# Emergency Preparedness in the case of a Tsunami - Evacuation Analysis and Traffic Optimization for the Indonesian city of Padang

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**Summary.** The "Last-Mile Evacuation" research project develops a numerical last mile tsunami early warning and evacuation information system on the basis of detailed earth observation data and techniques as well as unsteady, 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, West Sumatra, Indonesia. It is well documented that Sumatra's third largest city with almost one million inhabitants is located directly on the coast and partially sited beneath the sea level, and thus, is located in a zone of extreme risk due to severe earthquakes and potential triggered tsunamis. "Last-Mile" takes the inundation dynamics into account and additionally assesses the physical-technical susceptibility and the socio-economic vulnerability of the population with the objective to mitigate human and material losses due to possible tsunamis. By means of discrete multi-agent techniques risk-based, time- and site-dependent forecasts of the evacuation behavior of the population and the flow of traffic in large parts of the road system in the urban coastal strip are simulated and concurrently linked with the other components.

## 1 Introduction

Seventeen out of twenty of the most disastrous natural hazards, since 1950, have occurred in the last 10 years. Extreme environmental events grow in frequency and magnitude. Hence, the number of human losses since the 1950's has now reached 1.7 million; and the economic damage is exceeding USD 1.4 billion [1]. Most of the hazards affect more than just one region, the most prominent example being the devastating tsunami of 26 December 2004 in the Indian Ocean. This, according to the current estimates, killed more than 220,000, made more than 1 million people homeless, and left many thousands without any basis of existence. This clearly indicates that the aftermath of the seaquake to the west of Sumatra also consists of certain unforeseen dimensions. Therefore a significant shift in risk perception of an extreme event must follow. The aftermath of the tsunami, with all its consequences has already affected the development politics and the international, multi-sectoral research communities. The overarching goal of these initiatives is to improve disaster prevention by preparedness methodologies, including public and political awareness of the residual risk and addressing the global hazard resilience. The current multi-disciplinary project “Last-Mile” attempts to incorporate all of these guiding principles and 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 unsteady, 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, West Sumatra, Indonesia. It is well-documented that Sumatra's third largest city with one million inhabitants is located directly on the coast and partially sited beneath the sea level, and thus, is located in a zone of extreme risk due to severe earthquakes and tentatively triggered tsunamis.

An important aspect is the amount of time that is needed for the evacuation. Since the advance warning time before the tsunami wave reaches the coast line is only 20-40 minutes, the evacuation must be as quick as possible. 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[6] seems the only way.

Because of the complexity of the system, an analytic solution to this problem seems to be hard. Therefore a microscopic multi-agent simulation for the city with all its inhabitants will be developed. With this simulation it should be possible to get an estimate of the evacuation process. To develop a realistic evacuation simulation, a wide range of different input information is needed. The needed input information covers almost all aspects of the project. In

[6] Vertical evacuation means that it is planned to build quake and tsunami proof shelters, where the evacuees can flee to.

this paper we will give an overview about basic input data, show some preliminary simulation results, discuss some problems and open questions and finally we will give a conclusion and outlook. Since the focus of this paper is on evacuation simulation, we will not introduce the "Last-Mile Evacuation" project in detail. However, the interested reader is referred to [2] for detailed information about the project, project partners and their particular work packages.

## 2 Related work

"Last Mile" is based upon some of the information and evaluations that are developed or generated in GITEWS (German Indonesian Tsunami Early Warning System – www.gitews.org). Certain work packages of GITEWS are directly related to "Last Mile" since the tsunami risk assessment studies in GITEWS are being conducted for the whole Indonesian coastal stretches (approximately 4000 km) bordering the Indian Ocean (Sumatra, Java, Bali, etc.). However, the hydro-dynamical models used in former studies do neither incorporate local infrastructures nor do they consider street networks or urban waterways in the respective cities. Instead, those simulations make use of constant coastal slopes representing the near shore region and the urban hinterland without determining infrastructures. In addition, neither are numerical evacuation simulations envisaged in those research projects on tsunami preparedness nor is information produced that relies on detailed, time-dependent inundation dynamics and evacuation recommendations. Thus, it can be argued that "Last-Mile" erects its scientific basis upon previous scientific studies, but goes far beyond them by providing these much more microscopic aspects.

