Fatality Modeling of Tsunami Disaster Taking into Account Geographical Factors and Demographic Components

2018

Saki YOTSUI

Fatality Modeling of Tsunami Disaster Taking into Account Geographical Factors and Demographic Components

地形的要因と社会的要因を取り入れた地震津波による
人間被害推定モデルの構築に関する研究

2018

Doctoral Program in Global Environmental Studies

Graduate School of Global Environmental Studies
Kyoto University

Saki YOTSUI

Abstract

Fatality is one of the indexes that society uses to evaluate natural disaster risk and it is important to analyze the damage caused by natural disasters in order to develop models that can predict casualties under different scenarios. To calculate the number of deaths, an equation which can take into account the characteristics of the region is needed. A significant amount of research has focused on various types of evacuation, but to date little attention has been given to tsunami evacuation. Currently, in Japan, although there have been a large number of studies of disaster casualty models, the explanatory variables of each model are different and the prediction methods are not standardized. In addition, the models that have been proposed tend either focus on geographical or social factors. However, fatality models that incorporate both geographical factors and social features are still inadequate. One of the reasons is that damage from natural disasters reflect strong regional characteristics. Therefore, we need to understand the influence of variables included in fatality models. Models constructed in a certain region are not necessarily directly useful in other regions. Nevertheless, a model using the evidence from other regions can be useful.

This thesis proposes a new fatality model within a Geographic Information System (GIS). Fatality model takes into account the following three factors: tsunami characteristics, geographical features and demographic components. New explanatory variables have been developed based on the analysis of the 2011 Great East Japan Earthquake and Tsunami and the 2004 Indian Ocean Tsunami. These explanatory variables indicate local features such as the distance and elevation trend of evacuation routes. Characteristics of the distance and elevation trend of evacuation route are analyzed focusing on the Fukushima, Iwate and Miyagi Prefectures in Japan and Kecamatan (district in English) Kuta Raja, Kecamatan Meuraxa and Kecamatan Jata Baru in Indonesia. Additionally, social factors such as age and gender which affect evacuation decision making are considered.

Firstly, the detailed analysis of factors causing human damage (fatality rate, geographical features, evacuation distance, evacuation distance and human damage, and inundation depth) is summarized. Then using ArcGIS (ESRI), the inundation zone is divided into two areas, the area where fatalities occurred and the area where there were no fatalities. Secondly, the distance and elevation from a deceased's address to the non-inundated area through the road network was calculated in Fukushima and Iwate Prefectures. Thirdly, the distance and elevation, which are characteristics of evacuation routes were converted into numerals by an autoregressive moving average model (ARMA). This thesis determines the wavelength (L) and the damping ratio (h) of a single degree of freedom system which express the smoothness of the evacuation routes. Finally this thesis carried out multiple regression analyses against eight explanatory variables: population, average inundation depth, average evacuation distance, average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old and objective variable was the number of deaths in each 500m grid. The proposed model expresses actual fatality with good accuracy compared with the fatality equation used by the Central Disaster Management Council of Japan proposed in 2003. Fatalities

in 500m grid were evaluated with new explanatory variables including elevation and distance of evacuation route, intercept by ARMA model, wavelength and damping ratio simply by inputting population, inundation depth, road network data, and elevation data.

The proposed fatality model was tested to another affected area by tsunami disasters - Miyagi Prefecture which was affected by the 2011 Great East Japan Earthquake and Tsunami and Kecamatan Kuta Raja, Kecamatan Meuraxa and Kecamatan Jata Baru in Indonesia affected by the 2004 Indian Ocean Tsunami. Although the proposed model could be applied to Miyagi Prefecture, it was not fitted for Indonesia. Compared with the 2011 Great East Japan Earthquake and Tsunami, the proportion of the altitude of 0 m is 20%, and the area trends to have a topography where the plain continues beyond Japan. Moreover, the percentage of men was large and the percentage of people over 65 years old was low, which means that there were fewer deaths than in the 2011 Great East Japan Earthquake and Tsunami. However, the evacuation distance was significantly longer in Banda Aceh. Regarding disaster prevention measures, there was no warning sign in Banda Aceh. The proposed fatality model took into account the following three factors: tsunami characteristics, geographical features and demographic components. Therefore, this thesis considered the regional differences were among the factors that caused human damage. There were some significant influences on fatality model as well as significant differences situation between Japan and overseas. In the case of the 2004 Indian Ocean Tsunami, the experience of the past tsunamis, the degree of knowledge about natural disasters and tsunamis, and information provided by the national and local government that could not be expressed by this model were significant influences on human damages.

Developing the fatality model to a large extent depends on the quality and quantity of data. Hence, if the minimum amount of data is available and explanatory variables representing regional characteristics are used, it is possible to perform disaster damage analysis. On the other hand, in regard to the need for a global model, the United Nations Development Programme (UNDP) has described the importance of international risk assessment. Earthquakes, tsunamis, and floods have caused large numbers of casualties and losses throughout the world, with 54% of all casualties caused by the three disasters noted previously between 2000 and 2015, according to EM-DAT database. For example, the disaster risk index was developed by the UNDP. Many researchers have analyzed the damage of earthquakes and volcanoes as primary disasters. We should conduct the fatality model of tsunamis and landslides as secondary disasters as further the types of “naturally occurring disasters”.

This thesis confirmed the regional difference was one of the factors that influenced human damage. The framework of “environment surrounding human society in the event of a natural disaster” was summarized construction of globally applicable human damage model for natural disaster (earthquake, tsunami and flooding) based on past studies. It shows the differences between Japan and overseas against human damage caused by natural disasters. This thesis classified significant influences on fatality model, significant differences situation between Japan and overseas and the difficulty of obtaining a data.

In summary, this thesis has shown that it is possible to estimate fatalities using new explanatory variables simply by inputting population, inundation depth, road network data, and elevation data. This new fatality can be applied at the national level, prefecture level, and municipal level. The result of this thesis will give new worldwide criteria to estimate human damage for future tsunami events. Furthermore, this fatality model can help in communicating risk to local communities and disaster management, taking into account characteristics of a region.

概要

国・社会・地域が自然災害の「リスク」を判断する際には，その自然災害によって生じた「死者数」が有用な指標の一つとして用いられる．この死者数を算出するためには，被害を予測する地域の状況を正確に表現できる予測式が必要となる．これまで地震や津波が起きる可能性が低いと考えられていた地域においてすら，様々な自然災害が発生している現状を考えると，人的被害予測式に関する検討は，安心安全な社会を構築する上で不可欠な課題である．

現在，日本では津波災害に関する被害予測手法は複数提案されてはいるものの，それぞれ一長一短があり，統一された予測手法が存在するとは言えない．また，被害に影響を及ぼす地形の特徴や社会的要因それぞれに着目した式は提案されているものの，双方を組み込んだ予測式の研究例は少ない．さらに，国や県単位の予測式はあっても，地域レベルでの予測式はほとんど見当たらないのが現状である．これは，前述のような予測手法や予測式に組み込む変数が統一されていないこと，さらにこのような分析を行う際のデータの質・量がそれぞれの予測式によって大きく異なることも原因の一つである．しかし，このような状況下においても，地域資料の整備が遅れているような国や社会に対して，他の地域の資料を用いることにより，その地域が有する危険度が推定できるような予測手法が必要であることは論を俟たない．ここに，被害を予測する地域の状況を表現でき，人的被害をできるだけ正確に予測できる式を構築する意義が存在する．

既往の研究では，自然災害は多様であり，社会的要因や経済状況にも依存する複雑な様相であると考え，日本国内の分析に留まらず，国際統計を用いて災害に関わるリスクを評価している．著者らはこれまで，死亡率が地形によって変動する要因を明らかにするために，死者の居住地が番地レベルで得られている福島県を対象として分析を行った．平野部の地形であれば死亡率が高く，急峻な地形を有していれば，死亡率が低い傾向を示すことにより，地形すなわち標高分布により，死亡率に特徴があることを明らかにした．これより，人的被害予測式の提案に際しては，地形的要因だけでなく，地域を構成する社会的要因も組み込んだ式が求められていることが窺える．世界に目を向けると，それぞれの国によって直面している災害が異なることは明らかであるが，EM-DAT によると，2000 年から 2015 年の間の地震と津波被害による死者は, 自然災害の全死者数のうち 53%を占めることが報告されている．国連国際防災戦略（UNISDR）や国連開発計画（UNDP）の報告書の中にも，1980 年から 2000 年までに，世界人口の約 75%の人々が，地震，台風，洪水または干ばつに見舞われた地域に居住していたと記述されている．ただし，このような災害リスクに対して，必ずしも回避不可能ではないとの主張も加えられている．このように, 日本だけではなく, 世界においても国際的なリスクアセスメントの重要性が述べられている．さらに，人的被害の観点から，2011 年東日本大震災のように，地震による直接的な人的被害は相対的に少なく，津波，地すべりなどの 2 次災害によって発生する人的被害の分析の必要性を述べている．たとえば，東日本大震災では，死因の約 90%は，津波による溺死であった．これまでは，主に地震・火山などの直接的な災害に対する検討が多く行われてきたが，今後は 2 次災害に対する被害分析も急務となるであろう．本研究の目的は，津波による人的被害低減に向けた検討を推進し，データが揃っている日本の代表的な津波被害，すなわち 2011 年東北地方太平洋沖地震を対象とした分析を行い，新しい津波に対する人的被害予測式の提案を行う．

まず， 2011 年東北地方太平洋沖地震で被害を受け，死者の居住地が番地レベルで得られている福島県

と岩手県の市町村の死者を対象とし，死者が発生する状況を整理した．死亡率分析では，65 歳以上の高齢者の死亡率が高く，また年齢が上昇するにつれて死亡率が上昇していることが把握され，こどもの死亡率が高い地域も存在した．地形特徴分析より，平野を有している地域の死亡率が，リアス式海岸を有している地域よりも死亡率が高いことが確認された．避難距離分析では，福島県は避難距離 200m を超えると累積死亡率が 50%に達し，岩手県は避難距離 100m～200m で累積死亡率が 50%に達することが把握された．すなわち，岩手県の方が安全な場所までの距離が短かったことがいえる一方，短い距離でも死者が大勢発生したことが確認された．避難距離と人的被害の関係について，浸水域内の住家と死者全員に着目すると死者の避難距離が長く，死者の年齢が上昇するにつれて避難距離が短くなる傾向があった．浸水深分析では，福島県は浸水深 3m 以上で累積死亡率が 50%に達し，岩手県は少なくとも浸水深 2.5m 以上で累積死亡率 50%に達することが確認できた．すなわち，建物の 2 階に避難できていれば助かった地域もあるが，多くの地域で 2 階まで浸水すると死亡率が上昇することが把握された．

これらの結果をもとに，福島県と岩手県の 12 市町村の死者を対象とした「避難経路別距離・標高推移の特性分析」を行い，その特性を地形的要因として定量表現する．さらに上述の特性分析で得られた地形的要因に加え，個人属性を表す年齢と性別を組み込んだ式を新たに提案する．この「避難経路別距離・標高推移の特性」を自己回帰移動平均（ARMA）過程を用いたモデルで定量化する．この避難経路別標高推移パターンに着目することで，標高特性の違いについて定量的に分類することが可能となる．さらに，この ARMA 過程を用いたモデルで表現した避難経路別標高推移は，等価な線形 1 自由度の振動系に置換できるので, 物理的な意味がわかりやすい線形1自由度系の周期（本研究では空間を扱うので波長L）と減衰定数 h で表現する．ここで，算出された波長 L と減衰定数 h については，具体的には，避難経路の起伏の激しさと地形の上り下りに対応すると考えられる．福島県と岩手県を対象とした分析の結果に基づき，標高の特性を地域の状況を表現できる重要な変数として捉え，人的被害予測式に組み込む．最終的に，地形的特徴の指標として取り上げた避難経路別の波長，減衰定数および Intercept 値と避難経路の距離，浸水深，500 m メッシュ内人口，また，地域の人口構成を示す指標として取り上げた性別の割合と 65 歳以上の割合の 8 つの変数で，500 m メッシュ内の死者数を算出する．次に，実際の死者数と本研究で構築した人的被害予測式で算出した死者数にどれほどの差異が存在するのかを評価するために，平均予測誤差 E_a（人）を求める式を定義し，本研究で提案する式で算出した予測死者数と実値の平均予測誤差，中央防災会議を用いた死者数と実値の平均予測誤差を示した．各地域の結果も，福島県と岩手県全域で構築した式の結果も，ともに中央防災会議の式で算出した予測誤差を大きく下回っていることがわかった. 中央防災会議の式は, 2011 年東北地方太平洋沖地震の死者数において, 被災地全体で約 2,700 人と想定していたが，実際にはその約 7.6 倍にあたる死者が発生し，実際の災害のレベルとは大きく異なっていたという事実からも判断できるように，今回提案する式は，中央防災会議の式よりも高い精度で死者数を評価できるものと考えられる．さらに，地域によって人的被害予測式に差異がみられる原因として，地形の差異が考えられる．ここでは，地形の影響を考える際に，著者らの論文で取り上げた「地形による地域区分」を基に考察を加えた．地形による地形区分とは，GIS 場で浸水域内の標高を抽出し，横軸に浸水域内の「地形による地域区分」の標高モデル 10m メッシュを低い方から昇順に並べ，縦軸は標高を示した．ここで横軸は，ある特定の断面図を示したものではないものの，浸水域内の「地形による地域区分」を対象とした標高特性を示したものと位置づけられる．図中で示された線の傾きが小さければ，海岸から平坦な地形で高台に向かうような地形であることを意味し，傾きが大きければ海岸から

急激な標高上昇で高台に向うような，急峻な地形を有していることを意味する．したがって，地形特性と今回の津波による人的被害予測式の関係は，結果の図より，比較的に海岸線から遠くなるにつれて，徐々に標高が上昇する地域を有する地域，リアス式海岸のような地形を有する地域，それぞれでの人的被害予測が可能であると考える．さらに，福島県と岩手県全域で構築した式は，リアス式海岸のような地域と平野を有する地域の両方を含んだ地域の式として利用できるものと考えられる．

その精度をさらに高めるべく，2011 年東北地方太平洋沖地震で被害のあった宮城県，2004 年スマトラ沖地震で被害を受けたバンダ・アチェの 3 つの地区に対して，同様な方法で分析を行った．提案するモデルは，宮城県にはあてはめることができたが，バンダ・アチェの 3 つの地区には精度よく当てはまらなった．その要因として，浸水域内の「地形による地域区分」を対象とした標高特性に着目をして，岩手県，福島県の浸水域内標高分布と比較をすると，標高 0 m の地域が，全体の 20%を占めるなど平地が 2 県よりも広がっていることが確認できた．さらに，「自然災害時に人間環境を取り巻く環境」のフレームワークより，今回提案するモデルで表現できていない項目，すなわち，今までの津波の経験の有無，自然災害や津波に対する知識そのものの程度，また国や地方自治体が提供する情報の有無に，日本以上により大きな影響を受けた結果，多くの犠牲者が発生したと考えられる．すなわち，本研究で構築したモデルの地形要因や社会的要因以外の地域性の違いが，インドネシアで多くの死者が発生した要因になったと考えられる．また，スマトラ沖地震で取得可能なデータに制限があること，国内に比べてかなり精度が低い点も課題のひとつであると考えられる．本研究では，まず死者全員が自宅にいて亡くなったと仮定し，非浸水域に至るまでの分析から得られた結果を基に回帰式を構築した．しかし，実際には全員が自宅で亡くなったとは限らない．すなわち，実際の死者数とは，異なる場合も考えられるという点には留意する必要があろう．また，今回使用した国勢調査における人口は「常住人口」であり，すなわち，夜間人口と同等のものであり，昼間人口ではない．しかし，東日本大震災は実際には日中に発生したため，本来ならば昼間人口を利用して死亡率を算出するべきである．そのため，平成 22 年国勢調査による市区町村別昼夜間人口について検討を行った．夜間人口に対する昼間人口の比率は，100%以下の市区町村が多いものの，100%を超えている地域も存在し，全体的に見るとその差はそれほど大きくはない．これを踏まえると，多くの地域で夜間人口より昼間人口の方が少ないため，本研究で使用した人口は，昼間人口で算出したものよりも若干低く見積もられているものと考えられる．

既往の研究では取り上げられていなかった，各死者の住所と非浸水地点に至るまでの避難経路に対する標高と距離分析を行い，時系列解析で用いられている ARMA 過程を採用することにより，地形要因を定量化するとともに，個人属性を表す年齢と性別を組み込んだ式を提案した．死者数を算出できる精度の高い式が構築されれば，被害を予測し，災害に対してどこが弱点となるのか，それをどのように克服すれば災害に対する強靭な社会が築けるのかを明らかにすることに繋がる．今回提案した式は，人口，浸水深，道路ネットワーク情報および標高データを入力することで，県レベル，または市町村レベルで各 500m メッシュ内の死者数を算出することができる．これまでの式より，地域の状況を具体的に表現できる指標を取り入れた式で，人的被害を予測することが可能になったものと考えられる．しかし，海外で発生するであろう津波災害に今回提案するモデルを適用される際には，まだ議論の余地があると考えられるが，分析結果の表と図から，県レベル，市町レベルで各地域の地形特性ごとに人的被害予測式を使い分けることが可能となり，この結果を利用することで，他の地域に対しても，人的被害が推定できるような予測手法が提案できた．

Table of contents

Table of figures

It is referenced using the Harvard Referencing system.

Tables

Acknowledgements

This dissertation was conducted under the PhD course of Research Section of Earthquake Disaster Risk Management, doctoral program in Global Environmental Studies, Graduate School of Global Environmental Studies, Kyoto University, Japan.

I would like to deeply express my gratitude to Professor Junji Kiyono, my supervisor, for his guidance and continuous enthusiastic support. He has taught me the sprit of challenge and importance of studying basic knowledge through research during the five years. Alongside this, he has introduced me to a lot of people not only Japan but around the world. I have had a precious experience since I joined the laboratory of Prof. Kiyono. Special thanks to Associate Professor Aiko Furukawa of Kyoto University, Associate Professor Hirohide Kobayashi of Kyoto University, Associate Professor Maki Koyama of River Basin Research Center, Gifu University, Associate Professor Yoshihiro Okumura of Faculty of Societal Safety Sciences, Kansai University and Professor Kazuyuki Iuzuno from Ritsumeikan University for valuable advice. Especially, Assoc. prof. Koyama has always supported me and provided a lot of knowledge not only related to research but also life. I could continue my research in a wonderful environment with looking into my future career.

I should also mention Dr. Emily So of University of Cambridge and Cambridge Architectural Research Ltd.(CAR), Dr. Stephen Platt and Professor Robin Spence of CAR. They have always been accepting and encouraging me. I have leant that it is important to do research and how it can contribute to the reduction of risk associated with natural disasters. You gave me confidence in myself. Many thanks for your support from UK. Moreover I would like to express my appreciation to friends of Cambridge University Centre for Risk in the Built Environment (CURBE) and everyone who gave me a lot of suggestions in meetings and academic conferences. Also I would be thankful with Secretaries Ms. Yoshimi Yoshida, Ms. Yuko Takii and all members of Earthquake and lifeline Engineering Laboratory of Kyoto University, especially PhD students.

During my doctoral program, I have been able to study abroad in Cambridge thanks to the '*Tobitate! Next Japan*' program, which is promoted and sponsored by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese Government for six months. My sincere thanks also go to the Earthquake Engineering Field Investigation Team who provided me an opportunity to attend the 2013 Tohoku and the 2016 Kumamoto field mission. I greatly appreciate the help of Dr. Anthony Kimber, who is the chairman of REACT in Rye and helped to promote and collect the survey within the Rye community and Rye College.

I would also like to thank Ms. Hannah Baker, PhD student of University of Cambridge for supporting me during my time in Cambridge and setting a great example. With every smile we share together beyond the time difference, sometimes you say a tough thing. I am truly glad to have met you. I am grateful to have had such an awesome friend like you. Also I would be glad to have wonderful friends in high school, Ritsumeikan

University, friends in Cambridge, junior, colleagues and senior in Kyoto University, lots of precious friends all over the world especially during the DRC/RSDC Program. Although each person follows a different path, I am proud that I could meet many wonderful friends who always talk together. Moreover special thanks to students in department of architecture, University of Cambridge and people in Cambridge Architectural Research Ltd. for their help and guidance.

At the end, last but by no means least, I would deeply appreciate my beloved family for all their love and constant encouragement. You are the most important people to me in the world and forever. I cannot say thank you enough, but I greatly appreciate everything you have done for me. You have taught me that this is my life and to continue challenging every moment under sprit of cheering myself up, lots of effort and thinking positively. I believe where there is a will, there is a way. Just be myself with a beautiful smile and keeping lots of gratitude to everyone. “Learn from yesterday, live for today, hope for tomorrow”.

Acronyms

ABM	Agent based modeling
ARMA	Autoregressive moving average model
BMKG	Agency for Meteorology, Climatology and Geophysics
DEM	Digital elevation map
GIS	Geographic Information System
HTBD/PAC	The Historical Tsunami Database
IOC	Intergovernmental Oceanographic Commission
JMA	Japan Meteorological Agency
MLIT	Ministry of Land, Infrastructure and Transport
MRI	Megacity risk index
NGDC	National Centers for Environmental Information, the Global Historical Tsunami Database
NOAA	National Oceanic and Atmospheric Administration
QRA	Quantitative risk analysis
REACT	Rye Emergency Action Community Team
TI	Tsunami Index
TR	Tsunamigenic Ratio
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNDP	United Nation Development Programme
UNISDR	United Nations International Strategy for Disaster Reduction
UNU-EHS	United Nations University Institute for Environment and Human Security
URA	Urban Risk Assessment
WRI	World Risk Index

Chapter 1
Introduction

1.1 Background

Society should be aware of the risk that natural disasters pose in their locality and should have the appropriate knowledge and mitigation plans in place. Fatality is one of the indexes that a nation and its society determine the risk of a natural disaster. To calculate the number of deaths, an equation which can take into account the characteristics of the region is needed. Even for areas that have been considered to be unlikely to experience earthquakes and tsunamis, it is essential to build a fatality prediction formula under the current situation where various natural disasters are occurring. It is important to analyze the damage caused by natural disasters to develop models that can predict casualties under different scenarios. In 2015, Sendai Framework for Disaster Risk Reduction was adopted. This framework [1] aims for the four priorities for action; understanding disaster risk, strengthening disaster risk governance to manage disaster risk, investing in disaster risk reduction for resilience and enhancing disaster preparedness for effective response and to “Build Back Better” in recovery, rehabilitation and reconstruction.

Especially in Japan, the Great East Japan Earthquake which occurred on March 11, 2011 killed 19,575 people (including missing people) according to the National Police Agency as of September 1, 2017 [2]. The Pacific Coast of the Tohoku region has been damaged three times in the last 120 years, the Meiji Sanriku Tsunami in 1896, the Showa Sanriku Tsunami in 1933 and the Chile Earthquake in 1960. Tsunami disaster prevention measures have been established among the areas in the vicinity of the Sanriku Coast in Japan owing to the historical earthquake and tsunami disasters. Worldwide, earthquakes, tsunamis, and floods have caused a large number of casualties and losses throughout the world according to the EM-DAT database [3]. Especially, this thesis focuses on ground movement and tsunamis in Asia during the period from 1900 to 2017 where the event rate as well as the death rate is over 50%. When focusing on tsunamis, the most deaths occur in Asia as shown in Figure 1.1, Figure 1.2 and Figure 1.3. Among recent tsunami disasters worldwide, the 2004 Indian Ocean caused the most damage.

A significant amount of research has focused on various types of evacuations, but to date little attention has been given to tsunami evacuation [4]. Currently, in Japan, although a large number of studies have been conducted on disaster fatality models, explanatory variables by models are different and prediction methods are not standardized. In addition, the proposed models have been focusing on social and geographical factors separately. Nevertheless, fatality models that incorporate both geographical factors and social features are insufficient. One of the reasons is that the natural disasters reflect strong regional characteristics in damage. Therefore, we should understand the large influence of variables that should be included in the fatality models.

Another reason is that the model constructed in a certain region is not necessarily directly useful in other regions. However, even under such circumstances, the model to estimate the damage using the material in other regions is necessary for the countries and regions. Additionally, developing fatality model is being greatly depends on the quality and quantity of data. Hence, it is necessary to be able to perform disaster damage analysis using a minimum number of data and embedded variables representing regional characteristics.

On the other hand, with regard to the need for a global model, the United Nations Development Programme (UNDP) [5] has described the importance of an international risk assessment. For example, there is a disaster risk index developed by Peduzzi *et al.* [6] for the UNDP. Many researchers have analyzed the damage of earthquakes and volcanoes as primary disasters. We should conduct the fatality model of tsunamis and landslides as secondary disasters of the type "naturally occurring disasters" [7]. In terms of the relationship between altitude and mortality, Yotsui *et al.*'s analysis found that the difference in fatality occurrence by region in the Fukushima Prefecture was because of differences in terrain. We found high mortality in flat topography, but an inclination for low mortality if the elevation distribution was steep. Using the distribution of flooded buildings and the addresses where fatalities occurred, this research analyzed the distance to the non-flooded area. However, there were deaths despite of a short evacuation distance [8].

Therefore, this thesis analysis is on the information obtained by the occurrence of the disaster. Furthermore, a proposed model will be focusing on human damage. Finally, the fatality model can help in communicating risk to local communities and disaster management but at present there are not many models of tsunami disaster, and certainly none that take into account characteristics of a region. Figure 1.4 shows society cycle against natural disasters.

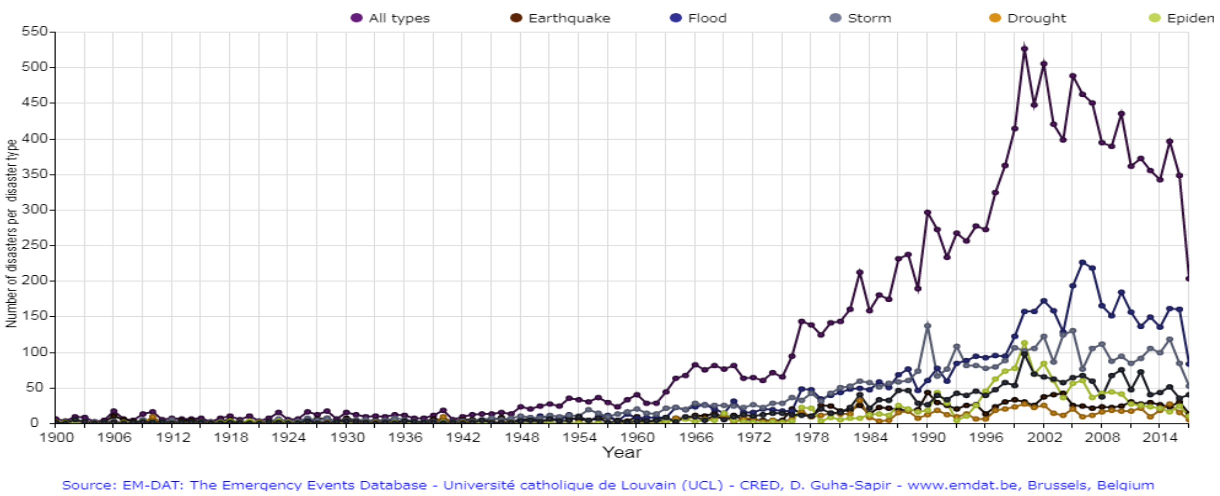


Figure1.1: Number of reported natural disasters between 1900 and 2017 according to EM-DAT database

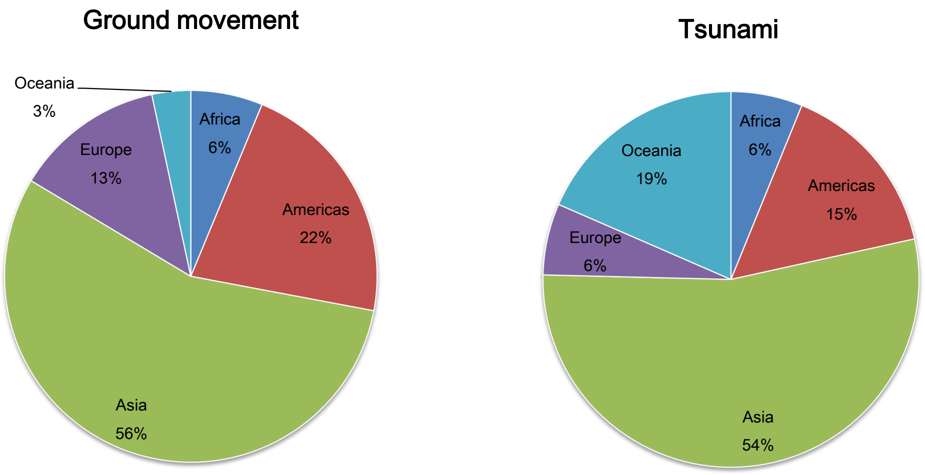


Figure 1.2: Event rate of ground movement and tsunami in the world between 1900 and 2017 according to EM-DAT database

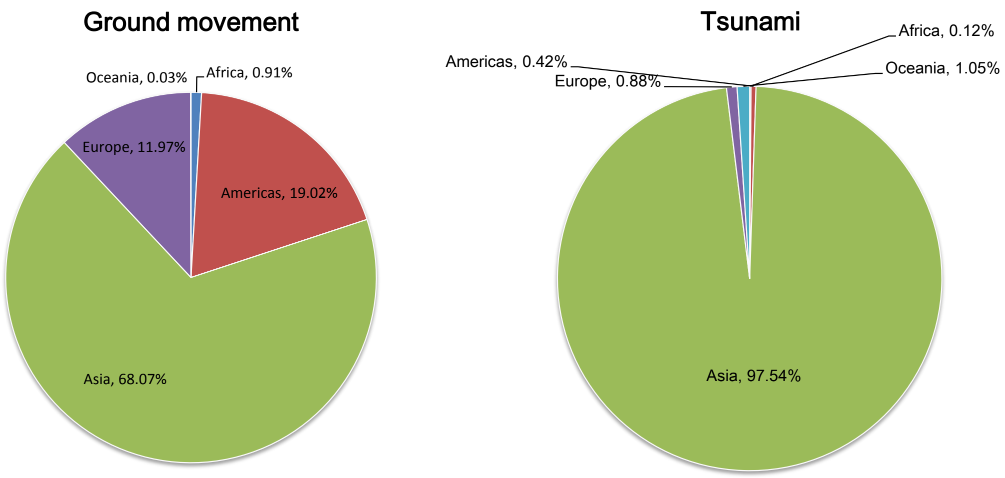


Figure 1.3: Death rate of ground movement and tsunami in the world between 1900 and 2017 according to EM-DAT database

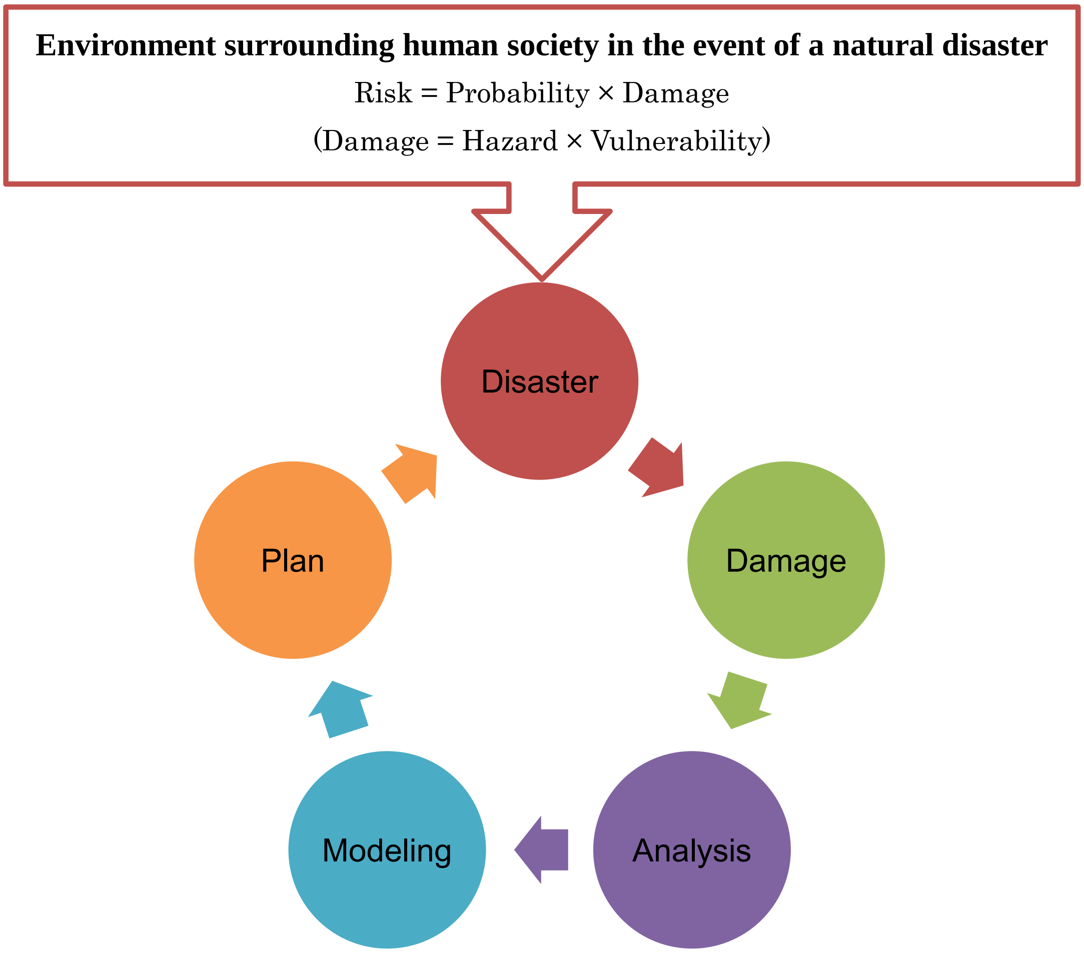


Figure 1.4: Society cycle against natural disasters (Reference: I. A. Ayala, 2001[9])

1.2 Problem statement

Here is statement of problems.

There are four problems related to the analysis of the fatality model for tsunami disasters.

1. Small number of tsunami disaster samples.
2. Few fatality models that can estimate the number of fatalities caused by a tsunami event at the regional level.
3. Few fatality models that takes into account geographical and demographic factors.
4. Need for new globally applicable criteria for a fatality model that can estimate the number of death from future tsunami events.

1.3 Aims and objectives

The aim of this thesis is to develop a new fatality model of tsunami disaster. To estimate the number of death caused by a tsunami event, it is proposed to take into account these three factors such as tsunami characteristics, geographical features and demographic components. The new explanatory variables based on equation of Central Disaster Management Council of Japan [10] and UNDP [6] indicate local features such as the distance and the elevation trend of evacuation route. The characteristics of distance and elevation trend of evacuation routes have been analyzed in the case of Fukushima Prefecture and Iwate Prefecture following the 2011 Great East Japan Earthquake and Tsunami. Analysis has been conducted within a Geographic Information System (GIS). The new approach focuses on geographical factor such as the distance and elevation which are characteristics of evacuation routes by converting them into numerals using an autoregressive moving average model (ARMA) [11].

The main objectives of this research are:

- Detailed analysis of the cause of fatality by tsunami based on the 2011 Great East Japan Earthquake and Tsunami.
- New fatality model for the estimation of loss of life due to tsunami.
- New fatality model that makes it possible to evaluate fatality at the national level, prefecture level, and municipality level as shown in Figure 1.5.
- New globally applicable criteria of tsunami fatality model.
- Results can be useful for a disaster prevention plan and to identify mitigation strategies.

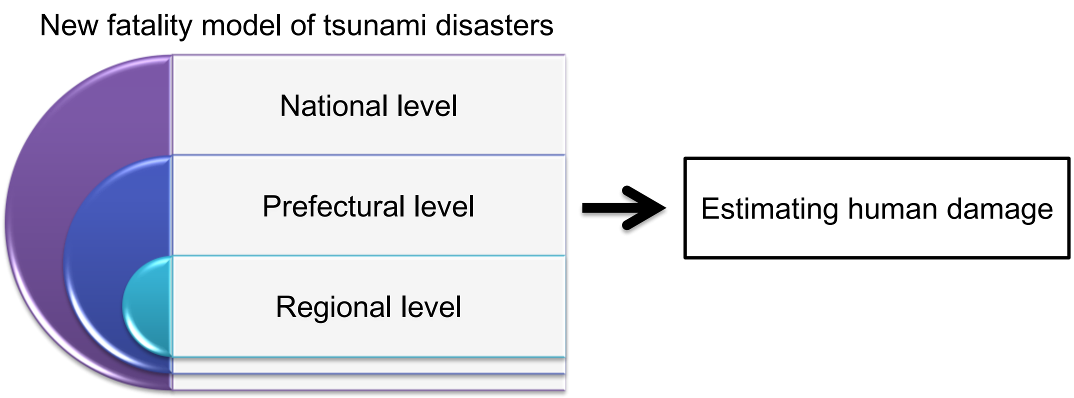


Figure 1.5: Concept of the proposed fatality model

1.4 Structure of thesis

Figure 1.6 displays the structure of this thesis. This literature review identifies background of fatality models for tsunami disasters and risk management comparing Japan and the UK. Fatality modeling is analyzed based on data of the 2011 Great East Japan Earthquake and Tsunami. This research validates the model in various ways. Finally, it examines the application of the model against past tsunami damage data of the 2004 Indonesian Ocean Tsunami as the case study.

