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PRELIMINARY RESULT OF A LARGE SCALE MICROSCOPIC EVACUATION SIMULATION FOR THE CITY OF PADANG IN THE CASE OF TSUNAMI

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ABSTRACT: The evacuation of whole cities or even regions is an important problem, as demonstrated by recent events such as evacuation of Houston in case of Hurricane Rita or the evacuation of coastal cities in case of Tsunamis. The city of Padang, Western Sumatra, Indonesia is located in a zone of extreme risk due to severe earthquakes and possibly triggered tsunamis. A robust and flexible simulation framework for such large-scale disasters helps to predict the evacuation process, in order to give evacuation relevant recommendations for a better preparedness for a real event of tsunami. Existing methods are either geared towards smaller problems (e.g. Cellular Automata techniques) or are not microscopic (e.g. methods based on dynamic traffic assignment). This paper presents a technique that is both microscopic and capable to process large problems. The simulation framework is applied to the city of Padang in the case of a Tsunami warning. In this paper we give a description of the simulation framework. Although the results are still preliminary, we show first simulation results and give an analysis with respect to evacuation time, evacuation process, and the outflow rate of evacuees.

1. INTRODUCTION

Disaster and evacuation planning has become an important topic in science and politics. A tsunami is a particular case of such disasters. The city of Padang, Western Sumatra, Indonesia is located in a zone of extreme risk due to severe earthquakes and possibly triggered tsunamis. For this city the expected advance warning time before the tsunami reaches the shoreline is only about 30 min (McCloskey et al., 2008). The current multi-disciplinary project "Last-Mile" jointly develops with local partners a numerical last mile tsunami early warning and evacuation information system on the basis of detailed earth observation data and techniques as well as hydraulic numerical modeling of small-scale flooding and inundation dynamics of the tsunami including evacuation simulations in the urban coastal hinterland for the city of Padang.

Padang has about 1,000,000 inhabitants. Even if not all of the estimated 1,000,000 inhabitants need to be evacuated, the number of evacuees could be hundreds of thousands. Therefore a detailed analysis of aspects that could influence the evacuation process is necessary. With this analysis it should be possible to:

- Give an estimate of the evacuation time.
- Detect bottlenecks that could for example emerge at bridges.
- Detect highly endangered areas, where a vertical evacuation seems the only way.

From these results, it is planned to derive evacuation recommendations. This could include evacuation maps telling the people where to flee to, or recommendations where to build tsunami proof shelters.

Because of the complexity of the system, an analytic solution to this problem seems to be difficult or impossible. One way to cope with this problem would be to develop a microscopic evacuation simulation for the city with all its inhabitants. With such a simulation, it should be possible to get an estimate of the evacuation progress. The methods currently used for evacuation simulation are:

Methods of dynamic traffic assignment (DTA) have been applied to evacuation simulation on the city or regional scale. Some examples are MITSIM (Jha et al., 2004), DYNASMART (Kwon and Pitt, 2005), or VISSIM (Han and Yuan, 2005). The DYNASMART approach is based on the analogy between traffic and hydrodynamic characteristics of fluids. On state of the art hardware it is possible to handle even large-scale scenarios with this approach. Both MITSIM and VISSIM are microscopic, meaning that every vehicle is individually resolved. They allow a more realistic representation of the traffic dynamics, but their computational performance is currently too slow for a problem of the Padang size. All current implementations of DTA approaches have in common that they model traffic streams rather than individual travelers or vehicles: Their typical input are time-dependent origin-destination matrices, which, in turn, are based on zones. For computational reasons, it is normally not possible to have more than approximately 5000 zones, meaning that it is not possible to resolve the starting points of the evacuation to a higher level than those 5000 zones.

