Evacuation and loss of life modelling to enhance emergency response

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Abstract

Recent major flood events from around the world have highlighted the importance of an effective emergency response in minimising loss of life and optimising the resources available. This paper describes the development of a dynamic, agent based, Life Safety Model (LSM) to estimate the flood risk to people in terms of loss of life and injuries, evacuation times and how improvements in emergency planning can reduce both of these. The LSM is the only tool that is currently available that allows for a dynamic interaction between people, vehicles, buildings and the floodwave. The model takes an approach based on the latest available physical equations rather than empirically deduced mortality rates and evacuation times. The model includes traffic and pedestrian models and also the ability to simulate the effectiveness of the dissemination of flood warnings on people's behaviour. This paper will give a general overview of the capabilities and features of the LSM, and will illustrate this with a range of applications. These will include: a dam failure in France, a major coastal surge in the Thames Estuary in 1953 and Pacific tsunami impacts for western Canada.

Introduction

Recent major flood events from around the world have highlighted the importance of an effective emergency response in minimising loss of life and optimising the resources available. This paper describes the development of a dynamic, agent based, Life Safety Model (LSM) to estimate the flood risk to people in terms of loss of life and injuries, evacuation times and how improvements in emergency planning can reduce both of these. The LSM is the only tool that is currently available that allows for a dynamic interaction between people, vehicles, buildings and the flood wave. The model takes an approach based on the latest available physical equations rather than empirically deduced mortality rates and evacuation times. The model includes traffic and pedestrian models and also the ability to simulate the effectiveness of the dissemination of flood warnings on people's behaviour.

The model was developed about 10 years ago by BC Hydro, initially to be used in planning the response to major dam failures in Canada. However, the model can be used to assess the consequences for any flood event as long as this can be simulated using a two dimensional model. HR Wallingford is currently working on version 2 of the software, which will include a range of enhancements. For example, it is now possible to use the model without a simulated flood hazard, so it can be used to test different evacuation strategies or the outcome of emergency exercises.

This paper gives a general overview of the capabilities and features of the LSM, and will illustrate this with a range of applications including: a major coastal surge in the Thames Estuary in 1953, a historical dam failure in France in 1959 and Pacific tsunami impacts for western Canada.

Background to the Life Safety Model (LSM)

The LSM models the "fate" of a set of receptors (i.e. people, vehicles and buildings), which are described by their position at each time step through the simulation. Each receptor can have a set of properties that describes its normal location/condition during a week, such as travel times, school/work hours, and weekend activities. Other time-varying properties include the ability of the receptor to withstand the effect of the flood wave, and how it would react to the approaching wave, with and without a formal evacuation warning.

The LSM uses a generalised event logic to determine the location of each object, whether it is aware of the flood wave, whether it is trying to find a safe haven, what happens if it encounters the flood, and whether the receptor survives or not. A loss function related to each receptor specifies the ability of a receptor to resist the impact from the flood wave, in terms of depth and velocity, and how these can change during an event. There can be instantaneous loss when an individual encounters fast-flowing water, or a group who have sought safety in a building can suffer cumulative loss if the building collapses or a slow deterioration in health if they are exposed to the flood water for a significant length of time, as a result of hunger or cold.

As a flood event evolves, the interaction of receptors with the flood wave will impact the ultimate loss of life. The timing of the event and the decisions made by individuals can determine whether or not they can escape the flood wave. As the flood progresses, escape routes can be eliminated by rising water, and with advancing time roads can become congested with evacuees. The LSM has been applied to a number of case studies that are described below.

Case studies

Canvey Island 1953 Great North Sea flood, UK

In the UK the Life Safety model (LSM) was applied to Canvey Island Canvey Island is an island in the Thames Estuary, covering an area of 18.5 km^2. It is formed on a flat, low-lying alluvial fan that has an average height of approximately 1 m below the mean high water level. Canvey Island is protected from the sea by a network of flood defences. In 1953, the island was inundated by the "Great North Sea Flood" that breached the island's flood defences and resulted in the deaths of 58 people and the destruction of several hundred houses. The LSM was used to recreate the consequences of the 1953 flood.