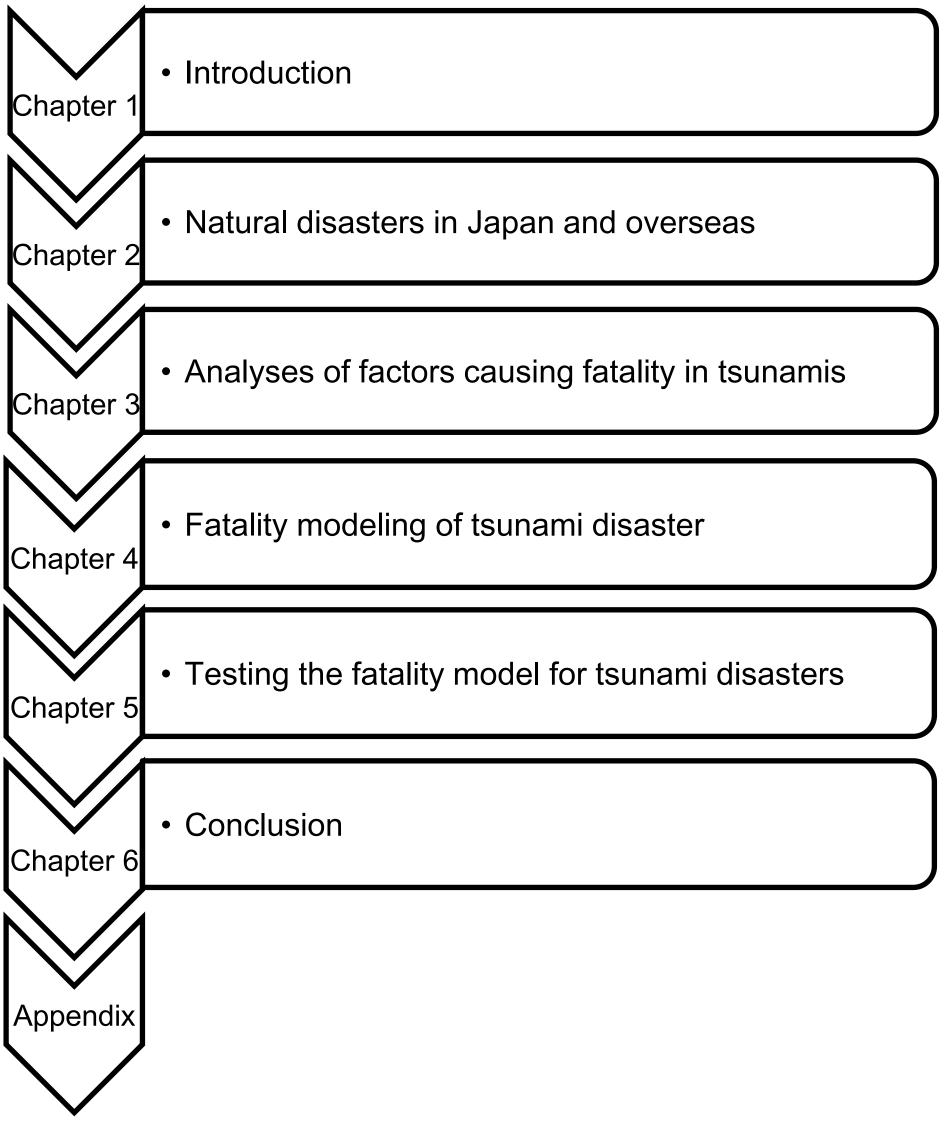


Figure 1.6: Thesis structure

References

[1] UNISDR (2015) "Sendai Framework for Disaster Risk Reduction 2015-2030", Available: http://www.unisdr.org/we/coordinate/sendai-framework. Last Accessed: 7th December, 2017

[2] National Police Agency (2017) "About the damage of the 2011 Great East Japan Earthquake, No. 156", Available: http://www.fdma.go.jp/bn/higaihou/pdf/jishin/156.pdf. Last Accessed: 24th October, 2017 (in Japanese)

[3] EM-DAT website (2016) Available: http://www.emdat.be/. Last Accessed:11th October, 2017

[4] T. Charnkol and Y. Tanaboriboon (2006) "Tsunami Evacuation behavior analysis-one step of transportation disaster response-", *IATSS Research*, Vpi.30, pp.83-96

[5] UNDP (2004) "World report, Toward Reduction of Disaster Risk -Issues imposed on development-" Available: http://www.undp.or.jp/publications/pdf/RDR_ES_J.pdf. Last Accessed: 2nd November, 2017 (in Japanese)

[6] P. Peduzzi, H. Dao, C. Herold and F. Mouton (2009) "Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index", *Nat. Hazards Earth Syst. Sci.*, 9, pp.1149–1159

[7] E. So (2016) "Estimating Fatality Rates for Earthquake Loss Models", SpringerBriefs in Earth Sciences

[8] S. Yotsui, M. Koyama, A. Furukawa and J. Kiyono (2015) "Mechanism Analysis of Casualty and Evacuation Route in the Case of Fukushima Prefecture", *Journal of Social Safety Science*, No.27. (in Japanese)

[9] I. Alcantara-Ayala (2002) "Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries", *Journal of Geomorphology*, Vol. 47, Issues 2–4, 1 pp. 107-124

[10] Cabinet Office, Government of Japan (2012) "Guidelines for damage prediction and techniques of building and human". Available: http://www.bousai.go.jp/jishin/nankai/taisaku/pdf/2_2.pdf. Last Accessed: 1st March, 2017 (in Japanese)

[11] K. Toki, T. Sato, J. Kiyono and J. Wakabayashi (1985) "Attenuation of Simulated Peak Accelerations Taking into Account Fault Extent and Rupture Process", *Disaster Prevention Research Institute*, Kyoto University 28B-2, pp. 1-11 (in Japanese)

Chapter 2
Natural disasters in Japan and overseas

A literature review was essential to identify what research had already been conducted regarding the loss estimation models and damage analyses of natural disasters. A summary of previous fatality model and damage analyses of past natural disasters, especially earthquakes, tsunamis and floods are detailed below.

2.1 Literature review of past studies in Japan

2.1.1 Modeling

The frequency of occurrence of tsunamis is low. However once they occur, the tsunami will cause widespread damage. In addition, human damage will be related to human evacuation activities. With regards to the fatality model of tsunami disasters, only a few extant studies have focused on developing a fatality model for tsunami disasters. Nevertheless, in the last few years after the 2011 Great East Japan Earthquake and Tsunami, some researchers have conducted these studies. Currently, in Japan, although a large number of studies have been made on disaster fatality models, explanatory variables by models are different and prediction methods are not standardized. Different fatality model are used depending on each region. Moreover, the models that have been proposed focus on social and geographical factors separately. Therefore, fatality models which incorporate both social factors and geographical factors are insufficient.

There are tsunami inundation prediction simulation methods and building damage prediction methods implemented by national and local governments in Japan. For each prefecture, 35 municipalities out of 39 municipalities with coastlines are conducting regional tsunami damage prediction methods. The Central Disaster Management Council of Japan [1] explains the equation dealing with inundation depth. This equation has a public record in Japan. This thesis adopts the equation of the Central Disaster Management Council of Japan shown in Eq. (2.1) [1] [2]. Eq. (2.1) has focused on the relationship between inundation depth and fatality. As shown in Eq. (2.1), the number of deaths is calculated based on the relationship between the exposed population in the inundated area and inundation depth. The exposed population is within the area where the inundated area is over 1 m or more, which is defined as the tsunami affected population.

$$Death = population\ in\ each\ grid\ square \times 0.0282 \times exp(0.2328 \times inundation\ depth) \qquad (2.1)$$

Also, some researchers have provided equations and methods to estimate casualties. First, Shimada *et al.* [3] described that it is difficult to predict human damage because it depends on the evacuation behavior of the residents. Hence, their research has proposed a new damage prediction method that considers residents' evacuation behaviors. Using data from a questionnaire survey and daily tsunami disaster prevention awareness, they identified an evacuation start time, evacuation speed, available evacuation road, size of target area and population. Their results showed that advancing evacuation start time leads to reduction of human damage. Second, Miyano and Lu [4] focused on physical damage by reexamining the damage survey data of Tonakai Earthquake, 1944. They analyzed the relationship between human damage and physical damage from a macroscopic point of view using regression analysis. Regarding human damage caused by the tsunami, the relationship between the number of deaths, total destruction and the number of houses washed away was plotted on a log logarithmic paper, and a regression expression was obtained by the least squares method. They proposed a human damage equation including total destruction and the number of houses washed away. Third, Kawata's study [5] on human damage estimation examines the degree of human damage as dependent on the success or failure of emergency responses and reconstruction projects. Therefore, it is important to estimate the maximum number of deaths caused by natural disasters. As a result, human damages varied depending on the season and time. To estimate human damage caused by a tsunami disaster, the number of deaths is calculated by multiplying the number of residences by using the graph of the relationship between the tsunami height and the death rate which was calculated by using past tsunami data such as the 1896 Meiji Sanriku Tsunami, the 1933 Showa Sanriku Tsunami, the 1944 Tonankai Earthquake, the 1946 Nankai Earthquake and the 1993 southwest Hokkaido Earthquake. Next, Shishido and Imamura [6] said it is important to know the risk of tsunami before the natural disasters occur. Their study developed a tsunami damage function based on analysis of the actual human damage survey following the 2004 Indian Ocean Tsunami. This study proposed an equation taking into account the evacuation time and effect of inundated starting time. For example, the explanatory variables were inundation starting time, preparation time to evacuate, and travel time to an evacuation center. Sugimoto *et al.* [7] have proposed a human damage prediction method for tsunami disasters which employs an accumulated death tool using the time needed to begin to seek refuge after an earthquake, tsunami inundation depth on land, flow velocity and evacuation speed as parameters. Imai *et al.*'s research [8] applied the tsunami flooding analysis using a synthetic topography model that is practical and highly expressive to various Kochi municipalities by organizing various damage occurrence conditions such as human damage and physical damage. Alongside, analysis of hazard map was described. Ishinomaki City, Miyagi Prefecture made an inundation area map in the city and marked evacuation places in each area, however they described only in the low embankment area. Also it was estimated the risk map using a data of smaller scale of tsunami disaster than that of the 2011 Great East Japan Earthquake. Suppasri *et al.* [9] analyzed tsunami characteristics, geographical features, damage area's characteristics and human behavior comparing to historical tsunami disasters. They proposed Eq. (2.2).

$$\text{Fatality Ratio (FR)(\%)} = \frac{no.of\ dead + missing}{population\ before\ the\ tsunami} \times 100 \quad (2.2)$$

Generally, the fatality ratio has been taken into account the magnitude of the earthquake and the shaking intensities of different building types as the primary parameters. Koshimura *et al.* [10] aimed to propose a new tsunami fragility which integrated tsunami damage information into GIS obtained from remote sensing, on-site survey and numerical analysis. This tsunami fragility is a probabilistic representation of the damage rate and the degree of human damage caused by the buildings in the target area, and houses of the settlement. This is a formula describing the hydrodynamic quantities such as tsunami flooding depth and flow velocity. It also described the limits of the number of samples at the time of the statistic. According to another paper, Koshimura *et al*. [11] proposed a method to evaluate an evacuation plan formulated focusing on information transmission at the time of the occurrence of the tsunami and evacuation behavior, then developed it in GIS. This research utilized the excellent information processing and analysis functions of GIS software. Nobuoka *et al.* implied the necessity of planar risk assessment [2]. The purpose of this research was to develop a quantitative assessment of facility tsunami risk, basic development of the calculation of tsunami height, quantification of inundation area and inundation damage, and mapping. There are many cases of disaster prevention research using GIS, and it is a useful tool for the disaster prevention filed. The benefits of effectiveness in disaster loss modeling of GIS are explained in a later section.

All presented papers so far have focused on geographical and physical measures to tsunami disasters. They mentioned that social factors and human behavior are a significant influence on human damage, but there is little research regarding a model that includes social factors. For example, Yun and Hamada [12] noted that *"This (The 2011 Great East Japan Earthquake) disaster reinforces again the lesson that best way to reduce loss of human lives in natural disasters is by establishing effective countermeasures and preparedness"*. They have analyzed factors influencing the cause of death owing to the tsunami based on the information of the 2011 Great East Japan Earthquake, and it was pointed out that age and evacuation start time have a significant influence on human damage. To implement disaster countermeasures effectively, it is necessary to understand the characteristics of disaster risk and to promote investment and technology development. Abe and Fujino [13] mentioned there are various forms of natural disasters and the damage related to them also depends on the state of the society and the economy. They showed a complex and uncertain aspect. As a risk prediction technology, there is an approach to use 4,729 samples of past natural disasters from 1990 to 2005 and statistical data on 2000. This was mainly a macroscopic analysis in a wide area such as at the country or 19 international level etc., which is obtained from a certain number of samples and enables statistical handling. As a result of the analysis, the disaster prevention investment was thought to be effective for reduction of human injury, but no reduction effect was observed on physical damage. In addition, Abe and Fujino stated that disaster damage can be greatly affected by geographical and socio-economic conditions.

2.1.2 Human damage

The tsunami damage is shown in Table 2.1 [14]. The total number of casualties caused by the reported earthquake and tsunami disasters is taken from to the National Oceanic and Atmospheric Administration (NOAA) database [15]. The 1896 Meiji Sanriku Tsunami, 1993 Showa Sanriku Tsunami and 2011 Great East Japan Earthquake have caused a huge damage to the Tohoku region. Based on the summary of the Cabinet Office, tsunamis that occurred to date in Japan, and those that occurred in remote areas but caused damage in Japan, are summarized in Table 2.1. Worldwide, enormous human injury occurred in the 1960 Chile Tsunami, 2004 Indian Ocean Tsunami, 2009 Samoa Tsunami and the 2013 Solomon Tsunami. Therefore, the papers mainly obtained from these past tsunami disasters are organized in this section.

First, the damage in the 2011 Great East Japan Earthquake is summarized. Ushiyama and Yokomaku [16] summarized the fundamental characteristics of human damage based on the data of the 2011 Great East Japan Earthquake. They analyzed the tsunami inundation area population and the number of victims. It appeared that major damage occurred in the area where a huge tsunami height occurred. Focusing on the rate of dead and missing people to the inundation population of the three prefectural (Miyagi, Iwate and Fukushima Prefectures) coastal cities by municipality, it was 11.63% in Onagawa Town which is the highest value, then 11.13% in Rikuzentakata City and 10.97% in Otsuchi Town. There was huge damage compared with recent victims of disasters in Japan. However, even though the fact that a large tsunami height occurred, it can be regarded that about 10% of the people who appeared to be in the range affected by the tsunami were victims. In other words, it was said that about 90% of people escaped from the tsunami in some way, and it was highly likely that they survived.

From the viewpoint of tsunami characteristics, according to the damage survey of Mizutani [17] of the 1933 Showa Sanriku Tsunami, the damage rate of residences rapidly increases when the inundation depth is over 2 m. If the inundation depth is over 4 m, the damage rate was 100% in the case of the 2011 Great East Japan Earthquake and Tsunami. Goto’s study [18] proposed the number of human damage which fatalities and missing divided the number of completely destroyed house. This result should be an index to compare the total value of the ease of evacuation and the evacuation ability of the residents if the tsunami arrival time is about the same throughout the area. In conclusion, this index is based on the relationship between the development status of the tide ridge and the crash resistance in the case of overflow, improvement status of the evacuation route, the level of awareness of the residents, the level of voluntary disaster prevention activities

Table 2.1: Tsunami disaster in Japan from data of disaster prevention measures promotion discussion meeting, tsunami evacuation measures study working group [14]

Date	Name	Location	Death toll including both earthquake and tsunami in Japan
15/6/1896	Meiji Sanriku Tsunami	Japan	21,959
1/9/1923	Great Kanto Earthquake	Japan	about 105,000
3/3/1933	Showa Sanriku Tsunami	Japan	3,064
12/7/1944	Tonankai Earthquake	Japan	1,223
21/12/1946	Nankai Earthquake	Japan	1,330
22/5/1960	Central Chile Tsunami	Chile	142
26/3/1983	Japan Sea Earthquake	Japan	104
12/7/1993	Southwest Hokkaido Earthquake	Japan	202
11/3/2011	the Great East Japan Earthquake and Tsunami	Japan	18,453

and the characteristics evaluated by evacuation support of the fire fighter. Therefore to utilize this index for evaluation of evacuation characteristics and analysis of issues in areas where there is a possibility of a tsunami affected area, it is necessary to develop a method to quantify the characteristics related to local evacuation.

In term of geographical characteristics, Takahashi and Matsuta [19] investigated the factors related to the differences between each region of human damages in terms of geographical characteristics. First, they considered why nearly 20,000 people lost their lives by analyzing and answering the following two questions. One was to understand the mortality rate in sub-region units such as village or smaller units than village, and to what extent can regional differences be explained by geographical factors. The other is how geographical factors were involved in human behavior. Suzuki and Hayashi [20] have assumed the indicators representing the population change situation which is compared the population using the national census data from 1985 to 2010 in the inundated area by tsunami and considered the factors that caused the difference in damage rate. As an index, they analyzed the relationship with human damage using average tsunami height difference in the inundated area, population density, area of inundated area and height of the assumed tsunami. In conclusion, hazards and damage were analyzed by municipal unit; however the area of municipalities, coastline distance and the number of bays vary, and the indicator showing the population change situation shown in this research necessarily represents the municipal indicators. They found that indicators showing the population fluctuation situation shown in this research do not necessarily represent indicators of municipalities and it is necessary to analyze using finer analytical units. In the study of Ushiyama *et al.*[21], they examined the relationship between the tsunami disaster and the situation of the occurrence of the victim, based on information about the death toll and the missing persons of the 2011 Great East Japan Earthquake, targeting the Sanriku Coast with few plains. Based on the results of the tsunami simulation, this study analyzed the relationship between nine predispositions and incentives. These were resident area and inundated area, tsunami flooding depth and victim rate, tsunami arrival time and victim rate, average elevation / rise ratio and victim rate, distance from the coastline and victim rate, population and victim rate, age distribution and victim rate, building structure and victim rate and tsunami inundation estimated area and victim rate. Among the nine, the distance from the coastline and victim rate still remains unclear, but there was significant correlation with the victim rate and the tsunami flooding depth and flow velocity. In addition, in this research, since it was targeted at the Sanriku region like rias area, it was expected that there would also be different trends in the plains.

Moving onto examining papers that analyzed social factors related to disaster, in Takeda *et al.*'s research [22], they studied effective evacuation from three multifaceted and multilateral perspectives; disaster prevention information and risk communication, improvement of evacuation hill and maintenance of the tsunami evacuation building. In Japan with a declining birthrate and aging population, to reduce human injury, it was effective to locate evacuation centers as safely as possible while considering vulnerable people and their ability to access them quickly. Not only damage caused by the tsunami, Sekiya *et al.* [23] noted that the evacuation decision making behavior such as whether people evacuate or not, the psychological mechanism is not clarified as a model. In other words, it is necessary to clarify the evacuation decision making structure of people and the psychological mechanism of evacuation. Nagaie *et al.'*s research [24] is that from the viewpoint of challenges to access to evacuation facilities, they analyzed the characteristics of the location of welfare facilities at altitude, distance from coastline and shortest distance to the hill by clarifying the location characteristics of social welfare facilities. As a measurement of the tsunami, they pointed out that it need to guide the location to the hill with less risk by the tsunami damage based on the recognition that vulnerable people and the evacuation aid person will be weak to the tsunami disaster. In the research of Kanbara *et al.* [25], they analyzed the actual condition and characteristics of the evacuation behavior of elderly people needed to escape to the elevation at a maximum of 300 m evacuation distance in the Akahama Village, Otsuchi Town. They evaluated how the environment surrounding the village had influenced the evacuation behavior of elderly people. In this research, they focused on the selection of evacuation starting time. As a result, it was stated that the damage rate of elderly people over 70 years old was high in Akahama Village. They concluded that evacuation behaviors against the tsunami may be attributed to the history of that town such as past disasters and space development projects. Moreover, this research indicated that it must also recognize that crisis awareness decline as small tsunami damage continues. In Murakami's research [26], for example, Miyagi Prefecture experienced an 8.8 m tsunami one hour after the 2011 Great East Japan Earthquake. In terms of the relationship between the tsunami hazard and topography, most people in Natori City, Miyagi Prefecture had underestimated the tsunami hazard because they knew little about tsunami history in the flat plains based on questionnaire survey. Therefore they had delayed evacuation. Dohi *et al.'*s study [27] focused on the start of the tsunami evacuation which is important in mitigating human losses from tsunami events. They specifically made a tsunami evacuation model based on the concept of "co-construction of society reality" and this model would be a more effective tsunami evacuation method than the approach so far. This research developed a simulation model for evacuee generation as the target area in Ishinomaki City, Miyagi Prefecture damaged by the 2011 Great East Japan Tsunami. In the results, they found that the ratio of the start of tsunami evacuation was 78.6% in the target area using their simulation.

From the viewpoint of demographic factors causing fatality, Yoshino [28] noted that the study of the tsunami from the view point of disaster history is lagging behind. By analyzing the number of deaths by age group and gender, the total number of people in their 20s and 30s amongst the dead is relatively small, but men outnumber women. This is the result since the 20s and 30s age group are the so-called workers, men had worked at or near the tsunami site. Furthermore, it can be seen that elderly people are affected more than other generations. In addition, at age 80, the difference between men and women would become stronger in their judgment ability to decide their own actions based on their view and knowledge about the past tsunami in 1933. Also he said that tsunami height is strongly related to human damage as well as demographic factors. Ohta and Koyama [29] analyzed the situation of the occurrence of deaths at the time of several earthquakes and tsunami focusing on age category. They took into account the earthquake ground motion (tsunami) strength, when and what time the disaster occurred as the input side, the strength of the disaster response ability of both hazard and software possessed and age-dependent of the ability of human behavior. As a result, it was found that there are mainly four shapes. Taking the age axis on the horizontal axis and the death rate on the vertical axis, U-shaped and J self-contained, respectively, those with low mortality rates and those not dependent on age (flow type), almost all of the affected areas died (fextreme type). The 2011 Great East Japan Earthquake confirmed that the deaths show a J pattern. If disaster response is insufficient, human beings are caught up in the tsunami itself. If that is the case, they mentioned that the characteristics of human behavior of the individuals subjected to external forces, such as tsunami, are greatly reflected in human damage. Koyama *et al.* [30] analyzed the situation of deaths occurring in Iwate, Miyagi and Fukushima Prefectures, which were the major affected areas in the 2011 Great East Japan Earthquake. Using 2005 census data to estimate gender and age class mortality by municipalities, it was found that the mortality rate for people aged over 60 was the same as that for any other age, according to comparison between the census and the age distribution of the deaths. It is speculated that the staying home rate for over 60 year olds was equal to or higher than the staying home rate (60% or more) of the full-time housewife at around the 2 p.m. on weekdays according to the 2007 White Paper on National Life. Additionally, the need for detailed analysis of the staying home situation by age and more detailed clarification of the death situation was highlighted. This research clarified the mortality rate due to the residence characteristics by age on the variation of the tsunami exposed population.

The greatest purpose of disaster prevention measures is to reduce human damage. Katada *et al.* [31] said it is thought that the occurrence of human damage will depend on the disaster characteristics, physical damage caused by the disaster characteristics and the spatial temporal relationship with the residents' activities. In the study of Ohta and Ohashi [32], surveys on human psychological reactions and behaviors at the time of an earthquake were actively started with the 1964 Niigata earthquake. The objective of earthquake disaster prevention was to protect human life and property against earthquakes and to preserve the functions of social systems and in the worst case scenario, it was important to protect only human lives. Ohta and Ohashi's paper conducted a questionnaire survey for the Miyagi Prefecture Ocean earthquake. Mizutani [33] analyzed the factors related to human damages due to earthquake and tsunami using statistical data of the 1896 Meiji Sanriku Tsunami and the 1933 Showa Sanriku Tsunami. Mizutani said "*Human casualties are greatly affected by various factors which influence people's behavior, mentality and general state of preparedness against such hazards*". Mizutani reiterated that minimizing human injury is the primary task of disaster prevention measures.

2.1.3 Past natural disasters in Japan and other countries

In this section the focus is on damages from earthquakes and tsunamis in Asia, as this is where the most of these disasters happened according to the data of EM-DAT [34]. Table 2.2 shows that a list of tsunami disasters in Asia from 1900 to 2017 from the EM-DAT database. Thirty five earthquakes and tsunamis have caused huge damage to countries. Some researchers state that a tsunami prevention plan is important to reduce the damage. The impact to human damage at the tsunami event is highly dependent on evacuation behavior. In Japan, some researchers have analyzed the psychology and human behavior against a tsunami after the 1983 Middle Japan Sea Earthquake [35] [36].

Table 2.2: Historical tsunami disaster in Asia from 1900 to 2017 from EM-DAT database

Start date	Country	Magnitude value	Disaster type	Disaster subtype	Total deaths	Associated disaster
10/08/1901	Japan	7.4	Earthquake	Tsunami	18	--
04/02/1907	Indonesia	7.4	Earthquake	Tsunami	400	--
07/07/1907	Japan	7	Earthquake	Tsunami	41	--
12/01/1914	Japan	7.1	Earthquake	Tsunami	35	--
01/09/1923	Japan	7.9	Earthquake	Tsunami	2,144	--
07/03/1927	Japan	7.3	Earthquake	Tsunami	2,925	--
04/08/1928	Indonesia	3	Earthquake	Tsunami	128	--
02/03/1933	Japan	8.3	Earthquake	Tsunami	3,064	Tsunami/Tidal wave
03/03/1933	Japan	8.3	Earthquake	Tsunami	3,000	--
07/12/1944	Japan	7.9	Earthquake	Tsunami	998	Tsunami/Tidal wave
/06/1955	Thailand	-	Earthquake	Tsunami	500	--
/09/1959	China	-	Earthquake	Tsunami	47	--
22/05/1960	Japan	-	Earthquake	Tsunami	138	Tsunami/Tidal wave
22/05/1960	Philippines (the)	-	Earthquake	Tsunami	32	--
16/06/1964	Japan	-	Earthquake	Tsunami	25	Tsunami/Tidal wave
15/08/1968	Indonesia	7.8	Earthquake	Tsunami	200	--
23/02/1969	Indonesia	6.9	Earthquake	Tsunami	64	--
18/07/1979	Indonesia	-	Earthquake	Tsunami	539	--
26/05/1983	Japan	7.8	Earthquake	Tsunami	102	Tsunami/Tidal wave
12/07/1993	Japan	7.8	Earthquake	Tsunami	239	Fire
10/10/2002	Indonesia	7.6	Earthquake	Tsunami	8	Slide (land, mud, sn
26/12/2004	Bangladesh	9.1	Earthquake	Tsunami	2	--
26/12/2004	India	9.1	Earthquake	Tsunami	16,389	--
26/12/2004	Indonesia	9.1	Earthquake	Tsunami	165,708	Tsunami/Tidal wave
26/12/2004	Malaysia	9.1	Earthquake	Tsunami	80	Tsunami/Tidal wave
26/12/2004	Maldives	9.1	Earthquake	Tsunami	102	Tsunami/Tidal wave
26/12/2004	Myanmar	9.1	Earthquake	Tsunami	71	--
26/12/2004	Sri Lanka	9.1	Earthquake	Tsunami	35,399	--
26/12/2004	Thailand	9.1	Earthquake	Tsunami	8,345	Tsunami/Tidal wave
14/03/2006	Indonesia	6.7	Earthquake	Tsunami	3	Tsunami/Tidal wave
17/07/2006	Indonesia	7.7	Earthquake	Tsunami	802	--
10/08/2009	Japan	6.2	Earthquake	Tsunami	1	Tsunami/Tidal wave
25/10/2010	Indonesia	7.8	Earthquake	Tsunami	530	Tsunami/Tidal wave
11/03/2011	Indonesia	9	Earthquake	Tsunami	1	Tsunami/Tidal wave
11/03/2011	Japan	9	Earthquake	Tsunami	19,846	Fire

Source: EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium

In Japan, the Nankai earthquake Mw. 8.1 with the Kii Peninsula as the epicenter occurred at 4:19 am on December 21, 1946 and caused significant damage in Kochi Prefecture, Tokushima Prefecture, Wakayama Prefecture and in a fairly wide range. Miyano and Mochizuki [35] conducted an interview survey and a questionnaire survey targeting of five districts in above three prefectures. As a result, it was found that there are many more deaths in general for females than males, and for age groups older than 10 years and over 60 years. In Yamashita's paper [37], regarding the death toll of the Showa Sanriku Tsunami in 1933, the death of ten years old (31.6%) accounting for about 30% of the total number was higher than any another ages. In the Southwest Hokkaido Earthquake in 1993, nearly half of the dead were elderly people aged 61 or older. The reason why many elderly people died was because they were incapacitated and could not evacuate on their own. Based on these results, they said that society should consider the evacuation and safety of children, disabled elderly and handicapped as disabled vulnerable people. Expectations for soft disaster prevention measures are increasing in each field of disaster prevention. Ushiyama *et al.* [38] also stated that it is necessary to fully discuss how much human damage can be alleviated. They analyzed the location where the earthquake occurred, what people were doing, whether people heard tsunami warnings or not, the time when people started evacuation (for example, after the earthquake, after hearing the alarm, or upon realizing that the sea is strange), the place to escape to, whether people caught a tsunami from literature and articles to estimate human behavior after the earthquake. The target disasters of this study were the Japan Sea Earthquake on May 26, 1983 and the Southwest Hokkaido Earthquake on July 12, 1993. Kimura [39] explained the reduction of human damage caused by the tsunami is positioned as an important measure in Japan. In addition to summarizing the lessons learned from tsunami disasters in another country, deriving lessons of past tsunami disasters in Japan is important to promote disaster reduction measures based on the regional characteristics.

Japan has various initiatives aimed at improving crisis awareness and advancement of disaster information to reduce human damage caused by the tsunami. On the other hand, developing countries are generally considered to be vulnerable to natural disasters [40]. The reasons are as follows: disaster prevention infrastructure development and structural measures are not advanced, warning alarm systems are not in place, the administration cannot respond adequately when a disaster occur economically weaker poor people live in low land or near the coast which is vulnerable to tsunami damage. In the case of September 29, 2009 American Samoa Tsunami, this earthquake and tsunami caused over 190 dead or missing people. Okumura [41] said that nearly no residents had knowledge about the tsunami and in addition there was no system to inform when the tsunami occurred. However, the mortality rate was low. Gokon's analysis [42] revealed that 80% of the buildings in American Samoa were seriously damaged when the depth of flooding was over 6 m. It also reported that 20 to 30% of houses were damaged even in the area where the inundation depth was about 2 m.

In Indonesian disaster, Marchand *et al.* [43] explain that *"Vulnerability reduction to tsunamis has become a major issue after the December 2004 Indian Ocean tsunami disaster"*. Differences in topographical features and population density will affect the impact of a tsunami as well as both physical and socioeconomic factors.

They collected data in Banda Aceh, Calang, Samatiga and Lhoksumaweh in Indonesia. Based on the analysis of the 2004 Indian Ocean tsunami, the number of houses destroyed was close to 100% if the inundation depth was about 150 cm. In terms of the relationship between casualties and inundation depth, the casualties were low for the inundation depth of up to 150 cm. If the inundation depth was above 400 cm, the casualty rates were above 80%. They noted the correlation coefficient between inundation depth and percentage of casualties is 0.82, on the other hand, the correlation between percentage of permanent housing and casualties is 0.32. From this result, inundation depth was a highly significant variable related to the cause of death. Goto *et al.* [44] surveyed the damage of the 2012 tsunami in Sumatra, Indonesia. The Agency for Meteorology, Climatology and Geophysics (BMKG) equivalent to the Japan Meteorological Agency (JMA) issued a tsunami warning 4 min 45 s after the earthquake occurred. Two hours after the first earthquake occurred, another earthquake occurred in the southern region and the issued warning was continued. As Banda Aceh was developed on flat land with a low altitude, evacuation for the tsunami was required only in the upper part of building heading inland. First, in the actual situation, the most people evacuated after experiencing a large tremor. Second, people evacuated because their neighbor evacuated. Because Banda Aceh has a poor public information system, most people rely on observing the movements of the surrounding people. On the other hand, regarding the evacuation rate and evacuation start time in the 2004 tsunami, the experience of being able to escape if there is a bike is affected. The evacuation route showed that it is more difficult to get to the safe destination as it is closer to the coast.

2.2 Literature review of past study of fatality model in the world

The UNDP [45] has described the importance of international risk assessment. Alongside the Intergovernmental Oceanographic Commission (IOC), the United Nations Educational, Scientific and Cultural Organization (UNESCO) mentioned tsunami preparedness [46] [47]. The Historical Tsunami Database (HTDB/PAC) Project conducted the most complete parametric tsunami data within the entire Pacific and full history of the the available observations (from 47 BC to present). According to this paper, earthquakes in the marginal seas such as Sea of Japan, the Okhotsk Sea and the Bering Sea have a higher tsunami efficiency as compared to the earthquakes in the Pacific Ocean [48].

Peduzzi *et al.* [49] mentioned that a global index for evaluating each country’s human vulnerability is useful to aid organizations and governments. This study was one of the components of the report “Reducing Disaster Risk” by the United Nations Development Programme (UNDP/BCPR, 2004). The study conducted analysis focused on droughts, earthquakes, tropical cyclones and floods. Eq. (2.3) shows the model of the number of estimated deaths.

$$\log(\mathrm{K}) = 10.97\ln\left(\mathrm{PhExp40}_{Eq.}\right) + 25.696U_g - 0.425\ln(WoodPc) - 17.344 \tag{2.3}$$

where *K* , *PhExp40*, *Ug* and *Wood PC* were number of estimated deaths, average population exposed to earthquakes (1964–2004), percentage of urban growth (computed using a three year moving average) and percentage of country forest coverage, respectively.

Parwanto and Oyama surveyed disasters of the past 112 years and used historical earthquake and tsunami data including both deaths and missing people (D&M) [50]. Geographical features are similar like archipelago with population of over 100 million people. Natural disasters such as earthquake, tsunamis, landslides and volcanic eruptions, and hydro meteorological disasters such as typhoons, rainstorms, floods, heavy snow, droughts, strong winds and heat waves have occurred in Japan and Indonesia. They understand that earthquakes are common in Japan and Indonesia, and earthquakes are the main trigger of most tsunamis. Hence they analyzed some factors related to the number of deaths by earthquakes and tsunamis using the probabilistic model to estimate the number of D&M per day shown in Eq. (2.4) and Eq. (2.5). However, because earthquakes and tsunamis are rare events and do not always cause D&M daily, they analyzed the number of D&M per month.

For earthquakes: (2.4)

$$\mathrm{E}\ (\mathrm{DM})_t = \beta_0 + \beta_1 Mag_t + \beta_2 Depth_t + \beta_3 Loc_t + \varepsilon_t$$

For tsunamis: (2.5)

$$\mathrm{E}\ (\mathrm{DM})_t = \beta_0 + \beta_1 Mag_t + \beta_2 Depth_t + \beta_3 Loc_t + \beta_4 Height_t + \varepsilon_t$$

where *DM* is the number of deaths and missing people (D&M), *Mag* is the magnitude of the earthquake (Mw), *Depth* is the focal depth (km), *Height* is the maximum water height (m), *Loc* is the dummy variable of the epicenter location: offshore/sea (o) and mainland (m) and *εt* is the error term. The results show that the Poisson and negative binomial distribution fit the actual data of D&M per month in Japan and Indonesia. It appears that the negative binomial has Chi-square values smaller than the Poisson.

Jonkmna *et al.* [51] have conducted the making of a general framework for the estimation of loss of life due to accidents such as floods, tunnel fires and chemical accidents. This study used the context of quantitative risk analysis (QRA). They defined evacuation as *"the movement of people from a (potentially) exposed area to a safe location outside that area before they come into contact with physical effects"*. Another paper of Jonkmna *et al.* proposed methods for the estimation of human damage from flooding shown in Eq. (2.6) and Eq. (2.7) [52]. They have stated that "*methods have been developed for different types of floods in different regions"*. This study have took into account three steps, analysis, estimation of the number of people exposed and assessment of the mortality amongst those exposed to the flood.

$$N = F_D N_{EXP} \tag{2.6}$$

where *N* is the number of fatalities, N_{exp} is the total number of people exposed to the floodwaters and F_D is the mortality in the exposed population. They analyzed the exposed population and evacuation as well.

$$N_{EXP} = (1 - F_E)(1 - F_s)N_{PAR} - N_{RES} \tag{2.7}$$

where N_{PAR} is the number of people at risk before the event, F_E is the fraction of the population that is evacuated out of the area before the flood, F_S is the fraction of the (remaining) population that has the possibility to find shelter and N_{RES} is the number of people rescued. In this study, *"evacuation is defined as movement of people from a (potentially) exposed area to a safe location outside that area before they come into contact with physical effects"*. Okumura *et al.* [53] made a fatality model for tsunami disasters which was included inundation depth, flow velocity, evacuation speed, delay times and exposed population based on equation (2.6) and (2.7).

In terms of the damage caused by earthquake, the damage of buildings correlated with the earthquake magnitude is directly related to human losses. The collapse situation of the building has a strongly influence on the deaths during and after the earthquake. However, people have more time to save their lives by evacuating to safe places in tsunami disasters. Yeh's study [54] mentioned that the effectiveness for evacuation against by tsunami is tsunami warning systems and education in a timely manner are more effective against tsunamis than the physical severity of the tsunami. According to the survey of the 2011 Great East Japan Tsunami, 94.5% of the total death is attributed to drowning. To determine human decision-making and behaviors, this study presented an agent based model which is a simplified technique using a digital elevation model (DEM), evacuation distance, location of maximum tsunami penetration, tsunami arrival time and the time of maximum tsunami penetration, warning time after earthquake, evacuation speed, time of day and time of year, ambient conditions of evacuation routes and the most probable preparation time for people to initiate evacuation after they receive a tsunami warning. Yeh's model was for estimating loss of life (casualties and injures). It was concluded that the important factors causing casualties are the level of education and the effectiveness of warning.

