Simulation Modelling Practice and Theory 000 (2018) 1–15

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Enhancing a tsunami evacuation simulation for a multi-scenario analysis using parallel computing

Fumiyasu Makinoshima[a,*], Fumihiko Imamura[b], Yoshi Abe[b]

[a] Graduate School of Engineering, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai 980-0845, Miyagi, Japan
[b] International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, 980-0845 Miyagi, Japan

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Agent-based modelling
Tsunami evacuation
Parallel computing
Real-time simulation

ABSTRACT

The numerical investigation of tsunami evacuation is becoming a major way to assess the potential evacuation risks and consider countermeasures, but it has been mostly limited to GIS-based static analysis or macroscopic agent-based modelling due to the costs of large-scale simulations. In this paper, we propose a simplified force-based evacuation simulation model and an easy-to-implement parallelization strategy for a large-scale microscopic tsunami evacuation simulation and demonstrate its applications in an actual urban environment. First, the simulation performance was verified and validated against experimental and observational results regarding basic pedestrian movement. The test results qualitatively and quantitatively showed good agreement with real pedestrian movements. The model was then applied to a case of tsunami evacuations in Kesennuma City, where the 2011 Tohoku tsunami caused devastating damage. The model was successfully scaled up to provide urban-scale characterization. In this application, the developed simulator was implemented by a hybrid MPI/OpenMP parallelized computing technique. By utilizing the proposed model with parallel computing, we achieved an urban-scale microscopic evacuation simulation five times faster than real-time and a stochastic simulation to evaluate the uncertainty in the evacuation simulation.

1. Introduction

Evacuation is an effective way to save lives during major disasters. Particularly in tsunami disasters, previous studies have statistically clarified that evacuation made a significant difference in the number of casualties in actual mega-tsunami disasters, such as the 2004 Sumatra tsunami [1] and the 2011 Tohoku tsunami [2]. However, effective evacuations are challenging to achieve [3]. Thus, workshops [4] and evacuation drills [5] have been conducted in disaster-stricken areas to improve evacuation safety and disaster preparedness during actual disasters [6]. These approaches are generally useful for enhancing disaster awareness. However, the approaches have some limitations, especially for the time required to assess an evacuation, since it is impossible to have all residents and visitors participate in evacuation drills. Consequently, it is challenging

* Corresponding author.
E-mail addresses: fumiyasu.makinoshima.r1@dc.tohoku.ac.jp (F. Makinoshima), imamura@irides.tohoku.ac.jp (F. Imamura), yabe@irides.tohoku.ac.jp (Y. Abe).

https://doi.org/10.1016/j.simpat.2017.12.016
1569-190X/

to estimate possible evacuation situations and determine countermeasures based solely on these activities. An evacuation simulation is an effective tool since it can offer a quantitative estimate of future evacuation behaviour under a variety of scenarios, which can provide useful information for disaster preparedness.

Based on this background, the numerical investigation of tsunami disasters has been widely developed and applied. The major method of investigation has been limited to static analysis using GIS [7–9]. As an advancement of statistic investigations, dynamic simulations using agent-based models have also become popular in recent years [10–13]. However, these investigations disregard microscopic interactions among agents, such as avoiding and overtaking, and are based on the macroscopic relationship between density and velocity. Due to these limitations, previous simulations had some shortcomings in that the investigation could not extract local problems such as bottlenecks. More importantly, macroscopic simulations cannot handle individual differences that are essential to the discussion of vulnerable people in tsunami disasters. Although crowd simulation techniques that can handle individual differences have been developed [14,15], these techniques have not been applied to tsunami evacuation problems. This situation occurs because the target calculation scales in tsunami evacuations must be urban- or city-scale, which is relatively large compared with those of other disasters, such as a localized fire [16,17].

However, the emergence of multiple-core CPU architecture and parallel computing enables us to conduct a detailed evacuation simulation faster and/or over larger areas. Giitsidis et al. [18] enhanced CA-based evacuation simulation using GPU and FPGA, but the simulation size was limited to a small environment. For larger areas, Lohner et al. [19] applied the PEDFLOW model [20] to a large-scale calculation with parallel computing in a CPU cluster. Grandison et al. [21] parallelized building EXODUS [22] and applied it to various cases including a large urban space of 46,000 m^2. Malinowski et al. [23] developed a parallel agent-based crowd simulation application and applied it to various cases that contained up to 100,000 agents in a 6 km^2 map. Nonetheless, this calculation area was still small compared to a scale of typical tsunami evacuation (e.g. 10^7 m^2), and the common challenge is improving the parallelization strategy. Since the evacuation phenomenon concentrates on evacuation sites, dynamic load balancing in the parallelized processes is essential to maintain stable performance increases with multiple CPU cores. A successful case of large-scale evacuation simulation with dynamic load balancing using the ORCA model [24] was conducted in [25], but it was achieved only in specific environments such as supercomputers. From these overviews, the parallelization of agent-based crowd simulation and its applications (especially on large scales) have not been sufficiently investigated, and the application of a detailed crowd simulation to a large-scale tsunami evacuation has rarely been achieved. It is important to investigate parallelization practices with different models and various parallelization strategies in diverse environments. Additionally, if a real-time simulation was possible, potential future applications would include a real-time congestion prediction and guidance during evacuation events.

In this study, we developed a simplified social force model for analysing tsunami evacuations on the scale of a city and applied it to an actual tsunami evacuation problem in a real urban environment (20 km^2) with parallel computing. First, the simulation ability was verified and validated against basic pedestrian movement and experimental results. The model was then applied to tsunami evacuation in Kesennuma City, Tohoku, Japan, where the 2011 Tohoku tsunami caused devastating damage. For this application, we implemented the agents' IDs based parallelization strategy rather than the domain decomposition strategy that has been discussed in previous works. The parallelization strategy is easy to implement and effective. The performance of the proposed parallelization strategy was investigated through a practical application to an actual urban environment. Lastly, a stochastic tsunami evacuation risk investigation was presented as a possible utilization of the parallel implementation of an agent-based evacuation simulation for tsunami evacuation analysis.

The rest of the paper is organized as follows. Section 2 introduces the basic methodology of the environment modelling and the crowd simulation of the developed model. Section 3 assesses the performance of the model using basic validation tests, various quantitative experiments and observational data sets. Section 4 details the parallel implementation. Section 5 reports the parallel computing performance in a real application and a stochastic large-scale evacuation simulation using 600 CPU cores in a clustered calculation environment. Finally, in Section 6, we present a discussion and conclusions based on the results of this paper.

2. Overview of the developed model

2.1. Environment modelling methodology

A grid-based potential model, which has been widely used in previous studies such as FDS + EVAC [26], was used to model geographical features in the simulation. Grid-based modelling can account for any detailed land use or obstacle if a sufficiently fine mesh size is used. It can also accommodate two-dimensional agent motion, which is required for analysing evacuations in large free spaces or bottlenecks. Additionally, a grid-based field model with sufficient resolution can be generated using GIS data, even at the scale of a large city. A distance-based potential field can be easily produced using a least-cost distance [27] in GIS. Human behaviour characteristics in the field can be considered when different cost assignments are specified for specific routes [28]. Obstacles in the field can also be considered by assigning much higher cost values to obstacle grids, as is shown in the following section.