Data from the 1951 census were used to assess the population of the island in 1953. Historical maps were used to assess the distribution of the properties on the island at the time of the flood. Figure 1 shows a snapshot of the model. The results of the reconstruction of the 1953 flood event agreed well with the available historical data. The LSM model indicated that approximately 100 fatalities had occurred during the 1953 event. This number is dependent on the "resilience factors" applied to both people and buildings. The actual number of people that died in 1953 was 58. The number of buildings destroyed during event is unclear. However, the anecdotal evidence available seems to be similar to the LSM model results. Further information on this work can be found in the paper by Di Mauro and Lumbroso [1]

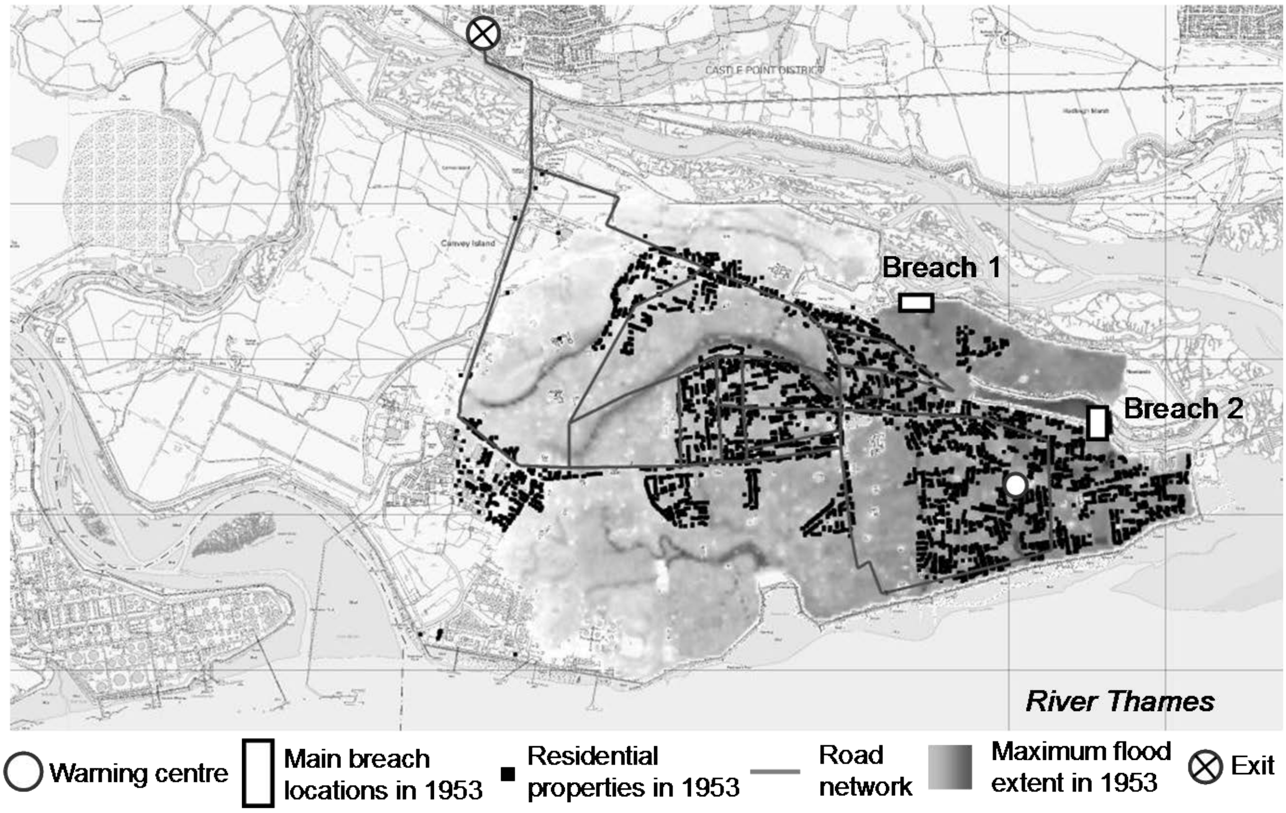

Figure 1: A snapshot of the LSM modelling carried out for Canvey Island in 1953

The 1959 Malpasset dam disaster, France

The Malpasset Dam was built for irrigation, the storage of drinking water and flood control. It was located in a narrow gorge of the Reyran River valley, in the Var Département in southern France approximately 12 km upstream of the town of Fréjus. The dam was a double curvature arch concrete dam 66.5 m high with a crest length of 223 m [2]. In the winter of 1959, torrential rains filled the new dam for the first time. On 2 December 1959 the Malpasset dam suddenly failed releasing nearly 55 million m3 of water [2]. Investigations showed that key factors in the failure of the dam were the pore water pressure in the rock, and the nature of the rock. Under the increasing pressure of rising water, the arch separated from its foundation and rotated about its upper right end. The whole left side of the dam collapsed, followed by the middle part, and then the right abutment [4].

The Malpasset Dam failure provided a suitable case study for validating the LSM because both physical and computational modelling of the resulting flood wave had been carried out, there was information available on the number and location of the people that were killed as a result of the event and there was sufficient historical data available to be able to “back-cast” to create a virtual representation of the town of Fréjus and its surrounding areas as it existed in 1959.

In the development of the Malpasset study, the model input parameters were tested to establish their impact on estimating loss of life. The parameters tested included: family size, building and individual strengths, building evacuation time (or choice of evacuation), flood awareness related to the depth of the floodwater required for people to start to react and building and individual strength reduction factors.