Microscopic simulations are sometimes also based on Cellular Automata (CA) (Nishinari et al., 2004; Hoogendoorn et al., 2001). In CA models each evacuee is designed as an individual; therefore it is possible to simulate population structures where people have different speeds or ranges, or more complex behavior. A CA based approach is once more not applicable for large-scale scenarios. For a large city with hundreds of thousands inhabitants and an area of several hundred square kilometers a CA-based model would consist of more then 10^9 cells, leading to rather long computing times.

One possible approach to deal with large-scale scenarios but to retain persons as individual agents is based up on a modified queuing model (Gawron, 1998; Simon and Nagel, 1999; Simon et al., 1999). The queuing model simplifies streets to edges and crossings to nodes; the difference to standard queuing theory is that agents (particles) are not dropped but spill back, causing congestion. This graph-oriented model is defined by lengths/widths, free speed and flow capacity of the edges. This simplification leads to a major speedup of the simulation while keeping results realistic.

This work shows preliminary results of the evacuation simulation for the Indonesian city of Padang. After a brief description of the simulation framework, we will introduce a simulation scenario and discuss the results with respect to the evacuation time and the outflow rate of the evacuees. We will not give a detailed description of the "Last-Mile" project, however the interested reader is referred to (Birkmann et al., 2007; Lämmel et al., 2008c) for a detailed description of the project.

2. SIMULATION FRAMEWORK

The evacuation simulation is based on the MATSim (multi-agent transport simulation www.matsim.org) framework, where each evacuee is modeled as an individual agent. The agents make independent decisions about escape routes or when to start with the evacuation (i.e. they decide about their response time). Consequently, the evacuation for every single agent has to be modeled separately and will be stored in a so-called plan containing the starting time and the evacuation route. All agents' plans are simultaneously executed in the simulation of the physical system. The underlying flow model simulates the traffic based on a simple queue model (Gawron, 1998; Simon et al., 1999) where only free speed and bottleneck capacities are taken into account. The queue simulation, albeit simple, captures the most important aspects of evacuations such as the congestion effects of bottlenecks and the time needed to evacuate the endangered area.

After a simulation run is finished, each agent is selected with a probability of 10% for re-routing. These agents generate new plans with new evacuation routes based on the information of the experienced travel times from the last run. For every agent that has not been chosen for re-routing, a probabilistic discrete-choice model selects a plan out of its memory, where the probabilities of the plans increase with decreasing evacuation time. After this, a new simulation run with these new plans will be started. Repeating this iteration cycle of learning, the agents' behavior moves towards a Nash equilibrium. If the system were deterministic, then a state where every agent uses a fixed plan that is a best response to the last iteration would be a fixed point of the iterative dynamics, and at the same time a Nash

Figure 1: Satellite imagery of the city shows the safe area (light green) and some preliminary results of the flooding simulation (blue area). Satellite imagery by the German Aerospace Center, Oberpaffenhofen (2007)

Equilibrium since no agent would have an incentive to unilaterally deviate. Since, however, the system is stochastic, this statement does not hold, and instead we look heuristically at projections of the system. From experience it is enough to run 200 iterations until the iterative dynamics has reached a steady state. In many evacuation situations, the Nash equilibrium leads to a shorter overall evacuation time than when everybody moves to the geographically nearest evacuation point.