## 3 Input data

The evacuation simulation depends on several input sources, which could be divided into three parts:

- Geographical information derived from remote sensing data (street network, safe places, surface conditions ...)
- Inundation scenarios
- Socio-economic data (e.g. population distribution as a function of time)

All this input data has to be compiled to a simulation framework which makes it possible to simulate different inundation scenarios at any desired time of day. Below we will discuss the different input sources, the data that has been obtained so far and the pending issues as well.

### 3.1 Geographical information derived from remote sensing

The geographical information mainly depends on remote sensing data. For the "Last-Mile" project, we draw on high resolution satellite imagery made by the Ikonos satellite. Ikonos data features four spectral bands (blue, green, red, nir) and a geometric quality of 1 m for the panchromatic band, 4 m multispectral, and 1 m pan-sharpened. The most important geographical input is the information about the street network and all the other walkable area like open spaces or meadows. Using an object-oriented hierarchical classification approach in combination with manual enhancement an area-wide and up-to-date land-cover classification has been derived [3].

In a first step the street network has been extracted from the satellite data. This is shown in Fig. 1 a). However, to make the street network usable for the physical evacuation simulation it had to be converted into a graph. This has been done by converting streets to links and crossings to nodes. A graph representation of the street network is show in Fig. 1 b). The original

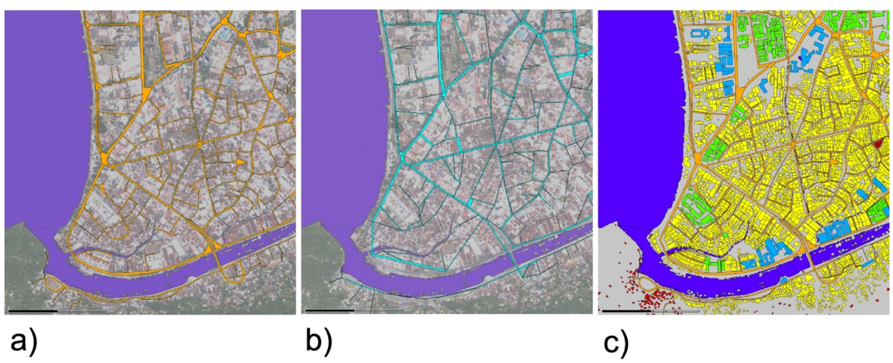


**Fig. 1.** Geographical information extracted from Ikonos imagery

length and width of the street segments has been appended as additional attributes to the links. An accurate model of the street network is all the geographic information that is needed for a basic simulation setup. However, it is planned to integrate much more detailed data from the satellite imagery. One example are shapes of all the buildings in the city, with a classification according to there vulnerability. A clipping of such a floor plan is shown in Fig. 1 c). The colors red, yellow and green are indicating the vulnerability (in descending order) and the blue colored buildings are suitable for vertical evacuation. However, the classification of the buildings is still work in progress and has to be verified by on-site examination. A detailed description of this work is given in [4, 5].

### 3.2 Inundation scenarios

The city of Padang has been hit by tsunamis in the past. The most well documented tsunamis are the ones from 1797 and 1833 [6]. Both tsunamis inundated large parts of the city. However, these past Tsunami events are hardly comparable with the current local situation due to major changes in land use pattern. What is more, population figures have risen strongly. Today the city has approx. 1,000,000 inhabitants and the most densely populated parts of the city are located directly at the shore line. The risk of future tsunami originating off the Sunda megathrust stipulates the need for applied research leading to a greater insight into tsunami run-up and inundation mechanisms. The city of Padang is located in a zone of extreme risk due to severe earthquakes and tentatively triggered tsunamis. Inundation dynamics of long-wave run-up in urban areas is basically conditioned by wave amplitude and period, coastal geometry and shape as well as characteristics of the incoming wave train. As a first consequence some parts of the city have to be evacuated faster then others. By means of small-scale inundation simulation information about temporal distribution of flow height and velocity on a building-specific level becomes available. Models with less accurate spatial resolution for Padang have been accomplished by Borrero [7] on a 200m grid basing on a coarse underlying datasets. Venturato et al [8] clearly outlines