Through the tests it was possible to determine suitable values for these parameters to simulate credible results. It was noted that certain parameters could result in a significant range of results. In particular, adjustments in the rate at which building's and individual's strength was reduced resulted in higher losses. Regardless, it was noted that all reasonable parameter values tested resulted in loss estimates that were never lower than the actual losses. Table 1 provides a summary of the modelled results compared with the actual number of lives lost and buildings that were destroyed during the event.

Table 1: Results of the loss of life modelling for Malpasset Dam

	Loss of life	Buildings destroyed
Estimated with the Life Safety Model	424	151
Actual number	423 to 500	158

Analysis of tsunami risk, Canada

The west coast of North America is at risk from a potential tsunami generated from a number of source zones including the Aleutians, Japan, and South America. Communities from Northern Vancouver Island in Canada, southwards to Mendocino County in Northern California, would be the first to feel the effects of the associated onshore waves [5]. Arrival times for the first wave are estimated to be on the order of 30 minutes to one hour after the seismic event, with associated run-up heights on the order of 10 m to 15 m. A tsunami on the west coast of North America combines a set of factors that could create a truly catastrophic event.

After the Indian Ocean tsunami in December 2004, the British Columbia Provincial Emergency Program (in partnership with the Canadian Federal Government) established the Tsunami Integrated Preparedness (TIP) programme part of which was a study was initiated to investigate methods to estimate floodwave arrival times, onshore run-ups, flow velocities, and losses, and to support emergency preparedness and evacuation planning [6].

The District of Ucluelet, a community of approximately 2,100 local citizens, was chosen as a pilot study. The population of this community doubles in size during the tourist season. The community sits on a peninsula with its western and southern limits facing the ocean, and its eastern edge forming a protected inlet. Two potential tsunami scenarios were modelled. The first was used by the Washington Department of Natural Resources in a study of tsunami hazards along the Washington State coastline [7], which describes a magnitude 9.1 event. The second was a modified version of the first, in which the vertical deformations are scaled by a 60% factor to reflect the notion that a modern day event might only dissipate the strain built up during the 300 year period since the last event in 1700. The estimated lead times for both scenarios are less than 40 minutes.

A study using the LSM was carried out to investigate evacuation scenarios in which 100% of the population were aware and chose to evacuate, the mobilization times were short, and everyone understood the evacuation route system. Four evacuation scenarios were specified based on two travel modes (i.e. vehicle only and pedestrian only) and two sets of safe havens (i.e. a single centralized safe haven, and a distributed set of multiple safe havens based upon the safe elevation line derived from the flood wave).