Suppasri *et al.* [55] have made a tsunamigenic ratio (TR) that is defined as the ratio between the number of earthquake-generated tsunamis and the total number of earthquake that occurred between 1900 and 2011. Earthquake magnitude, focal depth and sea depth compose the TR for each region, the three parameters were combined and dimensionless parameters for the tsunami index (TI) were proposed. Some 15 to 30 minutes after the main shock on May 22, 1960, an over 7m high tsunami occurred in some places. This earthquake mainly caused building damage, landslides and tsunami. Meanwhile 55.2% of the lives lost in Chile from May 21 to 22, 1960 was by tsunami event. Charnkol and Tanaboriboon [56] investigated evacuee behaviors and factors affecting tsunami evacuation focusing on a tsunami trip generation model in Baan Namkhem, Phang-Nga Province, Thailand of the area affected by the 2004 Indian Ocean Tsunami. They reported, *"A significant amount of research has focused on various types of evacuations, but little attention has been given to tsunami evacuation in the past"*. Based on these recommendations, the aim of Charnkol and Tanaboriboon's study was to establish the prediction of evacuation response patters based on the behavior factors. It was found that six factors, education level, ownership of the residence, distance to nearest seashore, disaster knowledge, number of household members and status of respondent were statistically significant. Moreover Pomonis [57] mentioned the damage in the Hawaiian Islands, Hiro City by the earthquakes. He explained *"a study of the behavior of the residents of the inundated area revealed that only a third of the people evacuated to high ground"*. Dash and Gladwin's study [58] examined actual evacuation behavior with a focus on evacuation modeling and the social context of events such as hurricanes. This study focused on three topics; warning, risk perception and evacuation. They found that the situation of evacuation differs between women and men, they said women have a greater objective risk (living in riskier housing). They determined *"risk perception, then, is a critical component in understanding how individuals decide to evacuate or to stay"*. Moreover, Alexander [59] proposed a new model which combines culture and history with physical hazards to influence vulnerability.

Some researchers have used ArcGIS to analyze the human damage. Katada [60] mentioned that the GIS is accumulated, such as a function of visually displaying information on the database and a function of spatially analyzing and grasping relationships among various pieces of information displayed by being divided into layers on the map. The GIS has functions to utilize information in various ways. Papathoma *et al.* [61] said that *"Tsunami may cause catastrophic loss of life, destruction of property and engineered structures and coastal infrastructure and lead to major economic and business interruption losses"*. A GIS was used as a tool in Papathoma's study. GIS is expected to be used for the following ideas: *(1) "to determine immediate post-tsunami disaster response needs by the emergency services; (2) to pre-plan tsunami mitigation measures by disaster planners; (3) as a tool for local planning by the municipal authorities or; (4) as a basis for catastrophe modelling by insurance companies"*. Hashemi's [62] study proposed a GIS-based model for earthquake loss estimation for a district in Tehran, Iran especially for the damage of earthquake. The GIS is useful for the visualization of spatially referenced data for the input, management, manipulation and analysis. The proposed model contributes to decision-makers making more reliable decistions based on various spatial datasets before and after an earthquake happened. Crooks [63] mentioned the *"Natural disasters such as earthquakes and tsunamis occur around the world, altering the physical landscape and causing severe disruption to people's lives"*. The objective of this study was demonstrating how GIS and agent based modeling (ABM) which is agent based models can be utilized to explore humanitarian relief at the individual level after a natural disaster, such as an earthquake. It is difficult to estimate damages to people and society as natural disasters are uncertain. Scheer *et al.* [64] defined "*managing this risk puts focus on reducing the vulnerability to a satisfactory extent"*. Hence the main objective was to reduce the human damage. To save lives against tsunami disasters, they described that a tsunami evacuation plan must show the evacuation routes towards safe locations so that all affected people could evacuate in time. They used digital elevation map (DEM), population distribution map, road and major paths map, classified buildings map, map of special places, hazardous and dangerous area map and a map showing evacuation-hindering particularities for indicating context and vulnerability data, expected wave height, currents' velocities map, inundation & safe areas map, horizontal shelters, vertical shelters map and possible amendments to vertical shelters as for indicating hazard and physical impact of waves to make an evacuation stakeholders within the GIS and simulation tolls. Thus the whole methodology mirrors a nested and recursive approach.

2.3 Significant studies to the new proposed model

Table 2.3 and Table 2.4 summarized past research throughout the literature described in Section 2.1 and Section 2.2. The UNDP [45] emphasizes the importance of international risk assessment, for example, in promoting a disaster risk index developed by Peduzzi *et al.* for the UNDP [49]. Natural disasters reflect strong regional characteristics and a fatality model constructed in a certain region is not necessarily directly applicable to other regions. Besides, each country faces different natural disasters, each country has different disaster prevention plans and there are differences in culture, risk perception and human behavior. However, developing the fatality model to a large extent depends on the quality and quantity of data. Hence, if the minimum amount of data is availabe and explanatory variables representing regional characteristics are used, it is possilbe to perform disaster damage analysis. Therefore, we need to understand the influence of variables included in fatality models. Based on previous literature, Table 2.4 expresses major example of the fatality models in Japan and world.

Table 2.3: Past research related to natural disasters

Fatality model	Author name	References number	Author name	References number
	Shimada (1999)	[3]	Jonkmna (2010, 2008)	[51] [52]
	Miyano (1992,1988)	[4] [35]	Parwanto (2013)	[50]
	Kawata (1997)	[5]	Nobuoka (2013)	[2]
	Sugimoto (2003)	[7]	Imai (2014)	[8]
	Gusiakov (2005)	[48]	Abe (2014)	[13]
	Katada (2007)	[31]	Yeh (2014)	[54]
	Shishido (2009)	[6]	Yun(2015)	[12]
	Koshimura (2009)	[10] [11]	Suppasri (2016)	[9]
	Pedussi (2009, 2003)	[49]	Okumura (2017)	[53]
Damage information				
	Ohta (1979,2015)	[29] [32]	Ushiyama (2012,2014,2004)	[16] [21] [38]
	Mizutani (1984, 2012)	[17] [33]	Koyama (2013)	[30]
	Yamashita (2005)	[37]	Yoshino (2013)	[28]
	Kimura (2008)	[39]	Takeda (2014)	[22]
	Goto (2009)	[18]	Kanbara (2014)	[25]
	Nagaie (2011)	[24]	Takahashi (2015)	[19]
	Suzuki (2011)	[20]	Sekiya (2016)	[23]
	Murakami (2012)	[26]	Dohi (2016)	[27]
GIS analysis				
	Katada (2000)	[60]	Hashemi (2011)	[62]
	Crooks (2003)	[63]	Scheer (2012)	[64]
	Papathoma (2003)	[61]		
Historical natural disaster				
	Charnkol (2006)	[56]	Gokon (2011)	[42]
	Marchand (2009)	[43]	Suppasri (2012)	[55]
	Okumura (2010)	[41]	Goto (2013)	[44]
	Pomonis (2010)	[57]		

Table 2.4: Significance of the study

Method in Japan	Field of application	Response variable	Factors
Miyako and Lu (1992)	Aomori, Kanagawa, Niigata, Miyazaki Prefectures	Death toll	Collapse of buildings, Population
Shizuoka equation	Shizuoka, Iwate, Aichi, Tottori, Tokushima, Ehime Prefectures	Death toll	Collapse of buildings
Saga equation	Saga Prefecture	Death toll	Collapse of buildings
Nagasaki equation	Nagasaki Prefecture	Death toll	Collapse of buildings, Population
Okinawa equation	Okinawa Prefecture	Death toll	Collapse of buildings
Central Disaster Management Council (2003)		Death toll	Population , Inundation depth
Kawata (1997)		Death toll	Tsunami wave height
Sugimoto (2003)		Death toll	Time necessary to begin seek refuge, Tsunami inundation depth, Flow velocity, Evacuation speed
Koshimura (2006)		Death toll	Current velocity of the tsunami inundation flow, Inundation depth, Evacuee's weight and height
Yun (2015)		Fatality Rate	Evacuation distance divided by the tsunami arrival time, Region indicative variable

Global method	Field of application	Response variable	Factors
Peduzzi (2009)	World	Earthquake death toll	PhExp40: Average population exposed to earthquakes (1964–2004) Ug : Percentage of urban growth (computed using a three year moving average) WoodPc : Percentage of country forest coverage
Jonkman (2008)	World	Mortality Rate	Tsunami wave height

2.4 Risk management

In Figure 1.4 of Section 1.1, this thesis described society cycle against natural against natural disasters focusing on environment surrounding human society in the event of a natural disaster. This thesis considered which vulnerability are significant influences to loss of life, which characteristic of tsunami defined as hazard are important factors of human damage. This section summarized definitions for words before analyzing detail. The United Nations International Strategy for Disaster Reduction (UNISDR) [65] has described these basic definitions for words related to disasters to promote a common understanding of the subject for use by the public, authorities and practitioners.

- Disaster : "*A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts*".
- Disaster risk: "*The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity. It is important to consider the social and economic contexts in which disaster risks occur and that people do not necessarily share the same perceptions of risk and their underlying risk factors*".
- Disaster risk management: "*Disaster risk management is the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses*".
- Exposure: "*The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas*".
- Hazard: "*A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation*".
- Vulnerability: "*The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards*".

According to Takemura, risk is an important concept in terms of safety in society [66]. The author also lists three risks. First, there is global social risk. Secondly, it is difficult to ascertain its cause and causality. Third, it is difficult to insure private companies and guarantee by the nation. Therefore, it is a very important matter for the society to consider the risks against a natural disaster which is a complex event. Regarding the global vulnerability index, the megacity risk index (MRI) by the Munich Re insurance company [67] was created for

50 large cities in the world with a population of over two million people having a large economic impact, and earthquakes, wind and flood damage, wind storms, volcanic eruptions and snow storms. Like Munich Re, the Swiss Re company announced world cities' disaster risk ranking. The Urban Risk Assessment (URA) proposed by the World Bank Urban Development and Local Government Bureau have made risk assessment indicators aimed at utilizing it for the urban policy of local governments. Three elements are indicated as institutional assessment, hazard assessment, and socioeconomic assessment. The risk assessment of major world cities by the Global Facility for Disaster Reduction and Recovery is calculated risk based on 1 km mesh. The World Risk Index (WRI) by the United Nations University Institute for Environment and Human Security (UNU - EHS) is created to evaluate disaster risks in 171 countries. Its components are largely composed of exposure and vulnerability, and the latter consists of three things: susceptibility, coping capacity and adaptive capacity. Ueda [68] has targeted earthquakes, typhoons, flood disasters, volcanic disaster, forest fires as the hazard, constructed and measured from the structural characteristics of housing, housing density, urban safety measures level as the vulnerability and based on indicators on economic size, households of each city, economic level as the exposed values.

Another characteristic of the disaster is damage aggregation. In the event of a disaster, many properties are damaged at the same time. Tatano [69] noted that not all households are necessarily affected by the damage. Furthermore, it is a feature of disaster risk that the damage has spatial correlation and is local. From the viewpoint of risk finance, it is suggested that if there are areas vulnerable to disasters and safe areas, it is suggested that cities in the area from that can become cities with a population / industry scale larger than other cities. Increasing the safety of vulnerable cities against disasters will benefit most other cities in the short term Even in terms of protecting the lives of people, if we improve the safety of fragile areas, there will be differences in the type of vulnerability in the area, however we think that this will also affect the surrounding areas.

2.5 Risk analysis for floods in the UK

The UNISDR [70] emphasizes the importance of the international risk assessment, for example, in promoting a disaster risk index developed by UNDP [49]. What kind of natural disaster will mainly depend on the natural and geographical conditions in a country. Although the occurrence of volcanic eruptions and earthquakes is small, river flooding and floods occur more often in European countries (excluding Italy) [71]. Natural disasters reflect strong regional characteristics and a casualty model constructed in a certain region is not necessarily directly applicable to other regions. Besides, each country faces different natural disasters, each country has the different disaster prevention plans and there are differences in culture, risk perception and human behavior.

This section focuses on water related disaster such as tsunamis and floods comparing the UK and Japan. During these disasters, casualties can be reduced by evacuating people to safe places before the disaster happens with an early warning [72]. Social factors which affect evacuation decision-making are analyzed and the section aims to understand if human behavior in Japan and the UK varies under the different types of natural disaster and geographical contexts. The section firstly discusses warning systems and hazard maps to understand the level of tsunami risk awareness based the 2011 Great East Japan Earthquake damage and flood at Iwate Prefecture in 2016. Secondly, this section analyzes people's attitude to flood risk using questionnaire in Rye, UK.

2.5.1 Outline of questionnaire

(1) Warning system and hazard maps in Japan

This section describes disaster management plan for tsunami in Japan based on the 2011 Great East Japan Earthquake and Tsunami. This tsunami occurred on March 11, 2011 killed 19,575 people (including missing people) according to the National Police Agency as of September 1, 2017 [73]. Tsunami evacuation warnings are provided by the JMA. These warnings automatically deliver information by TV, radio, cellular phones, smartphone and disaster management radio communications systems giving estimated arrival times and heights. If disastrous waves are expected in coastal regions, the JMA issues a Tsunami Warning/Advisory for each region expected to be affected based on estimated tsunami heights [74]. It is not necessary for citizens to be registered on this system. There are also hazard maps in Japan which describes the probable tsunami inundation area and the location of evacuation centers. The Ministry of Land, Infrastructure and Transport (MLIT) and municipalities make these hazards and evacuation centers maps for both tsunami and flood. In the case of the 2011 Great East Japan Earthquake and Tsunami, there were significant differences in the actual and estimated inundated areas – the actual inundated area was bigger than estimated area [75].

The section also discusses flooding in Japan, focusing on the flooding caused by a typhoon in Iwate Prefecture on August 30, 2016 that killed 21 people, nine of which died in facilities for the elderly. In Japan, there is currently an increasing frequency of heavy rain as well as flooding because of the climate change. However, it this flood, evacuation information was not transmitted to residents.

(2) Warning system and hazard maps in the UK

The Royal Life Saving Society UK [76] said that more than 12% of the UK people live in areas at risk of flooding from rivers or the sea. The Environment Agency has provided three warning codes: flood alert, flood warning and severe flood warning. Severe flood warning indicates the most dangerous flood. The flood warning direct service, sends an automatic warning direct to people's mobile, work and home landline, text email or pager if you register to the service. Flood maps, provided by Environment Agency show the areas that are at risk from flooding.

(3) Study site in the UK

The case study site is Rye, Rother District, East Sussex, which is located in south of England. There are three rivers in Rye which affect flood risk and there is housing that is situated close to their banks. Previous events include the tidal surge which hit the east coast of Britain in early December 2013 when much of southern England was affected as well as Rye. The Environment Agency says that flood risk in Rye is high, with approximately 1,190 properties lying within the 1 in 100 year flood event floodplain [77]. Flooding is largely caused by rivers, although tide locking effects can be significant [77]. In Figure 2.2, the red area shows flood warning area and the light blue of area shows flood alert area (information issued in October 2015). The data that represents the risk of flooding is obtained from the Environment Agency's website [78].

(4) Questionnaire in Rye, the UK

The objective of this survey is to explore the awareness of flood and the needs and behaviors of people who live in UK to mitigate against the flood risk. For example, the questionnaire included the awareness of flood and disaster prevention in normal times and at the time of flood. The questionnaire was multiple-choice and consists of 19 questions related to 5 categories, general flood risk and information, the respondent's future evacuation plan, future response, building structure and insurance. The survey was organized with the cooperation of the Rye Emergency Action Community Team (REACT), which works with Rye Town Council to develop emergency plans for the local community. 100 questionnaire sheets were distributed in a city-wide newspaper called the RYE NEWS and were randomly distributed to citizens. A web questionnaire survey was placed on the Facebook page of REACT.

Table 2.5: Question in Rye, UK

List of question	
<General flood risk and information>	
1	Have you been affected by flooding?
2	From which sources do you gather information about flood risk?
3	What kind of information would you like to have during a flood?
4	Have you registered for the Flood Warning Direct Service?
<Your Future Evacuation Plans>	
5	When would you consider evacuating?
6	What transportation would you use to evacuate during a flood?
7	Where would you evacuate to during a flood?
8	If you were not at home, to which location would you evacuate?
9	How far is your home from a safe location away from any flood?
10	Once you decide to evacuate, how long do you think it would take you to get the necessary items together and leave the property?
<Helping others during flood events>	
11	Have you ever discussed evacuation with family members or friends (for example agreed on meeting points in case of separation)?
12	Do you have any neighbours who would be vulnerable during a flood? (i.e. disabled people, elderly people)
13	What kind of help do you think you could provide during a flood?
<Future Response >	
14	How do you think evacuation preparedness can be improved?
<Building Structure>	
15	How many floors does your home have?
<Insurance>	
16	Do you have flood risk insurance?
17	Profession
18	Age group
19	Please provide any additional comments

2.5.2 Organizing the results of the questionnaire

The total of 83 people responded; 52 by paper questionnaire and 31 on-line. Table 2.6 summarizes the sample attributes. The data of Rother and England shown in Table 2.6 are a summary of data from the Office for National Statistics [79]. The response rate of each profession was higher than the Rother and England census. In addition, age distribution of respondents was similar to the census data. This section presents the main findings (see Figure 2.2 to Figure 2.5). This shows the registration rate of flood warning direct service, the level of flood risk insurance and anticipated evacuation behavior, for example with family members or friends.

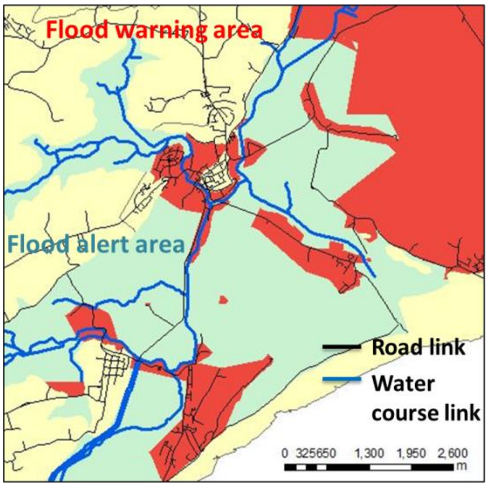


Figure 2.1: Flood warning area and flood alert area in central of Rye

Table 2.6: Sample attributes

		Sample attributes	Rother (Non-Metropolitan District)	England (County)
Profession	Student	10%	1.4%	1.2%
	Part time job	16%	In Employment	In Employment
	Full time job	39%	41.5%	47.5%
	Unemployed	6%	Not In Employment	Not In Employment
	Retired	28%	27.9%	25.9%
	Other	2%		
Age	18 years old and under	11%	19.3%	22.7%
	19-40years old	24%	17.8%	29.8%
	41-64years old	37%	34.5%	31.2%
	65 years old and over	28%	28.4%	16.3%

2.5.3 Analyses of result from the questionnaire

In the UK, it is necessary for residents need to register themselves for the flood warning direct service. In England the number of properties registered for the flood warning direct service is 1,146,146 properties out of a total of 23,765,650 properties, i.e. 4.8%, according to figures released by the Environment Agency [80] and official statistics of GOV.UK [81]. In Rye the registration rate for this service was 33%. Clearly the level of registration depends on the sense of crisis and flood awareness amongst residents and people who live in a high risk area are more likely to register for a warning service.

In contrast, in Japan the warning is delivered automatically by TV, radio, phones, etc to everyone and there is no need to register for the service. Whether or not they evacuate is of course up to them. There is a difference in the detail of hazard mapping between Japan and the UK. The map details the location of evacuation centers, but not in the UK. There is also a difference in insurance coverage. Flood insurance penetration is higher in the UK than in Japan. In Japan, the national average level of household earthquake insurance coverage before the 2011 Great East Japan Earthquake and Tsunami was 23.7% and the level of water related insurance (including flood risk) was 31.1%. The level of flood insurance amongst people responding to the survey in Rye was 60%. Finally, in terms of planning to evacuate with family members or friends, the rate which people answered yes was lower than expected in Rye.

In Japan, when people discuss natural disasters, people say that casualties occur because evacuation information was not transmitted to residents or because the victims had poor understanding of disaster management. The general view is that local government officers and experts who understand disaster risk should encourage evacuation by transmitting good information [41]. The results of the following question no.3, 5, 6 and 7 are understood when, how and where to evacuate. People in Rye seem to judge that it is dangerous from the flooding situation around the resident area rather than the flooding arrival time. This research expected that people in the UK would have much stronger self-reliance about when to evacuate than do people in Japan. However, 66% of respondents said that they would consider evacuating only when informed by authorities. This was a surprising finding.

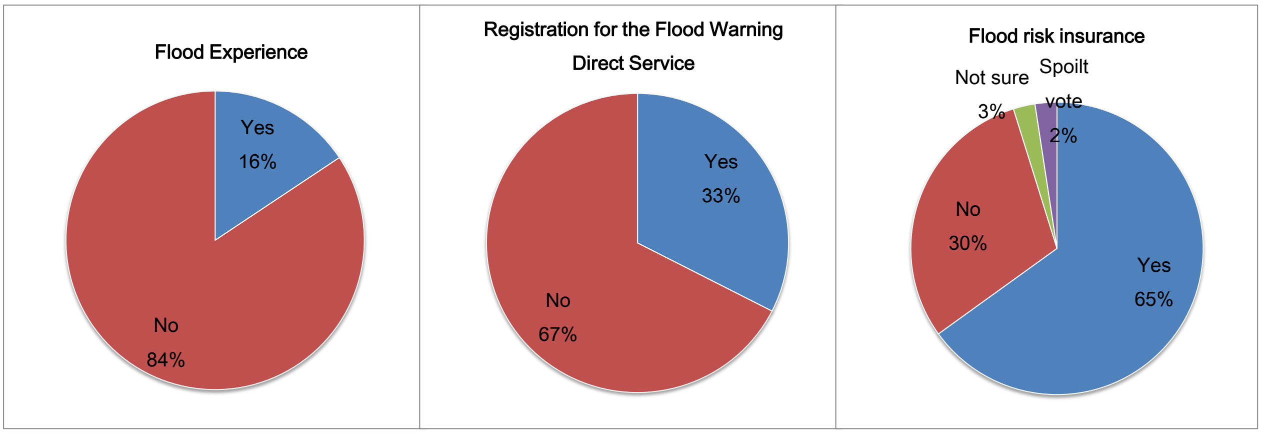


Figure 2.2: Results of Question No. 1, 14 and 16

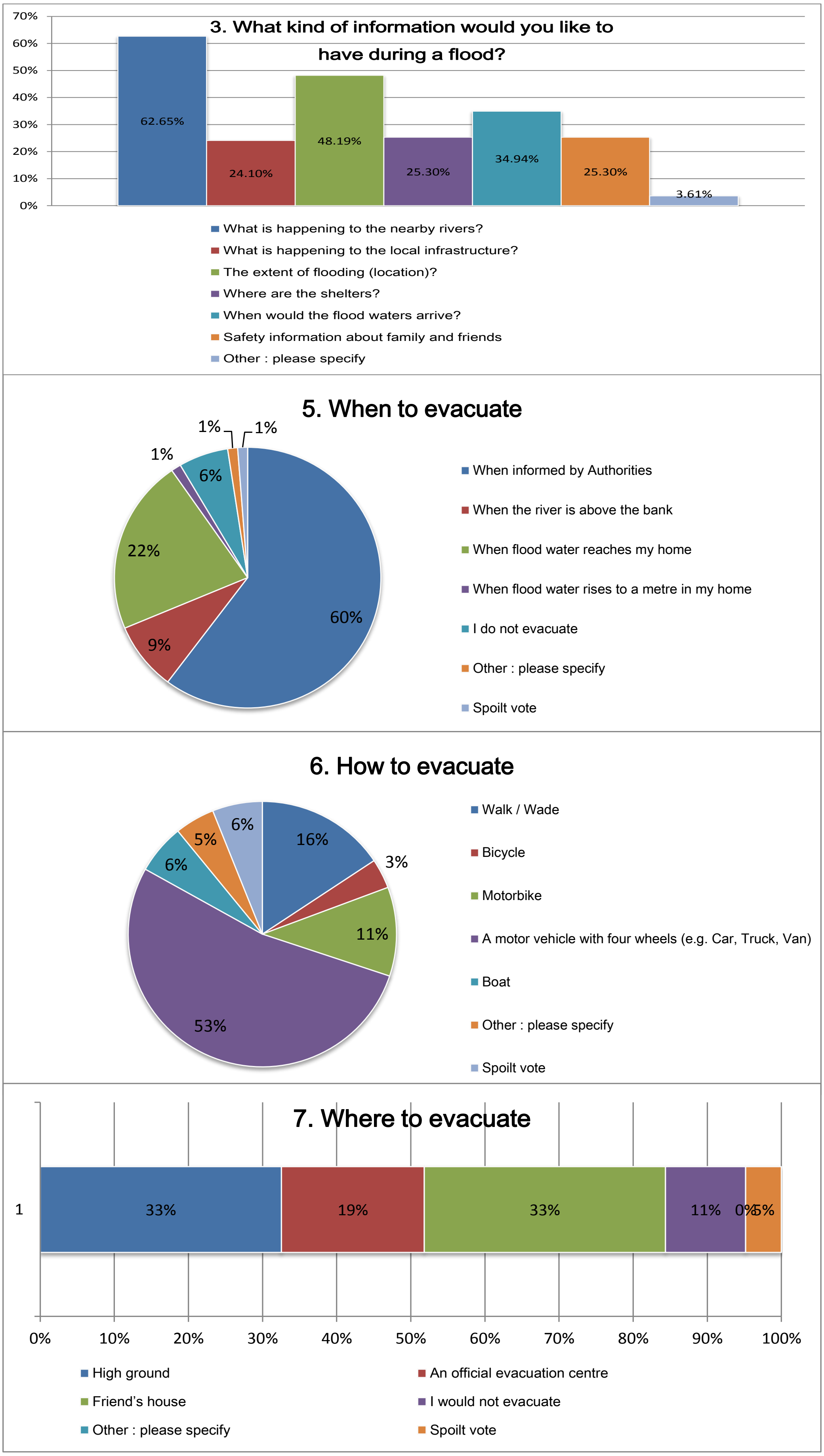


Figure 2.3: Results of Question No. 3, 5, 6 and 7

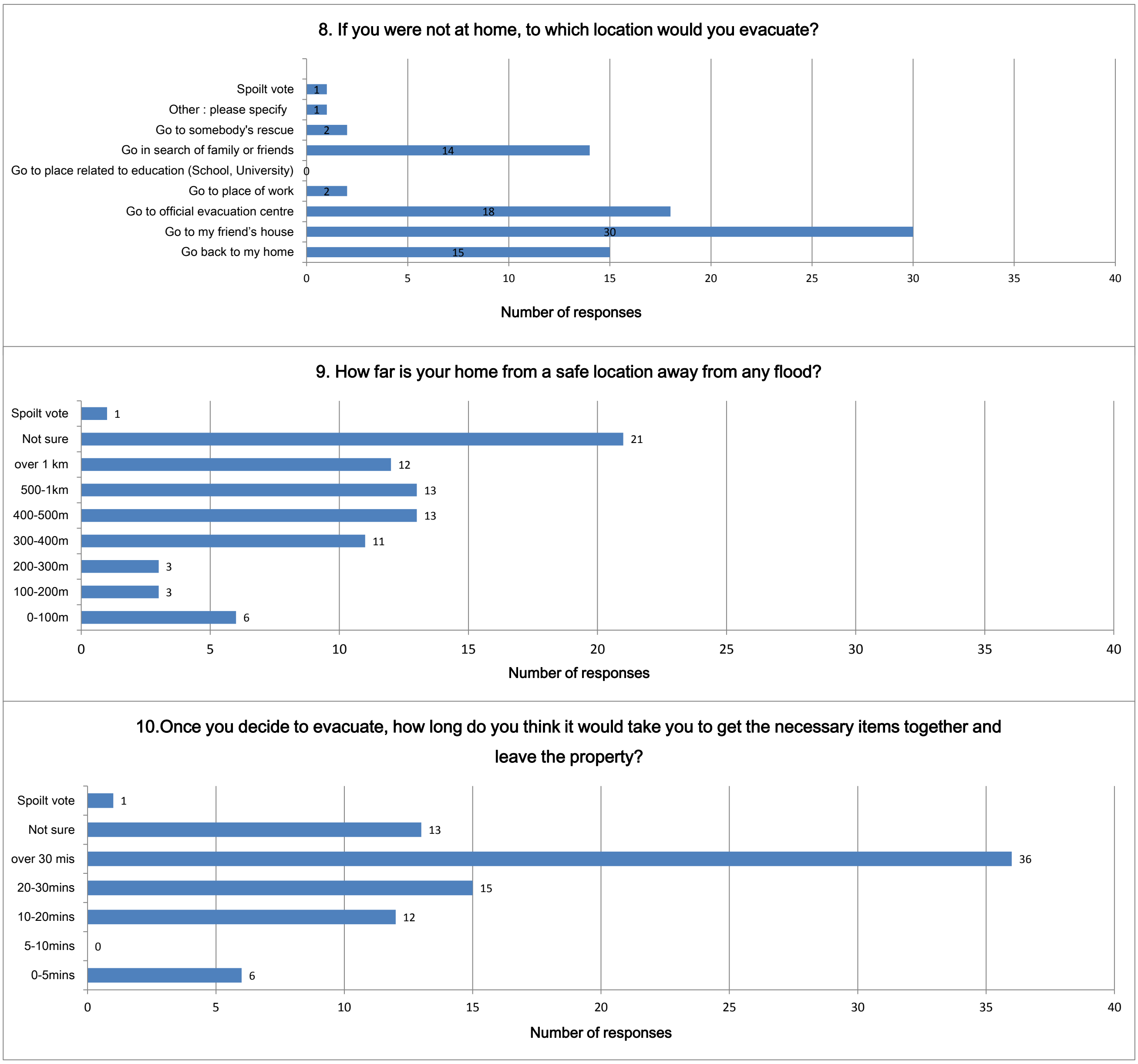


Figure 2.4: Results of Question No. 8, 9 and 10

In addition, 53% of people said they would evacuate by a motor vehicle with four wheels like cars, vans and truck. Surprisingly, one-third of people said that they would escape to high ground and one-third said they would escape to their friend's house. Also, if people were not at home, many people responded that they should evacuate to their friends' houses. Moreover, there was a difference in the British's way of thinking about the word "evacuation" of the question against Japanese. When Japanese hear the word to evacuate, they will be reminded of places to evacuate immediately after the disaster, but it is highly likely that British people consider a place to evacuate in the long term after a disaster, that is, a place to live. Therefore, more people answered that people may evacuate to a friend's house.

Regarding the question of the distance to a safe place, the results tended to be dispersed at a distance of 300 m to 1 km, and the number of people who said that they did not know the distance to a safe place is large. Furthermore, there were quite a few people who said they took more than 30 minutes to evacuate. As for 58% of respondents saying that they are aware of the existence of vulnerable people in their area, it is seemed that the connection of the community is strong. On the other hand, it is seemed to be few people to discuss about evacuation with family members of friends.

Here, the results are compared the case of Japan. Okikawa and Katada [82] state that knowledge acquired in various forms is important for residents to evacuate safely in the case of river floods. Especially, their experience of flooding, tradition, school education and social education are included. According to a questionnaire survey conducted by Okikawa and Katada, the residents who experienced the flood damage have a significantly higher the risk of flood than residents without experience of damage. It also pointed out that there are many residents who do not recognize the danger unless actually inundating is coming near house as a characteristic of residents' consciousness to river flooding the same as the results of the UK. As a conclusion, in terms of human damage, early evacuation behaviors takes a major role in any disaster, no damage will occur if the evacuation behavior is fully achieved. Therefore from the survey in Rye and past research, it can be confirmed that soft countermeasures are important.

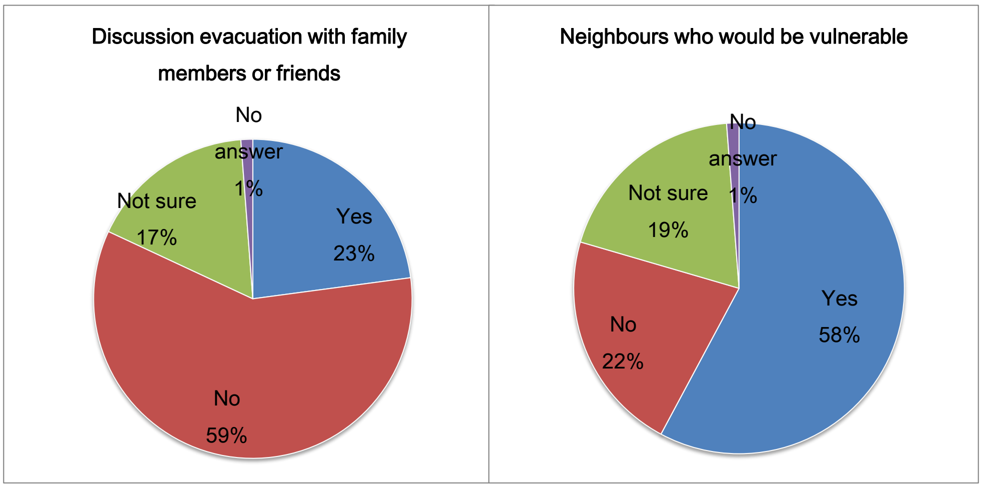


Figure 2.5: Results of Question No. 11 and 12

The results provide new insights for evacuation planning and how to estimate casualties in future events. This questionnaire and previous report have found that awareness of flood evacuation and human behavior are different in Japan and the UK. In addition this section suggests risk perception is not the only important factor for decision-making about evacuation. Social factors, such as government policy on warning systems and hazard maps, insurance penetration, and strength of the local community also impact on the risk perception. Flood casualties can be higher in Japan than in the UK. This is related to the differences in scale, geographical differences and occurrence of flooding disasters. However, this section does not make mention of the topography factors that influence the occurrence and damage of natural disasters. It is necessary, therefore, to consider these factors to build an equation which can estimate casualties against water related disaster [83].

2.6 Summary

First, the GIS is a useful tool for analyzing the disaster damages and the benefits of effectiveness in disaster loss modeling of GIS were explained from the literature. Therefore, this thesis proposes a new fatality model within a GIS. Second, some research found that evacuation characteristics are important factors to evaluate the human damage, but it is not still quantized a value to the prediction method by tsunami disasters. It is necessary to develop a method to quantify the characteristics related to local evacuation. Therefore, a new fatality model takes into account the following three factors: tsunami characteristics, geographical features and demographic components. Third, human behavior is different in Japan and another country. For example, the way of thinking about disaster prevention, information acquisition and insurance penetration are different in Japan and the rest of the world based on the results of Section 2.5. Although there are differences in the disaster in the scale of flood and tsunami disaster, it other national characteristics and disaster prevention measures are also important. Under such circumstances, the disaster analysis requires disaster information, but it is difficult to obtain such data on all areas. However the number of natural disasters is increasing all over the world. Therefore, to create a universal framework for human damage caused by tsunami disasters is important. Hence, it could confirm the necessity of human damage analysis by the tsunami, the importance of the model construction, and the usefulness of the analysis using GIS.

Therefore, this thesis focuses on natural disasters with the aim to predict the number of death. This thesis specializes in tsunamis and considers the risk of tsunami disasters. It is recognized that the risk of fatality caused by the tsunami is affected by human vulnerability and the tsunami exposed population. The population exposed to the tsunami is affected by the following two factors.

- The size of the tsunami itself defined as a hazard, geographical condition, and flood condition as a result of the maintenance situation such as the tide breakwater.
- Human behavior at the time of the tsunami attack, which is the factor of the risk variation.

To reduce the risk of fatalities caused by the tsunami, it is necessary to reduce the exposed population to the tsunami. There are three measures for reducing damages.

- Hard measures such as construction of tide breakwaters and improvement of tsunami warnings
- Reduction in exposed population in the inundated area due to relocation of high grounds
- Reduction of exposed population in inundated area at the time of the tsunami attack by evacuation

* Demographics (exposed population) are used not only as a population but also as a concept that considers age structure and gender as an indicator of individual vulnerability and characteristics.

Therefore this thesis defines exposure, hazard and vulnerability as follows. Figure 2.6 shows the image of human life and tsunami disaster.