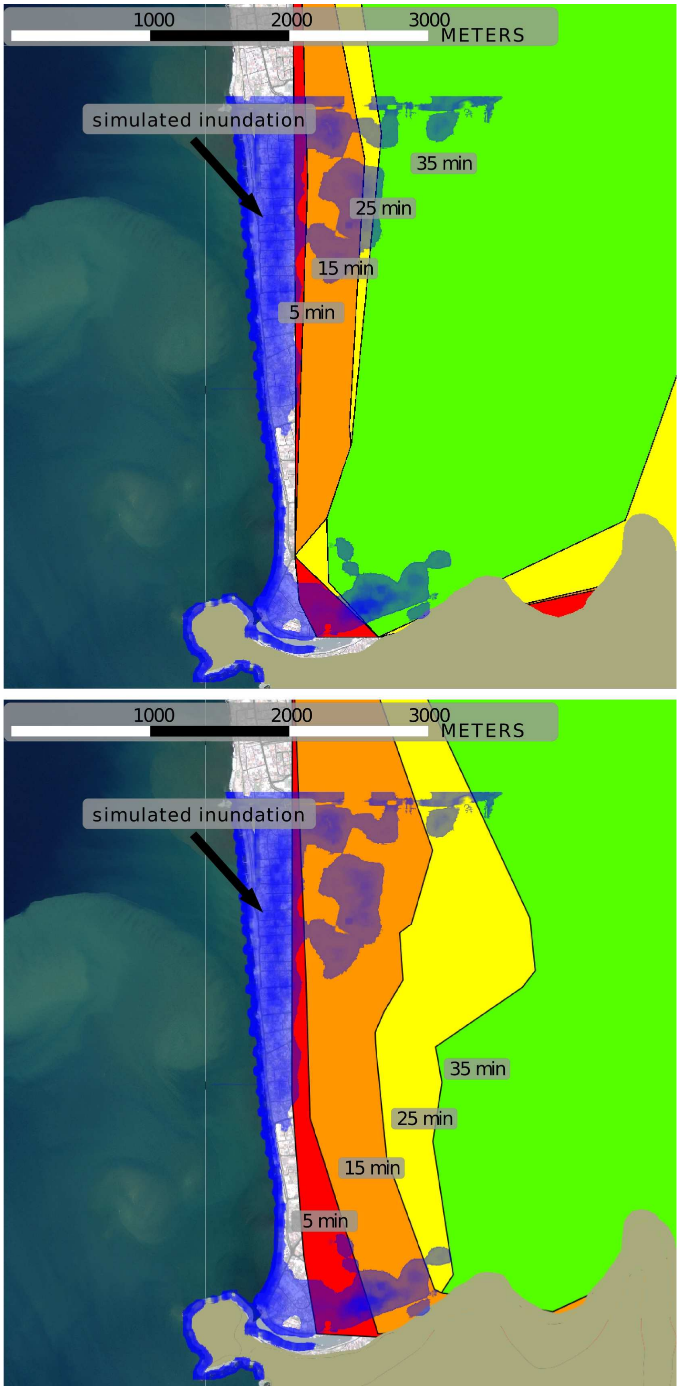

Figure 2: Evacuation progress after 5 min, 15 min, 25 min and 35 min. Top: Results of the first iteration (shortest path solution). Bottom: Results of the last iteration ("Nash equilibrium" approach). One observes that, in the last iteration, for given times much larger areas are evacuated. Satellite imagery by the German Aerospace Center, Oberpaffenhofen (2007)

There might also be a system optimal solution, evacuating agents even faster, but forcing some agents to do something that is not optimal for themselves. Compared to the system optimal solution, the Nash equilibrium solution has the advantage that one could attempt to reach it by training: Since the solution is constructed in a way that nobody could (unilaterally) gain by deviating from this solution, there might be a chance to convince people that it is in their self-interest to follow that solution.

Clearly, a Nash equilibrium can only be considered as benchmark solution. In evacuation situations, people tend to display herd behavior (Helbing et al., 2000; Lieberman et al., 2005). Still, if even the Nash equilibrium solution does not leave enough time, then this would be a strong indicator that major measures would need to be taken to rectify the situation.

Because of the limited amount of space and the more general character of this paper we will only give this brief description of the simulation framework. A more detailed and more technical description of the framework is given in (Lämmel et al., 2008b, 2008a).

3. SCENARIO

The aim of this work is to find feasible solutions for the evacuation of the city of Padang in the case of a tsunami. There are several aspects that have to be taken into consideration. At first one needs a synthetic population for the agent database. In this case study it is assumed that all people are at home. The information about the distribution of the population was derived from existing census data (BPS, 2005). The agent database consists of about 320,000 agents living in the endangered area.