Figure 2 and 3 present an example of a simple spatial analysis of the differences in the travel distances between the single and multiple haven options. Figure 2 shows of the population at risk, which is summarized as a function of distance to the nearest safe haven. Figure 3 shows that by simply changing the number of available havens in the LSM, the population within 500 m of a recommended safe area increases from 50% to 96% of the total population at risk. However, an approach which only considers distance to safety cannot estimate the possible reduction in losses, nor can it assess whether evacuation is feasible [6].

In an effort to understand the maximum possible mitigation benefits, the team modelled a set of evacuation scenarios in which 100% of the population chose to evacuate, the mobilization times were short, and everyone understood the evacuation route system. Two travel modes were defined: vehicle-only and pedestrian-only. The multiple-haven pedestrian scenario is the most effective option with 37% of the population reaching safety within 20 minutes, and 82% within 45 minutes. The LSM simulations suggest that the other options are two to four times less effective. It is unclear whether the large subpopulation of tourists will show a preference for vehicular egress, which could increase mortality.

Before the initiation of this study the community did not fully understand the potential losses within each hazard zone. The original evacuation plan did not estimate traffic demand, assess the capacity of the road network, or estimate the times required to leave the hazard zones. The expanded set of candidate safe havens will make more evacuation pathways available, shorten the average distance to safety, and provide a much larger receiving area for the evacuating population. Evacuation movements on foot will help reduce the congestion problem and increase the efficiency of movement to safety. The use of the LSM has also allowed authorities to signpost places that can act as safe havens, which were not obvious before the modelling was carried out.

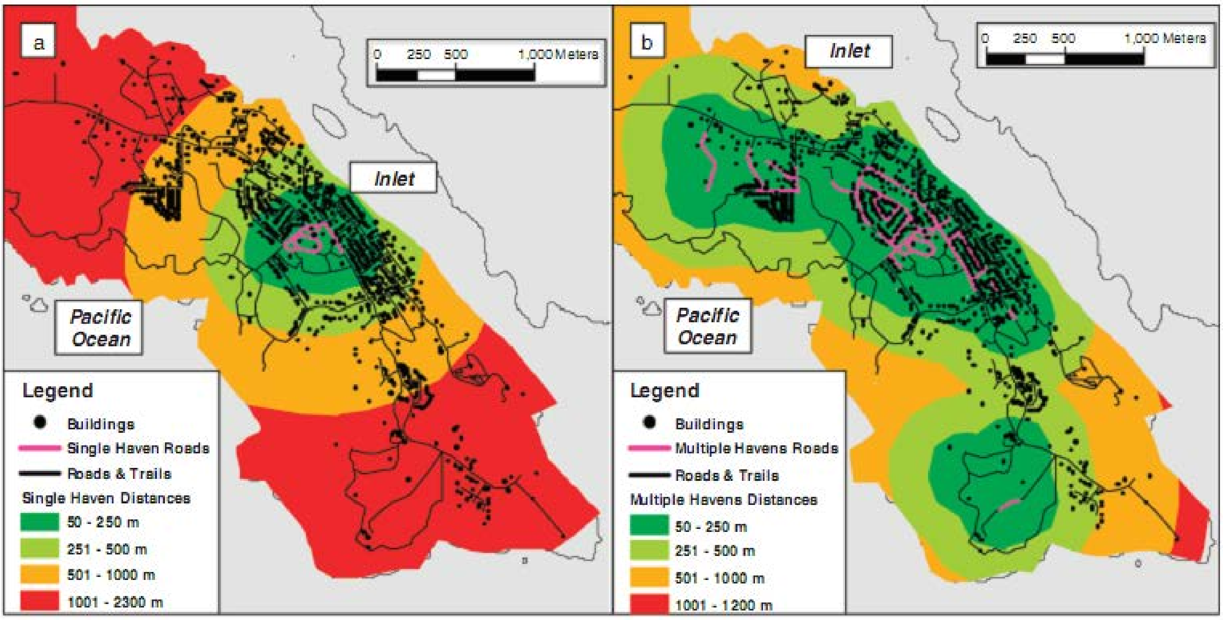

Figure 2: Evacuation analyses: (a) single haven evacuation distances, (b) multiple havens evacuation distances for District of Ucluelet, Canada