- Exposure: The situation of people located in hazard-prone areas
- Hazard: A process, phenomenon of tsunami
- Vulnerability: The conditions determined by tsunami characteristics, geographical features and demographic components to the impacts of hazards

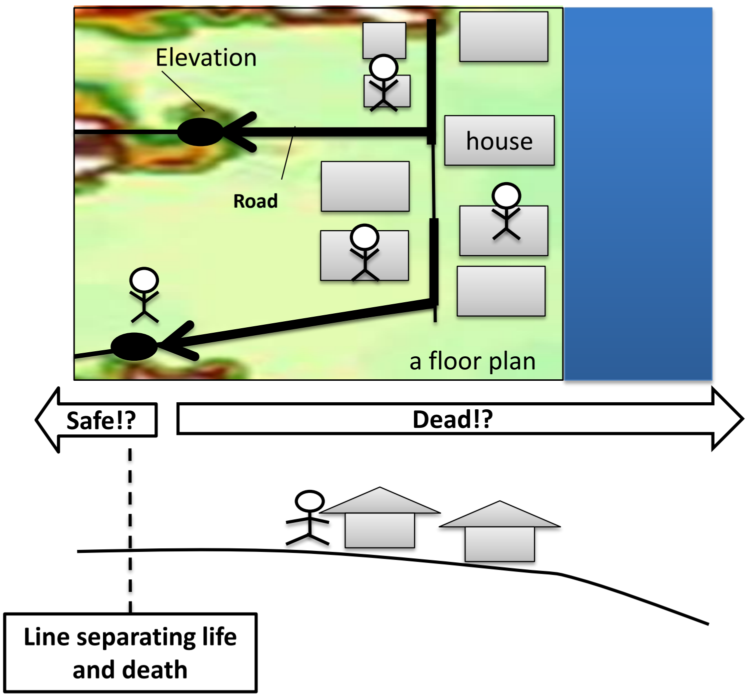


Figure 2.6: Image of human behavior during a tsunami

Based on these literature, this thesis incorporates new explanatory variables based on the equation of the Central Disaster Management Council of Japan shown in Eq. (2.1) [1] and Eq. (2.3) [2] provided by Peduzzi *et al.*, which was one of the components of the report "Reducing Disaster Risk" by the United Nations Development Programme, shows the model of the number of estimated fatalities. New explanatory variables explored/included local features such as distance of evacuation route and elevation trend of the evacuation route in this research. As the first step, the characteristics of distance and elevation trend of evacuation route are analyzed in the case of Fukushima Prefecture and Iwate Prefecture under the 2011 Great East Japan Earthquake. In particular, the distance from the deceased's address to the non-inundated area is calculated and the elevation of each fatality's evacuation route is extracted.

References

[1] Cabinet Office, Government of Japan (2012) "Guidelines for damage prediction and techniques of building and human". Available: http://www.bousai.go.jp/jishin/nankai/taisaku/pdf/2_2.pdf. Last Accessed: 1st March, 2017 (in Japanese)

[2] H. Nobuoka, Y. Nabetani, N. Sumioka, and T. Katano (2013) "Basic Study of Tsunami Risk Map based on Extreme Value Analysis", *Japan Society of Civil Engineers B2*, Vol.69, No.2, pp. 1-1351-1- 1355 (in Japanese)

[3] T. Shimada, H. Muramaki, K. Yasunori, T. Sugimoto and K. Nishikawa (1999) "A Study on Prediction of Human Damage by Tsunami", Proceedings of Coastal Engineering, Vol. 46, pp. 361-365 (in Japanese)

[4] M. Miyano and H. Lu (1992) "Study on human damage at the time of earthquake based on past damage survey data", *Journal of Social Safety Science (2),* pp.127-135 (in Japanese)

[5] Y. Kawata (1997) "Prediction of loss of human lives due to catastrophic earthquake disaster", *Journal of Japan Society for Natural Disaster Science*, Vol.16 (1), pp.3-13 (in Japanese)

[6] N. Shishido and F. Imamura (2009) "Study on the Evacuation Method of Human Loss fir Making Tsunami Risk Map", *Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering)*, Vol. 65 , No. 1, pp.1346-1350 (in Japanese)

[7] T. Sugimoto, H. Murakami, Y. Kozuki and K. Nishikawa (2003) "A Human Damage Prediction Method for tsunami Disasters Incorporating Evacuation Activities", *Natural Hazards* 29, pp. 585-600

[8] K. Imai, F. Imarura, S. Iwama and A. Suppasri (2014) "Tsunami hazard and damage evaluation by using practical method for human casualty and structural damage mitigation" , *Journal of Japan Society for Natural Disaster Science*, pp.1-12 (in Japanese)

[9] A. Suppasri, N. Hasegawa, F. Makinoshima, F. Imamura, P. Latcharote and S. Day (2016) "An analysis of fatality ratios and the factors that affected human fatalities in the 2011 Great East Japan Tsunami", *Front. Built Environ. 2:32*

[10] S. Koshimura, Y. Namwgaya and H. Yanagisawa (2009) "Fragility Functions for Tsunami Damage Estimation", *Journal of Japan Society of Civil Engineers B*, Vol.65, No,4, pp.320-331 (in Japanese)

[11] S. Koshimura,T. Katada, T. Kuswasawa and A. Ishibashi (2003) "Study on evaluation method of evacuation strategy for human damage reduction by tsunami", *Proceedings of Coastal Engineering*, Vol. 50 , pp.1336-1340 (in Japanese)

[12] N. Y. Yun and M. Hamada (2015) "Evacuation Behavior and Fatality Rate during the 2011 Tohoku-Oki Earthquake and Tsunami", *Earthquake Spectra*, Volume 31, No.31, pp.1237-1265

[13] M. Abe and Y. Fujino (2014) "Statistical Analysis on Characteristics of Risk of Natural Disasters", *Journal of Japan Society of Civil Engineers A*, Vol. 64, No. 4, pp. 750-764 (in Japanese)

[14] Disaster Management, Cabinet Office (2010) "Special working group on evacuation in case of disaster Working group on tsunami disaster prevention, Summary of Major Tsunami Damage"
Available: http://www.bousai.go.jp/jishin/tsunami/hinan/1/pdf/2.pdf. Last Accessed: 1st November, 2017 (in Japanese)

[15] National Oceanic and Atmospheric Administration (NOAA), Available: https://www.ngdc.noaa.gov/nndc/struts/results?bt_0=&st_0=&type_8=EXACT&query_8=None+Selected&op_14=eq&v_14=&st_1=&bt_2=&st_2=&bt_1=&bt_10=&st_10=&ge_9=&le_9=&bt_3=&st_3=&type_19=EXACT&query_19=None+Selected&op_17=eq&v_17=&bt_20=&st_20=&bt_13=&st_13=&bt_16=&st_16=&bt_6=&st_6=&ge_21=&le_21=&bt_11=&st_11=&ge_22=&le_22=&d=7&t=101650&s=70. Last Accessed: 1st November, 2017

[16] M. Ushiyama and S. Yokomaku (2012) "Characteristics of human damage", *Japan Society for Disaster Information Studies,* No.10, pp.7-13 (in Japanese)

[17] T. Mizutani (2012) "Emergency Evacuation and Human Losses from the 2011 off the Pacific Coast of Tohoku Earthquake and Tsunami", *National Research Institute for Earth Science and Disaster Resilience*, No. 48, pp.91-104 (in Japanese)

[18] Y. Goto (2014) "Index to Discriminate Tsunami Evacuation Capability of a Community and its Verification in Yamada town, Iwate prefecture", The 14th Earthquake Engineering Symposium Proceedings (in Japanese)

[19] M. Takahashi and N. Matsuta (2015) "What Differentiated Local Casualties Caused by the Tsunami?", *Journal of Geography*, Vol.124(2), pp.193-209 (in Japanese)

[20] S. Suzuki and H. Hayashi (2011) "A Preliminary Critical Causal Analysis on the Mortality Caused by the 2011 East Japan Earthquake Tsunami", *Journal of social safety science / Institute of Social Safety Science,* No.15, pp.179-188 (in Japanese)

[21] M. Ushiyama, M. Honma, S. Yokomaku and K. Sugimura (2014) "Relationship between primary causes ad rate of victim caused by the 2011 off the Pacific coast of Tohoku Earthquake in Sanriku District", J.JSNDS 33-3, pp.233-247 (in Japanese)

[22] F. Takeda, H. Ikeya, S. Ando and N. Hibino (2014) "Research on effective evacuation against the tsunami disaster", *National Graduate Institute for Policy Studies Discussion Paper* 14-05, pp. 1-26 (in Japanese)

[23] N. Sekiya and A. Tanaka (2016) "Evacuation Decision Making Process: Analysis of Questionnaire Survey in Coast of the Japan Sea", *Journal of Japan Society for Natural Disaster Science* , Vol. 35, pp. 91-103 (in Japanese)

[24] T. Nagaie, K. Hokao, K. Kitagawa and T. Inohae (2011) “Location Characteristics of Social Welfare Facilities in Affected Areas of the Great East Japan Earthquake”, *Papers of Research Meeting on Civil Engineering Planning*, Vol 44 (in Japanese)

[25] K. Kambara, A. Kobota, T. Kurose, T. Hagiwara, K. Fukushi and A. Tanaka (2014) “Study on the evacuation behaviors of elderly residents in rural communities during the Great East Japan Earthquake in relation to the built environment”, *Journal of architecture, planning and environmental engineering*, Vol.79, No. 701, pp.1593-1602 (in Japanese)

[26] H. Murakami, M. Takimoto and A. Pomonis (2012) “Tsunami Evacuation Process and Human Loss Distribution in the 2011 Great East Japan Earthquake – A Case Study of Natori City, Miyagi Prefecture-“, The 15th World Conference on Earthquake Engineering

[27] Y. Dohi, Y. Okumura, M. Koyama and J. Kiyono (2016) “Evacuee Generation Model of the 2011 Tohoku Tsunami in Ishinomaki”, *Journal of Earthquake and Tsunami*, Vol. 10, No.2, pp.1-17

[28] M. Yoshino (2013) “Injury to human beings caused by the tsunami of the Great East Japan Earthquake”, *Chikyu Kankyo, Association of International Research Initiatives for Environmental Studies*, Vol.18, No.1, pp. 13-22 (in Japanese)

[29] Y. Ohta and M. Koyama (2015) “Severity of mortality in the 2011 Great East Japan Earthquake: age dependency in comparison with past major earthquakes”, *Journal of Earthquake Engineering*, Vol. 15, No. 2, pp.11-24 (in Japanese)

[30] M. Koyama, Y. Ishii, A. Furukawa, J. Kiyono and A. Yoshimura (2013) “Municipality’s mortality rate according to inundation level and age classes on the 2011 Great East Japan Earthquake”, *Structural Engineering & Earthquake Engineering / Journal of Japan Society of Civil Engineers*, Vol.32, pp.161-170 (in Japanese)

[31] T. Katada, N. Kuwasaku and M. Kanai (2007) “Study of casualty eastimation method due to the tsunami that considers resident’s activities during normal circumstances and during a disaster”, *Journal of Japan Society of Civil Engineers D*, Vol. 63, No.3, pp.275-286 (in Japanese)

[32] Y. Ohta and H. Ohashi (1979) “Field Survey on Human Response during and after a Large Earthquake Part (1)-Collection of Data by Questionnaire Method and its Tentative Analysis”, *Journal of the Seismological Society of Japan*. 2nd ser. Vol. 32, No.4, pp.399-413 (in Japanese)

[33] T. Mizutani (1984) “On the scale of human casualties due to earthquake and tsunami”, *Comprehensive urban studies* , No. 20, pp.15-28 (in Japanese)

[34] EM-DAT website (2017) Available: http://www.emdat.be/. Last Accessed:30th September, 2017

[35] M. Miyano and T. Mochizuki (1988) “The casualty of the 1946 Nankai Earthquake and its Effect Upon Human Behavior”, *Comprehensive urban studies (35)*, pp.75-86 (in Japanese)

[36] T. Isagawa and O. Murao (2010) "RESIDENTS CONSCIOUSNESS AND INTENTION OF TSUNAMI EVACUATION BASED ON SPATIAL DATA ANLYSIS a case study of Onjiku town, Chiba", *J. Archit, Plann.*, AIJ, Vol. 75, No. 648. pp. 395-402 (in Japanese)

[37] F. Yamashita (2005) "Children or the old were the largest in causalities from drowning ― In the cases of Showa Sanriku Tsunami and the tsunami of the Southwest off Hokkaido Earthquake―", *Historical Earthquakes*, Vol. 20, pp.165-167 (in Japanese)

[38] M. Ushiyama, M. Kanata and F. Imamura (2004) "A Study on Mitagation in Human Damage by disaster information for Tsunami disaster." *Journal of Japan Society for Natural Disaster Science*, Vol 23, No. 3, pp.433-442 (in Japanese)

[39] R. Kimura (2008) "Proposal of Efficient Tsunami Evacuation Based on Clarifying Tsunami Cognition –A case study of the Victim's Past Experience of the 1944 Tonankai Earthquake in Japan-", *Historical Earthquakes*, No. 23, pp.131-141 (in Japanese)

[40] S. Mimura (2014) "Research report on landslide and pacific Geopolitics,
Institute of Developing Economies,
Available: htttp://www.ide.go.jp/library/Japanese/Publish/Download/Report/2013/pdf/C32_ch4.pdf, Last Accessed: 1st November, 2017

[41] Y. Okumura, K. Harada and Y. Kawata (2010) "Field Survey of Evacuation Behavior in the 29 September 2009 American Samoa Tsunami Disaster", *Coastal engineering / Japan Society of Civil Engineers B2*, Vol. 66, No.1, pp.1371-1375 (in Japanese)

[42] H. Gokon, S. Koshimura, M. Matsuoka and Y. Namegaya (2011) "Developing Tsunami Fragility Curves Due to the 2009 Tsunami Disaster in American Samoa", *Coastal engineering / Japan Society of Civil Engineers B2*, Vol. 67, No.2, pp.1321-1325 (in Japanese)

[43] M.Marchand, J.Buurman, A.Pridadi and A.Kurniawan, (2009) "Damage and casualties modelling as part of a vulnerability assessment for tsunami hazards: a case study from Ache, Indonesia", *Journal of Flood Risk Management* 2, pp.120-131

[44] Y. Goto, J. Inmami, M. Affan and N. Fadli (2013) "Survey and analysis on the mass evacuation of the people in Band Aceh triggered by the Mw. 8.6 earthquake of April 11. 2011", *Structural Engineering & Earthquake Engineering / Japan Society of Civil Engineers A1*, Vol.69, No.4, pp.182-194

[45] UNDP (2004) "World report, Toward Reduction of Disaster Risk -Issues imposed on development-" Available: http://www.undp.or.jp/publications/pdf/RDR_ES_J.pdf. Last Accessed: 2nd November, 2017 (in Japanese)

[46] UNESCO (2013), "Preparing for Tsunamis in the Mediterranean",

Available: https://www.youtube.com/watch?v=w3hZ79lu6Hw. Last Accessed: 1st November, 2017

[47] UNESCO (2008), "TSUMANI PREPAREDNESS INFORMATION GUIDE FOR DISASRE PLANNRESz2, Available: http://unesdoc.unesco.org/images/0016/001600/160002e.pdf. Last Accessed: 1st November, 2017

[48] V. K. Gusiakov (2005) "Tsunami generation potential of different tsunamigenic regions in the Pacific", Marine Geology, Vol. 215, Issue 1-2, pp. 3–9

[49] P. Peduzzi, H. Dao, C. Herold, and F. Mouto (2009) "Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index", *Nat. Hazards Earth Syst. Sci.*, 9, pp. 1149–1159

[50] N. B. Parwanto and T. Oyama (2014) "A statistical analysis and comparison of historical earthquake and tsunami disasters in Japan and Indonesia, International Journal of Disaster Risk Reduction", *International Journal of Disaster Risk Reduction*, Vol.7, pp.122-141

[51] S. K. Jonkmna, A. Lents and J.K. Vrijling (2010) "A general approach for the estimation of loss of life due to natural and technological disasters", *Reliability Engineering & System Safety*, Vol.95, Issue 11, pp.1123-1133

[52] S. K. Jonkmna, J. K. Vrijling and A. C. W. M. Vrouwenvelder (2008) "Methods for the estimation of life due to floods: a literature review and a proposal for a new method", *Nat Hazards*, 46, pp.353-389

[53] N. Okumura, S. N. Jonkman, M. Esteban, B. Hofland and T. Shibayama (2017) "A method for tsunami risk assessment: a case study for Kamakura, Japan" *Nat Hazards*, 88, pp. 1451-1472

[54] H. Yeh (2014) "Tsunami Hazard and Casualty Estimation Model", Tenth U.S. national Conference on Earthquake Engineering, Frontiers of Earthquake, July 21-25, Anchorage, Alaska

[55] A. Suppasri, F. Imamura and S. Koshimura (2012) "Tsunamigenic Ratio of the Pacific Ocean earthquake and a proposal for tsunami Index", *Nat Hazards Earth Syst. Sci.*, 12, pp.175–185

[56] T. Charnkol and Y. Tanaboriboon (2006) "Evacuee Behaviors and Factors Affecting the Tsunami Trip Generation Model: A case study in Phang-nga, Thailnad", *Journal of Advanced Transportation*, Vol.40, No.30, pp.313-330

[57] A. Pomonis (2010) "The Great Chile Earthquake Sequence of May 21-22, 1960: An Analysis of the Human Casualties By Event, Location and Cause", *Mizutami International Symposium on Earthquake Casualties and Hearth Consequences*, 15-16 November, Mizutani, Gifu, Japan, pp.21-24

[58] N. Dash and H. Gladwin (2007) "Evacuation Decision Making and Behavioral Responses: Individual and Household", *Natural Hazards Review.* 8. 10.1061/(ASCE)1527-6988(2007)8:3(69).

[59] D. Alexander (2012) "Models of Social Vulnerability to Disasters", RCCS Annual Review, 4, pp.22-40

[60] T. Katada, J. Asada and N. Kuwasawa (2000) "Simulation analysis of disseminate of disaster information using GIS", *Journal of Civil Engineering Information Processing System*, Vol. 9 , pp. 49-58 (in

Japanese)

[61] M. Papathoma, D. Dominey-Howes, Y. Zong and D. Smith (2003) “Assessing tsunami vulnerability, an example from Herakleio”, *Crete, Natural Hazards and Earth System Sciences*, 3, pp.377-389

[62] M. Hashemi and A.A. Alesheikh (2011) “A GIS-based earthquake damage assessment and settlement methodology”, *Soil Dynamics and Earthquake Engineering*, Vol. 31, pp. 1607-1617

[63] A. T. Crooks and S. Wise (2013) “GIS and agent-based models for humanitarian assistance”, *Computers, Environment and Urban Systems* 41, pp.100–111

[64] S. J. Scheer, V. Varela and G. Eftychidis (2012) “A generic framework for tsunami evacuation planning”, *Physics and Chemistry of the Earth* 49 , pp.79–91

[65] UNISDR (2017) Terminology, Available: http://www.unisdr.org/we/inform/terminology. Last Accessed: 1st November, 2017

[66] K. Takemura (2006) “Judgment and Decision Making in Risk Society”, Cognitive Studies : bulletin of the Japanese Cognitive Science Society 13(1), pp.17-31 (in Japanese)

[67] S. Nagamatsu, K. Sato, Y. Tanaka and K. Yamamoto (2015) “Research on mid to long term guidance for disaster resistant land use” , New ESRI Working Pater No.34,
Available: http://www.esri.go.jp/jp/archive/new_wp/new_wp040/new_wp034.pdf. (in Japanese)

[68] K. Ueda (2011) “The Role of Soft Control and Social Capital in Disaster Risk Management”, *The journal of social capital studies*, Vol.2, pp.29-48 (in Japanese)

[69] H. Tatano (2003) “Major characteristics of disasters risk and its management strategies”, SOCIOTECHNICA, Vol.1, pp.141-148 (in Japanese)

[70] Y. Matsuoka (2013) “Global efforts on disaster prevention: UNISDR and Hyogo Framework, Discussion on disaster prevention disaster reduction and gender ”
Available: http://www.gender.go.jp/kaigi/senmon/kansi_senmon/wg02/pdf/giji_04.pdf. Last Accessed: 1st September, 2016 (in Japanese)

[71] S. Iwaki (2003) “Natural disasters and emergency response”, Dealing with emergency situations in major countries: Comprehensive survey report, National Diet Library (in Japanese)

[72] A. E. Collins (2013) “Application of the disaster risk reduction approach to mitigation influenced by environmental change”, *Environmental Science & Policy* 27S, pp. S112-S125

[73] National Police Agency (2017) “About the damage of the 2011 Great East Japan Earthquake, No. 156”, Available: http://www.fdma.go.jp/bn/higaihou/pdf/jishin/156.pdf. Last Accessed: 24th October, 2017 (in Japanese)

[74] Japan Meteorological Agency (2016) Earthquakes and Tsunamis -Disaster prevention and mitigation efforts-

[75] S. Yotsui, M. Koyama, A. Furukawa and J. Kiyono (2015) "Mechanism Analysis of Casualty and Evacuation Route in the Case of Fukushima Prefecture", *Journal of Social Safety Science*, No.27 (in Japanese)

[76] The Royal Life Saving Society UK (RLSS UK), Available: http://www.rlss.org.uk/. Last Accessed: 1st September, 2016

[77] Environment Agency (2009) "Rother and Romney Catchment Flood Management Plan Summary Report December 2009", Available:https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/293880/Rother_and_Romney_Catchment_Flood_Management_Plan.pdf. Last Accessed: 1st September, 2016

[78] DATA.GOV.UK, Available: http://environment.data.gov.uk/ds/catalogue/index.jsp#/catalogue. Last Accessed: October, 2015

[79] The office for National Statistics, Available: http://www.neighbourhood.statistics.gov.uk/dissemination/ Last Accessed: 1st September, 2016

[80] Parliament UK (2016), Available:http://www.parliament.uk/business/publications/written-questions-answers-statements/written-question/Commons/2016-03-07/30058/1. Last Accessed: 1st September, 2016

[81] GOV.UK (2016) "Council Tax: Stock of properties 2016", Available: https://www.gov.uk/government/statistics/council-tax-stock-of-properties-2016. Last Accessed: 27th September, 2016

[82] Y. Okikawa and T. Katada (1999) "A study on the Effect of Flood Experience on the Evacuation Activity", *Journal of Japan Society for Natural Disaster Science* 18-1, pp.103-118 (in Japanese)

[83] S. Yotsui, M. Koyama, E. So, S. Platt and J. Kiyono (2016) "Comparing Human Behaviour in Japan and the UK during Natural Disasters", 4th International Conference on Urban Disaster Reduction Sustainable Disaster Recovery, New Zealand, October 17-20.

Chapter 3

Analyses of factors causing fatality in tsunamis

Fatality is one of the indexes that society uses to evaluate the risk of natural disaster. To calculate the number of deaths, an equation that can take into account the characteristics of the region is needed. Analyzing the damage caused by natural disasters is important to develop models that could predict fatalities under different scenarios. This section analyzes factors causing fatality in tsunamis.

A Mw 9.0 earthquake hit off the coast of Tohoku in north east Japan at 14:46 (Japan Standard Time) on March 11, 2011. This earthquake, called the 2011 Great East Japan Earthquake and Tsunami, triggered tsunami waves that caused major damage to the country (Figure 3.1). The National Police Agency [1] confirmed 16,278 deaths, of which 92.4% were drowning, and 2,994 missing people (as of April 11, 2011). They also confirmed that 129,198 houses were destroyed (as of March 11, 2012). The MLIT [2] revealed that about 78,000 houses (60% of those destroyed) were washed away by the tsunami (as of August 4, 2012). Figure 3.2 shows the death estimates in the most affected areas (Iwate, Miyagi and Fukushima Prefectures). It can be seen that the fatality rate in Miyagi Prefecture was higher than the other two prefectures. Also, the death count of elderly people was higher than any other age group in the three prefectures.

Figure 3.1: Location of affected area (Fukushima, Miyagi and Iwate Prefectures)

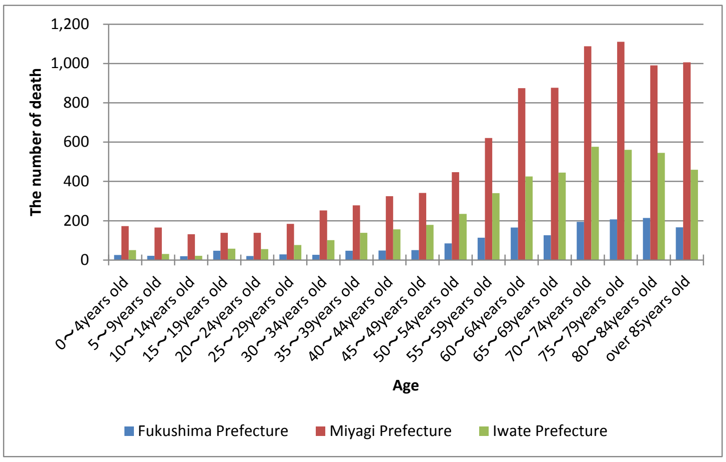


Figure 3.2: Total number of deaths in each affected prefectures

According to a report by Nagoya University [3], deaths from tsunami disasters occur when buildings are washed away, and the fatality rate increases when the inundation of houses is over 3 m from the viewpoint of house damage by the tsunami events. Moreover, Aoki [4] found that the proportion of death increased when the flood depth exceeded 4 m. The height from the floor to the second floor of a general wooden house is approximately 3.5 m. Since this inundation depth corresponds to the height at which the first-floor portion of two-storied building is submerged, there is a high possibility that death can be avoided by evacuating to the second floor. Aoki's study suggested a situation where the likelihood of death increases if flooding exceeds the height of the second floor. Against this background, this thesis succinctly organizes the direct damage situation caused by tsunamis. If the residential area is outside the inundated area when a tsunami occurs, it is considered that the house will be safe and not face inundation. On the other hand, if the residential area is within the inundated area, it will be inundated or washed away. Regarding human damage due to tsunami, there are three causes of fatality as shown in Figure 3.3: (1) the case of people staying in the residential area in the inundated area when a tsunami occurs; (2) the case of people entering the inundated area due to daily behavior, regardless of whether their residence is in that area or not when a tsunami occurs; (3) the case of people in the inundated area when a tsunami occurs, such as rescue activities, regardless of whether their residence is in that area or not. Hence, the occurrence of fatalities due to tsunami depends on the exposed population.

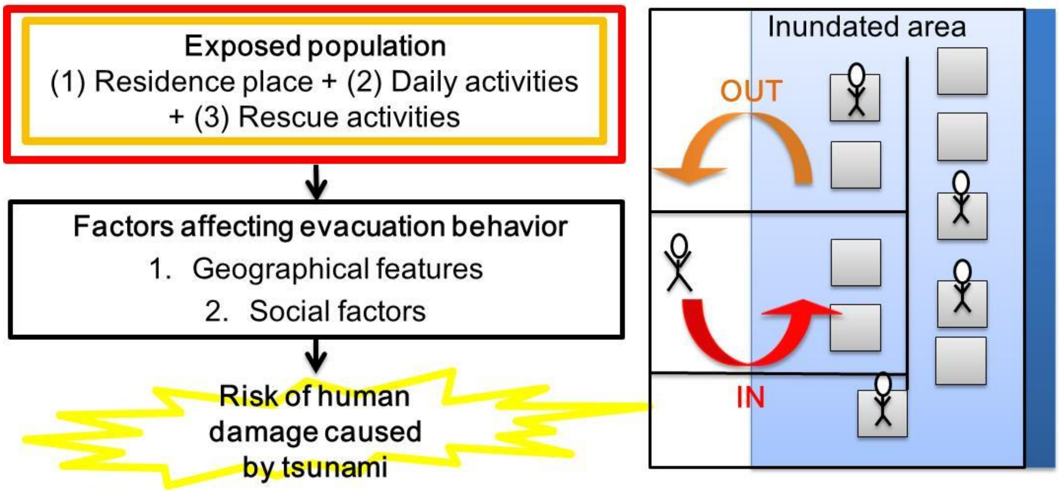


Figure 3.3: Outline of the direct damage situation caused by the tsunami

In addition, geographical features and social factors can be considered as factors affecting evacuation behavior. These factors in this thesis are described below.

1. **Geographical features:** The inundation condition varies depending on characteristics such as plain or rias topography, as well as elevation. Here, it is considered that not only the topography and altitude of the residential area but also the route from each location to the non-inundated area also affect human damage.

   In terms of the relationship between altitude and fatality, Yotsui *et al.*'s analysis [5] found differences in the probability of fatality in Fukushima Prefecture varied with terrain. We found high fatality in areas of flat topography, and lower fatality if the elevation distribution was steep. Using the distribution of inundated buildings and the deceased's address, this paper analyzed the distance to the non-flooded area. There were deaths in spite of a short evacuation distance.

2. Social factors: As a social factor affecting the population exposed to the tsunami, there are hazard maps, the location of schools, welfare facilities, and evacuation shelters which are considered as week points for natural disasters, stories of earthquake experience, knowledge of disasters, age, gender, family and the role of society.

Yun and Hamada [6] analyzed the factors affecting the causes of death in the 2011 Great East Japan Earthquake and Tsunami, and pointed out that age have a significant influence as well as evacuation start times. Moreover, for example, 74 children (70% of the total 108 school children deaths from the disaster) died at Okawa Elementary School in Ishinomaki City, Miyagi Prefecture. The school was not supposed to be located within the inundated area, based on an assumption of likely damage before the 2011 Great East Japan Earthquake and Tsunami. According to a report of Okawa Elementary School Accident Verification Committee [7], the school's risk management manual at the time of the earthquake (tsunami) did not include a description of evacuation routes and methods. It only described the second evacuation place as the nearest park or vacant space if the schoolyard (the first evacuation site) came close to the danger. There was no description of a definite evacuation site of route. Furthermore, it was stated that school staff at the time may not have been familiar with the situation of the area around the school, such as geographical features, the disaster history of the area, the social environment, etc.

Therefore, based on the above factors, the risk of human damage caused by a tsunami is increased. This thesis restates the occurrence of fatalities due to tsunami depends on the exposed population and environment surrounding human society. This thesis proposes a new fatality model within a geographic information system (GIS). To estimate the number of deaths caused by a tsunami event, this thesis utilizes a fatality model that takes into account the following three factors: tsunami characteristics, geographical features, and demographic components. New explanatory variables are developed based on an analysis of the 2011 Great East Japan Earthquake and Tsunami and the 2004 Indian Ocean Tsunami. These explanatory variables indicate local features, such as the distance and elevation trend of evacuation routes. Additionally, social factors such as age and gender, which affect evacuation decision-making, are considered. The new fatality model is outlined in Figure 3.4 [8].

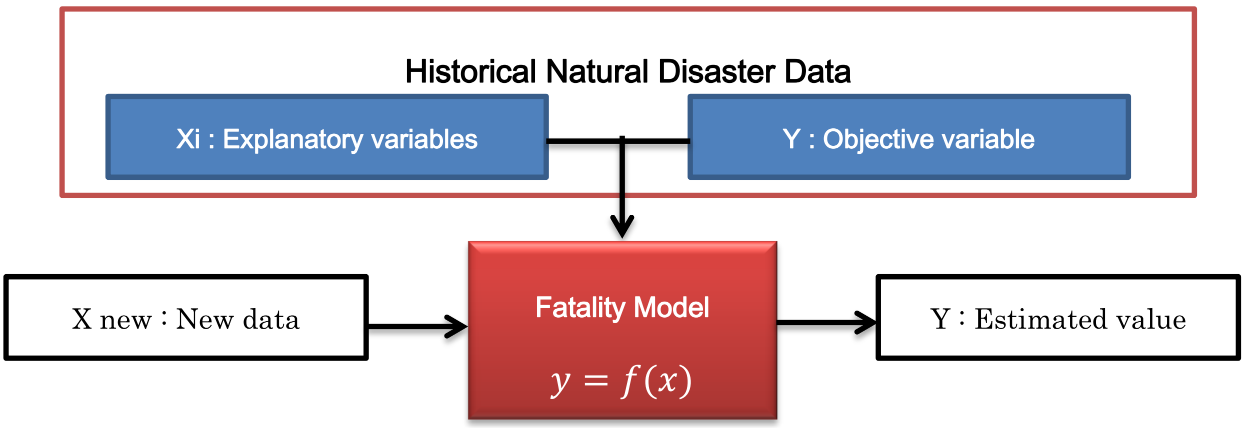


Figure 3.4: Image of new fatality equation （*Reference: Kaneko 2013*）

3.1 Analytical tool and use of data

The following section discusses this thesis's analytical tool and use of data. This methods use ArcGIS10.3 (ESRI) [9] for the spatial analysis in order to analyze the cause of human damage and uses ArcGIS Network Analyst for the analysis on evacuation route. The GIS is a comprehensive system for collecting, organizing, managing, analyzing, communicating and distributing geographic information. Furthermore, it is possible to superimpose various kinds of information and visualize information considering positional relations. Analyzing the mechanism of human damage and developing a fatality model greatly depends on the quality and quantity of data. Moreover, the contents and precision of the analysis are examined carefully. From the viewpoint of data quality, it is desirable to utilize detailed data provided by disaster affected municipality, but in reality, it is difficult to obtain such data on all areas. Hence, this method used publicly released data as much as possible, so that a similar analysis can be done for future disasters. However, it is conceivable that more detailed information will become analyzed and the data will be updated as time passes after a disaster. Therefore, it is also necessary to proceed with the analysis while checking for the updated data. Additionally, regarding similar analyses overseas, it is difficult to imagine that detailed data will always exist, like in Japan. We need to use open license programs such as Open Street Map [10] which is a project aimed at creating free geographical information data. In the future, when constructing a human damage model, it will be necessary to construct one that can be evaluated by applying published information without requiring additional information. Ease of use and quality are required for any model of a disaster.

This thesis analyzes on the basis of data that have been published on website to date. Using datasets are as follows:

1. 2010 Population Census of Fukushima Prefecture, Iwate Prefecture and Miyagi Prefecture [11]
   Census is the most important statistical survey of the country to be carried out for the purpose to clarify the actual situation of the population and households. It is conducted every five years of all people and households living in Japan. Population in this census is a permanent population, which are residents in the area of interest at the time of investigation. This is equivalent to the nighttime population. This data is obtained by aggregating the 5 age groups across different population based on 1/2 area mesh units of the standard area meshes. One grid is 500 m grid square.
   (http://www.stat.go.jp/data/kokusei/2010/)

2. Necrology by Fukushima prefectural police by the end of March, 2012
   This information was provided by Fukushima prefecture police on website by the end of March, 2012. This is included fatality's name, address. Therefore, it is possible to analyze geographical factor based on the the deceased's address. Necrology is based on the address of the person who used to live, hence note that it is not the location of person who died. Normally, we should analyze the location that person was in at the event of tsunami, where person was caught up in the tsunami and how to evacuate to safe place in order to explain human damage caused by the tsunami. However, this thesis

analyzed based on the deceased's home address.

3. Necrology by Iwate and Miyagi prefectural police by the end of March, 2012

This information was provided by Iwate and Miyagi prefectural police on website by the end of March, 2012 same as Fukushima prefectural police. However, the data of these two prefectural police are included victim's name, address which was recorded only municipalities' name. Although it is difficult to analyze geographical factors, statistical analysis is possible.

4. Necrology of Iwate prefecture by Iwate Nippo Co Ltd.(*Iwate Nippo sya* in Japanese)

Iwate Nippo Co Ltd. is a newspaper publishing company. This is interview data on the circumstances of the fatalities in Iwate Prefecture. This is a distribution / collection by mailing during November 1, 2015 to January 31, 2016. If there are people who are difficult to enter the answers by themselves in 80-90 years, the reporters visited their house. The target areas are Noda Village, Tanohata Village, Miyako City, Yamada Town, Otsuchi Town, Kamaishi City, Ofunato City and Rikuzentakata City. They had contacted all fatalities' families of the necrology database (about 2,400 people) by Iwate Nippo by telephone and sending a survey form only to those who agreed with it. The response rate was about 30% of the database. The data items are the data of 1,331 people who were located at the time of the earthquake, where they were at the time of the tsunami and gender. In addition to the above, there are statements about ages, facility names, behaviors after the earthquake, but there are also blanks.

The data of the interview of Iwate Nippo and necrology (unpublished as of February 24, 2017) that Iwate prefectural police had published on the website were compared. The interview data shows the proportion of the municipality's death in the whole in Table 3.1.

Table3.1: Number of interview

	Death toll by interviews	Necrology by Iwate prefectural police	Rate (%)
Noda Village	4	27	14.8
Tanohata Village	7	24	29.2
Miyako City	109	417	26.1
Yamada Town	175	585	29.9
Otsuchi Town	305	757	40.3
Kamaishi City	221	790	28.0
Ofunato City	127	346	36.7
RikuzentakataCity	383	1,473	26.0
Total	1,331	4,419	30.1

Source: Necrology of Iwate prefecture by Iwate Nippo Co Ltd. (*Iwate Nippo sya* in Japanese) and necrology by Iwate prefectural police

5. Inundated area map by the MLIT [12]

The MLIT has been created by the Ministry of Land, Infrastructure and Transport city station. Inundation are has been created based on the local confirmation in reference to the aerial photograph after the tsunami and a view of inundated area by Geospatial Information Authority of Japan. (http://fukkou.csis.u-tokyo.ac.jp/dataset/show/id/1110)

6. Inundated area 5 m mesh by Reconstruction Support Survey Archive [13]

The Urban Bureau of the MLIT conducted field confirmation based on the tsunami inundation map of the Geographical Survey Institute and aerial photographs after the disaster. They have posted data on the area which the tsunami reached in the reconstruction support survey archive.

7. Inundated building polygon provided by the MLIT [14]

This is building polygon data associated with the damage category as a result of investigation of damage on buildings in the inundated area. However, due to the accident at the Fukushima nuclear power plant, the data is not included in Namie Town, Futaba Town, Okuma Town, Tomioka Town and Hirono Town where almost all of the inundated area was designated as an evacuation zone. Therefore, the areas affected by the afflicted buildings in the coastal area of Fukushima Prefecture are only Shinchi Town, Soma City, Minamisoma City and Iwaki City.
(http://www.mlit.go.jp/common/000162412.pdf)

8. Road center line from Land, Infrastructure and basic information [15]

The positional accuracy of the map is scale size 1: 2,500 or equivalent in the urban and scale 1: 25,000 or equivalent in another region. Road centerline is provided as polylines data. This thesis was utilized to convert to network data by ArcGIS Network Analyst.
(http://www.gsi.go.jp/kibanjoho/kibanjoho40027.html)

9. Base information by Geospatial Information Authority of Japan [16]

This thesis used the data of the water line, outer circumference of the building, boundary line of city, town and village.

