provide some variation to examine the affect on shelter location decisions. In this study, the recognition level of the preparation or understanding of the evacuation plan was considered; each person's recognition level was treated as a random variable for illustrative purposes. The delay time was then computed based on the recognition level, shown in Table 1. The objective function, expressed in Equation (7), was computed as the distance to evacuate. Thus, Equation (7) can then be modified to reflect the delay times and expressed as:

$$f(x) = \sum_{i=1}^{N_{House}} (L_i / W_{speed} + T_i) \tag{9}$$

where W_{speed} is human walking speed which will be discussed later and T_i is the delay time of the building occupants.

Review of Genetic Algorithms

In genetic algorithms, the problem can be represented as a population of strings which is a set of binary bit strings of 0s and 1s for defining a solution to the problem. Each binary bit in this string can represent some characteristic of the solution or the whole string can represent an integer or floating point number. The basic mechanics in GAs is analogous to Darwinian evolution: weak traits are eliminated from the population and strong traits survive and are mixed by recombination to form a better generation through evaluating, mating, and evolving. To do this, the population, defined as a set of chromosomes, is randomly generated to make an initial solution of problems covering the entire range of the possible solution space and then four operators, which are defined as selection, reproduction, crossover, and mutation operators, are employed to mimic the concept of Darwinian evolution (Goldberg 1989).

Selection is the process in which a portion of the existing population is selected to breed a new generation during each successive generation by using fitness-based measurement criteria like natural selection. The fitness in terms of the objective function can be represented by some measure of profit, utility, or goodness to maximize or minimize the function. In nature, it can be determined by a creature's ability to survive predators, pestilence, and other such obstacles. The next step is the reproduction operator which generates an offspring of solutions from selected chromosomes. Each chromosome is dealt a parent either a father or mother in genetic terms. During the process, two important operators, crossover and mutation, are needed to evolve the solutions to seek the best one(s). Crossover is accomplished by taking two random chromosomes from those already selected to form the next generation and randomly exchanges the selected strings between them. After a crossover is performed the mutation takes place. Mutation randomly changes the new offspring by randomly switching a few bits from 0 to 1 or 1 to 0 to restore diversity that may be lost from the repeated application of the selection and crossover operators, and prevent all solutions falling into an optimum of the solved problem (Goldberg 1989). The overall procedure of GAs is depicted in Figure 1.

A roulette wheel rule, selecting a chromosome according to the weight of its fitness, can be adopted as a selection operator. This means that chromosomes with a higher value have a higher probability of contributing one or more offspring in the next generation. The use of a one-point crossover rule can be used. This rule is to choose one point randomly and everything before this point is copied from a first parent and everything after that point is copied from the second parent. There are many crossover rules and specific crossovers can improve the performance of the optimization. Finally, a program was developed and termed TOGA (**T**sunami evacuation **O**ptimization program via **G**enetic **A**lgorithms).

Initially, the shelter location is considered as a design variable, which is expressed as Equation (6), in this optimization problem. So, the location of the shelter(s) which guarantees the minimum distance between the shelter(s) and each house in the community (i.e. minimizing the objective function as expressed using Equations (1) to (9)) should be optimized. To do this, the location of each house in the community and the boundary of the community are needed as input data. TOGA then performs the optimization procedure outlined earlier to find the optimum location using a GA (i.e. repeating genetic operators until obtaining an optimum solution). Finally, it determines the optimum location of the shelter(s) based on the aforementioned constraints.

Fragility curves

A fragility curve is a conditional distribution for the probability of exceeding a specified threshold (e.g. drift, damage, or collapse) as a function of one or more hazard intensity measures. For earthquake hazard, intensity can be expressed in terms of spectral acceleration at the buildings fundamental period. For structures in the inundation zone, the tsunami intensity can be selected based on such factors as inundation depth, current velocity, or hydrodynamic force (Koshimura et al. 2009a; Koshimura et al. 2009b). In essence, a fragility defines the conditional probability of the demand (D) placed upon the structure exceeding its capacity (C) for a given level of tsunami intensity (I). For the case of tsunami survivability including vertical evacuation, the survival of an individual in time rather than the integrity of a building in space is considered.

Therefore, we express the tsunami intensity in terms of the possible evacuation time (*T*), and the fragility can be expressed as:

$$F = P[D \geq C \mid T] \tag{10}$$

where *F* represents a fragility, or likelihood of fatality, under given conditions.

Generally, the lognormal distribution function is a convenient way to express a fragility curve and can be expressed as (Shinozuka et al. 2000; Ellingwood 2001; Rosowsky and Ellingwood 2002; Koshimura et al. 2009a; Koshimura et al. 2009b; Park and van de Lindt 2009):

$$F_R(x) = \Phi\left(\frac{\ln(x) - m_R}{\xi_R}\right) \tag{11}$$

where $\Phi(\cdot)$ is a standard normal distribution function, x is a possible evacuation time, m_R is the logarithmic mean, and ξ_R is the logarithmic standard deviation.

Illustrative Examples

Cannon Beach along the U.S. northern Oregon coast was selected as an illustrative example and is shown in Figure 2. Residential structures are only considered in this study since they are the structure most susceptible to tsunamis. It is noted that pedestrians, people in cars and in offices were not counted and only people in residential structures were utilized in this study. Initially, the location of each house in Cannon Beach is computed based on a satellite image and calibrated based on the south-west city boundary, which is designated as the origin in Figure 3. In the schematic overview of Cannon Beach shown in Figure 3, the black solid line shows the city boundary and each blue dot represents an individual house; approximately 1400 houses were identified in the study area. Detailed information on the houses can be found in Park (2011).

From FEMA-P646 (2008), a combination of vertical evacuation facilities and the use of natural high ground is recommended for evacuation when available. Figure 4, excerpted from FEMA P-646 (2008), illustrates this concept. Thus, two evacuation concepts such as evacuating to shelters or places of high elevation and their combinations are considered in this study. Additionally, one large shelter which is large enough to serve all citizens of the community may not always be efficient when considering total time to "evacuate". Therefore, two or more shelters may be needed to provide the optimal solution. In that case, a proper shelter location should be selected to obtain the shortest distance among the multiple shelters for the evacuees in a community.

Shelter(s) can be located anywhere in the community (assuming no additional constraints), thus the location of the shelter must be determined to maximize survival while balancing cost or construction funding available. Of course, to examine this problem the number of persons to be admitted or accommodated and human walking (or running) speed for each age must be accounted for in the analysis. Also included in the analysis is the optimal number of shelters for the entire community.