As discussed in **Fehler! Verweisquelle konnte nicht gefunden werden.**, the traffic flow simulation is performed on a network representing the walkable area of the city. The network was extracted from satellite imagery by remote sensing technologies. The resulting simulation network consists of 6,289 nodes and 16,978 unidirectional links.

Another important aspect is the information about safe places. In future it is planned to identify buildings that are suitable for a vertical evacuation. For the time being we use a simpler approach: All areas with an elevation of more the 10 m above sea level are defined as safe. Fig. 1**Fehler! Verweisquelle konnte nicht gefunden werden.** shows an image of the city with the safe area. However, based on models of small-scale flooding and inundation dynamics of the tsunami (Goseberg et al., 2008) it is not expected that all the area below 10 m will be flooded. Based on these simulations, one also learns that the estimated time between the earthquake and the inundation of the city is about 28 min. The results are backed by the results of large-scale tsunami simulations for the west coast of Sumatra Island (McCloskey et al., 2008). Adding this to the simulation, the framework makes the agents learn a more risk averse behavior, they are not only trying to reach the safe area as fast as possible, but they also try to increase the distance to the endangered areas. In some places the flooding will reach locations that are more than 2 km away from the shoreline.

4. RESULTS

The simulation run was stopped after 200 iterations of learning. The overall runtime was about 15 hours on a 3 GHz CPU using up to 2 GB of RAM. After 200 iterations of learning, the evacuation time is about 75 min. This is the time that is needed to evacuate all the area with an elevation lower than 10 m. An interesting aspect is the time that is needed to evacuate all the area that is expected to be inundated. Fig. 2 shows the evacuation progress of the coastal strip for the first and the last iteration. The first iteration could be seen as a strategy where every evacuee follows the path that would be fastest in an empty network. The last iteration is the “Nash equilibrium” approach discussed earlier, where, via iterations, every evacuating person attempts to find a route that is optimal for him-/herself under the given circumstances.

The results show that the "Nash equilibrium" approach leads to a substantially faster evacuation of the coastal strip. But not only the evacuation of the coastal strip is much faster, but also the overall evacuation of all the area below 10 m. Figure 3 shows the evacuation progress for the first and the last iteration. After 200 iterations of learning, the overall evacuation time is about 75 min. This is much better compared to the first iteration, where only 75% of the evacuees manage to escape within 75 min.

5. DICUSSION

As described earlier, the iterations start from a solution where all agents take the fastest path to safety, and iterate to a stochastic version of the Nash equilibrium. The fact that the number of evacuated persons per time unit increases during the iterations (Fig. 3) indicates that the initial solution is overly congested on some evacuation paths, and some evacuees are better off taking a longer route.