10. The foundation map – information digital-elevation model 10 m – by the Geospatial Information Authority of Japan [17]

It was created by the Geographical Survey Institute as a basic survey and was created by interpolation of the altitude of the center point of about 10 m mesh from the contour of 1/5000 and /10000 of basic map. (http://fgd.gsi.go.jp/download/menu.php#)

11. Point data of welfare facilities and school by National Land Numerical Information download service（http://nlftp.mlit.go.jp/ksj/）[18]

12. Washed away areas by Tsunami Damage Mapping Team, Association of Japanese Geographers [19]

Tsunami damage area maps with scale of 1:25,000 were made by interpretation of the aerial photographs taken just after the earthquake by Geospatial Information Authority of Japan. Washed away polygon is based on the area where the tsunami has reached the residential area, but the area where the house is not located like paddy field is not included in this data.
(http://danso.env.nagoya-u.ac.jp/20110311/map/)

3.2 Case study area

Detailed information on the fatality is needed to analyze factors causing fatality by the tsunami. For example, where people died, how people evacuated, when the tsunami occurred and so on. Therefore, in the 2011 Great East Japan Earthquake and Tsunami, this section analyzes factors causing fatality in municipalities that can grasp the deceased's address in detail. In addition, social factors such as age and gender, which affect evacuation decision-making, should be analyzed. In designing countermeasures for tsunamis, it is important to understand the geographical characteristics of the damaged locations in detail for the 2011 Great East Japan Earthquake and Tsunami. Moreover, natural disasters reflect strong regional characteristics and a fatality model constructed in a certain region is not necessarily directly applicable to other regions. Besides, each country faces different natural disasters, each country has different disaster prevention plans, and there are differences in culture, risk perception, and human behavior. Therefore, we need new globally applicable criteria for a fatality model that can estimate the number of death from future tsunami event through analyses of factors causing fatality in tsunamis.

In the following section, an overview of the analysis conducted on three prefectures is presented (see Section 3.3.1). Then, the analysis conducted on Fukushima Prefecture and Iwate Prefecture is covered in detail (see Section 3.3.2, Section 3.3.3, Section 3.3.4 and Section 3.3.5). In this thesis, characteristics of the distance and elevation trend of evacuation route are analyzed focusing on Fukushima and Iwate Prefectures in Japan where the deceased's address can be obtained in detail. Using the deceased's address by tsunami and the distribution of buildings within the inundated area, the distance of the route from the inundated area to the non-inundated area is analyzed. Figure 3.5 shows the location of case study. In particular, the target areas are Shinchi Machi, Soma Shi, Minami soma Shi and Iwaki Shi in Fukushima Prefecture and Noda Mura, Tanohata Mura, Miyako Shi, Yamada Machi, Otsuchi Cho, Kamaishi Shi, Ofunato Shi and Rikuzentakata Shi in Iwate Prefecture shown in Figure 3.5. "Shi" in Japanese means city in English, which is a place with a population of more than 50,000 people, "Mura" in Japanese means village in English and "Machi" in Japanese means town in English [20]. It was prepared based on the data of each prefectural police until by the end of February 2012. Fatality within the inundated area could not be accurately determined, except Fukushima Prefecture where detailed the deceased's address were recorded. The number of deaths and the fatality rate in inundated area are as follows to grasp the outline of the damage of the 2011 Great East Japan Earthquake and Tsunami shown in Table3.2 (1), Table3.2 (2) and Table3.2 (3).

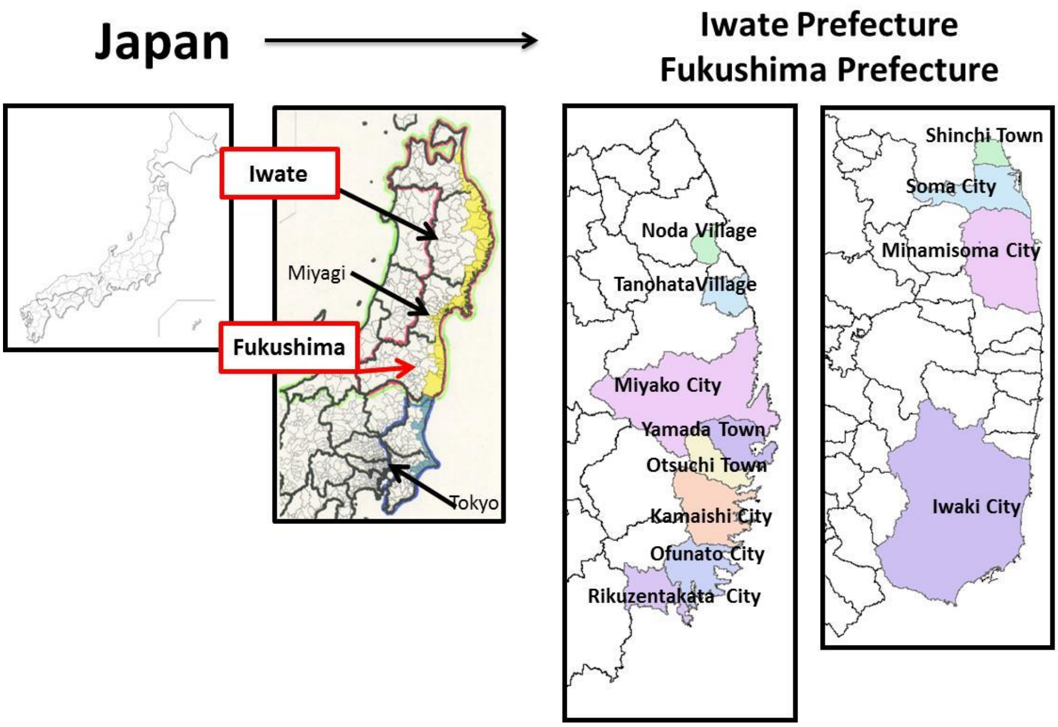


Figure 3.5: Location of the case study area in Iwate and Fukushima Prefectures

Table3.2 (1): Number of deaths in inundated area and death rate in Iwate Prefecture based on this thesis

Name	Number of death in inundated area	Population in inundated area	Death rate in inundated area (%)
Iwate Prefecture			
Miyako City	417	21,030	1.98
Ofunato City	346	23,972	1.44
Kuji City	4	9,404	0.04
Rikuzentakata City	1,473	17,417	8.46
Kamaishi City	790	15,859	4.98
Otsuchi Town	757	12,622	6.00
Yamada Town	585	12,956	4.52
Iwaizumi Town	9	872	1.03
Tanohata Village	24	1,069	2.25
Fudai Village	8	654	1.22
Noda Village	27	3,036	0.89

Table3.2 (2): Number of deaths in inundated area and death rate in Miyagi Prefecture based on this thesis

Name	Number of death in inundated area	Number of death in inundated area	Death rate in inundated area (%)
Miyagi Prefecture			
Sendai City, Miyagino	286	18,525	1.54
Sendai City, Wakabayashi	319	8,648	3.69
Sendai City, Taihaku	57	693	8.23
Ishinomaki City	3,127	121,754	2.57
Shiogama City	48	23,647	0.20
Kesennuma City	951	46,143	2.06
Natori City	873	14,492	6.02
Tagajo City	112	29,834	0.38
Iwanuma City	151	7,706	1.96
Higashimatsushima City	1,023	35,642	2.87
Watari Town	285	14,214	2.01
Yamamoto Town	601	9,998	6.01
Matsushima Town	14	3,689	0.38
Shichigahama Town	89	18,034	0.49
Rifu Town	10	601	1.66
Onagawa Town	511	9,315	5.49
Minamisanriku Town	538	14,598	3.69

Table3.2 (3): Number of deaths in inundated area and death rate in Fukushima Prefecture based on this thesis

Name	Number of death in inundated area	Population in inundated area	Death rate in inundated area (%)
Fukushima Prefecture			
Iwaki City	293	48,024	0.61
Soma City	434	12,154	3.57
Minamisoma City	534	11,800	4.53
Hirono Town	2	1,985	0.10
Naraha Town	149	2,250	6.62
Tomioka Town	18	1,592	1.13
Okuma Town	11	431	2.55
Futaba Town	15	914	1.64
Namie Town	149	2,250	6.62
Shinchi Town	101	3,550	2.85

3.3 Relationship between human damage, geographical features and tsunami characteristics

According to a report by the Cabinet Office [21], human damage will likely be caused by a tsunami disaster caused by a Nankai Trough Earthquake in the near future. Currently at the Cabinet Office, the focus is on evacuation behavior, the completion of evacuation before the arrival time of the tsunami and the degree of death related to the tsunami. A formula for estimating the fatality number, taking age into consideration, is presented in the report, but it does not provide a comprehensive evaluation of both the hard and soft measures. Alongside the model input parameters of human damage has not been determined yet as this thesis mentioned in Chapter 2 (Table 2.4). Although it is difficult to decide which evaluation method is correct against the social background relating to such models, we should be clear that the influence of the parameters is large as shown in Chapter 3. Moreover, if standardization of the evaluation method becomes possible in human damage assessments for tsunami disasters, surveys could be conducted in accordance with the standard in each place, allowing mutual comparison of the damage between regions under the same conditions [22]. Therefore, in this thesis, in order to standardize the human damage assessment method, an index is analyzed with a focus on human behavior, which is thought to have a significant influence on evacuation behavior. First, this thesis considered the relationship between the fatality rates and geographical features of areas damaged in the 2011 Great East Japan Earthquake and Tsunami. Then, a fatality model was built in Chapter 4.

3.3.1 Fatality rate

This section discusses the fatality rate of the 2011 Great East Japan Earthquake and Tsunami. The target areas are Iwate, Miyagi, and Fukushima Prefectures. These methods used the proportional division technique to calculate the populations in the inundated and washed away areas. A notable characteristic of this analysis is that the populations within the inundated and the washed away area were calculated and the respective fatality ratios were analyzed (Figure 3.6).

(1) Methods

The collected data were distributed according to the proportion of the areas, and the fatality rates in the three affected prefectures' municipalities were calculated. The number of deaths by municipality and age group is based on information used to establish victims' safety released by the Iwate prefectural police, the Miyagi Prefectural Police, and the Fukushima Prefectural Police. This method calculated populations by age group in inundated and washed away areas within GIS based on tsunami damage maps and 500 m grid statistics from the 2010 population census, which covered inundated areas located in each municipality. This method assumed that individuals died in inundated areas, as a majority of the deaths were due to drowning (Table 3.2(1), (2) and (3)).

(2) Results

The number of deaths came from safety confirmation information released by the Japanese police. Figure 3.7, Figure 3.8 and Figure 3.9 show age-specific fatality rates by municipality and age group in the three prefectures based on the night-time populations in inundated and washed away areas. Figure 3.7, Figure 3.8 and Figure 3.9, it should be noted that the maximum value shown on the vertical axis is 40%. However, in the highlighted graphs (surrounded by thick borders), the maximum value depends on the individual result. As the age rises, there is a common tendency for the fatality rate to increase, although the degree of increase differs. The figure also shows that fatality rate for over-65 age group is the highest. However, some municipalities with high child fatality rates, such as Okuma Town and Taihaku Ward in Sendai City, can also be seen.

(3) Discussions

The fatality rates in washed away areas were found to be higher than in inundated areas. This inundation situation was affected the overall fatality rate. On the other hand, there were regions where the death rate in the inundation zone and that in the lost region are not very different. This difference occurs because some flooded areas cover all of the lost area, while some only cover part of it. In other words, a region where the inundation region and the runoff region almost overlap was located along a rias coast, while an area where the flooded area is wide has a plain area.

In addition, the number of people out of the entire city population who lived in the inundated area was examined. Areas where more than 50% of the people lived in the inundated zone included Ofunato City, Rikuzentakata City, Otsuchi Town, Yamada Town and Noda Village in Iwate Prefecture, Ishinomaki City, Kesennuma City, Higashimatsushima City, Shichigahama Town, Onagawa Town and Minamisanriku Town in Miyagi Prefecture. On the other hand, in cities in the coastal areas of Fukushima Prefecture, this number was below 50%. However, even in these cities, there were variations in fatality. This may be due to problems of topography, as well as the abovementioned factors. The cities are concentrated in the plains or along narrow coasts (rias coastlines), plains spread along the coast of Fukushima and Miyagi Prefectures, and fields are widely distributed in Iwate Prefecture. The fatality rates in Sendai City, Ishinomaki City, Kesennuma City, Higashimatsushima City and Natori City, which are plain areas, were higher than the rias areas of Rikuzentakata City and Ofunato City.

Furthermore, in terms of topographical features, the increase in the fatality rate due to the rise in age is remarkable in the plains. Fatality rates in places with rias coastal areas (e.g., Rikuzentakata City and Ofunato City) were higher in all ages than in plains areas like Sendai City. As a general trend in fatality, the death rates in the plains tended to be higher than along the rias coasts. In the plains, since the distance from residential areas to high ground is significant, the time from the start of evacuation to the completion of evacuation is longer than in the case of rias coast terrains. Therefore, it is thought that the fatality rates rise because older people have difficulty evacuating quickly. Moreover, Koyama *et al.* [23] analyzed the situation of deaths occurring in Iwate, Miyagi and Fukushima Prefectures, which were the major affected areas in the

2011 Great East Japan Earthquake and Tsunami. Using 2005 census data to estimate gender and age class fatality by municipalities, it was found that the fatality rate for people aged over 60 was the same as that for any other age, according to comparison between the census and the age distribution of the deaths. It is speculated that the staying home rate for over 60 year olds was equal to or higher than the housewife from the staying home rate (60% or more) of the full-time housewife around the 2 p.m. on weekday according to the 2007 White Paper on National Life.

By comparing the above results, this section found that the fatality rates increased along with age; however, some municipalities had high child fatality rates. To explore the cause of high fatality in elderly people and children, the location and number of related facilities were examined. Information on kindergartens, elementary school, nurseries, and welfare facilities in washed away areas was collected from the National Land Numerical Information [18]. The elementary school and welfare facilities in the washed away area were calculated using GIS. Students in schools and universities reported 617 deaths and 231 injured by Ministry of Education, Culture, Sports, Science and Technology (MEXT) [24]. In case of school property damage, around 12,000 facilities in social education, physical education, and cultural facilities were damaged in 24 prefectures. In particular, the Okawa Elementary school in Ishinomaki City, Miyagi Prefecture, reported 74 deaths (and still has missing people), which corresponds to 70% of the total 108 school children deaths from the disaster. Okawa Elementary School was never marked as a potential flooding area on the disaster prevention map at the time of the disaster. According to the analysis, Iwate Prefecture had 23 educational facilities and 28 welfare facilities in the inundated area. Rikuzentakata City had a high fatality rate for elderly people, possibly because its three welfare facilities were washed away. Kamaishi City contained six welfare facilities. Comparatively, Miyagi Prefecture had 47 welfare facilities and nine elementary schools in the washed away area. Fukushima Prefecture had two welfare facilities and one primary school in the washed away area. It can be seen that Miyagi Prefecture contained the highest number of welfare facilities.

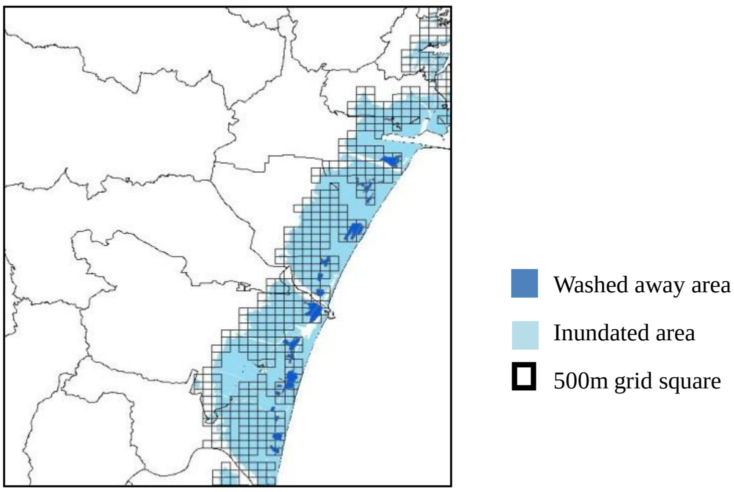


Figure 3.6: Example of the geographical relationship that exists between the inundated, washed away areas and the 500m grid statistics

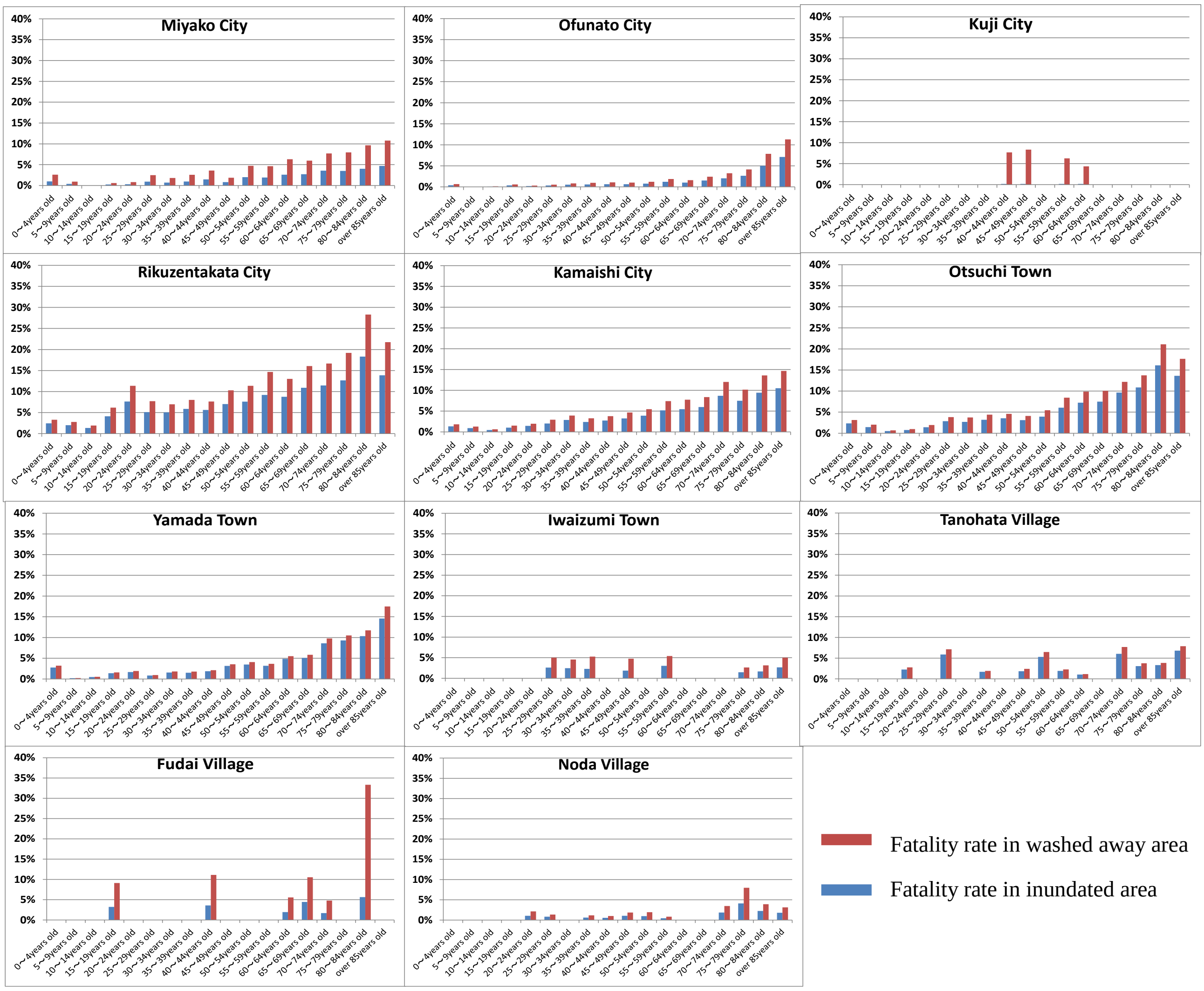


Figure 3.7: Fatality rates by municipality and age groups in Iwate Prefecture based on night time population in inundated and washed away areas

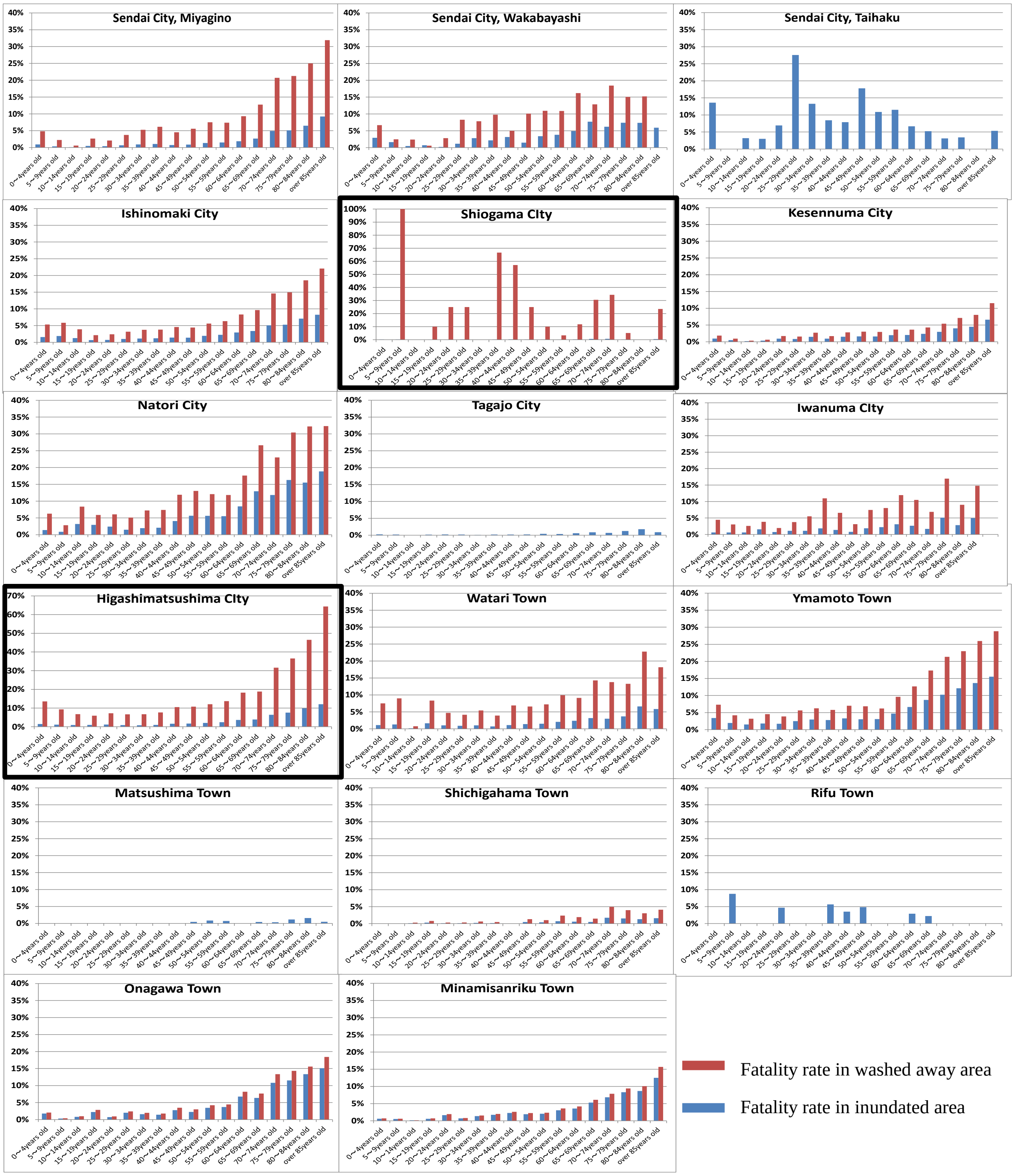


Figure 3.8: Fatality rates by municipality and age groups in Miyagi Prefecture based on night time population in inundated and washed away areas (The maximum value is shown on the vertical axis in 40 %. However, in graphs with thick borders, the maximum value depends on each result.)

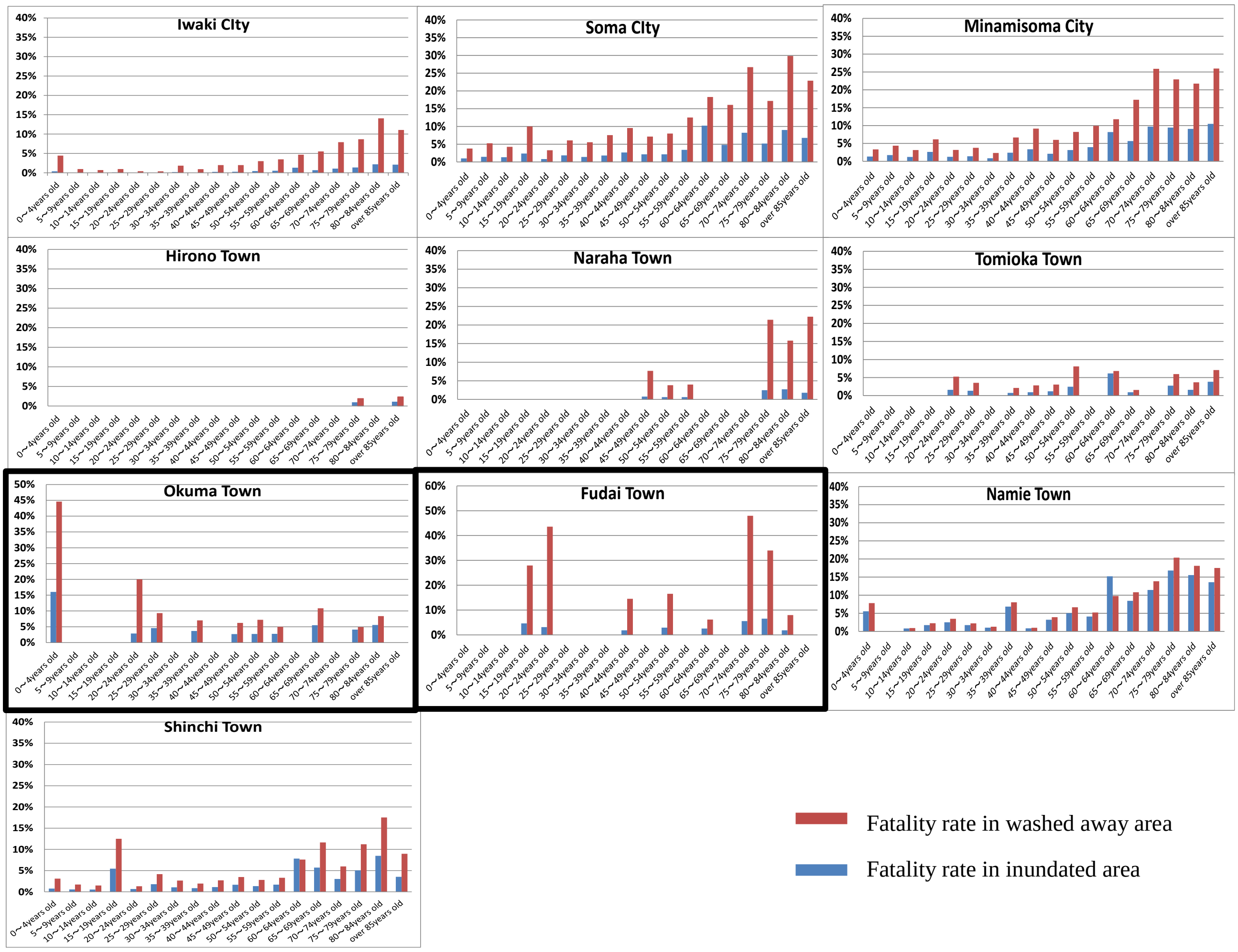


Figure 3.9: Fatality rates by municipality and age groups in Fukushima Prefecture based on night time population in inundated and washed away areas (The maximum value is shown on the vertical axis in 40 %. However, in graphs with thick borders, the maximum value depends on each result.)

3.3.2 Geographical features

In Miyagi and Fukushima Prefectures, the coastlines are relatively flat and the plains extend away from them. On the other hand, the coastline of Iwate Prefecture has a northern region with many linear coastlines and a southern region with complex micro topography [25] [26]. Iwate Prefecture has the complexity coast lines and the ground height has a terrace area formed from a lowland area, narrow lowlands, and steep cliffs [25].

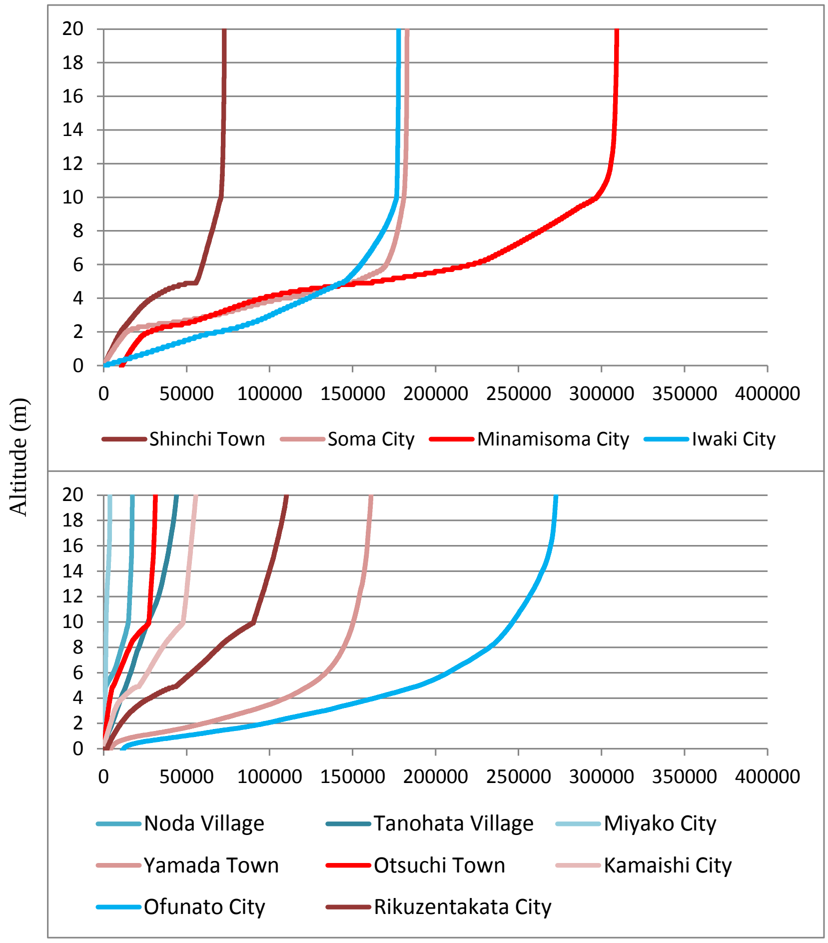
(1) Methods

First, this section analyzed the geographical features of Fukushima and Iwate Prefectures. This thesis considered the influence of the terrain, focusing on regional classification by terrain. This section explores the altitude distribution in the inundated areas and an elevation model (10 m) of the inundated areas is extracted. Therefore, the horizontal axis shows a reordering, in ascending order, of the altitude of the region, and the vertical axis shows the altitude (Figure 3.10). Here, the horizontal axis represents the altitude characteristics of the inundated area in the “regional classification by terrain” not a specific cross-sectional view.

(2) Results and Discussions

Most of the land in Fukushima and Iwate Prefectures is mountainous, so there are fewer plains. In the case of topography featuring slopes, death becomes concentrated in regions at a lower altitude. If the altitude distribution is gentle sloped, it is conceivable that the fatality rate will be high. On the other hand, if there is terrain such as a rias coast, the fatality rate will be low, because hills are found near to the coast.

Figure 3.10 shows the topographies of Minamisoma City, Shinchi Town, Soma City and Iwaki City in Fukushima Prefecture, Noda Village, Tanohata Village, Miyako City, Yamada Town, Otsuchi Town, Kamaishi City, Ofunato City and Rikuzentakata City in Iwate Prefecture. Regarding the relationship between altitude and fatality rate, in the figures, a blue line indicates when the fatality rate is 1% or less, and a red line when the fatality rate is 1% or more. In Soma City and Minamisoma City, there were smooth topographies with no high places in the inundated areas. However, in Shinchi Town, there were some high altitude areas in some inundated areas. Noda Village, Tanohata Village and Miyako City had terrains with a steep elevation in the elevation distribution from the sea coastal line. For Soma City, Iwaki City, and Minamisoma City, it can be seen that they have similar topographies, because the distribution shapes are similar. In Yamada Town, Otsuchi Town, Kamaishi City and Rikuzentakata City, the fatality rate was high. However, Iwaki City and Ofunato City are low fatality rate even if there were smooth topographies. Therefore, effects other than topography may also be related to the fatality rate.



Reordering in ascending order altitude in the region

Explanatory notes

(Color gradient) Fatality Rate in region is over 1%

(Color gradient) Fatality Rate in region is less than 1%

Figure 3.10: Relationship between altitude distribution and fatality rate

3.3.3 Evacuation distance

In the literature so far, some papers introduced evacuation distance as a parameter in their models. For example, Yun and Hamada [6] analyzed factors influencing causes of fatality by tsunami based on information on the 2011 Great East Japan Earthquake and Tsunami, and pointed out that age and evacuation start time have a significant influence on human damage. Here, distance of the evacuation route from the deceased's home address or the distribution of buildings in the inundated areas to non-inundated areas was analyzed. This analysis focuses on Fukushima and Iwate Prefectures, where the deceased' address is known.

(1) Methods

① The deceased's address was defined as the starting point for evacuation, with the goal point being set at the overlap between the inundated area and the road network using the road center line on a digital map (i.e., a point on the road out of the inundated area).

② The distance on the evacuation route from the starting point to the goal point was calculated using the nearest facility detection tool of ArcGIS Network Analyst.

(2) Results and Discussions

The results (Figure 3.11 and Figure 3.12) from the analysis of evacuation distance of fatalities in Fukushima and Iwate Prefectures are discussed below. "Fatality" here means the cumulative fatality rate. It refers to the percentage of fatalities associated with different distance of evacuation route. Focusing on the results for municipalities in Fukushima Prefecture, it was found that the fatality rate exceeded 50% when the evacuation route was over 200 m. Also focusing on municipalities in Iwate Prefecture, the fatality rate exceeded 50% when the evacuation route was 100 to 200 m in many municipalities. When it was 500 m in Soma City and 600 m in Rikuzentakata City, the fatality rate exceeded 50%. These trends in the two cities differ from other areas. As seen in Figure 3.12, looking at the trends throughout the prefecture, when the evacuation route was 300 to 400 m in Fukushima Prefecture and 200 to 300 m in Iwate Prefecture, it was found that the fatality rate exceeded 50%.

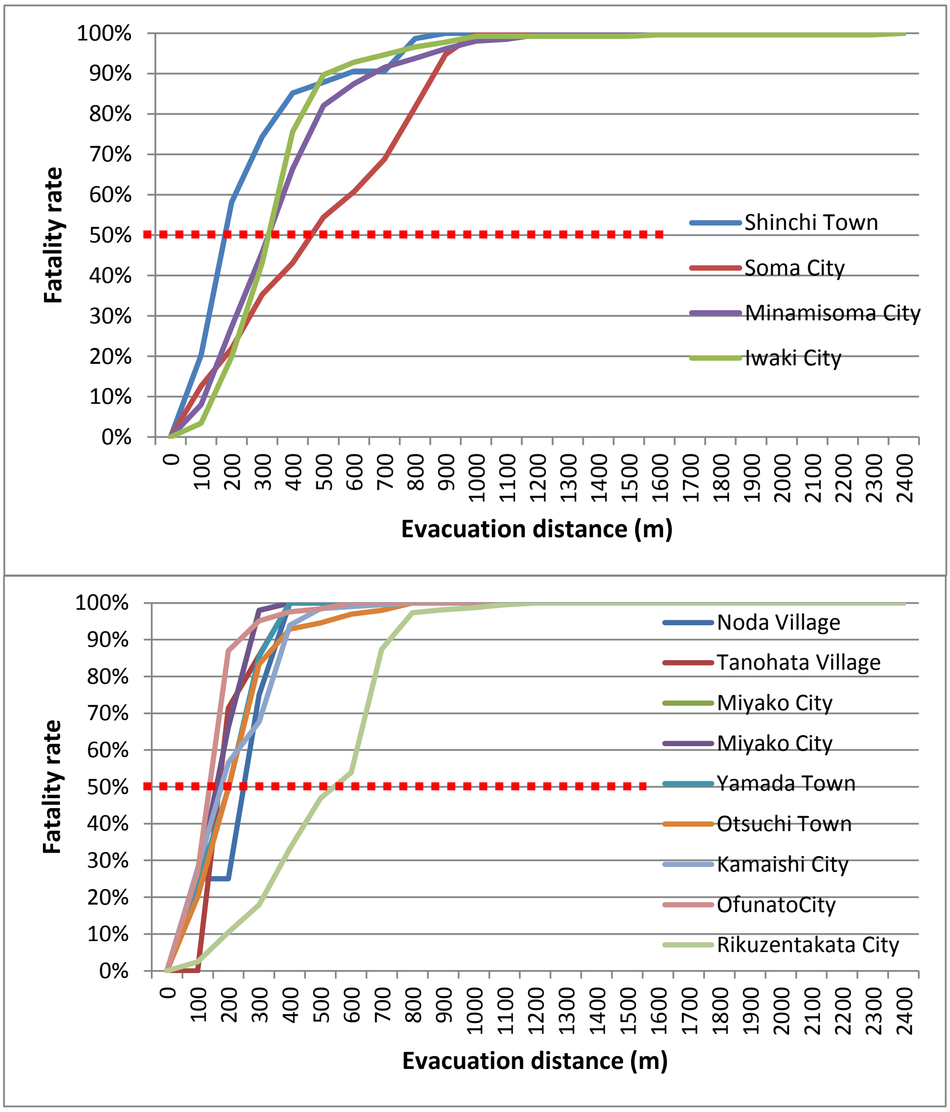


Figure:3.11 Relationship between evacuation distance and fatality rate

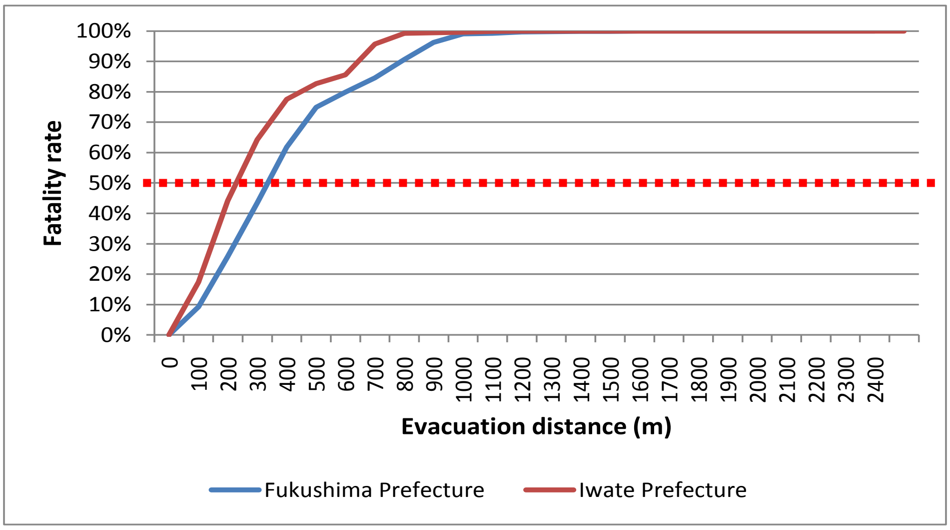


Figure 3.12: Relationship between evacuation distance and fatality rate at the prefectural level

3.3.4 Evacuation distance and human damage

To compare human evacuation tends by age, this section analyzes evacuation distance and human damage. From the address of each fatality and the distribution of buildings within the inundated area, this section analyzes the distance of the evacuation route from each building to the non-inundated area. This analysis uses the necrology data published by the Fukushima prefectural police on the website and by Iwate Nippo which provided the name of the the deceased and a detailed home address.