It should be noted that the shelter(s) do not always need to be new construction; rather they can be selected from existing structures in the community such as a city hall, hospital, school, or fire station. In that case, the selected structure should be retrofitted properly to serve as a shelter. Another item of note is that the methodology presented in this paper examines the problem from an engineering point of view and only moderately takes into account psychological variables as discussed in Table 1 earlier. More complex human behaviors such as fear, panic, confusion, etc are not considered in the present study. For example, a person evacuating may run toward higher ground rather than a shelter-in-place in a vertical evacuation facility even though their designated evacuation site is the shelter. Such occurrences could be examined using agent-based modeling where agents are assigned probabilistic propensities toward certain behaviors, but that is beyond the scope of this study.

The software TOGA was used to solve this illustrative example. The design variables are converted into a binary string array: the chromosome. The lower and upper bound of the design variable (the location of the shelter) was provided and can be determined from the community details and then the size of the binary string array can be computed.

As an illustrative example, consider a community that has a rectangular shape and is idealized as a 1.0 x 2.0 kilometer shape. One large shelter is assumed to be sufficient to serve the entire community. The location of the shelter is assumed to be at the mid-point of the community area, (500m, 1000m) simply for illustrative purpose. In this case, the 21 binary strings can be represented by one design variable, illustrated in Figure 5, and summarized in Table 2. It should be noted that the optimum location of the shelter may not be the mid-point of the community and more shelters may be needed to meet the community evacuation needs. It should also be mentioned that the configuration of the community such as elevations, direct street access, etc must be considered when determining the optimum location since it affects the human evacuation paths taken in the optimization presented herein.

If a community is a large metropolitan area, then the grid can be modified to reduce the size of the chromosome, which can reduce the computation cost significantly, but this is not mandatory. In that case, the shelter is assumed to be located only at the grid point. The space of the grid can be selected as half of the shelter size or some other arbitrary size, if desired.

Once the location of the shelter has been determined, the survival fragility which is the inverse of the fatality fragility can be computed based on the possible evacuation time in the community. To do this, human walking speed is used to provide a conservative estimate and applied as defined in Table 3 (Knoblauch et al. 1996). With proper community education and training it is likely that many people would travel faster than a typical, or average, walking speed. It should be noted that very old people, very young children, and persons with disabilities will be even slower because of delayed response or an inability due to age or potential injury from the earthquake. In this study, the average walking speed was felt to be a good measure, albeit slightly conservative, of the time needed for community inhabitants to move from their home to the vertical (or other) evacuation shelter.

Each house is assumed to have four inhabitants and their walking speed is assumed to be the mean speed, 1.381 m/sec. It is noted that the people in the house can vary by gender and age, or they may not be at home but rather at work, but that type of time dependence is not accounted for in this study. Their speed can also vary, so they are categorized into two groups. Also, their recognition or information level related to the evacuation plan including the assigned shelter(s) was considered and then their time delay computed. As mentioned earlier, each person's level of understanding of the evacuation plan was generated randomly using a basic level of uncertainty, so their evacuation time can be computed directly using the values in Table 1 and Table 3. The survival fragility was then computed using TOGA based on Equation (10) or Equation (11). The shelter location without optimization which is located in the middle of the community in the present example is shown in Figure 6. In this figure, one can see that a 22% survival probability can be increased to 79% when the available evacuation time increases from 5 minutes to 10 minutes, assuming people begin walking toward the shelter immediately upon feeling the earthquake. However, immediate response is not always likely since people will often gather belongings, or join together in small groups, as discussed earlier. Therefore, inclusion of a time delay was considered. The difference for the survival probability when the time delay is included is shown in Figure 7. This simple example shows that for a near-field earthquake with only a 10 minute arrival time, the survival probability is reduced from 79% to 24% when just a short delay occurs. If as much as 17 minute is available, a 79% survival can still be achieved when delay time was included, according to the analysis presented in this study. Of course, it is again noted that this is without optimizing the shelter location.

The target survival probability for a specific evacuation time can be selected as one of the constraints and can be expressed and normalized as:

Probability:

$$\begin{aligned} g_1(x) &= S_{T_a} \leq S_L \\ &= \frac{S_{T_a}}{S_L} - 1.0 \leq 0 \end{aligned} \tag{12}$$

where S_{T_a} is the survival probability at a given evacuation time T_a and S_L is the target survival probability.

Additionally, the number of shelters, their capacity, the shape of the community, and either the maximum distance or the maximum time to the shelter can all be constraints as well. These constraints can be selected and activated for the specific problem at hand and can be expressed as:

Number:

$$\begin{aligned} g_2(x) &= N_S \le NS_L \\ &= \frac{N_S}{NS_L} - 1.0 \le 0 \end{aligned} \tag{13}$$

Capacity:

$$\begin{aligned} g_3(x) &= \max(H_i) \le H_L \\ &= \frac{\max(H_i)}{H_L} - 1.0 \le 0 \end{aligned} \tag{14}$$

Shape:

$$\begin{aligned} g_4(x) &= \begin{cases} \max(L_i) \le L_L & : \quad \text{distance} \\ \max(L_i)/W_{speed} \le T_L & : \quad \text{time} \end{cases} \\ &= \begin{cases} \dfrac{\max(L_i)}{L_L} - 1.0 \le 0 & : \quad \text{distance} \\ \dfrac{\max(L_i)/W_{speed}}{T_L} - 1.0 \le 0 & : \quad \text{time} \end{cases} \end{aligned} \tag{15}$$

where N_S is the current number of shelters, NS_L is the possible number of shelters for the community, H_i is the number of people in one shelter and H_L is the maximum capacity per shelter, L_i is the shortest distance between the i^{th} house and a shelter, W_{speed} is human walking speed, and L_L and T_L are the limits of distance and time, respectively.

To handle an arbitrary community shape, the lower and upper bounds for the design variable are needed:

$$x_{L_i} \le x_i \le x_{H_i} \ , \ y_{L_i} \le y_i \le y_{H_i} \tag{16}$$

where $\left(x_{L_i}, x_{H_i}\right)$ and $\left(y_{L_i}, y_{H_i}\right)$ are the lower and upper boundary of the x_i and y_i location, respectively. In this manner, the approach described above can incorporate an arbitrary community shape, such that outside the regions can be treated as impossible or a violation of the constraints and inside the regions can be treated as satisfying the constraints.