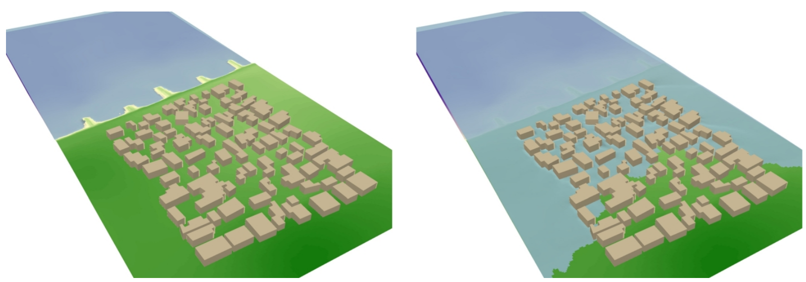

**Fig. 2.** Flow around structures and buildings due to a hypothetical earthquake of Mw= 8,5 southwest of Padang

the importance of high-quality geo datasets for proper modeling of onshore inundation pattern. Therefore we achieved a highly resolved spatial database by extensive multi-beam echo sounder surveys in the shallow waters in front of the coast and airborne topographical field data surveys in the hinterland. To obtain a final digital elevation model (DEM) as basis for the simulations these data were merged with manually taken DGPS data of relevant boundaries and infrastructures as well as cross section data of flood water canals and rivers.

In the applied numerical model the shallow-water equations are solved by a finite-volume technique [9]. The flexible mesh capabilities and a robust wetting and drying algorithm allow modeling run-up, overtopping and inundation as well as wave-structure interaction.

Numerical studies of credible tsunami run-up and inundation scenarios in urban agglomerations confirm that the impact of a tsunami and the extent of inundation areas generally depend on the roughness parameters, but if buildings and structures are explicitly considered in the numerical grid the situation changes (Fig. 2). In this case flow velocities between structures get remarkably higher and near shore water levels at the Padang sea wall rise while areas onshore are less inundated. This additional information is essential for adequate evacuation planning in the city of Padang and can further be employed into an upcoming decision support system (DSS).

### 3.3 Socio-economic data

The socio-economic profile of the city has a major impact on the evacuation itself and is therefore an important input for the simulation framework. Moreover, a detailed knowledge on the socio-economic vulnerability of the population will also help to give recommendations of preparedness strategies for potential tsunami events. In the scope of this project, a detailed assessment of socio-economic vulnerability components according to the tsunami early warning chain is carried out. It focuses, among others, on dynamic exposure based on performed daily activities in the different tsunami hazard zones, predicted evacuation, behavior and evacuation capability of different social groups. To obtain the needed input data different data sources will be used. Information about land use or the detection of critical infrastructures like hospitals or schools will be detected by remote sensing techniques, complementary to data of infrastructure distribution per village obtained from the official statistical office [10].

There are potential data sources from the official statistical bureau (BPS), which are collected regularly at residential district and village level and may contain relevant socio-economic data, such as Population Census [11] and Sub-district in Figures [12]. These data sources provide information on population density, sex and age composition of the population at the village level, which describe to some extent the static distribution of the population (assuming that all people are at home the whole time) and physical capability to perform an evacuation.

As far as it has been assessed by the project, more detailed information with regards to work places or daily activities, from which it is possible to reconstruct the distribution of the population during day time, is not available. There are available data on travel pattern in the city for different transportation zones (a transportation zone covers more than one village) obtained from the Transportation Agency [13]. As a preliminary approximation, data on travels from and to different transportation zones by various travel purposes (working, going to school, etc.) may also be used to weight the population distribution at daytime. In addition to data from different agencies, it is planned to undertake a household survey with a sample of 1000 households selected based on their socio-economic characteristics and the physical structure of their homes. The developed questionnaire also includes questions about the daily activities of the households. The survey results will allow derivation of the distribution of the population as a function of time. This is important since we want to develop evacuation scenarios for different times of the day. The preparation, implementation of the survey as well as analysis of the results will take several months. In the mean time a population distribution based on census data—assuming that all people are at home—is used for the evacuation simulation.