(1) Methods

① The point overlaps the inundated area and the road network was extracted using the road center line on a digital map

② This method defined the deceased's address as the starting point for evacuation and a point on the road out of the inundated area as the goal point. Through the road network, the distance of the evacuation route from the starting point to the goal point was calculated using the nearest facility detection tool of ArcGIS Network Analyst.

③ This method focused on residences in inundated areas. This method defined the address of the residence as the starting point for evacuation and a point on the road out of the inundated area as the goal point. (In other words, it was possible to grasp the distance that the resident needed to travel [both the fatalities and survivors could be included].)

④ As in ② and ③, the distance on the evacuation route from the starting point to the goal point was calculated using the nearest facility detection tool of ArcGIS Network Analyst.

⑤ Based on the results obtained, the distance of the evacuation route from the starting point to goal point by age was organized as a box-and-whisker plot. Originally, the fatality rate should have been calculated with the total residents in the target area as the population, but since the number of residents in each building was unknown and it was impossible to analyze the fatality rate of all residents as the population, the analysis was carried out with the determined death rate using all buildings in the inundated area as the population.

Here, for Fukushima Prefecture, the residences could be extracted because there were data on the buildings damaged by flooding. However, it should be noted that the number of buildings in Iwate Prefecture includes all buildings, because there were no data on inundated buildings.

(2) Results

The analysis results on the relationship between the distance of the evacuation route from the deceased's address and the distance from the building to the non-inundated area in Fukushima and Iwate Prefectures are shown in Figure 3.13 (1) and (2). It shows the basic statistics (minimum value, quartile, average value, third quartile, and maximum value) of the distances from the building to the non-inundated area and all deaths separated by age group (0 to 18 years old, 19 to 64 years old, and 65 years old or more). To verify whether there was a difference between the evacuation distance for the fatality and the evacuation distance of all buildings in the area, the evacuation distance distribution from buildings in the inundated area was examined for all fatalities. Also, two groups of t-tests on the evacuation distance distribution were conducted for the buildings and all death, the buildings and the 0 to 18 years old, the buildings and the 19 to 64 years old, the buildings and 65 years old or more. The significance level was set at 1%. In the figures, a boxplot diagram shown in red represents significant differences in the evacuation distance distribution of all residences in the inundated area.

(3) Discussions

First of all, the results of Fukushima Prefecture will be explained;

- The evacuation route was significantly longer for the fatality than for all residents in the inundated areas, except in Shinchi Town. No significant differences were found in Shinchi Town, but on the point that the evacuation route was longer for the fatality, the results were consistent in other areas.
- In Soma City in particular, the evacuation route for the 65-year-or-more group was found to be significantly longer than that of buildings in the inundated area.
- Looking at the age groups of the fatality, evacuation routes tended to be shorter as age increased in Soma City, Minamisoma City and Shinchi Town. In cases where the evacuation route was short, the possibility of being safe was higher than where it was long (the time required for evacuation could be shortened). There are many cases of elderly people not evacuating even when the evacuation route is short, and the reason for this might be that even when travelling the same distance as another people, elderly people take longer to evacuate because of the deterioration of their physical functions, and so on. Although such a trend was not seen in Iwaki City alone, given the analysis in the previous section, considering that the trend differed only in Iwaki City, it is conceivable that another factor is at work there.

Second, the results of Iwate Prefecture will be explained;

- The evacuation routes were significantly longer for the fatality than for inundated areas, except in Noda Village, Miyako City and Ofunato City, where no significant differences were found, but there was a tendency for the fatality to need longer to evacuate. Moreover, the evacuation distances for the fatality and buildings were not very different, except in Rekuzentakata City.
- In Rikuzentakata City, evacuation routes for the 65-year-and-over age group were remarkably long comparing with other municipalities in Iwate Prefecture.
- By looking at the age groups of the fatality, it was found that the tendency did not differ from the result for Fukushima Prefecture. In other words, although everyone’s evacuation distance was the same, the fact that people died is due not only to the evacuation distance, but also the influence of the topography and social factors, and this is likely true for Fukushima as well.

Finally, Fukushima and Iwate Prefectures will be compared;

- It was found that the evacuation routes were shorter in Iwate Prefecture than in Fukushima Prefecture.

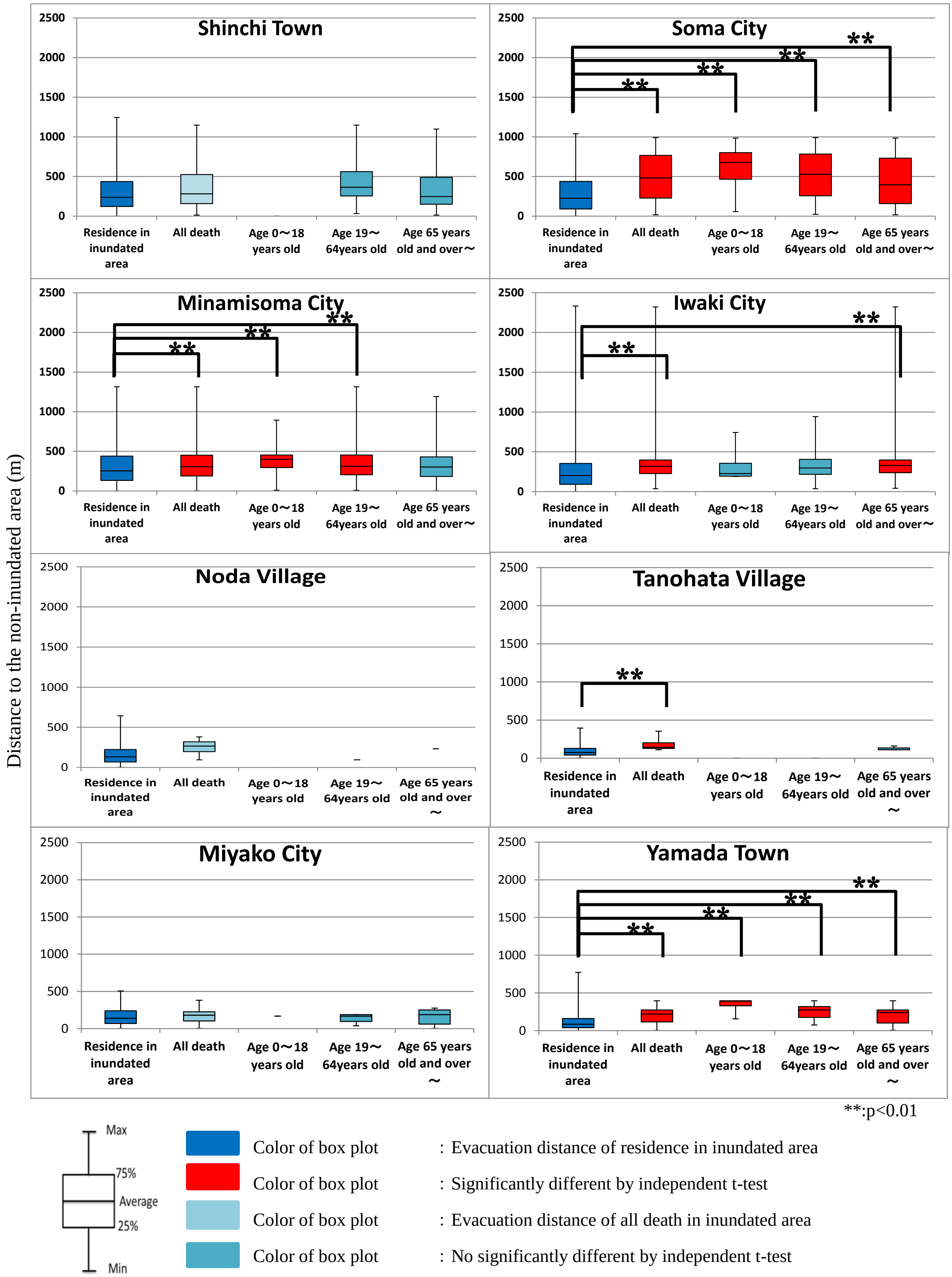


Figure 3.13(1): Box plot of relationship between evacuation distance and age

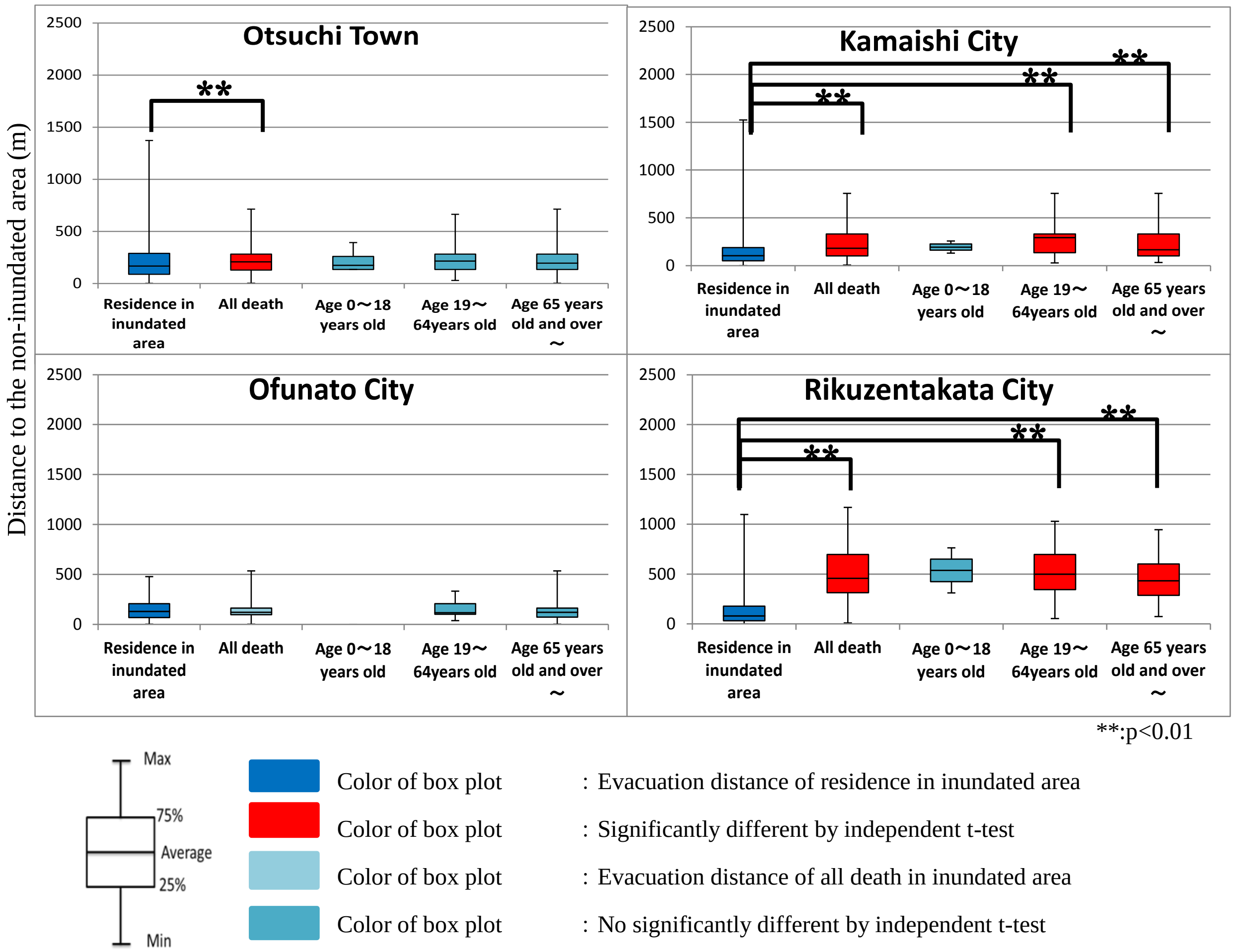


Figure 3.13 (2): Box plot of relationship between evacuation distance and age

3.3.5 Inundation depth

The JMA has provided a relationship between tsunami damage and the tsunami height of past disasters. In addition, the relationship between the inundation depth and the degree of damage to buildings has been explored [27]. Wooden houses are completely destroyed by over 2 m of inundation, and stone houses are destroyed by over 8 m of inundation. Steel-reinforced-concrete buildings are expected to be destroyed at an inundation depth of 16 m or more [27]. According to a report by Nagoya University [3], deaths from tsunami disasters occur when buildings are washed away, and the fatality rate increases when the inundation of houses is over 3 m from the viewpoint of house damage by the tsunami events. Moreover, Aoki *et al.*[4] found that the proportion of death increased when the flood depth exceeded 4 m based on the 2011 Great East Japan Earthquake and Tsunami. The height from the floor to the second floor of a general wooden house is approximately 3.5 m. Since this inundation depth corresponds to the height at which the first-floor portion of two-storied building is submerged, there is a high possibility that death can be avoided by evacuating to the second floor. Aoki's study suggested a situation where the likelihood of death increases if flooding exceeds the height of the second floor. Additionally, according to Cabinet Office [28], residences begin to face partial damage at approximately 1m of inundation, followed by total destruction at 2 m for wooden houses. Inundation and washing away are related to life and death. Given that buildings are susceptible to total destruction at 2 m, people in buildings more than 2 m of inundation face a higher probability of death.

(1) Results and Discussions

The relationship between the inundation depth distribution and the cumulative fatality rate in Fukushima and Iwate Prefectures (that is, what percentage of the people died at different inundation depths) is shown in Figure 3.14. Although each region is different, it can be seen that the death rate tends to rise when the depth of flooding exceeds 2 m. From the results, Fukushima Prefecture had a fatality rate exceeding 50% at a 3 m or more inundation depth. In other municipalities in Iwate Prefecture, the fatality rate exceeded 50% at an inundation depth of 2.5 m at least. In other words, it is conceivable that fatality could occur if ordinary two-story houses were flooded.

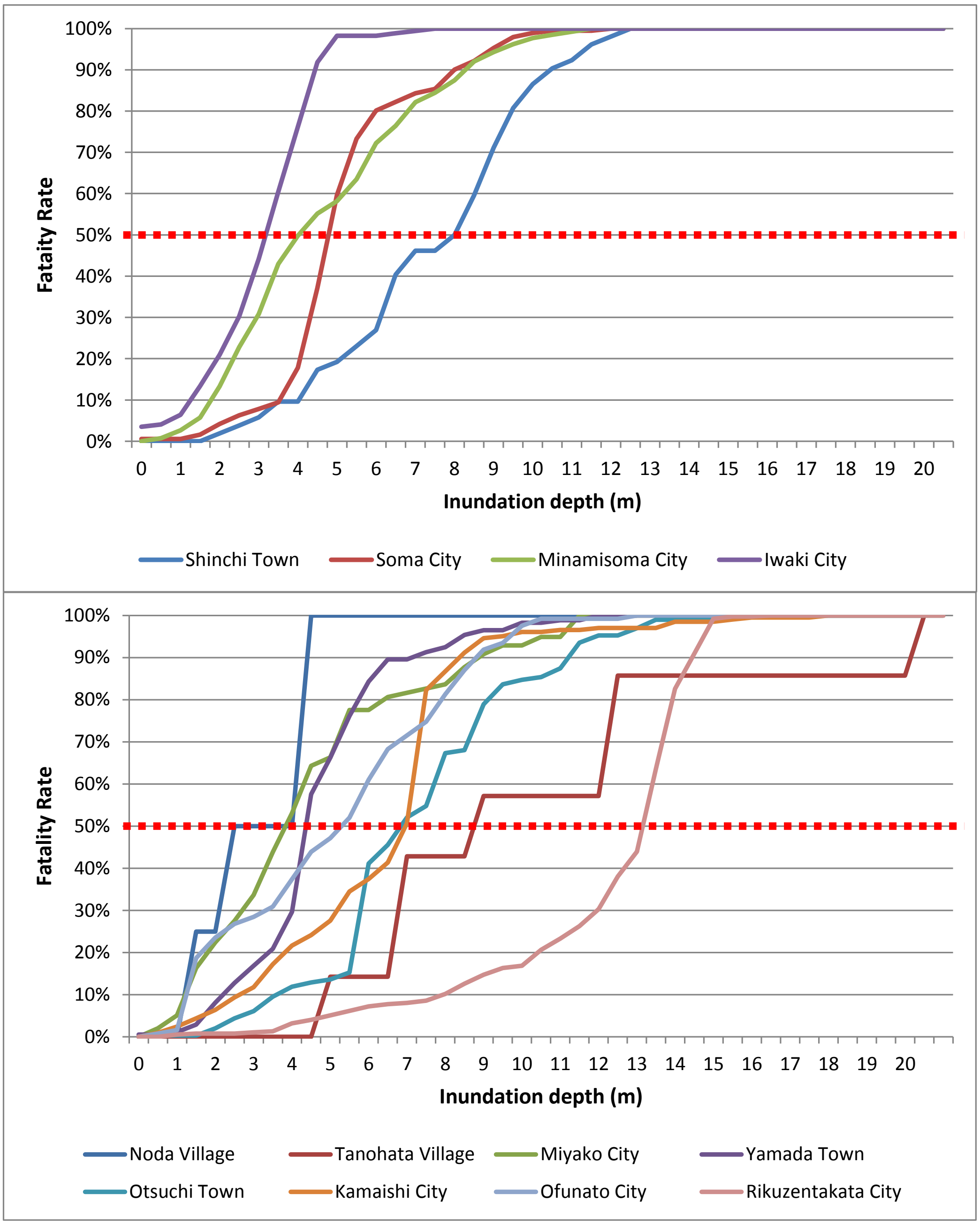


Figure 3.14: Relationship between inundation depth and fatality rate

3.6 Summary

Chapter 3 summarized the detailed analysis of factors causing human damage (fatality rate, geographical features, evacuation distance, evacuation distance and human damage, and inundation depth) based on the 2011 Great East Japan Earthquake and Tsunami. To briefly summarize, the fatality rate of elderly people was high. It was found that flat areas had a higher fatality rate than those where the elevation distribution from the coastal line had a steep slope. Furthermore, in terms of evacuation distance, the fact that evacuations were delayed despite the evacuation route being short is considered to be a reason for people not being able to escape (because they thought they were safe). In terms of inundation depth, although each region is different, it can be seen that the death rate tends to rise when the depth of flooding exceeds 2 m. Therefore, the next chapter will explain the method for constructing a fatality model based on the above results.

References

[1] National Police Agency (2017) "About the damage of the 2011 Great East Japan Earthquake, No. 156", Available: http://www.fdma.go.jp/bn/higaihou/pdf/jishin/156.pdf. Last Accessed: 24th October, 2017 (in Japanese)

[2] City Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (2011) "About the result of a survey of damage by the Great East Japan Earthquake (the first report), Retrieved October 3, 2011" Available: http://www.mlit.go.jp/common/000162533.pdf. Last Accessed: March 2014 (in Japanese)

[3] Report of Nagoya University, report of the 2004 Indian Ocean Tsunami V, Available: http://www.seis.nagoyau.ac.jp/INFO/sumatra/sumatra_report_5.pdf. Last Accessed: 16th February, 2015

[4] T. Aoki (2017) "Analysis of factors causing death in the Great East Japan Earthquake based on Iwate Nippo Interview data", Bachelor's degree thesis, Department of Civil Engineering, Gifu University

[5] S. Yotsui, M. Koyama, A. Furukawa and J. Kiyono (2015) "Mechanism Analysis of Casualty and Evacuation Route in the Case of Fukushima Prefecture", *Journal of Social Safety Science*, No.27. (in Japanese)

[6] N. Y. Yun and M. Hamada (2015) "Evacuation Behavior and Fatality Rate during the 2011 Tohoku-Oki Earthquake and Tsunami", *Earthquake Spectra*, Vol. 31, No.3, pp.1237-1265

[7] Memory Ever Daishinsai (2011) "Tragedy of Ishinomaki city that tsunami hit Okawa Elementary School", Available: http://memory.ever.jp/tsunami/higeki_okawa.html. Last Accessed: March, 2014. (in Japanese)

[8] H. Kaneko (2013) "Development of prediction performance evaluation index of nonlinear regression model", Available: https://www.jstage.jst.go.jp/article/ciqs/2013/0/2013_O11/_pdf. Last Accessed: 1st November, 2014.(in Japanese)

[9] ArcGIS by ESRI
Available: http://resources.arcgis.com/ja/help/getting-started/articles/026n00000014000000.htm. Last Accessed: 1st November, 2017. (in Japanese)

[10] Open Street Map, Available: https://openstreetmap.jp/. Last Accessed: 1st November, 2017.(in Japanese)

[11] Statistics Bureau, about national census (2010) Available: http://www.stat.go.jp/data/kokusei/2010/. Last Accessed: 1st November, 2017 (in Japanese)

[12] Inundated area map by the Ministry of Land, Infrastructure and Transport (MLIT) on the Reconstruction Support Survey Archive, Available: http://fukkou.csis.u-tokyo.ac.jp/dataset/show/id/1110. Last Accessed: 1st November, 2017 (in Japanese)

[13] Inundated area 5m mesh, Available: http://www.mlit.go.jp/common/000162412.pdf. Last Accessed: 1st November, 2017 (in Japanese)

[14] Ministry of Land, Infrastructure and Transport (MLIT) (2011) "Measurement of inundated housing in municipalities damaged by the tsunami in Tohoku Earthquake" Available: http://www.mlit.go.jp/common/000162412.pdf. Last Accessed: 1st November, 2017 (in Japanese)

[15] Geospatial Information Authority of Japan, Road center lines from the Ministry of Land, Infrastructure and Transport (MLIT), Available: http://www.gsi.go.jp/kibanjoho/kibanjoho40027.html. Last Accessed: 1st November, 2017 (in Japanese)

[16] Geospatial Information Authority of Japan, Elevation model 10m, Available: http://fgd.gsi.go.jp/download/menu.php#. Last Accessed: 1st November, 2017 (in Japanese)

[17] Digital Elevation Model 10 m, Available: http://nlftp.mlit.go.jp/ksj/. Last Accessed: 1st November, 2017 (in Japanese)

[18] Point data of welfare facilities and school by National Land Numerical Information download service, Available: http://nlftp.mlit.go.jp/ksj/. Last Accessed: 1st November, 2017 (in Japanese)

[19] Japan Geographical Society Disaster Response Headquarters Tsunami Affected Map Creation Team, washed away polygon (in Japanese)

[20] Ministry of Internal Affairs and Communications, Available:http://www.soumu.go.jp/main_sosiki/jichi_gyousei/bunken/chihou-koukyoudantai_kubun.html. Last Accessed: 1st November, 2017 (in Japanese)

[21] Cabinet Office, Government of Japan (2012) "Guidelines for damage prediction and techniques of building and human", Available: http://www.bousai.go.jp/jishin/nankai/taisaku/pdf/2_2.pdf. Last Accessed: 14th November, 2014 (in Japanese)

[22] M. Abe and Y. Fujino (2008) "Statistical Analysis on Characteristics of Risk of Natural Disasters", *Journal of Japan Society of Civil Engineers A*, Vol.64, No.4, pp.750-764 (in Japanese)

[23] M. Koyama, Y. Ishii, A. Furukawa, J. Kiyono and A. Yoshimura (2013) "Municipality's mortality rate according to inundation level and age classes on the 2011 Great East Japan Earthquake", *Structural Engineering & Earthquake Engineering / Journal of Japan Society of Civil Engineers*, Vol.32, pp.161-170 (in Japanese)

[24] Ministry of education, culture, sports, science and technology Japan (2010) "The 2010 White Paper on Education, Culture, Sports, Science and technology, Response to the Great East Japan Earthquake" Available: http://www.mext.go.jp/b_menu/hakusho/html/hpab201001/detail/1312138.htm (in Japanese), Last Accessed: March, 2014 (in Japanese)

[25] R. Yanagawa and S. Sakai (2014) “Topographical Propagating Tsunami and Suffering Building Features by the Great East Japan Earthquake Tsunami in the Iwate Coastal Region”, *Journal of Japan Society for Natural Disaster Science*, 33(2), pp. 145-159 (in Japanese)

[26] K. Wakamatsu (2011) “Japan Society of Civil Engineers East Japan Earthquake damage investigation team Earthquake damage survey report, chapter 3, The topography and geology in the affected areas”, Available: http://committees.jsce.or.jp/report/system/files/Chapter3_1.pdf. Last Accessed: March, 2014. (in Japanese)

[27] Japan Meteorological Agency, About Tsunami
Available: http://www.jma.go.jp/jma/kishou/know/faq/faq26.html. Last Accessed:11th December, 2017. (in Japanese)

[28] Cabinet Office, Available: http://www.bousai.go.jp/jishin/nankai/taisaku_wg/8/pdf/sub2.pdf, Last Accessed: 25th January, 2018. (in Japanese)

Chapter 4
Fatality modeling of tsunami disaster

4.1 Methodology

Natural disasters such as earthquakes, tsunamis and typhoons are often difficult to predict the future damage with data on accidents that have occurred so far. There are many uncertain factors about the occurrence of disasters [1]. However, an evaluation method considering regional characteristics is necessary. Additionally, natural disasters such as large-scale earthquakes, typhoons, torrential rains, heavy snowfalls will not only occur in areas where damage has occurred once such as the 2004 Sumatra Earthquake, the 2005 Pakistan Northern Earthquake, the 2005 Hurricane Katrina and Rita. There is a possibility that damage to a wide area is caused. In Japan, the 2011 Great East Japan Great Earthquake is also an example. Irikura states that “prediction”, “estimation” and “forecast” of natural disaster phenomena are important [2].

To briefly summarize, the fatality rate of elderly people was high. It was found that flat areas had a higher fatality rate than those where the elevation distribution from the coastal line had a steep slope. Furthermore, in terms of evacuation distance, the fact that evacuations were delayed despite the evacuation route being short is considered to be a reason for people not being able to escape (because they thought they were safe). These factors include not only the problem of evacuation distance but also the geographical and societal factors. It is assumed that these factors have some influence. Based on the above results of the detailed analysis of factors causing human damage (fatality rate, geographical features, evacuation distance, evacuation distance and human damage, and inundation depth), the following section explains the method for constructing a fatality model. First, using ArcGIS (ESRI), the inundated area was divided into two areas: areas where fatalities occurred and areas where there were no fatalities in Fukushima and Iwate Prefectures due to damage from the 2011 Great East Japan Earthquake and Tsunami. This method used ArcGIS Network Analyst for the analysis of evacuation routes. Figure 4.1 presents a flowchart of this chapter.

4.1.1 Analysis of areas where the fatalities occurred

This thesis used necrology data published by the Fukushima Prefectural Police and Iwate Nippo, which provided the names of the fatality and detailed home addresses. This section was a characteristic analysis of the distance and elevation trends of each fatality’s evacuation route in four municipalities in Fukushima Prefecture and eight municipalities in Iwate Prefecture. The number of grids used for the analysis is shown in Table 4.1. The processes are outlined below.

Step A1. Calculating population in the inundated area using the 2010 population census. Each 500m grid population was defined as one mesh as shown in Figure 4.2 and Figure 4.3.

Step A2. Defining the deceased's address as the starting point for evacuation, extracting the point as the goal point that overlaps the inundated area and the road network using the road center line of the digital map (i.e., the point on the road out of the inundated area).

Step A3. Organizing the inundation depth of each fatality from the MLIT information.

Step A4. Through the road network, calculating the distance of the evacuation route from the start point to the goal point using the nearest facility detection tool of the ArcGIS Network Analyst shown in Figure 4.4 and Figure 4.5.

Step A5. For the evacuation route corresponding to each fatality, using an altitude model of 10m mesh to extract the altitude's distribution shown in Figure 4.5.

Step A6. Organizing the age and gender of each grid where the fatalities occurred according to the 2010 population census.

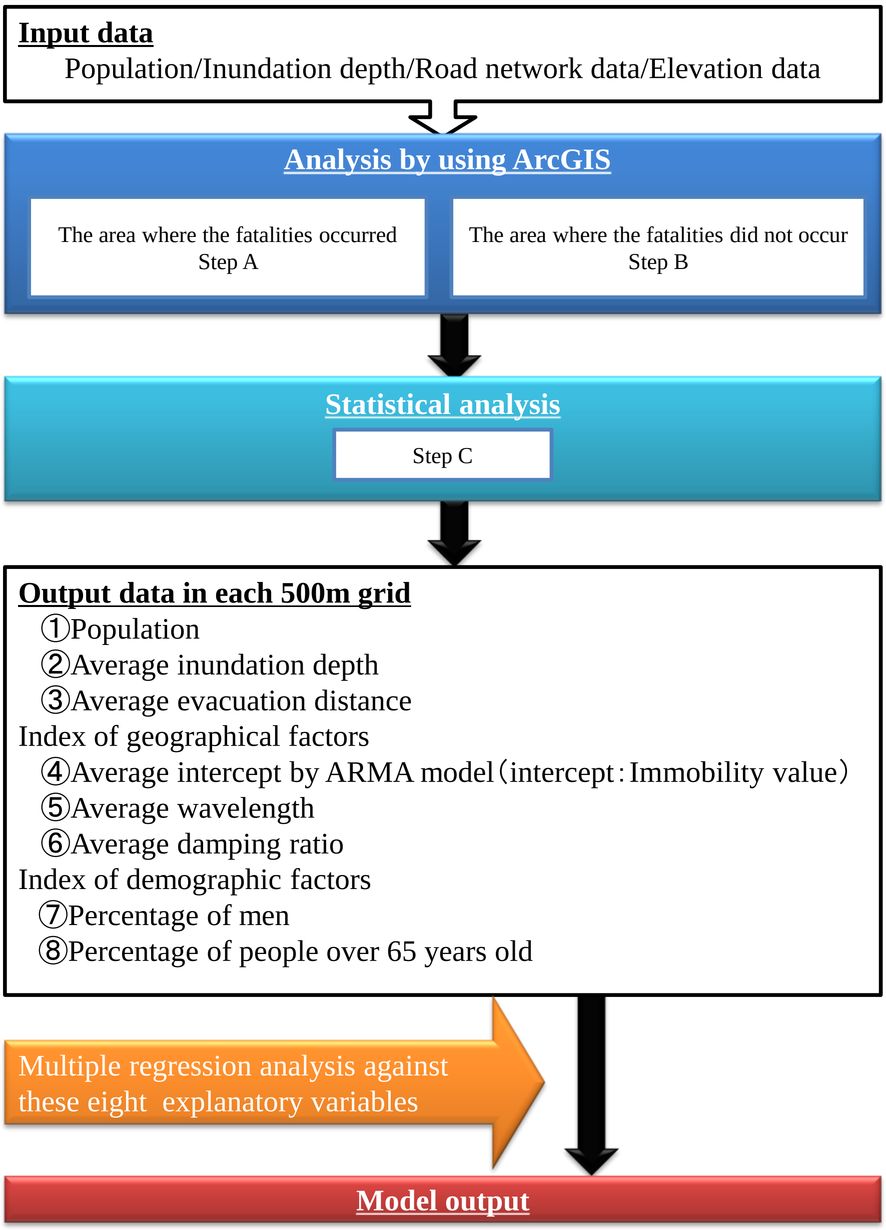
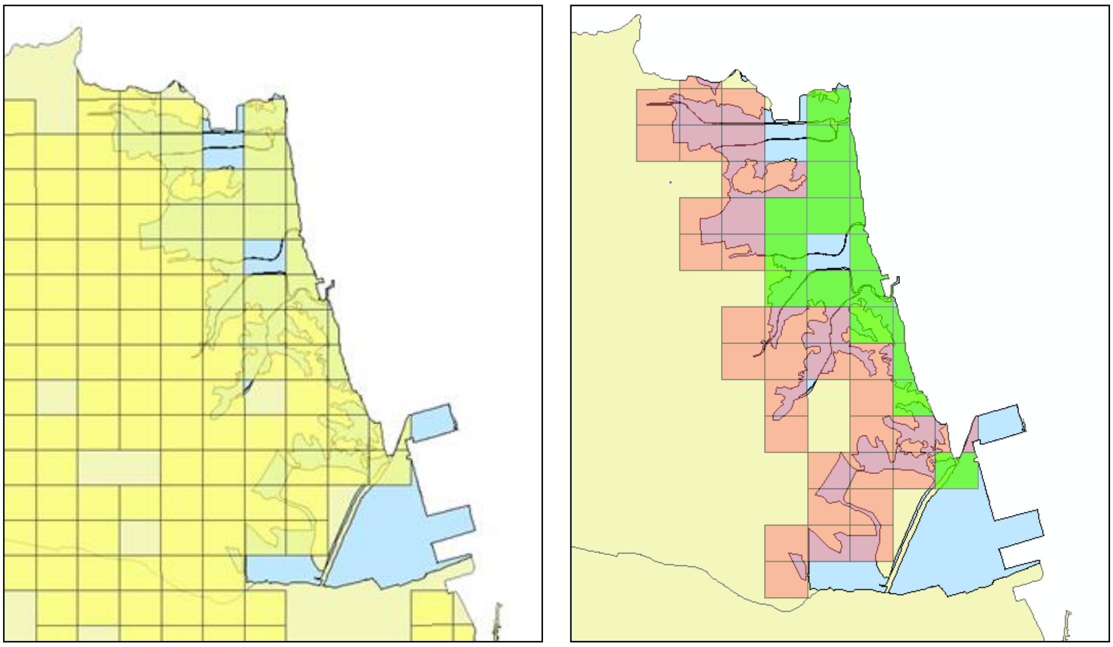


Figure 4.1: Research framework



Explanatory notes

The 2010 National Census

Inundated area

Explanatory notes

Grid where the fatalities occurred based on the 2010 National Census

Grid where the fatalities did not occur based on the 2010 National census

Inundated area

Figure 4.2: Example of areas where the fatalities occurred and areas where fatalities did not occur

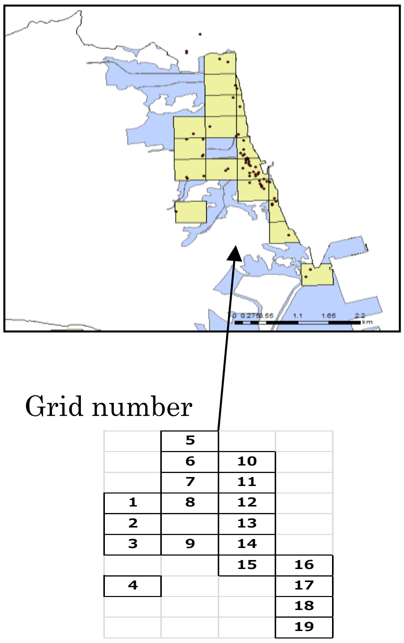
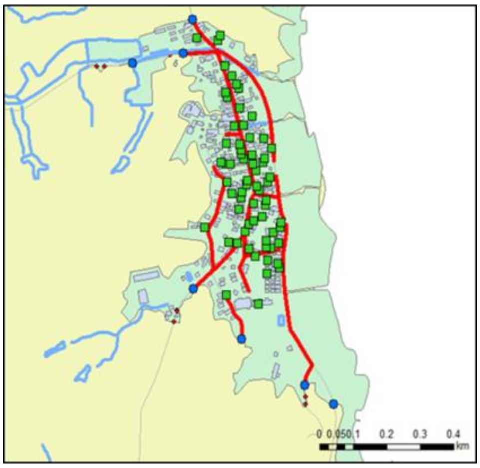


Figure 4.3: Inundated area and mesh (500m grid population) in Shinchi Town as the example (Image of StepA1 and StepA2)



Explanatory notes

Evacuation route

Start point

Goal point

Figure 4.4: Evacuation route and the point on the road out of an inundated area (Image of Step A4 and StepA5)

4.1.2 Analysis of areas where the fatalities did not occur

In reality, the inundated zone is divided into two regions: the area where the fatalities occurred, and the area where they did not. Here, this thesis is looking at the area where fatalities did not exist. Additionally, the number of grids targeted when analyzing area where fatalities occurred and the area where they did not shown in Table 4.1. The processes are shown below.