Optimization for one, two, and three shelter cases was performed and the results are presented in Table 4. The results of these three analyses for Cannon Beach are combined and illustrated in the fragility plots in Figure 8. The survival probability increases substantially as the number of shelters increases, as expected. When the available evacuation time is equal to 20 minutes, the survival probabilities increase to 53%, 81%, and 91% for one, two, and three shelters, respectively. Based on the abovementioned results, the effect of the number of evacuation shelters have on the survival probability of members of a coastal community can be quantified. It is then possible to determine the optimal number of shelters based on virtually any constraint. Finally, the approach can also provide useful information to better prepare vertical evacuation plans.

In many cases there may be a location which has a high elevation in or near a community. This location may be high enough to avoid tsunami inundation and suitable to occupy for a duration necessary for survival. To illustrate this, the tsunami evacuation map from the Cannon Beach is presented in Figure 9, which contains the locations of high elevation sites near or within the city. In Figure 9, the left image is the tsunami evacuation map provided by Cannon Beach which shows six places of high elevation to be used for vertical evacuation. The right window shows a computer generated model showing the location of each house in the community which was used in the model. The black solid line shows the city boundary, and the blue dots represent individual houses. Each large red star represents a single location of high elevation.

The six locations of high elevation were located based on the tsunami evacuation map and calibrated based on the south-west corner of the boundary of the city which is the same approach used for computing the location of each residential building in the community. The coordinates for the six places of high-elevation are tabulated in Table 5.

Fragilities for the community can also be constructed based on the six aforementioned locations with high elevations. One of the six places is assigned to each residential building based on obtaining the shortest distance between the house and the evacuation locations. Survival fragilities for evacuation using the six locations combined with the three shelter case are presented in Figure 10. It is assumed that there is a delayed reaction and, as before, the average walking speeds are used in all analyses.

The survival probability increases as the number of shelters increases as one would expect, as previously shown in Figure 8. Based on the aforementioned assumptions, the survival probability can be computed as 53%, 81%, 91%, 84%, and 92% for the one, two, three cases, the six high elevation location case, and finally the one large shelter plus six places of high elevation case, respectively. Thus, one can see that the locations of naturalhigh elevation give a high survival probability because the six locations are geographically well distributed. These six locations provide a calculated survival probability distribution greater than a single optimized shelter, but lower than two optimized shelters. If the community has one shelter and six high elevation locations for evacuation, it yields a very high survival rate when the possible evacuation time is greater than 10 minutes, which would be the case for most near-field cities such as Cannon Beach, OR.

The possible evacuation time is now assumed to be 20 minutes which is similar to a tsunami generated on the west coast of the U.S. from the Cascadia Subduction Zone earthquake. Clearly, the combination of one shelter and six high elevation locations is the best solution for tsunami evacuation of this community. It can be observed that the high elevation locations can be very helpful in increasing the survival probability for city residents but not as significantly as the addition of several optimized shelters.

Additionally, one more constraint would likely need to be added which is related to the maximum capacity per shelter. This was expressed in Equation (14) and was considered for the three shelter case. Two different analyses were performed, namely one with no limitation on the capacity per shelter and then one with a capacity of two thousand people per each shelter. It was assumed that four inhabitants live in each house and there are 1422 houses, thus there are 5688 people in the modeled community. The unconstrained case performed only slightly better than the constrained case as shown in Figure 11. In Figure 11, one can see that a 91% survival probability can be decreased to 88% when the possible evacuation time is assumed to be 20 minutes. A 3% difference in considering this constraint is not a big difference but the ability to model this constraint is important because the number of shelters and their size affect the community. Thus, this information could be helpful for emergency planners or decision-makers. The results of the optimal location of three shelters are presented in Table 6.

Recall that the objective of this study was the development of a methodology to determine the quantity and location of evacuation shelters for a community subjected to constraints to provide guidance for tsunami vertical evacuation planning in the community. Although there were a number of assumptions and simplifications to facilitate the illustrative example, the methodology and the TOGA software can provide the necessary optimization to make informed decisions.

Summary and Conclusion

The objectives of this study were to develop a method that can help determine locations of tsunami vertical evacuation shelters using: (1) optimization to find the best location of the shelters to secure a survival probability agreed upon by all stakeholders; and (2) fragilities to quantify the survival rate for residents of a coastal community.

The methodology for tsunami vertical evacuation planning presented in this paper was intended to ultimately provide key information to better understand and mitigate risks caused by tsunamis. The methodology developed herein can optimize the location and number of shelters in combination with existing locations of naturalhigh elevation in a community to quantify and increase survival rate and reduce tsunami risk. This study presented the theory and demonstrated that for a typical small coastal community, it may be possible to achieve near full evacuation provided optimization is performed.

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Table 1: Delay time for various recognition levels.

Level	Recognition Level (%)	Delay Time (minutes)
Very Good	80~ 100	0
Good	50 ~ 80	2
Average	20 ~ 50	5
Poor	0 ~ 20	10

Table 2: Design configurations of the one shelter.

Design Variable	Lower / Upper bound	Binary	Size
x_1	0 / 1000 m(3281 ft)	2^{10}(1024)	10
y_1	0 / 2000 m(6562 ft)	2^{11}(2048)	11
Sum			21

Table 3: Human walking speed.

Age	Typical walking speed
Old (over 65)	1.253 m/sec(4.11 ft / sec)
Young (over 13)	1.509 m/sec(4.95 ft / sec)
Mean	1.381 m/sec(4.53 ft / sec)

Table 4: Optimum location of the shelters.

Case	Shelter No.	Location(meter) (x, y)
One Shelter	1	(350, 3293)
Two Shelters	1	(371, 3890)
	2	(284, 1327)
Three Shelters	1	(381, 5325)
	2	(306, 3694)
	3	(264, 1369)

Table 5: The six places of high elevation (Cannon Beach 2011).

