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Sensitivity analysis of the tsunami warning potential

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Abstract

Tsunamis are normally generated by underwater earthquakes. The earthquakes are normally easily detected by seismographs. However, the earthquake may not always generate a tsunami. Further, the severity of the earthquake is not linearly related to the severity of the tsunami. The tsunami may be detected by a deep-sea pressure transducer communicating through a surface rider buoy, through satellites to a tsunami warning centre. The detectors are expensive to build and maintain, need to be placed near surface-rider buoys, and the placement of these detectors needs to be optimal. The provision of adequate warnings from the network of detectors, called the tsunami warning potential, depends on the network of the deployed detectors, the number of detectors used, and the response times of the detectors, warning centre, and of the emergency services which need to convey the warning. The warning potential is also a function of the number in the population at risk. The sensitivity of the warning potential is analysed for first-order effects, particularly with respect to time delays arising from detection and operation of the emergency services to deliver the warning to the population. The sensitivity of the warning potential to population shifts is also considered. Areas for improvement are identified, together with suggestions of how the system can be optimised.

Keywords: Sensitivity analysis; Tsunami; Wave-rider buoys

1. Introduction

In the past, tsunamis have caused considerable loss of life and destruction of property in coastal areas [1]. Various tsunami warning systems have been designed and used to detect the generation of a tsunami, and to warn of its approach to coastal regions [2]. Currently, seismic observations are used to detect the occurrence of earthquakes, act ‘at a distance’, and communications are rapid.

The real-time detection of a tsunami is usually through direct observation. This is a hazardous operation, as the observer needs to be near the destructive zone, and the means of communication are often destroyed, disrupted or utilised by non-essential traffic. Fortunately, tsunamis are far less damaging in the open ocean and may be detected by suitable sea-floor-mounted detectors [3]. These detectors use acoustic coupling to communicate to the surface, to wave-rider buoys which can then communicate via satellite [3].

The detectors and wave-rider buoys are expensive to make and are currently limited in number. Some six possible sites have been selected, after consideration of regular NOAA ship passages and other maintenance and cost factors (Tsunami Hazard Mitigation Federal/State Working Group, 1996 [THM]). The problem is to locate a small number of detectors at a selection of the possible communication-buoy locations, so as to give the maximum warning of the generation of a tsunami, i.e. to maximise the warning potential function. This problem has been formulated and solved; it leads to an integer programming problem which can be solved using standard enumeration techniques [4].

The solution for the optimal warning potential function depends on parameters such as population numbers at risk, and response times for detection of the tsunami and for conveying the warning to the population. These parameters can be considered to vary continuously in their ranges. The maximum warning potential function also depends on the number of buoys which are deployed, and this is a discrete variable with up to six buoy locations.

The aim of this paper is to investigate the sensitivity properties of the maximum warning potential function to its input parameters. This will assist in determining the subset of more influential parameters with respect to sensitivity. The results will provide valuable feedback to the operation of a tsunami warning system.

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2. Methodology

2.1. Model

The locations of the six wave-rider buoys are denoted by b_w, $w = 1, \ldots, 6$. The latitudes and longitudes for these positions are given in Refs. [1,5] and the data will not be repeated here. The representative locations of the generation points are denoted by g_u, $u = 1, \ldots, 18$ [5]. Major representative population centres were selected to provide a general estimate of the population at risk in the Pacific Ocean. These are located at points denoted by p_v, $v = 1, \ldots, 27$ (see Ref. [5] for data). The population at each point p_v is denoted by π_v, $v = 1, \ldots, 27$.

Let

$$y_w = \begin{cases} 0, & \text{if buoy location } b_w \text{ is not occupied by a detector} \\ 1, & \text{if buoy location } b_w \text{ is occupied by a detector} \end{cases}$$

The total number of detectors, Y, may be limited by capital or maintenance costs. The vector $\underset{\sim}{y}$ of 0s and 1s then represents a particular deployment of detectors.

Now consider the generation of a tsunami at time $t = 0$ at the generation point g_u. Let

$$T_{u,v} = t_u^*(\underset{\sim}{y}) + t_\mathrm{d} + r_v - t_{u,v}, \tag{1}$$

where $t_u^*(\underset{\sim}{y})$ is the travel time of the tsunami from g_u to the nearest occupied wave-rider buoy, t_d, the detection time for processing, detecting and signalling to confirm the generation of the tsunami, r_v, the reaction time of the emergency services and population to move to safety, $t_{u,v}$ is the travel time of the tsunami from the generation point to the population.Note that $t_u^*(\underset{\sim}{y})$ and $t_{u,v}$ can be calculated from travel time charts [2,5]. Also let

$$e_{u,v}(\underset{\sim}{y}) = \begin{cases} 0, & T_{u,v} > 0 \\ \pi_v, & T_{u,v} \le 0 \end{cases} \tag{2}$$

The total warning potential is then defined as

$$E(\underset{\sim}{y}) = \frac{\left[\sum_{u=1}^{18} \sum_{v=1}^{27} e_{u,v}\right]}{\left(18 \sum_{v=1}^{27} \pi_v\right)} \tag{3}$$

Table 1
Sensitivity analysis of the tsunami warning potential

Factor number	Factor	Morris mean (μ)	Rank using μ	Morris standard deviation (δ)	Euclidean distance	Morris rank
1	t_d	0.009	11	0.005	1.1×10^{-4}	11
2	t^*	0.011	7	0.042	1.9×10^{-3}	4
3	r^*	0.105	1	0.331	1.2×10^{-1}	2
4	Y	0.092	2	0.347	1.3×10^{-1}	1
5	π_1	0.001	18	0.002	5.0×10^{-6}	16
6	π_2	0.004	12	0.003	2.5×10^{-5}	14
7	π_3	0.001	18	0.000	1.0×10^{-6}	25
8	π_4	0.013	6	0.009	2.5×10^{-4}	7
9	π_5	0.003	13	0.006	4.5×10^{-5}	13
10	π_6	0.019	5	0.010	4.6×10^{-4}	6
11	π_7	0.000	NR	0.000	0	NR
12	π_8	0.001	18	0.000	1.0×10^{-6}	16
13	π_9	0.001	18	0.002	5.0×10^{-6}	20
14	π_{10}	0.001	18	0.001	2.0×10^{-6}	20
15	π_{11}	0.000	NR	0.000	0	NR
16	π_{12}	0.002	15	0.001	5.0×10^{-6}	16
17	π_{13}	0.054	3	0.037	4.3×10^{-3}	3
18	π_{14}	0.002	15	0.001	5.0×10^{-6}	16
19	π_{15}	0.001	18	0.000	1.0×10^{-6}	25
20	π_{16}	0.001	18	0.000	1.0×10^{-6}	25
21	π_{17}	0.001	18	0.000	1.0×10^{-6}	25
22	π_{18}	0.000	NR	0.000	0	NR
23	π_{19}	0.010	10	0.008	1.6×10^{-4}	9
24	π_{20}	0.001	18	0.001	2.0×10^{-6}	20
25	π_{21}	0.001	18	0.001	2.0×10^{-4}	20
26	π_{22}	0.011	7	0.010	2.2×10^{-4}	8
27	π_{23}	0.001	18	0.001	2.0×10^{-6}	20
28	π_{24}	0.002	15	0.003	1.3×10^{-5}	15
29	π_{25}	0.024	4	0.013	7.5×10^{-4}	5
30	π_{26}	0.011	7	0.005	1.5×10^{-4}	10
31	π_{27}	0.003	13	0.008	7.3×10^{-5}	12