**Fig. 3.** Population figures of Padang's subdistricts

Fig. 3 shows the population figure for Padang's residential districts. This data rest's upon the census for 2005 and was provided by the statistical bureau of Padang [12]. The initial population for the evacuation simulation framework is based on this data. Moreover, other parameters that will be derived from the socio-economic vulnerability survey, such as lagging time due to performing other activities before evacuating, non-participating evacuation rate, and other social-related difficulties during evacuation are interesting factors to be integrated or taken into consideration in the simulation in the later phase of this project.

## 4 Simulation framework

The evacuation simulation is based on the MATSim (multi-agent traffic 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 [14, 15] 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, every agent will be 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 will move towards a Nash equilibrium. If the system were deterministic, then a state where every agent uses a 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 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 more then enough to run 100 iterations until the iterative dynamics has reached a steady state. In most (but not all) evacuation situations, the Nash equilibrium leads to a shorter overall evacuation time than when everybody moves to the geographically nearest evacuation point. On the other hand, a Nash equilibrium means that nobody has an incentive to deviate. The Nash equilibrium in an evacuation situation can therefore be considered as a solution that could be reached by appropriate training.

Clearly, a Nash equilibrium can only be considered as benchmark solution. In evacuation situations, people tend to be irrational and to display herd behavior [16, 17]. 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 could only give this brief description of the simulation framework. However, a more detailed and more technical description of the framework is given in [18, 19].

## 5 Results

As discussed earlier not all of the proposed attributes (i.e. a detailed socio-economic profile of the city, spatially highly resolved inundation scenarios, etc.) are yet available. For that reason a simpler scenario has been chosen to test the simulation framework. In this scenario it is assumed that all people are at home. And instead of an inundation based on simulations, it is assumed that the entire area with an elevation below 10 m has to be evacuated. A software agent has been created for every person that lives within this area. In the end, there were about 450000 agents. With this setup a simulation run of 100 learning iterations has been executed. Some snapshots of the last iteration of the simulation run are shown in Fig. 4. After these 100 iterations of learning

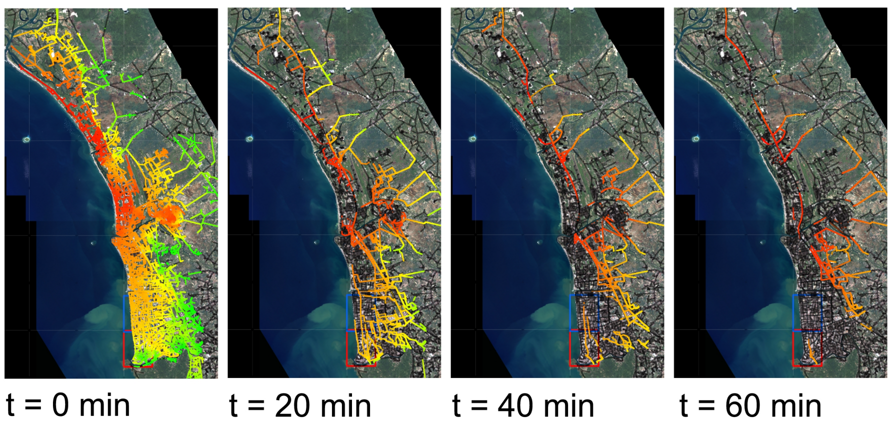


**Fig. 4.** Visualizer snapshots of the evacuation simulation

the evacuation of the endangered area took about 2 hours. However, these results are preliminary and an inundation of the entire area below 10 m seems to be unrealistic and so it is expected that this results will change with the integration of better inundation scenarios or other population distributions.