No.	Location(meter) (x, y)	Name
1	(167, 6110)	8th Street
2	(1197, 5864)	North Entrance
3	(789, 2948)	Sunset Hill
4	(663, 2444)	Milepost 30
5	(751, 879)	Haystack Heights
6	(260, 105)	Tolovana Mainline

Table 6: Allocated people in the three shelters

Shelter No	Unconstrained		Constrained	
	People	Location(meter) (X, Y)	People	Location(meter) (X, Y)
1	872	(381,5325)	1912	(334,1241)
2	2704	(306,3694)	1776	(302,4433)
3	2112	(264,1369)	2000	(441,3412)

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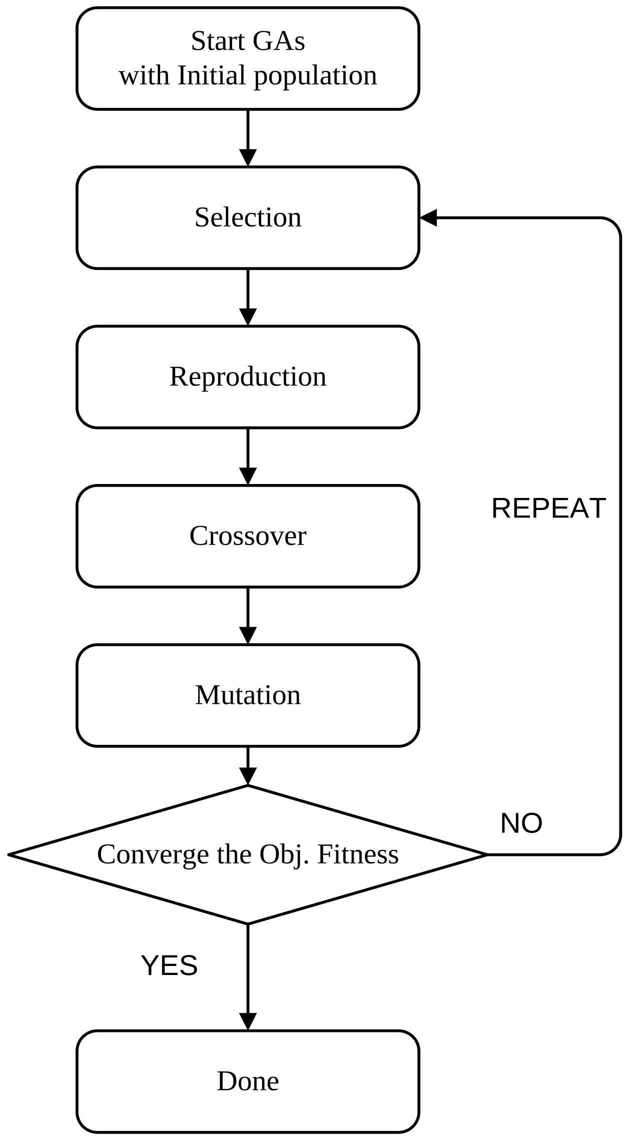


Figure 1: Overall procedure for Genetic Algorithms.

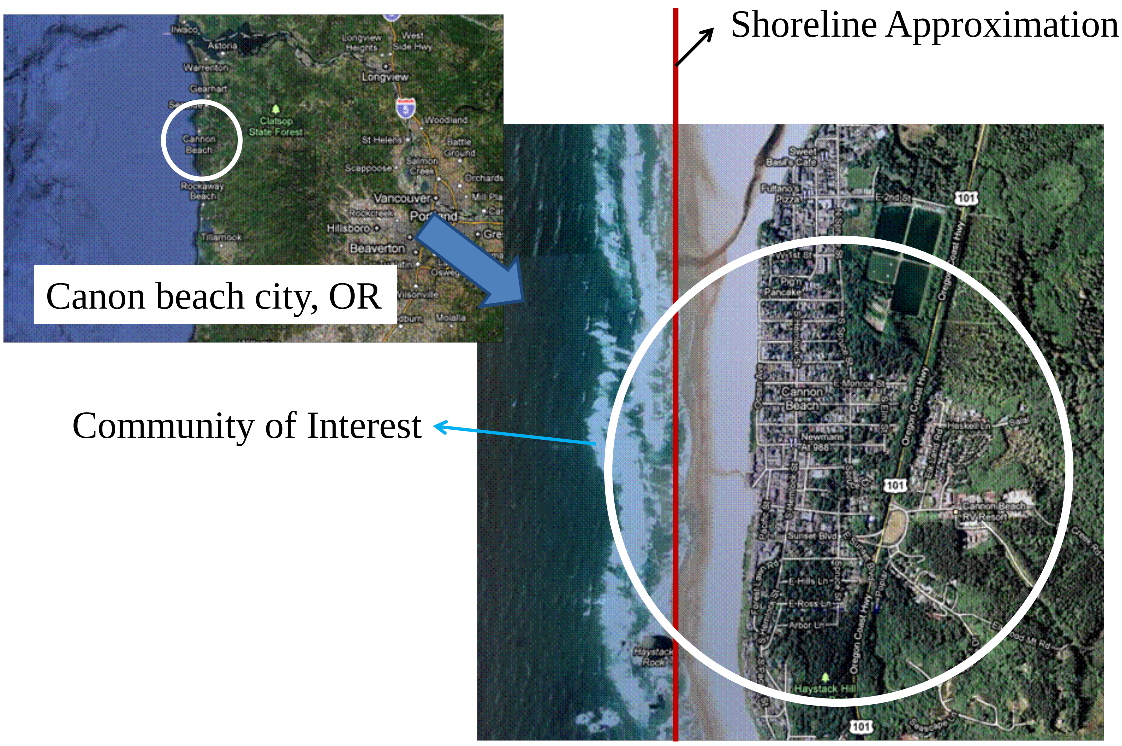


Figure 2: Cannon Beach, Oregon, U.S.A.