Step B1. Calculating the population in the inundated area using the 2010 population census.

Step B2. Extracting the area that overlaps the inundated area and the 2010 population census. A center of gravity point was then determined for a 500 m grid cut by the inundated area polygon and defined as a start point. This step subsequently extracted the points that overlap the inundated area and the road network (the point on the road exiting the inundated area was determined as the goal point). It should be noted that there are several points where the center of gravity is set outside the inundated area because of the analysis on ArcGIS shown in Figure 4.6.

Step B3. Organizing the inundation depth of the fatality from the MLIT information.

Step B4. Calculating the distance and elevation from to the center of gravity point the non-inundated areas through the road network using ArcGIS Network Analyst.

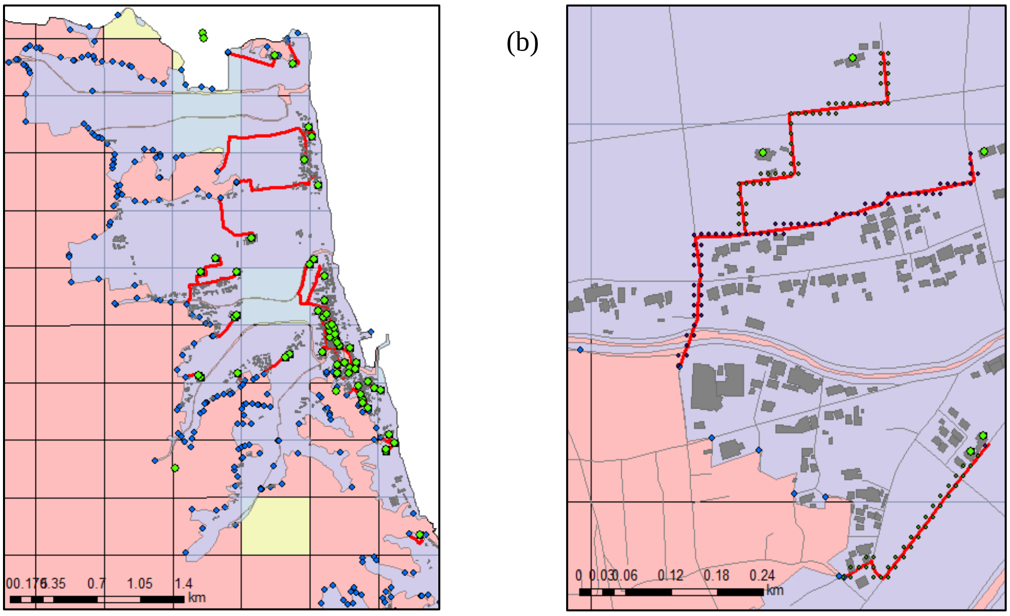
Step B5. For the evacuation route, using an altitude model of 10m mesh was to extract the altitude's distribution shown in Figure 4.6.

Step B6. Organizing the age and gender of each grid where fatalities did not exist according to the 2010 population census.

Table 4.1: Number of deaths and grids in Fukushima and Iwate Prefectures

	Death	Grid of death	Grid of no fatality
Fukushima Prefecture			
Shinchi Town	76	18	16
Soma City	397	21	61
Minamisoma City	462	75	87
Iwaki City	262	34	92
Iwate Prefecture			
Noda Village	4	2	19
Tanohata Village	7	5	14
Miyako Village	98	28	85
Yamada Town	172	30	33
Otsuchi Town	294	26	22
Kamaishi City	203	38	58
Ofunato City	123	35	101
Rikuzentakata City	373	35	109

(a) (b)



Explanatory notes

— Evacuation route

● Start point (the deceased's address)

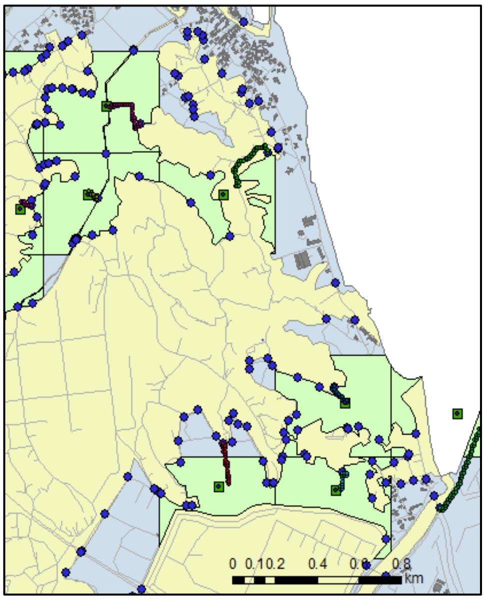
● Goal point

■ The 2010 national census

■ Inundated area

■ Damaged building in inundated area

Figure 4.5: Positional relation death and inundated area on ArcGIS (a) and example of elevation distribution on each evacuation route on ArcGIS (b)



Explanatory notes

— Road Network

■ Start point

● Goal point

● Elevation distribution on each evacuation route

■ The 2010 national census

■ Inundated area

Figure 4.6: Analysis example on ArcGIS of areas where fatality did not occur

4.2 Result of analysis by using GIS

The results of the elevation analysis of the evacuation route from the deceased's home address in Fukushima or Iwate Prefectures to the non-inundated area are shown below. It is the result of Step A and Step B. The horizontal axis shows the distance from the deceased's home address to the non-inundated area, and the vertical axis shows the difference of elevation between non-inundated area and the deceased's address or a center of gravity point. In Figure 4.7 to Figure 4.8, the blue line shows the altitude distribution which is the route from the deceased's home address to non-inundated area and the green line shows the altitude distribution which is the route from the center of gravity to non-inundated area in no fatality area (that is, it is defined as survivors). The right side of the diagram represents the residence of the fatality, and the left side of the diagram represents the non-inundated area point.

4.2.1 Fukushima Prefecture

This is the results of the detail altitude distribution in Fukushima Prefecture (Figure 4.7 (1) and Figure 4.7 (2)). Each line in figure shows each fatality or survivor's evacuation route.

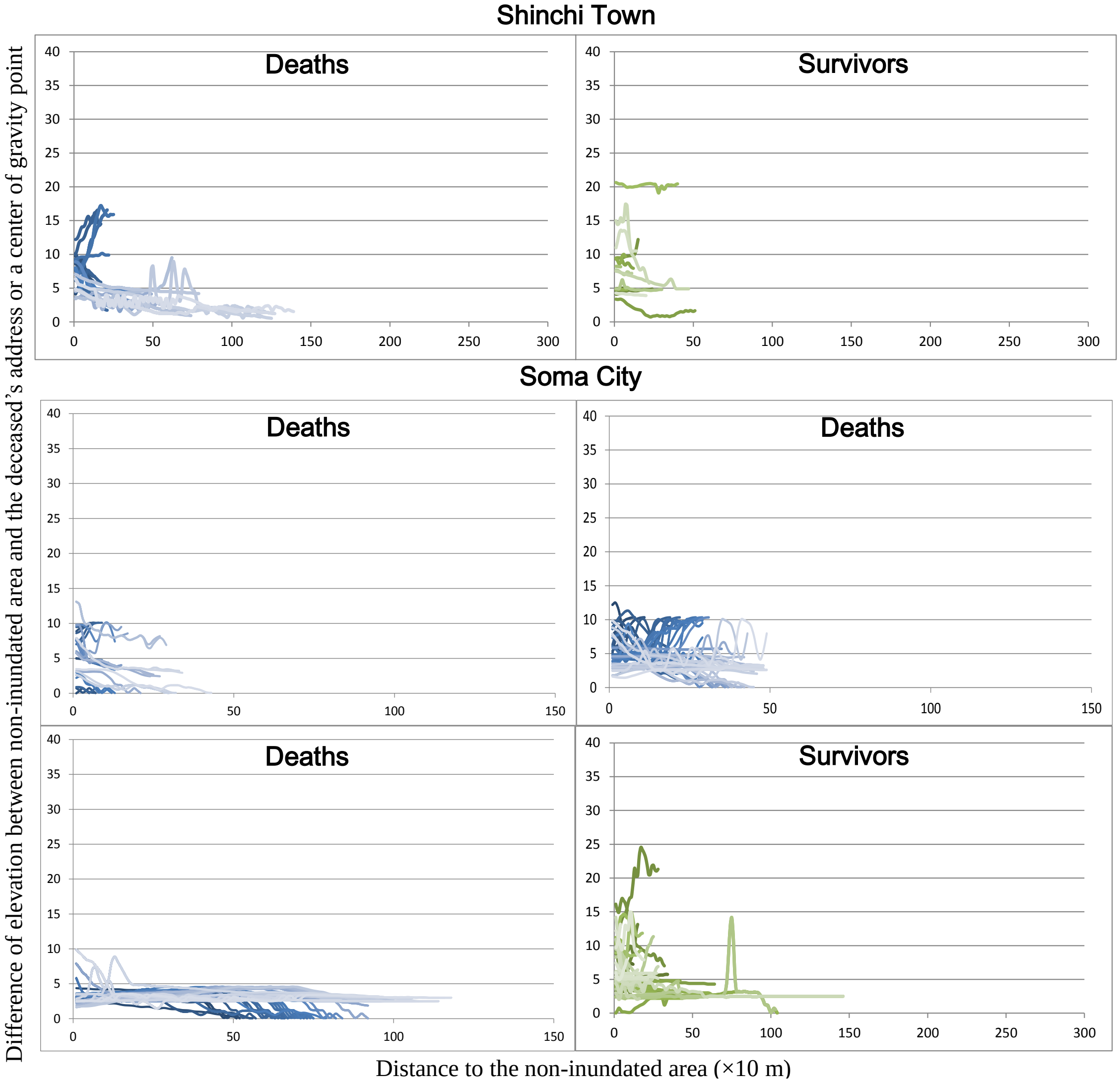


Figure 4.7(1): Altitude distribution in Fukushima Prefecture

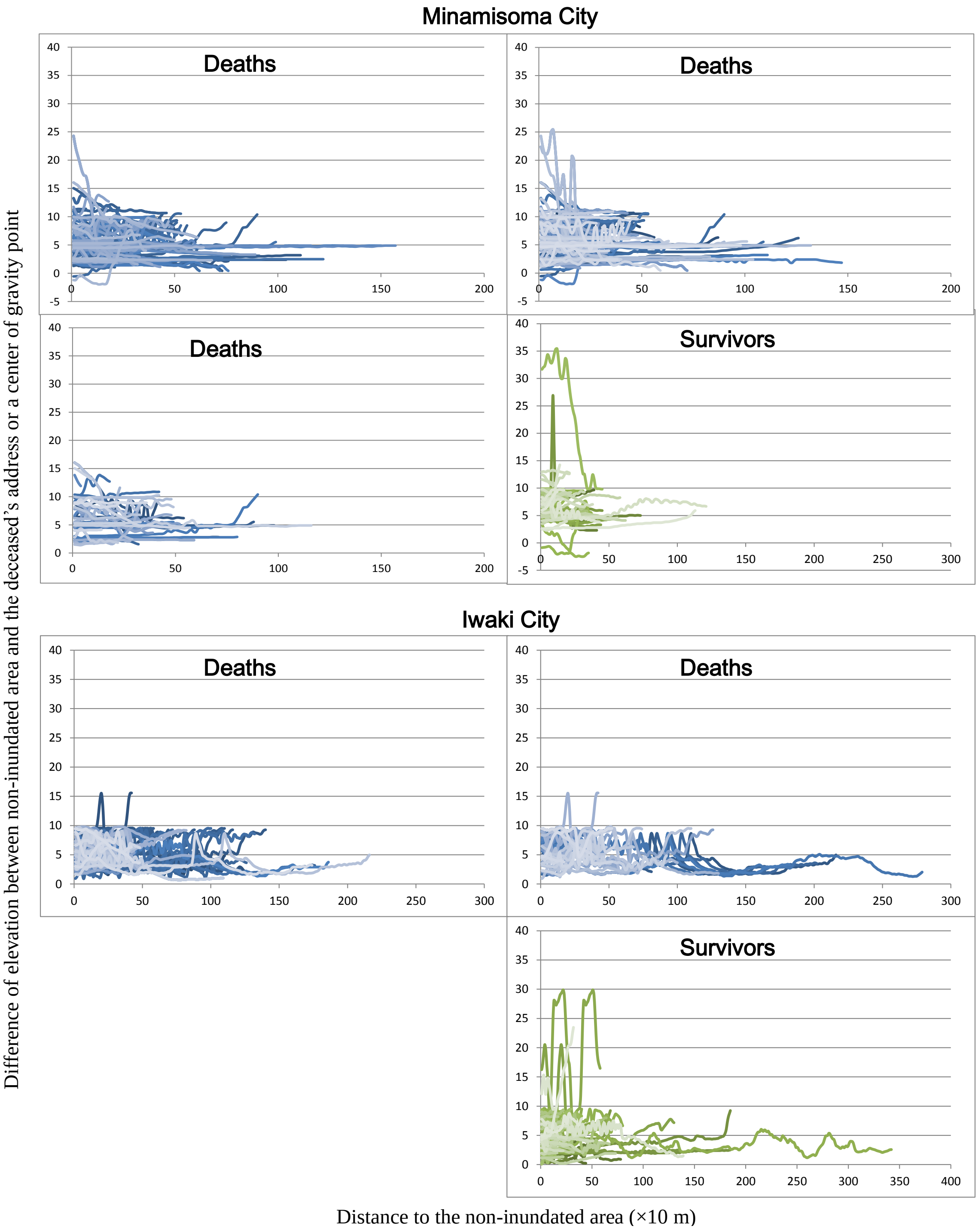


Figure 4.7(2): Altitude distribution in Fukushima Prefecture

4.2.2 Iwate Prefecture

This is the results of the detail altitude distribution in Iwate Prefecture (Figure 4.8 (1), Figure 4.8 (2) and Figure 4.8 (3)). Each line in figure shows each fatality or survivor's evacuation route.

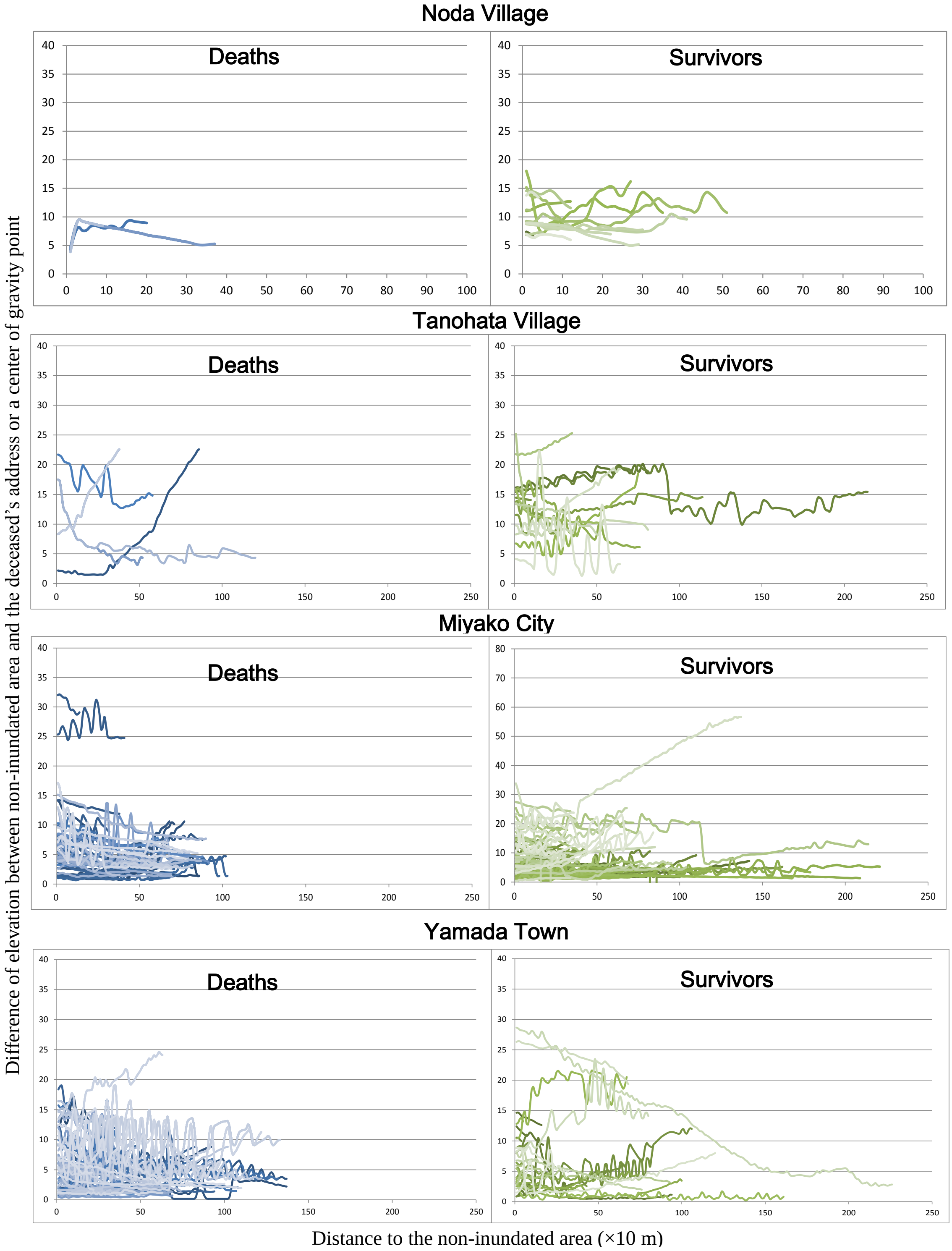


Figure 4.8 (1): Altitude distribution in Iwate Prefecture

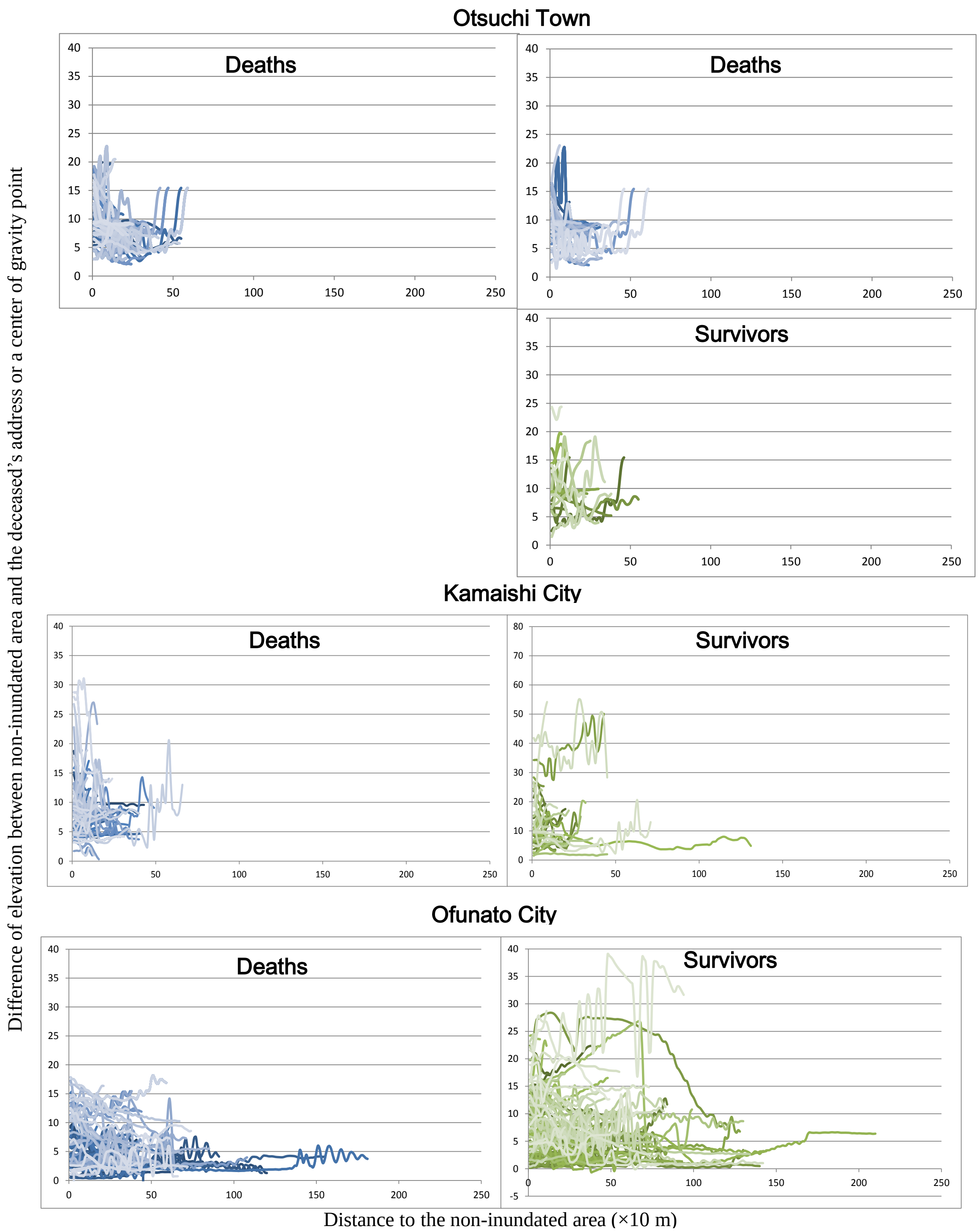


Figure 4.8 (2): Altitude distribution in Iwate Prefecture

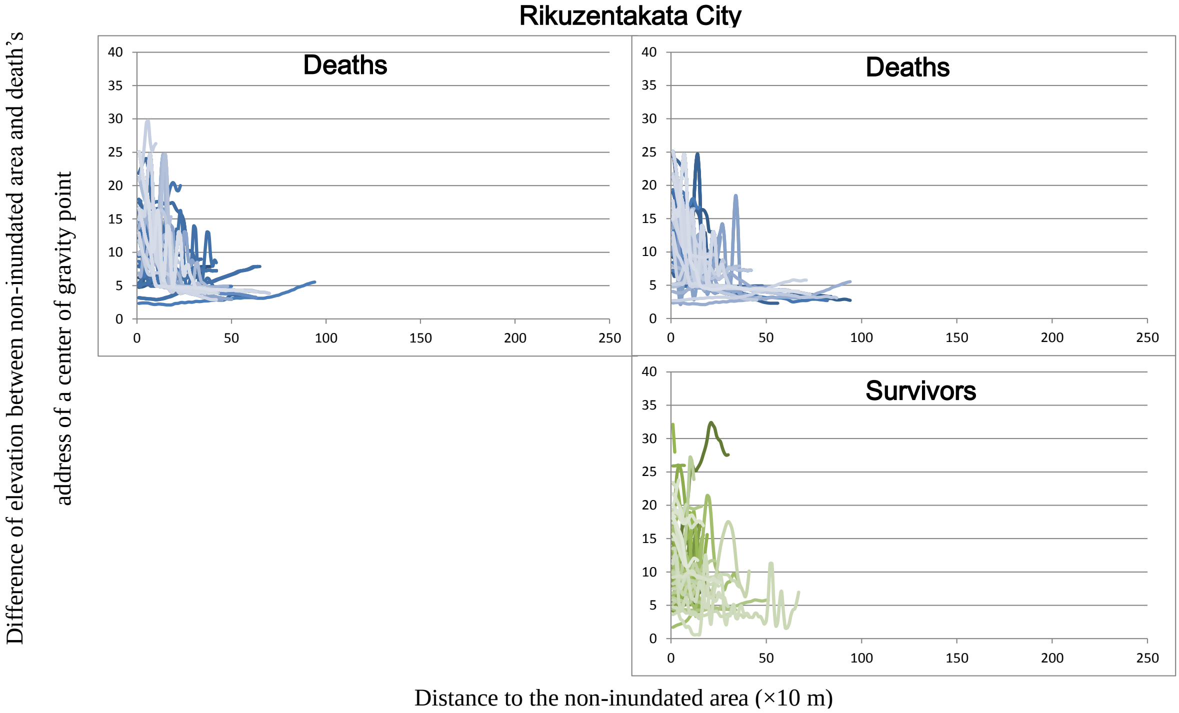


Figure 4.8 (3): Altitude distribution in Iwate Prefecture

4.3 Social factors

Factors that caused fatalities include not only physical factors such as topography, but also social factors.

Aldrich and Sawada [3] found that stocks of social capital and level of political support (as the social factors) as well as tsunami height influenced the fatality rate. Alexander's study [4] proposed a new model combined culture and history with physical hazards to show how vulnerability is influenced. Yamashita and Mikami [5] explained that physical impacts do not necessarily affect the magnitude of human injury, and stated that various social factors should be recognized. They cited family composition, community ties, local industry/economy, and municipalities' degree of damage as social factors. Otsuchi Town was the area that seemed to have the greatest social damage caused by the 2011 Great East Japan Earthquake and Tsunami. The government building was damaged, and many officers died there. Many town functions, including the industrial base of the town, schools, hospitals, public halls, and so on have also been lost. Noda Village saw damage to half of the city area. However, administrative organizations survived, the number of deaths was lower. Yoshino [6] said that tsunami height is strongly related to human damage. Also, he indicated that research on tsunamis from the viewpoint of disaster history is behind schedule. By analyzing the number of deaths by age group and gender, it was found that the total number of people in their 20s and 30s who died was relatively small, but more men died than women. Also, more men were working at tsunami-damaged sites, since they dominated the age group of the so-called workers. Furthermore, it could be seen that the elderly suffered more damage. Moreover, at the age of 80 and above, this study found that the difference between men and women became stronger in terms of the ability to decide one's actions based on one's knowledge of a past tsunami in 1933. Ohta [7] recognized that there are differences in the damage faced by each country, as countries have different social and economic states. The objective of Ohta's study was to develop mathematical models and investigate via numerical equations the damage to humans. Moreover, he included tsunamis because of Japan's long coastline. Ohta explained that *"the damage features are strongly affected by the country's developing state and it is sometimes more significant than that by the difference of earthquake magnitude".*

In Japan, the population and assets are concentrated in coastal areas, and it has geographical conditions that ensure that tsunamis hit very hard. Ochi *et al.* [8] conducted an evacuation behavior simulation that considered the characteristics of street closures due to a building collapse at the time of an earthquake and the ages of evacuees. Also, the evacuation success rate based on the ages of evacuees was considered. The targeted disaster was the tsunami caused by the 1854 Ansei Tokai earthquake. Based on the evacuation starting time and evacuation classification by age, the success evacuation rate suddenly decreased at age 30 when they began to evacuate 6 minutes later. Elderly people with slow walking speeds saw declining success rates from early on in the evacuation process. Overall, the higher the age is the lower the evacuation success rate. In other words, in the paper by Yun *et al.* [9], used information obtained on the 2011 Great East Japan Earthquake to analyze the factors that affected deaths caused by the tsunami, and noted that age and evacuation starting time had a significant influence. Doocy *et al.* [10] investigated the tsunami mortality and injury rates, as well as the surviving displaced population in Aceh, Indonesia, using a questionnaire. They administered the questionnaire to displaced persons with the help of local authorities in Meulaboh, Aceh Jaya, Aceh Besar, and Lhoksumawe. The highest mortality rate was 23.6% in the Aceh Jaya district on the west coast. In Banda Aceh/Aceh Besar, the crude mortality rate was 22.9%. As for the age-specific mortality rate, the highest mortality was seen in older people (over 70 years old) and young children (0–9 years old). Females suffered from greater damage than males in all survey areas. According to the results, females were 1.44 times more likely to die in the tsunami. In terms of the topographical characteristics, the Banda Aceh/Aceh Besar area is on an alluvial flood plain with a relatively low elevation. The reason for the gender disparity was suggested to be the fact that men were fishing far out at sea, or working the fields in agricultural areas. Regarding physical ability, women and young children could not stay on their feet in the face of the huge tsunami wave. Ginige *et al.* [11] indicated that gender differences are seen in the effects of natural disasters. Some research has found that women are more vulnerable to disasters because of their distinct roles and different responsibilities to their society or family. From a different point of view, Bateman and Edwards [12] explained that women are more likely than men to evacuate from hurricanes. Moreover, Charnkol and Tanaboriboon [13] conducted a behavioral analysis on human responses to future tsunami warnings, with a specific focus on determining evacuees' response patterns under various conditions in the Phuket and Phang-nga provinces of Thailand. The results showed that the probability of exhibiting a quick response pattern diminishes as the number of family member increases. If the distance the respondents lived from the evacuation site was short, they were more likely to evacuate earlier. Also, prior experiences of tsunami disasters caused people to evacuate earlier than those who lacked such experiences. Dash and Gladwin's study [14] examined actual evacuation behavior with a focus on evacuation modeling and the social context of events such as hurricane. This study focused on three topics: warnings, risk perception, and evacuation. Dash found that the evacuation situation differs between women and men. Women face a greater objective risk (because they live in risker housing). It was determined that *"risk perception, then, is a critical component in understanding how individuals decide to evacuate or to stay"*.

Figure 4.9 summarized construction of globally applicable human damage model for natural disaster (earthquake, tsunami and flooding) based on past studies. "Environment surrounding human society in the event of a natural disaster" shows the differences between Japan and overseas against human damage caused by natural disasters. This thesis classified significant influence on fatality model, significant differences situation between Japan and overseas and difficulty of getting a data

So far, this thesis has been able to organize the fatality factors related to natural disasters. Therefore, this thesis proposes a fatality model that takes into account the following three factors: tsunami characteristics, geographical features, and demographic components. Inundation depth is adopted as a tsunami characteristic; factors such as constructed evacuation distance and evacuation route are adopted as geographical features; and factors such as the age and gender of the exposed population that researchers have used as parameters in studying evacuation of natural disasters from these past studies are adopted as demographic components.

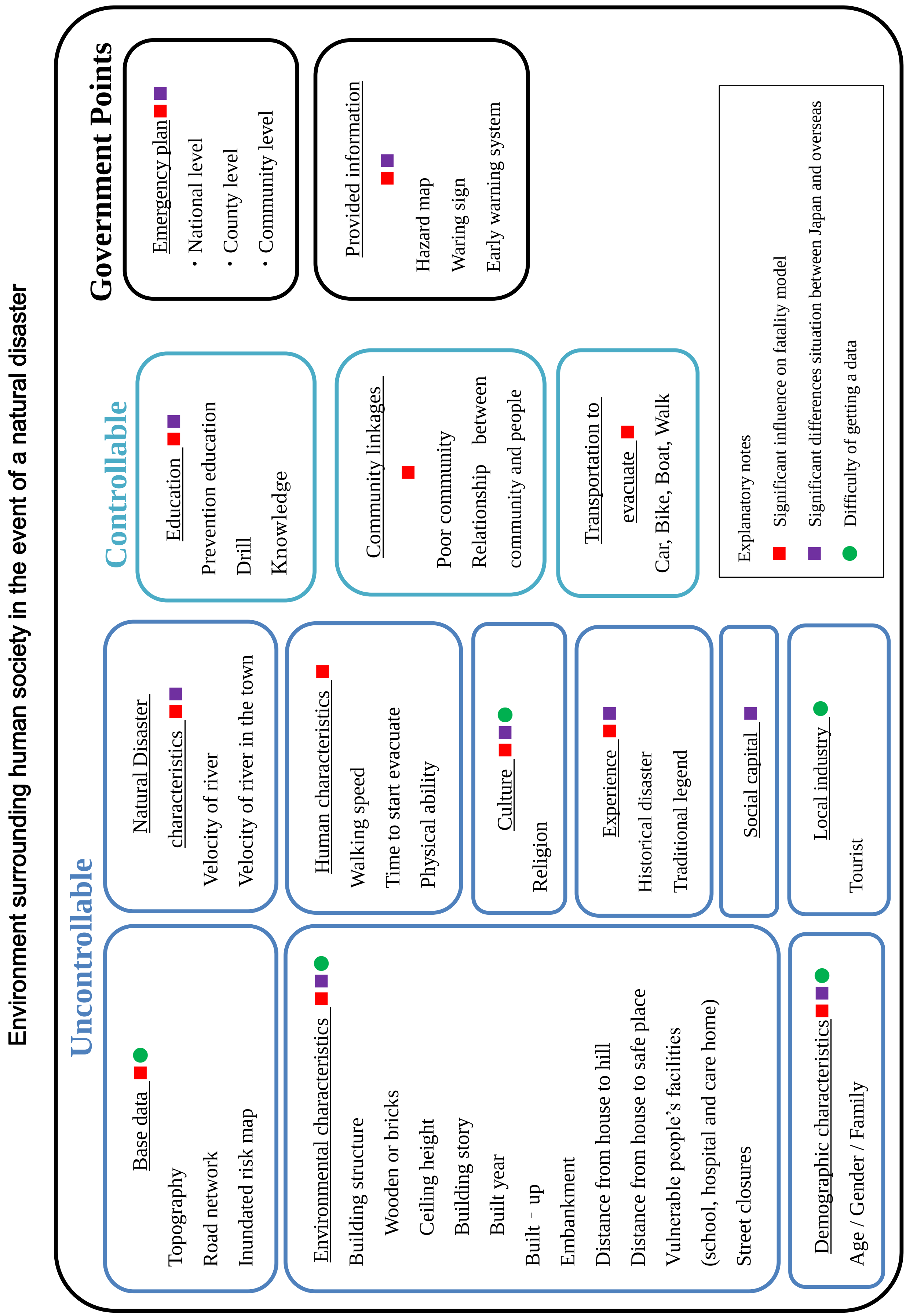


Figure 4.9: Construction of globally applicable human damage model for natural disaster (earthquake, tsunami and flooding)

4.4 Statistical analysis

The distance and elevation, which are characteristics of evacuation routes, were converted into numerals by obtaining an autoregressive moving average model (ARMA). Focusing on the altitude transition pattern of evacuation routes makes it possible to quantitatively classify the difference in altitude characteristics. This thesis determines the wavelength (*L*) and the damping ratio (*h*) of a single degree of freedom system, which expresses the smoothness of the evacuation routes. The processes are shown below.

Step C1. Organizing distance and elevation trend of evacuation route to non-inundated area based on analysis Section 4.1.1 and Section 4.1.2

Step C2. ARMA can be the most accurate representation of the elevation distribution. Therefore, this analysis creates a formula using the ARMA process. It is possible to classify the differences in elevation characteristics by focusing on the elevation trend of the evacuation route. ARMA model is a time series analysis, however in this analysis, the time to be distance of the evacuation route is considered.

$$y_n = \sum_{i=1}^{m} a_i y_{n-i} + v_n + \sum_{i=1}^{l} b_i v_{n-1} \quad (4.1)$$

where y_n and v_n are elevation (m), m and a_i are the autoregressive order and autoregressive coefficients, and l and b_i are the moving average order and moving average coefficient, respectively. In addition, the intercept value (intercept: immobile value) is also calculated by the ARMA process. The elevation trend of evacuation routes expressed in the ARMA process (2, 2) can be expressed by a single degree of freedom system in this thesis.

StepC3. This step determines the wavelength (*L*) and the damping ratio (*h*) using Eq. (4.1). These *L* and *h* can express the smoothness of the evacuation routes.

$$\lambda^2 + a_1\lambda + a_2 = 0$$
$$\left.\begin{array}{c}\lambda \\ \lambda^*\end{array}\right] = \exp\left(\frac{-2\pi h x}{L} \pm \frac{-2\pi\sqrt{1-h^2}x}{L}\right) \quad (4.2)$$

where x, L and h are the data sampling interval (10m), wavelength, and damping ratio. These L and h can express the geographical trend of the evacuation route. Wavelength (*L)* represents long or short wavelengths, which refers to the smoothness of the evacuation routes. Damping ratio (*h*) expresses divergence or convergence. The autoregressive parameters a_1, a_2 are obtained by Eq. (4.2) while λ, λ* represent conjugate complex numbers [15].

Step C4. Calculating the average value in each 500 m grid of population, inundation depth, evacuation distance, wavelength, damping ratio, and intercept by ARMA model in the inundated area where fatalities occurred. In the area where there were no fatalities, the value of these is sorted by the eight parameters above. Specifically, the calculated wavelength and damping ratio corresponds to the severity of the undulation of the evacuation route and the uphill/downhill of the terrain (Figure 4.10). The intercept value takes a positive value when the land tends to be higher than the coastal altitude. One the other hand, in the case of area which has a plain, it is defined as (0, 0, 0) in this ARMA model. It is noted that the area is judged to be directly affected by population and inundation depth.