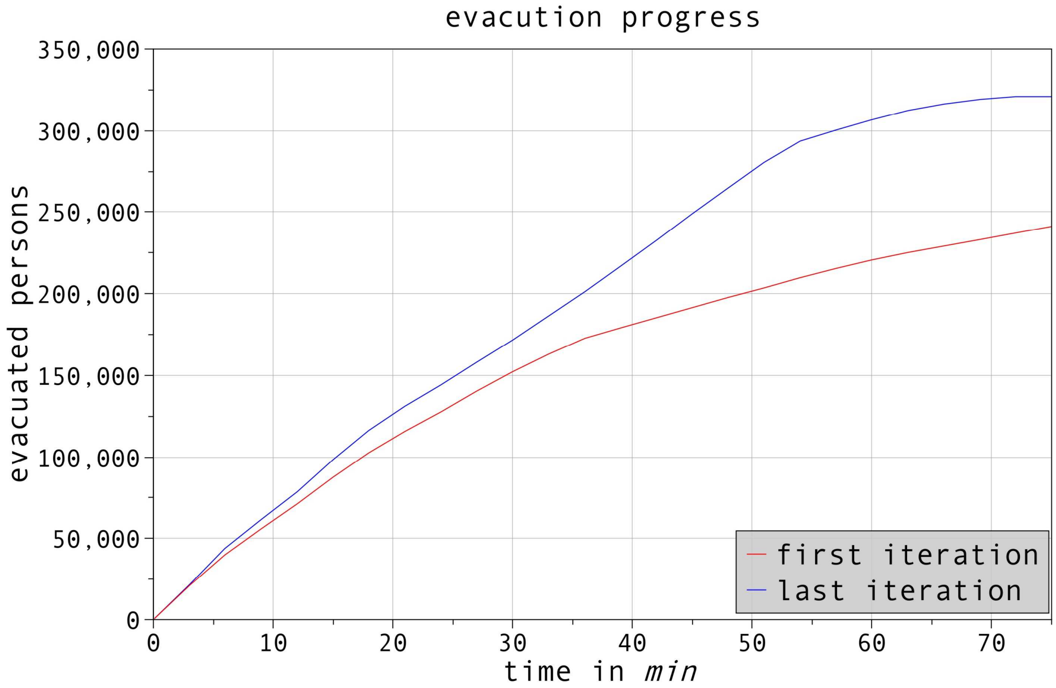

Figure 3: Comparison of the evacuation curves of the first iteration (shortest path solution) and the last iteration ("Nash equilibrium" approach). The curves are truncated at 75 min.

As discussed earlier, this can only be considered as a benchmark solution. Still, given a warning time of about 30 min, even the "rational" Nash equilibrium solution does not seem to leave enough time. However, the situation is not only a question of Nash equilibrium vs. system optimum vs. "non-rational" behavior:

The preliminary inundation simulations indicate that our evacuation area is too large for most situations, i.e. the tsunami wave will not reach that far. A problem here, however, is that even if one assumes a functioning warning system, it will probably not include the tsunami wave height, and so a tailored evacuation seems not possible. At the same time, it seems impossible to implement an evacuation scheme that makes people evacuate for about an hour when this is not necessary in most cases: The compliance rate will not be very high.

Tsunami proof shelters for vertical evacuation could be a solution for those areas from where horizontal evacuation takes a long time. Since the local government in Padang plans to build some kind of shelters for vertical evacuation, one could use the simulation to find appropriate locations for these shelters. It might also be possible to use the roofs of stable buildings for shelter.

Another issue concerns the mode choice: The investigation assumes that all evacuation is done by foot while it might be reasonable to assume that some people use cars or cycles, and they might even leave vehicles in the street to continue on foot if progress by vehicle becomes too slow. For the time being, such issues are not considered. The queue model could, to a certain extent, be parameterized to deal with mixed traffic, as long as all modes move with the same speed. The effect of "stranded" vehicles could be included by a parameterization of the flow capacity of the queue model, although a behavioral model for abandoning vehicles would be needed. Beyond that, one would arguably need to switch to a true two-dimensional model such as (Helbing et al., 2000) or (Klüpfel, 2006). Such models could still operate on networks (Gloor et al., 2004).

6. CONCLUSION

We introduced the evacuation related part of the "Last-Mile" project. The microscopic large-scale evacuation simulation is based on the MATSim framework. It is implemented as a Multi Agent Simulation, where every agent tries to optimize its individual evacuation plan in an iterative way. We discuss the simulation framework, the necessary input data, show preliminary results, and discuss these results.

In the current base case it is assumed that all people are at home. Currently we are working on more detailed picture of the population. Based on census data and the results of a survey with 1000 households, that took place in April/Mai 2008, we are developing a synthetic population with individual daily plans. From this synthetic population it will be possible to derive a model of the population distribution at any time of day.

In future work it is also planed to integrate tsunami proof shelters into the simulation framework. Therefore the simulation framework could be extended in a way to find optimal location for the tsunami proof shelters.

7. ACKNOWLEDGEMENTS

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