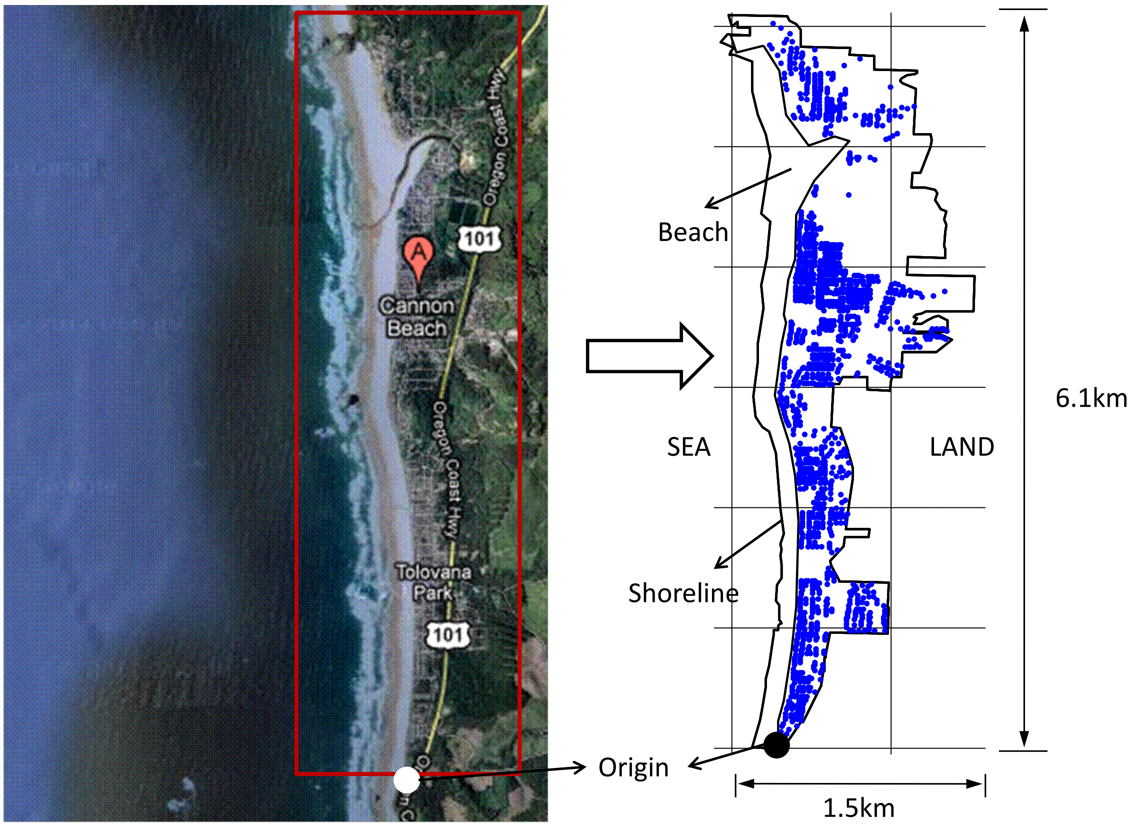
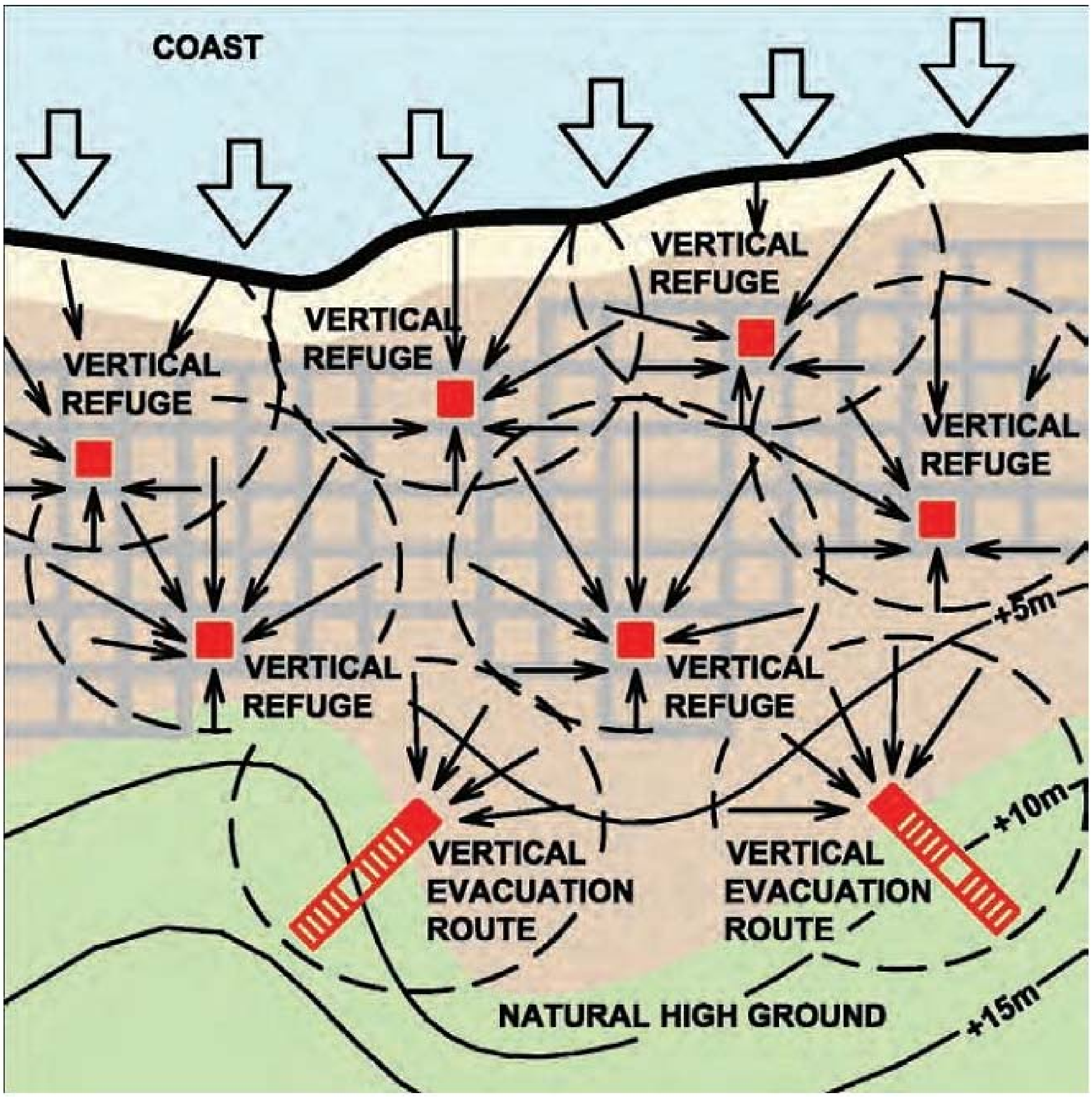