## 6 Existing problems

There are some problems and open questions that have to be addressed. First there are many streets with a median. This causes problems by the automatic extraction of the street network from satellite imagery. The extraction algorithm classifies streets based on the surface conditions and will consequently produce two parallel streets if there is a median. This issue is depicted in Fig. 5 a). If an evacuee wants to flee from *origin* to *destination* she has to make a detour along the red colored path. However, there is no simple solution for this problem, since it is not possible to detect obstacles (e.g. fences) on the median and so it is not clear if the median is traversable by pedestrians.

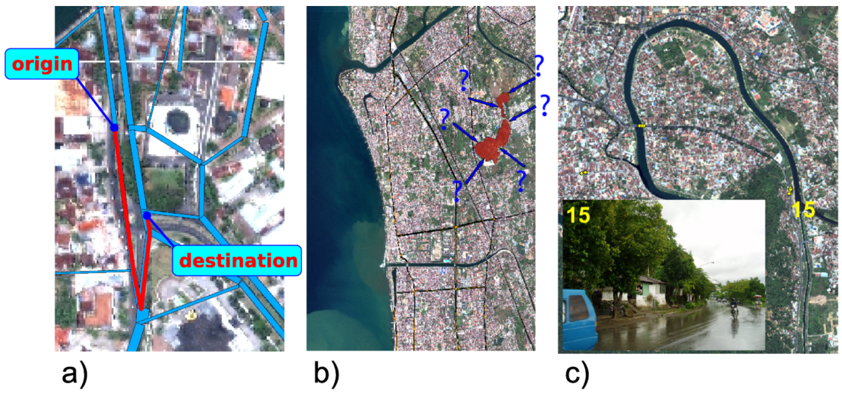


**Fig. 5.** Problems and open questions

Another issue is the lack of information about the accessibility of safe places. For example there are some hills in the city that could be used as evacuation places (see Fig. 5 b)). About 80000 agents escape to these hills in the current simulation results. But from the available information we could neither determine if there is enough space nor if there are sufficient access possibilities. A reasonable solution to these problems would be to examine the hills, streets with median etc. on site. This could be done by taking GPS tagged photos of those places for a manual correction of accessibility parameters. This has already been done for some parts of the city (as shown in Fig. 5 c)), but with other simulations there will emerge other (potential) bottlenecks that need to be examined in detail.

## 7 Conclusion

We introduced the "Last-Mile Evacuation" research project with a focus on a microscopic large-scale evacuation simulation based on the MATSim framework. It is implemented as Multi Agent Simulation, where every agent tries to optimize its individual evacuation plan in an iterative way. We discussed the needed input data for such an evacuation simulation, showed preliminary simulation results and discussed some open problems.

As discussed, the objective is to develop a toolbox, which gives the option to simulate different inundation scenarios at different times of day. The results will be an estimation of the occurrence of bottlenecks and of the overall evacuation time. A major determinant for the overall evacuation time will be the number and place of shelters and places of refuge. In the simulation, these are modeled as sinks. Different to the natural places of refuge like hills, the number and place of shelters (including buildings used as shelters like concrete multi-storey buildings) can be influenced by the administration (and potentially the city's inhabitants and especially owners of buildings). Therefore, a second strategy within "Last-mile" (next to providing information and guidance on evacuation strategies) is to provide recommendations on the number and place of shelters and to identify buildings and recommend there use as shelters.

But before we could use the simulation results to formulate concrete recommendations, the validity and reliability of those results have to be ensured. Therefore, it is planned, besides the integration of inundation scenarios and a more detailed model of the socio-economic profile of the city, to validate the results of the physical simulation. Since there is no real world data to validate the evacuation simulation, we could fall back on other simulation models that are known to be realistic (e.g. models based on Cellular Automata (CA) [20, 21]). However, such models are geared towards smaller problems (cf. [18]). But even if a standard CA-based approach is not applicable here, one could validate the physical simulation based on a clipping of the street network. The improvement of the behavioral model (e.g. herd behavior [16] modified for large-scale scenarios [22]) could also be a topic of future work.

## Acknowledgements

This project was funded in part by the German Ministry for Education and Research (BMBF), under grants numbers 03G0666E ("last mile") and 03NAPI4 ("Advest").

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