Source: Reference [6]

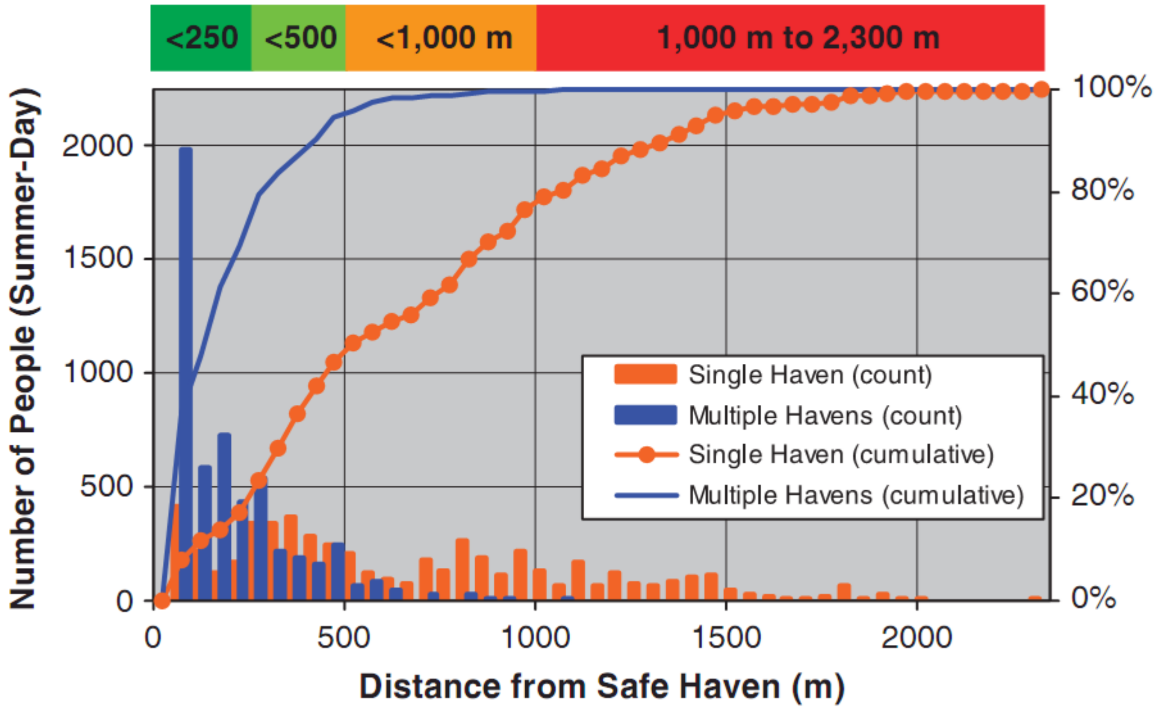

Figure 3: Results from the LSM evacuation analysis showing the population at risk in a costal zone as a function of distance from safe haven(s) for summer daytime

Source: Reference [6]

Conclusion

The LSM offers a scientifically robust method of assessing residual risk behind flood defences and downstream of dams in terms fatalities. Although time consuming to set up the LSM provides not only can evacuation but also models also computes the injuries and loss of life for each method. The LSM model is the only model that has a dynamic interaction between the receptors (e.g. people, vehicles) at risk and the flood hazard. Other loss of life and evacuation models only generally provided first order of magnitude in terms of the evacuation times and fatalities. These could be useful at high level planning stage but are unlikely to be useful for detailed emergency planning

Importantly, the LSM allows the comparison of different emergency management strategies (e.g. the use of safe havens) that can assist in reducing the loss of life during future floods and dam breaks. The model was validated against historical data from the Canvey Island flood in 1953 and the failure of Malpasset Dam in 1959. Recently the LSM has been used assist with the planning of the emergency response to tsunamis on the west coast of Canada.

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