Figure 3: Schematic overview of Cannon Beach, OR and dataset



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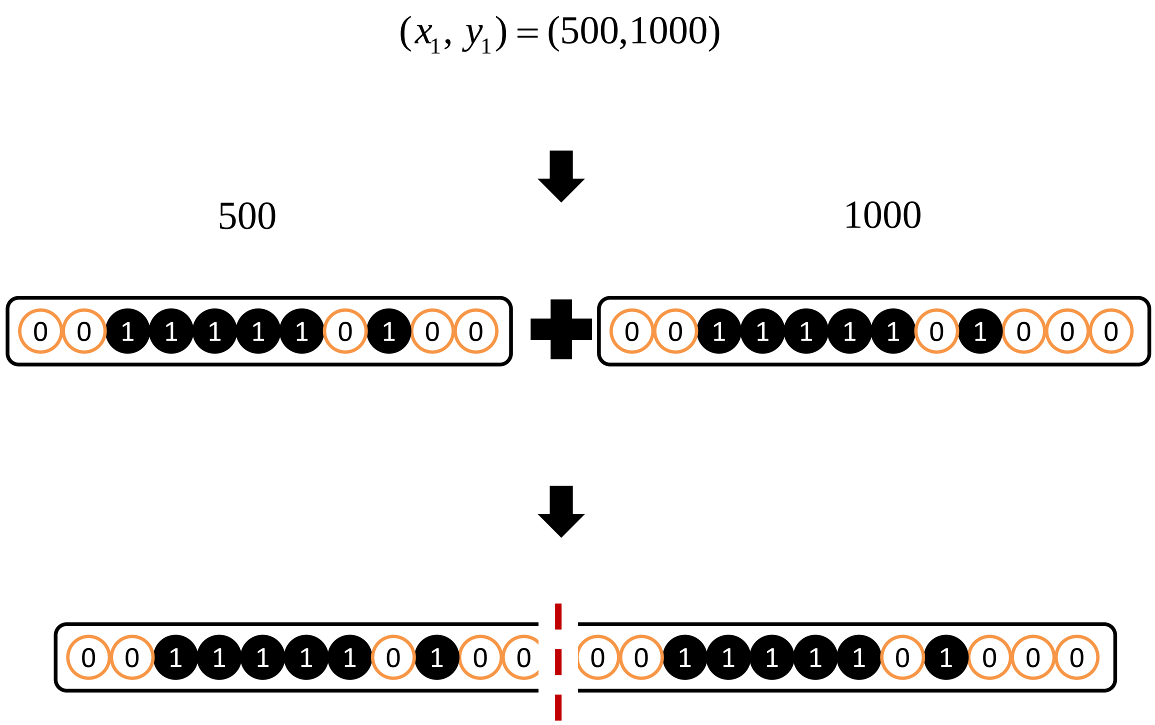
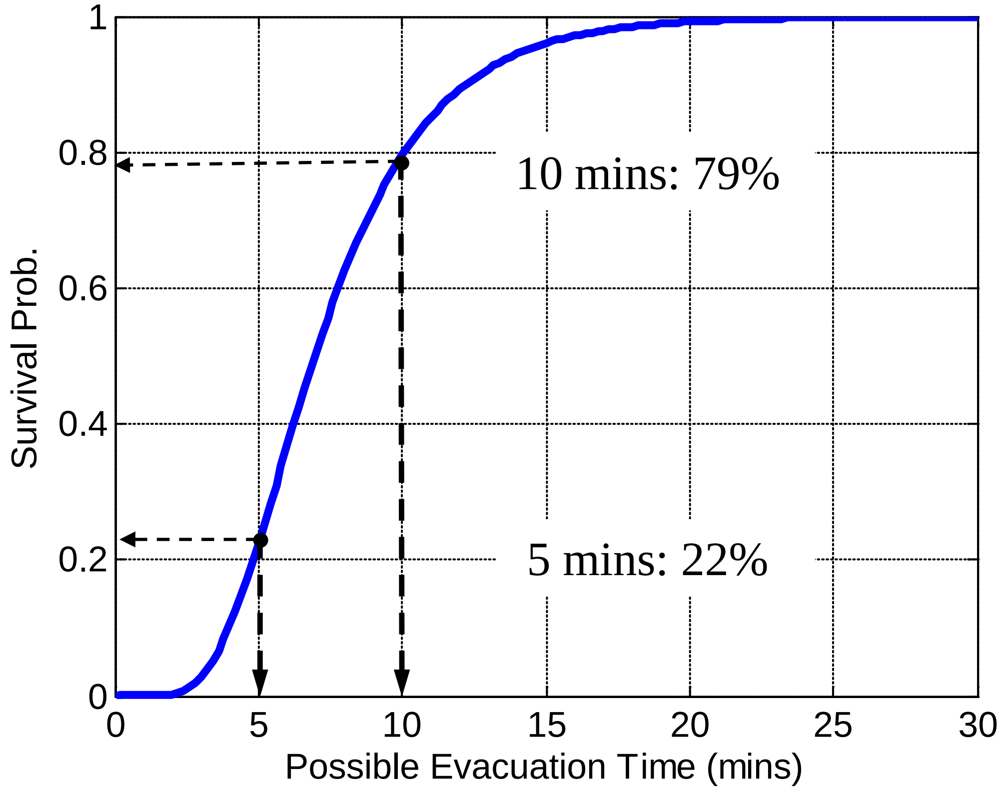


Figure 5: An example of a chromosome as array of binary strings.



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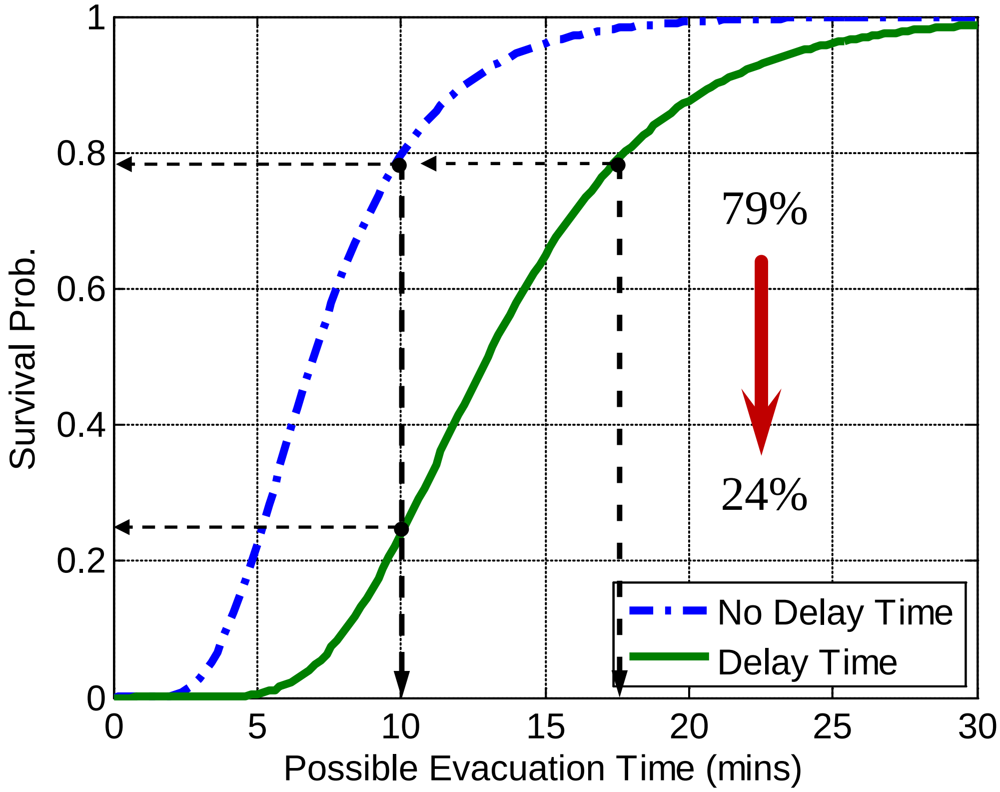

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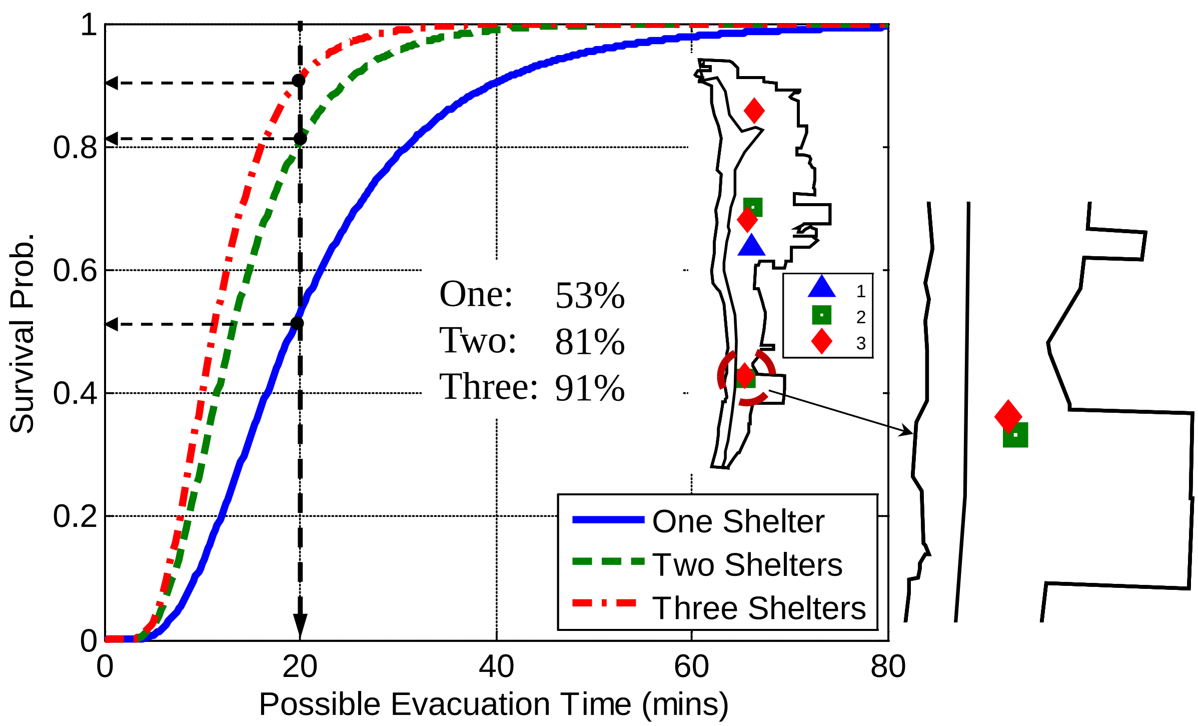

Figure 8: Fragility analysis results for the three cases.

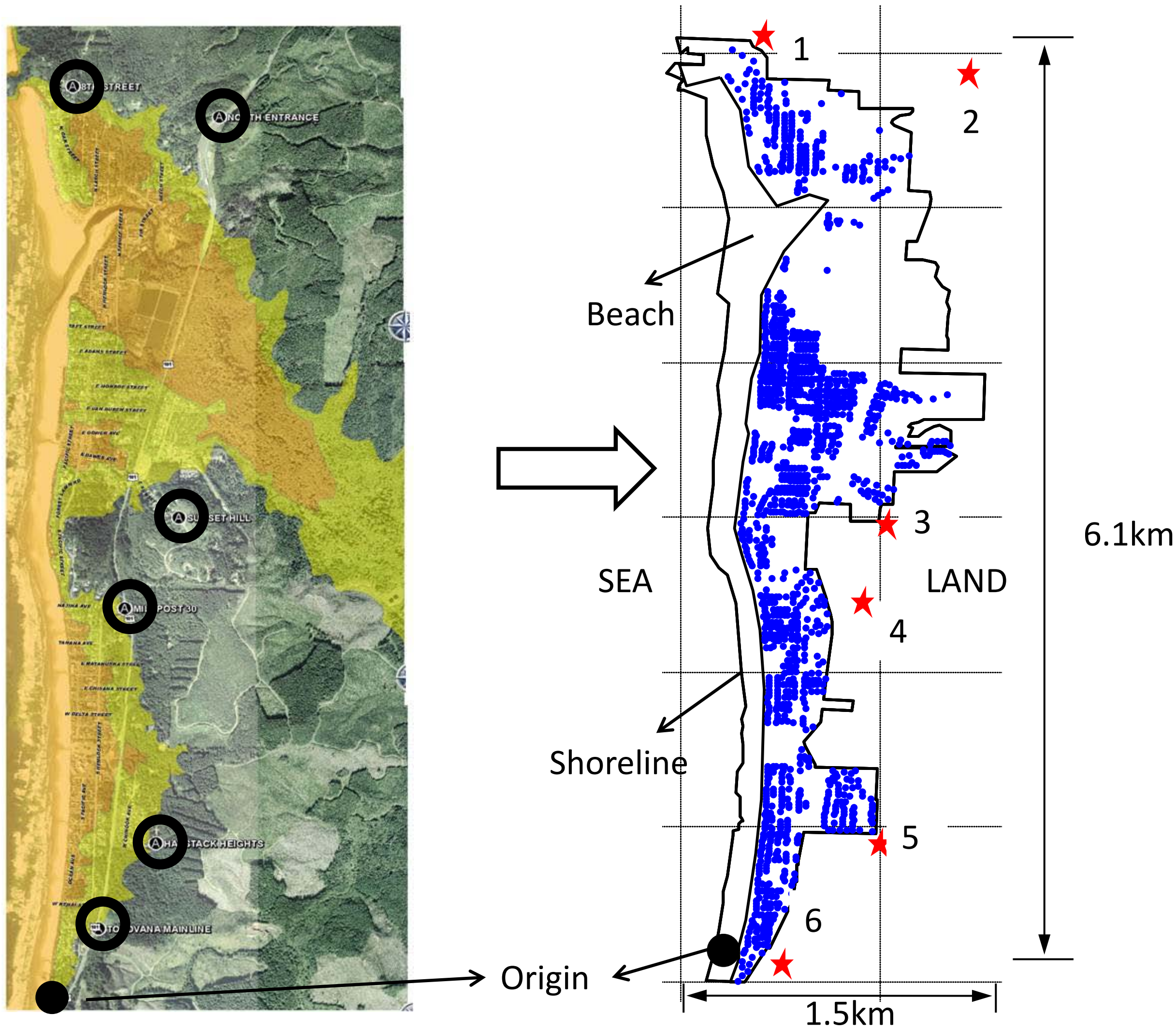

Figure 9: The six locations of high elevation (Cannon Beach 2011).

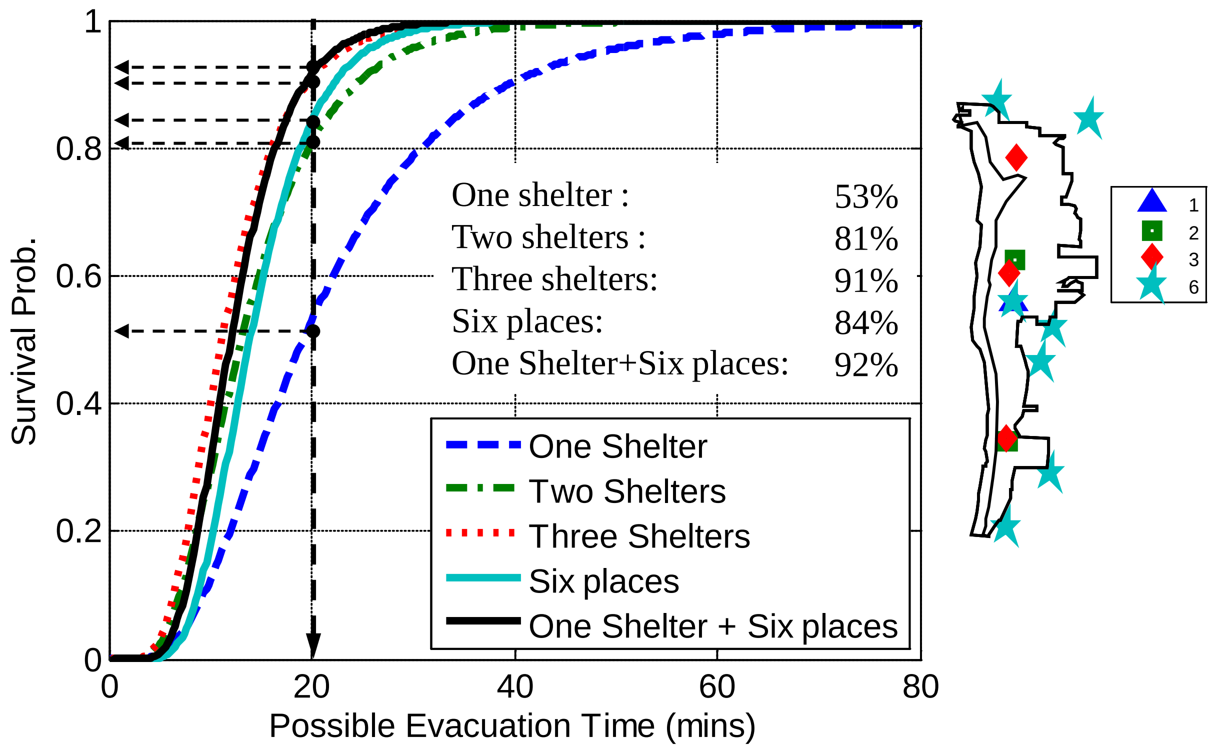

Figure 10: Fragility analysis results for the four cases.

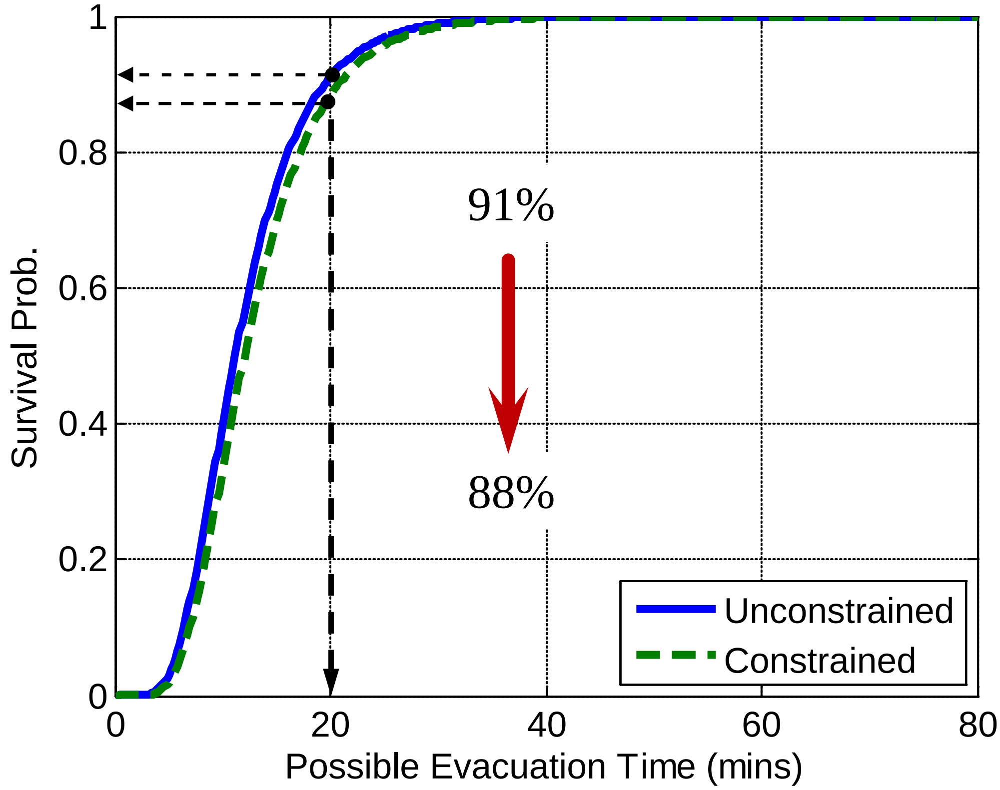

Figure 11: Reduction in survival probability when a capacity constraint is considered.