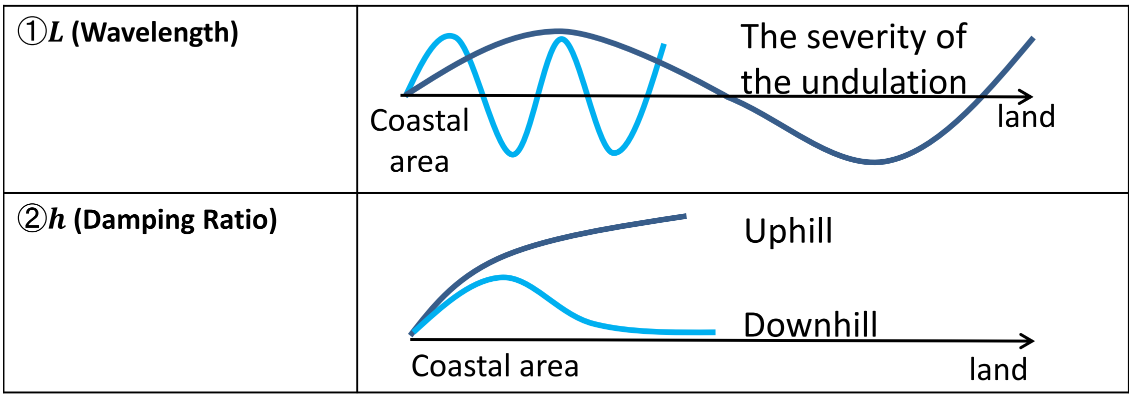


Figure 4.10: Trend of the evacuation route

Step C5. Based on this analysis, multiple regression analyses were carried out against eight explanatory variables: population, average inundation depth, average evacuation distance, average intercept by ARMA model, average wavelength, average damping ratio, percentage of men, and the percentage of people over 65 years old; the objective variable was the number of deaths in each 500 m grid.

Step C6. The fatality model is proposed in Eq. (4.3).

$$D = a_1 P + a_2 x_1 + a_3 x_2 + a_4 x_3 + a_5 x_4 + a_6 x_5 + a_7 x_6 + a_8 x_7 + \mathrm{C} \tag{4.3}$$

where D, P, $x_1, x_2, x_3, x_4, x_5, x_6$ and x_7 are the death toll in a 500 m grid, population before the event, average inundation depth (m), average evacuation distance (m), average intercept by ARMA model, average wavelength, average damping ratio, percentage of men, and people over 65 years old in each 500 m grid, respectively.

Second, the average prediction error is defined as follows to evaluate how much difference exists between the actual death toll and the estimated death toll.

$$E_a = \frac{1}{N} \sum_{i}^{N} |Y_{ai} - y_{ei}| \tag{4.4}$$

Here, N is the number of grid, Y_{ai}, y_{ei} are the actual number of deaths in a 500 m grid, and the estimated death toll is calculated by the proposed model in this thesis.

4.5 Result of statistical analysis

Ordinarily, to explain the human damage caused by a tsunami, this thesis would analyze the location where a person was at the time of the tsunami, where a person was caught up in the tsunami, and how to evacuate to a safe place. However, this analysis was based on the deceased's address. This thesis assumed that all residents died at home and constructed a regression equation based on the results obtained from the above analysis. However, in reality, not everyone died at home. From a questionnaire survey targeting all households in Kamaishi City, Iwate Prefecture, and with regard to the elderly who had a particularly high fatality rate, Kanai and Katada indicate that about 58% of those who did not evacuate were affected by the tsunami at home [16]. Therefore, it is necessary to take into account that the number estimated may be different from the actual number of deaths. Moreover, the 2010 population census used in this thesis is the resident population; that is, it is equivalent to the nighttime rather than the daytime population. However, since the 2011 Great East Japan Tsunami actually occurred during the daytime, the fatality rate should be calculated by using the daytime population. Here investigated the population of case study areas' municipalities from the 2010 population census (Table 4.2). The daytime population means the sum of the population except for the population of commuters to other municipalities plus the population from other municipalities. Although the daytime to nighttime ratio is less than 100% in many municipalities, there are also a few regions where daytime to nighttime ratio is more than 100%. Overall, the difference is not that large. From the results, this thesis regard the population used as slightly lower than the one calculated for the daytime population because the number of people in the daytime is smaller than in the nighttime population in many areas.

As a result of performing multiple regression analysis on all data, it was not possible to obtain accurate results. For example, it can be seen that the predicted value is capped at about ten fatalities in any region. The reason is that the data on more than ten fatalities is not sufficient, or there is the tendency of the occurrence of fatality to differ depending on the circumstances. Therefore, only data with estimated fatalities of more than ten people were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. According to the report of Nagoya University [17], the occurrence of fatalities by tsunami disasters occurs when buildings are washed away by tsunami events and the fatality rate increases when the inundation of houses is over 3 m from the viewpoint of house damage. Moreover, Aoki [18] found that the proportion of fatality increased when the flood depth exceeded 4 m. The height from the floor to the second floor of a general wooden house is approximately 3.5 m. Since this inundation depth corresponds to the height at which the first-floor portion of two-storied building is submerged, there is a high possibility that fatality can be avoided by evacuating to the second floor. Aoki's study suggested a situation where the likelihood of fatality increases if flooding exceeds the height of the second floor. Hence, only data with estimated inundation depth of more than 4m were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. The flow of construction of fatality model is shown in the Figure 4.11.

Table4.2: Daytime to nighttime ratio

Name of region	Employment areas Daytime population	Residential areas Nighttime population	Daytime/Night time Ratio (%)
Fukushima Prefecture			
Shinchi Town	7,348	8,224	89.3
Soma City	37,848	37,817	100.1
Minamisoma City	69,455	70,878	98.0
Iwaki City	340,569	342,249	99.5
Iwate Prefecture			
Noda Village	3,954	4,632	85.3
Tanohata Village	3,692	3,843	96.1
Miyako City	60,406	59,430	101.6
Yamada Town	16,983	18,617	91.2
Otsuchi Town	13,695	15,276	89.7
Kamaishi City	41,514	39,574	104.9
Ofumato City	41,963	40,737	103.0
Rikuzentaka City	21,284	23,300	91.3

Source: 2010 Population Census of Fukushima Prefecture and Iwate Prefecture

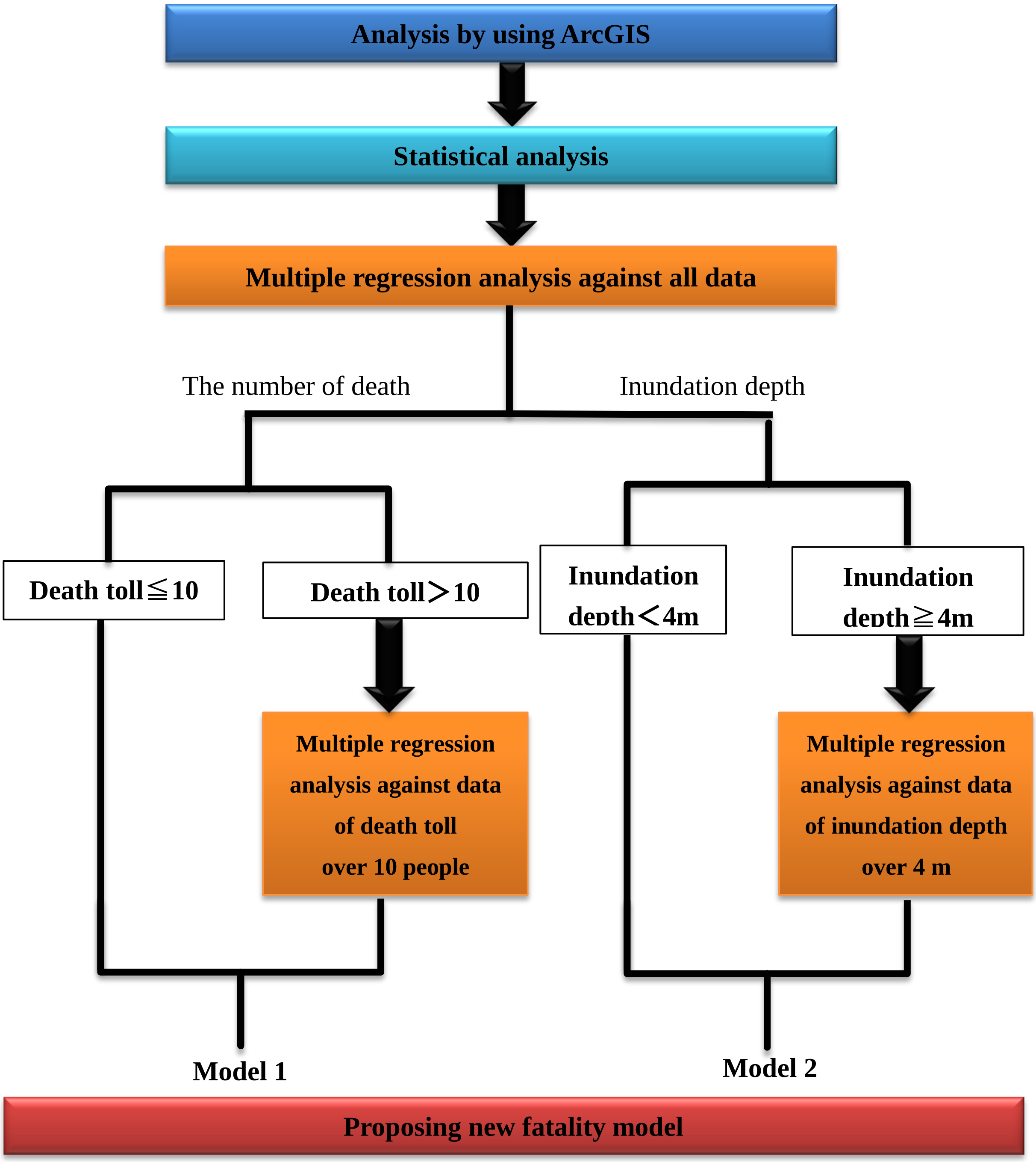


Figure 4.11: Research framework using in Chapter 4

4.5.1 Fukushima Prefecture

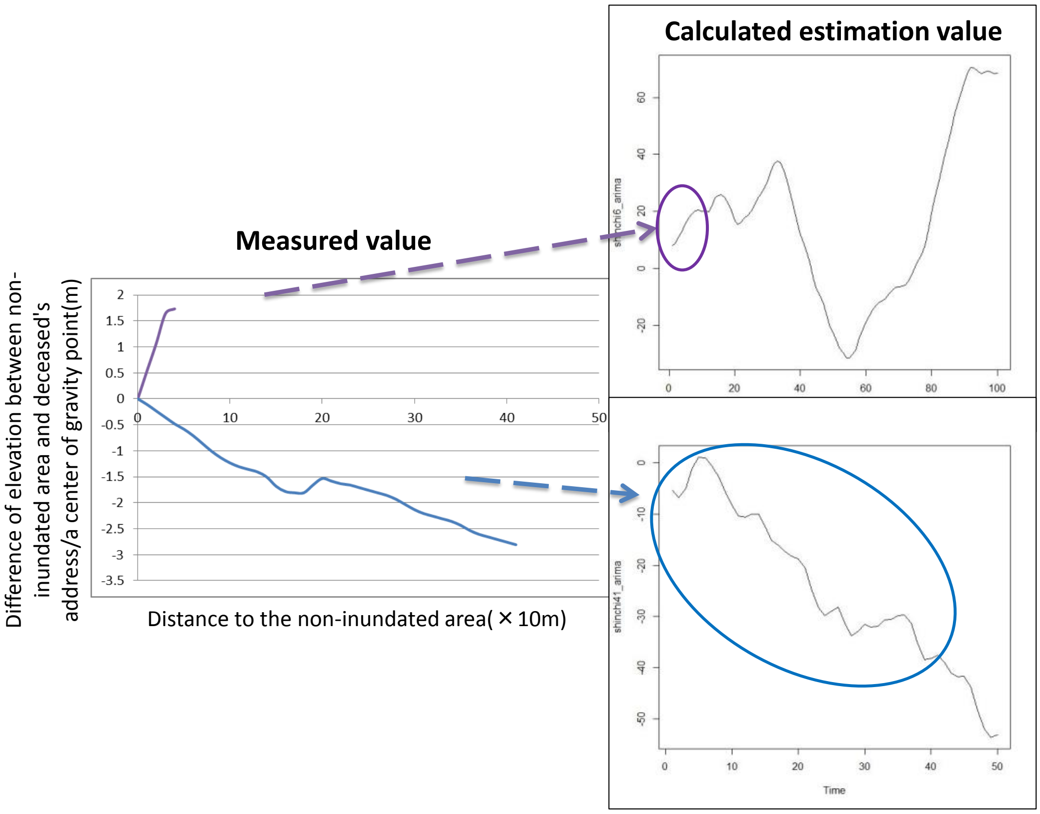
Figure 4.12 shows the results of quantifying the actual evacuation route by ARMA model and the features of evacuation route. Right side of figure indicates the deceased's home address and left side of figure indicates point that overlaps the inundated area. Specifically, it is considered that the calculated wavelength *(L)* and damping ratio (*h*) correspond to the severity of the undulation of the evacuation route and the uphill/downhill movement of the terrain. The intercept by ARMA model value often takes a positive value when the land tends to be higher than the coast altitude.

Based on analysis, this thesis calculated population in each grid, average inundation depth in each grid, average evacuation distance in each grid, average intercept by ARMA model in each grid, average wavelength in each grid, average damping ratio in each grid, percentage of men in each grid and percentage of people over 65 years old in each grid. Each grid indicated 500 m grid provided by the 2010 population census. The result is shown in Table 4.3 (1) and (2). Then, this method carried out multiple regression analysis against these eight explanatory variables *P* and x_1~x_7, and the number of deaths *D*. The result obtained by the multiple regression analysis equation is shown in Eq. (4.3). Moreover result of analysis using all municipal data collectively is shown in Figure 4.13 as Fukushima Prefecture. The death toll (◯ mark and ■ mark) in the 500 m grid calculated by using the proposed model and the death toll (× marks) in the 500 m grid calculated by Eq. (2.1) are shown in Figure 4.13. Looking at the number of death, first of all, the ◯ mark in Figure 4.13 is a result of multiple regression analyses on all data of the target areas and calculation of the death toll in the 500 m grid by Eq. (4.3). It can be seen that the predicted value is capped at about ten fatalities in any region. The reason is that the data on more than ten fatalities is not sufficient, or there is the tendency of the occurrence of fatalities to differ depending on the circumstances. Therefore, only data with estimated fatalities of more than ten people were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. Finally, the result of calculating the death toll with the result of D≦10 and the result of D>10 is the ■ mark in Figure 4.13. Hence, if the estimated death toll is ten people or less, the parameters of the upper table are used, and if the predicted death toll is more than ten people, the parameters of the lower table will be used shown in Table 4.3 (2) (All results of model1).

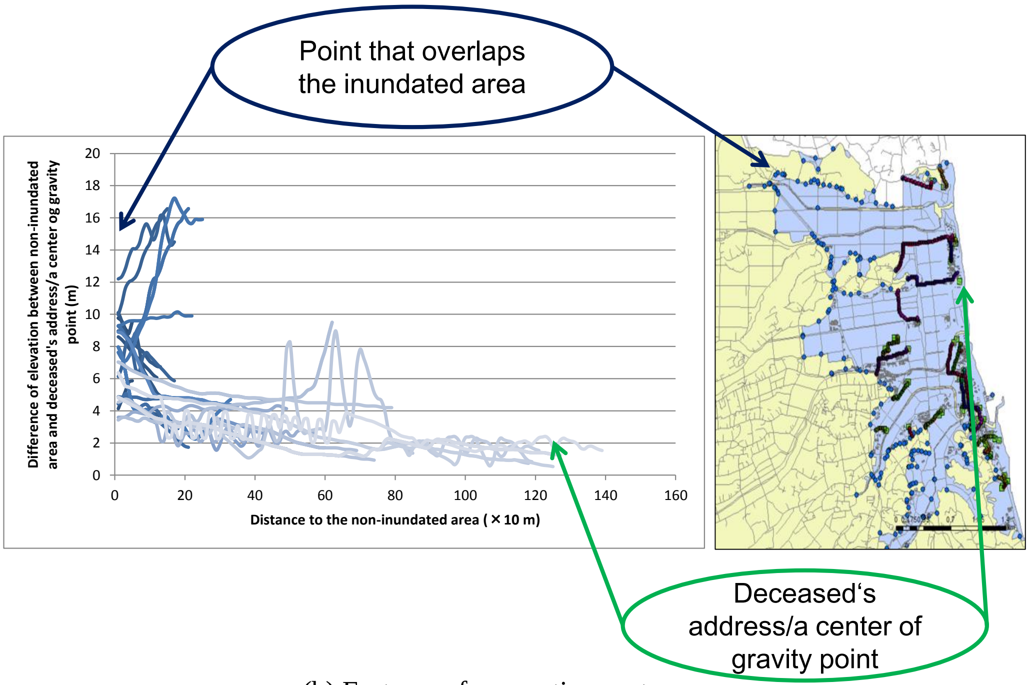
Next, looking at the inundation depth, the ◯ mark in Figure 4.14 is a result of multiple regression analyses on all data of the target areas and calculation of the death toll in the 500 m grid by Eq. (4.3). As also discussed above, multiple regression analysis using Eq. (4.3) was performed using all data. Next, only data with of observed inundation depth more than 4 m were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. The result of calculating the death toll with the result of inundation depth < 4 m and the result of inundation depth≧4 m is the ■ mark in Figure 4.14.

Ea (◯), *Ea* (■) and *Ea* (■) represent the average prediction error using Eq. (4.4), and *Eac* (×) represents it using Eq. (2.1). Here understood that the death toll calculated by the proposed model in this method was much lower than the prediction error calculated by Eq. (4.4) as shown in table in Figure 4.13 and Figure 4.14.

The equation of the Central Disaster Management Council assumed the number of deaths to be about 2,700 in the affected area as a whole, but in reality, deaths of about as much 7.6 times occurred. The formula proposed here is thought to be able to evaluate the death toll with a higher degree of accuracy than the formula of the Central Disaster Council [19].

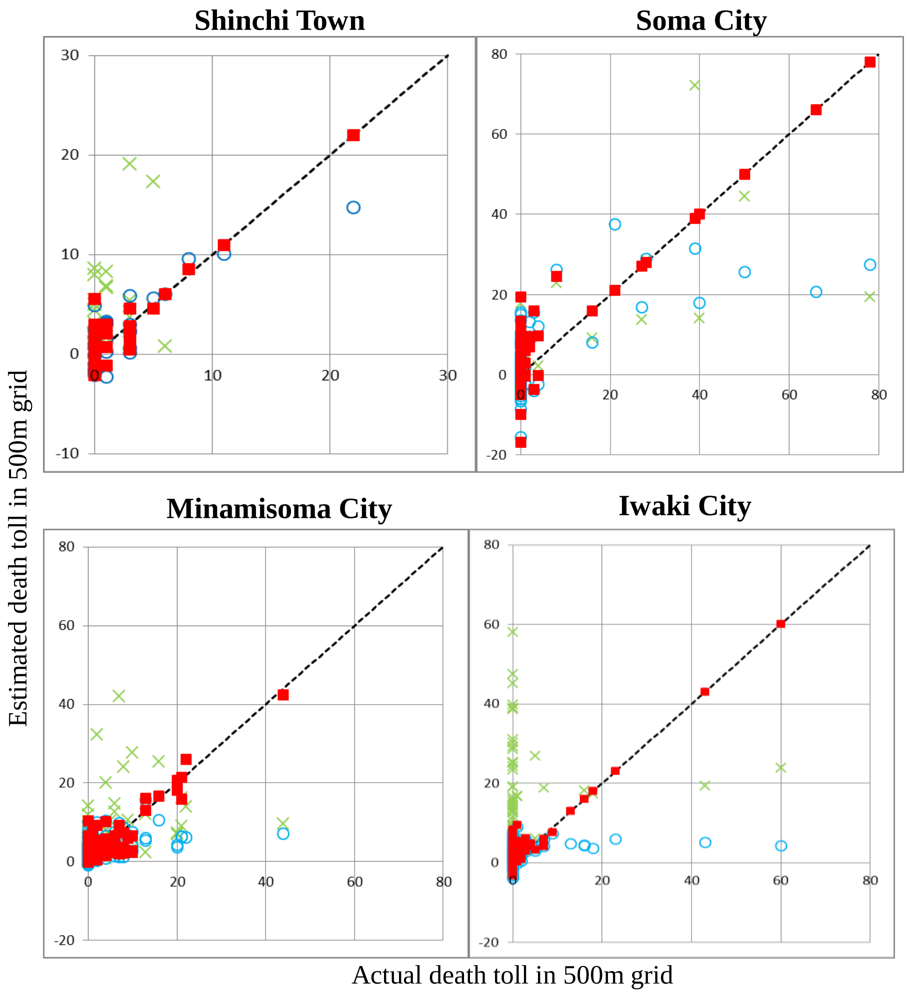


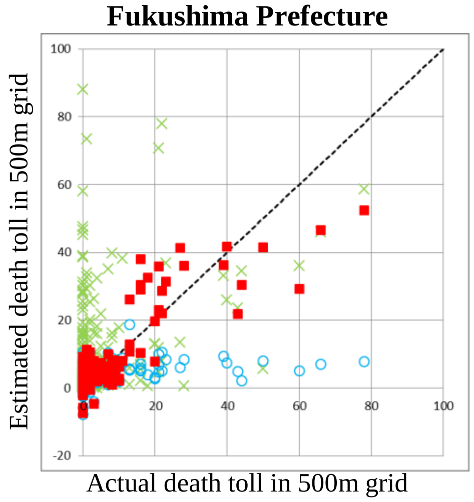
(a) Results of quantifying the actual evacuation route by ARMA model



(b) Features of evacuation route

Figure 4.12: Results of the features of evacuation route





Average prediction error

	Ea(○)	Ea(■)	Eac(×)
Shinchi Town	1.62	1.39	8.79
Soma City	6.82	4.8	7.45
Minamisoma City	2.82	2.51	7.55
Iwaki City	3.17	3.32	17.47
Fukushima Prefecture	4.01	3.15	10

Explanatory notes

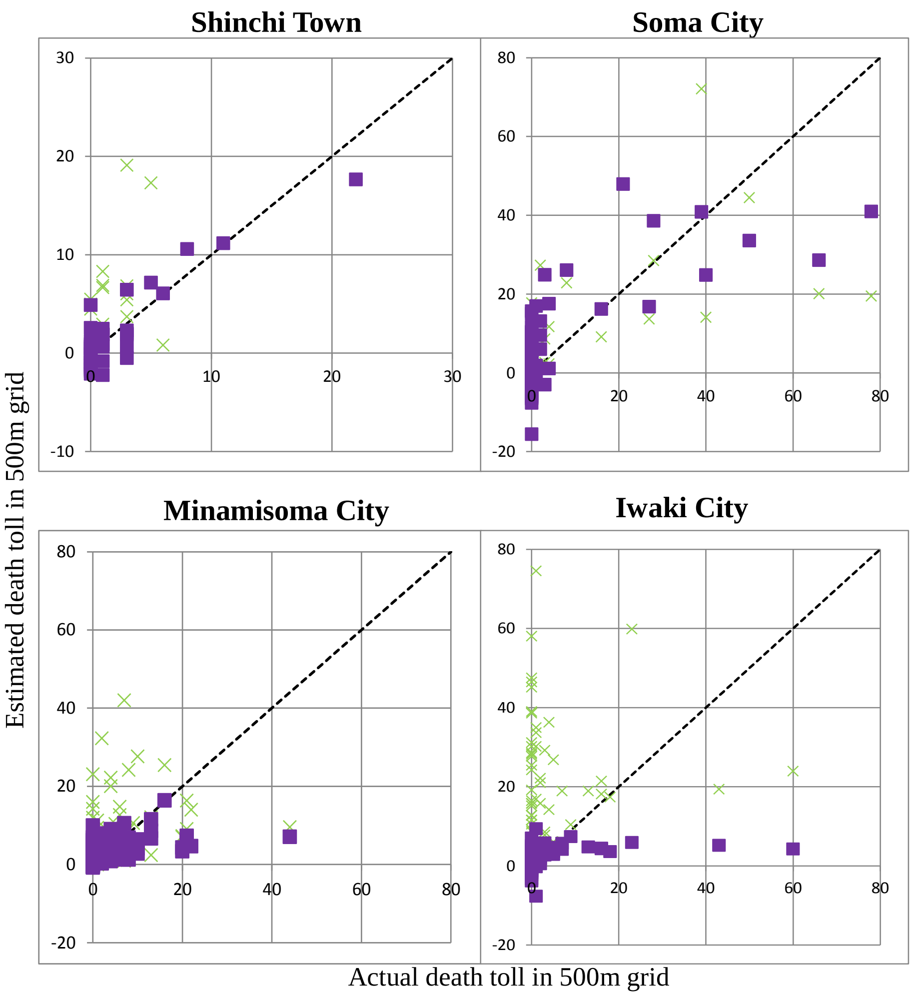
.... Actual death toll

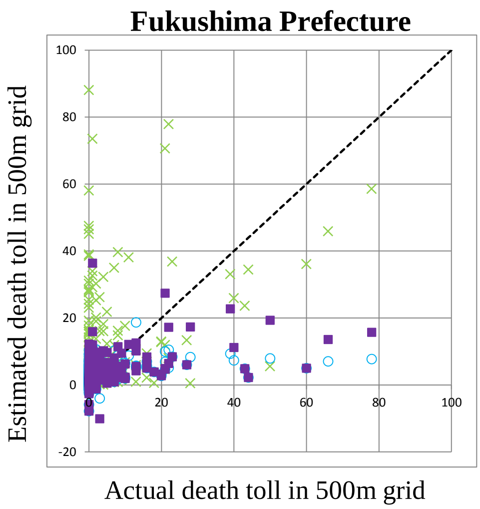
■ Estimated death toll using new fatality model (Model 1, the result of D≦10 and the result of D>10)

○ Estimated death toll (Model 1, the result of D≦10)

× Estimated death toll using equation of Central Disaster Management Council

Figure 4.13: Correlation between actual death toll and estimated death toll using Eq. (4.3) in Fukushima Prefecture (Model 1)





Average prediction error

	Ea(○)	Ea(■)	Eac(×)	Ea(■)
Shinchi Town	1.62	1.39	8.79	1.52
Soma City	6.82	4.8	7.45	6.63
Minamisoma City	2.82	2.51	7.55	2.74
Iwaki City	3.17	3.32	17.47	2.83
Fukushima Prefecture	4.01	3.15	10	3.79

Explanatory notes

………… Actual death toll

■ Estimated death toll using new fatality model (Model 2, Inundation depth< 4m and Inundation depth≧4)

○ Estimated death toll (Model 2, Inundation depth< 4m)

× Estimated death toll using equation of Central Disaster Management Council

Figure 4.14: Correlation between actual death toll and estimated death toll using Eq. (4.3) in Fukushima Prefecture (Model 2)

Table4.3 (1): Results of coefficient in Fukushima Prefecture

Shinchi Town

	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.03015	0.00562	5.36300	0.00002	***
Average inundation depth	0.69580	0.23810	2.92300	0.00745	**
Average evacuation distance	0.00066	0.00370	0.17900	0.85929	
Average intercept	-0.03034	0.13990	-0.21700	0.83010	
Average wavelength	0.00003	0.00001	2.05300	0.05114	+
Average damping ratio	-0.08559	0.11780	-0.72700	0.47451	
Gender(men)	0.00115	0.00676	0.17000	0.86658	
Age(over 65 years old)	0.03287	0.03519	0.93400	0.35965	
Intercept	-4.51700	1.71100	-2.64000	0.01436	*

Soma City

	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.05431	0.01075	5.05200	0.00000	***
Average inundation depth	0.53350	0.49910	1.06900	0.28897	
Average evacuation distance	0.02158	0.00641	3.36500	0.00127	**
Average intercept	-0.22640	0.28810	-0.78600	0.43487	
Average wavelength	-0.00003	0.00015	-0.17100	0.86484	
Average damping ratio	-0.06048	0.20710	-0.29200	0.77119	
Gender(men)	0.12170	0.17170	0.70900	0.48082	
Age(over 65 years old)	0.10570	0.10360	1.02000	0.31138	
Intercept	-15.74000	8.91900	-1.76500	0.08212	+

Minamisoma City

	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.0335	0.0079	4.2280	0.0000	***
Average inundation depth	0.4621	0.1808	2.5560	0.0117	*
Average evacuation distance	0.0019	0.0020	0.9160	0.3613	
Average intercept	-0.0110	0.0893	-0.1240	0.9017	
Average wavelength	0.0005	0.0005	0.9470	0.3452	
Average damping ratio	0.0003	0.0010	0.3500	0.7271	
Gender(men)	-0.0185	0.0500	-0.3700	0.7121	
Age(over 65 years old)	0.0096	0.0085	1.1270	0.2617	
Intercept	-0.8110	2.7434	-0.2960	0.7680	

*** P<0.001, **P<0.01, *P<0.05, +P<0.1

Table4.3 (2): Results of coefficient in Fukushima Prefecture

Iwaki City

	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.001476	0.0022	0.684	0.49539	
Average inundation depth	1.359000	0.4770	2.849	0.00529	**
Average evacuation distance	-0.000086	0.0024	-0.035	0.97178	
Average intercept	-0.378500	0.2494	-1.518	0.13212	
Average wavelength	-0.000004	0.0004	-0.012	0.99067	
Average damping ratio	0.042710	0.0563	0.759	0.44986	
Gender(men)	-0.126600	0.1495	-0.847	0.39904	
Age(over 65 years old)	-0.000129	0.0289	-0.004	0.99644	
Intercept	7.105000	7.5520	0.941	0.34897	

Fukushima Prefecture (4 municipalities)

	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.005791	0.001931	2.999000	0.002900	**
Average inundation depth	0.704900	0.174200	4.047000	0.000064	***
Average evacuation distance	0.003337	0.001758	1.898000	0.058400	+
Average intercept	-0.242800	0.092700	-2.619000	0.009200	**
Average wavelength	0.000001	0.000040	0.029000	0.976900	
Average damping ratio	0.000451	0.001584	0.284000	0.776200	
Gender(men)	-0.009686	0.012610	-0.768000	0.443000	
Age(over 65 years old)	0.003878	0.011640	0.333000	0.739200	
Intercept	0.766400	1.303000	0.588000	0.556000	

All results of model 1 (result of D≦10 and result of D>10)

		a1	a2	a3	a4	a5	a6	a7	a8	C
		Population	Inundation depth	Evacuation distance	Intercept by ARMA model	Wavelength	Damping ratio	Gender	Age	Intercept
Shinchi Town	D≦10	0.0302***	0.6958**	0.0007	-0.0303	0.00003+	-0.0856	0.0011	0.0329	-4.5170
	D > 10	–	–	–	–	–	–	–	-2.6650	97.6240
Soma City	D≦10	0.0543***	0.5335	0.0216**	-0.2264	-0.00003	-0.0605	0.1217	0.1057	-15.7400+
	D > 10	0.1782	-40.6152	-0.0619	-99.7969	-0.0140	0.2662	3.8122	2.3065	-133.4540
Miamisoma City	D≦10	0.0335**	0.4621*	0.0019	-0.0110	0.0005	0.0003	-0.0185	0.0096	-0.8110
	D > 10	0.2411	0.8168	-0.0219	1.0842	-0.0025	-0.8617	1.1306	0.0381	-59.5698
Iwaki City	D≦10	0.0015	1.359**	-0.0001	-0.3785	-0.000004	0.0427	-0.1266	-0.0001	7.1050
	D > 10	–	-39.2030	-0.4111	42.0880	-0.0912	43.9320	–	23.1737	-733.7588
Fukushima Prefecture	D≦10	0.0058**	0.7049***	0.0033+	-0.2428 **	0.000001	0.0005	-0.0097	0.0039	0.7664
	D > 10	0.0099	-1.8641	0.0386	0.1713	-0.0017	-2.2986	-0.1067	-0.0111	33.1758

*** P<0.001, **P<0.01, *P<0.05, +P<0.1

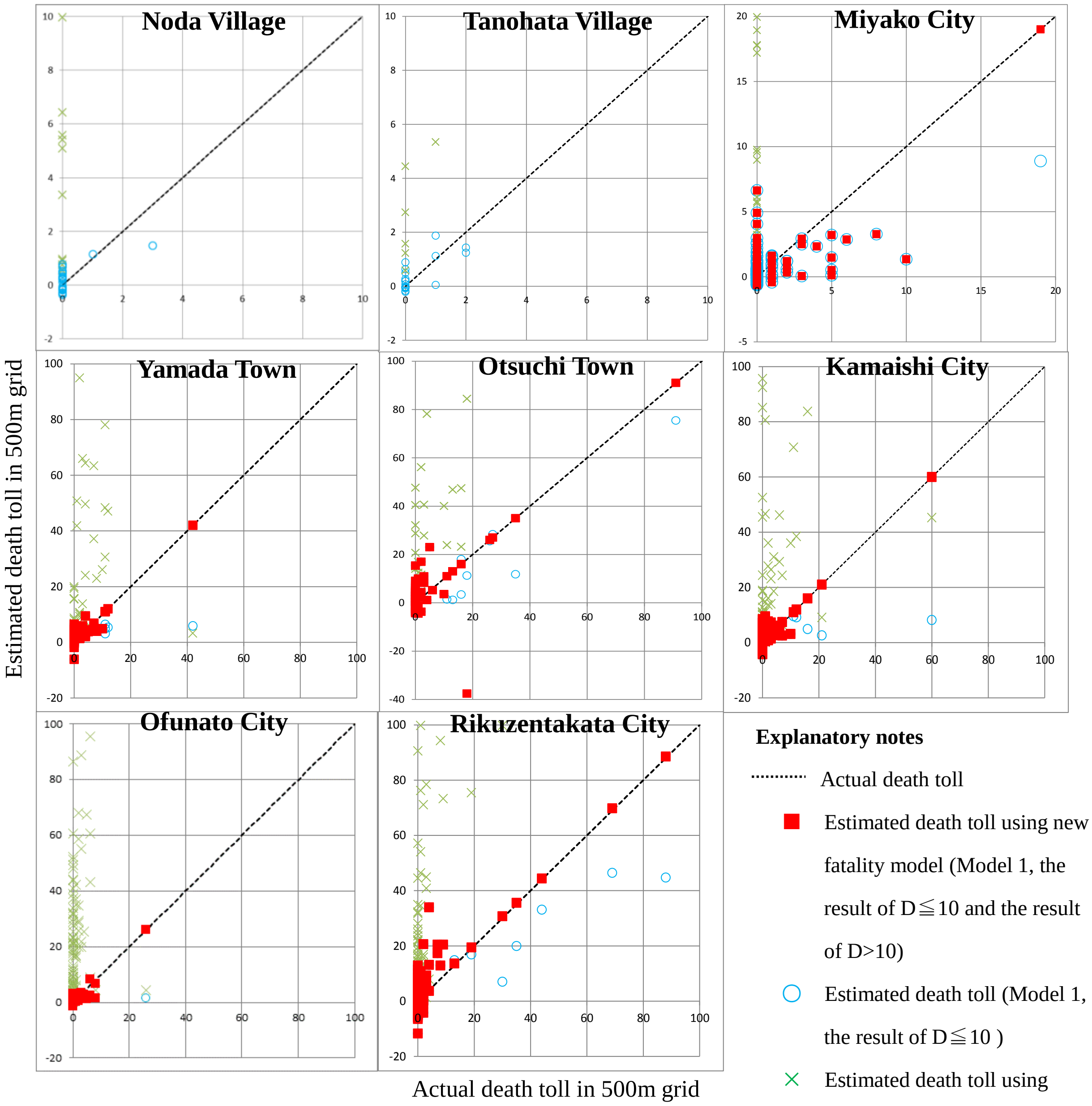
4.5.2 Iwate Prefecture

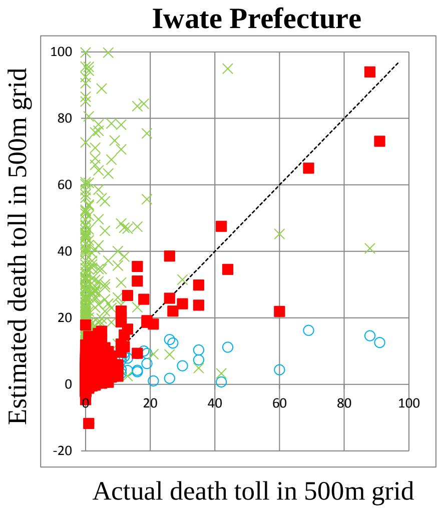
Here results are Noda Village, Tanohata Village, Miyako City, Yamada Town, Otsuchi Town, Kamaishi City, Ofunato City and Rikuzentakata City in Iwate Prefecture. The target sample was fatalities in the inundated area in each municipality. Using data is provided by the result of analyzing the interview data on the human behavior of the deceased in Iwate Prefecture of Iwate Nippo.

Based on analysis, this thesis calculated population, average inundation depth, average evacuation distance, average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old in each grid same as the analysis on Fukushima Prefecture. Each grid indicated 500m grid provided by the 2010 population census. The result is shown in Table 4.4 (1) and (2). Then, this method carried out multiple regression analysis against these eight explanatory variables P and x_1~x_7, and the number of deaths D. The result obtained by the multiple regression analysis equation is shown in Eq. (4.3). Moreover result of analysis using all municipal data collectively is shown in Figure 4.15 as Iwate Prefecture. The death toll (○ mark and ■ mark) in the 500 m grid calculated by using the proposed model and the death toll (× marks) in the 500 m grid calculated by Eq. (2.1) are shown in Figure 4.15. Looking at the number of death, first of all, the ○ mark in Figure 4.15 is a result of multiple regression analyses on all data of the target areas and calculation of the death toll in the 500 m grid by Eq. (4.3). It can be seen that the predicted value is capped at about ten fatalities in any region as well as Fukushima Prefecture. The reason is that the data on more than ten fatalities is not sufficient, or there is the tendency of the occurrence of fatality to differ depending on the circumstances. Therefore, only data with estimated fatalities of more than ten people were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. Finally, the result of calculating the death toll with the result of $D \leqq 10$ and the result of $D>10$ is the ■ mark in Figure 4.15. Hence, if the estimated death toll is ten people or less, the parameters of the upper table are used, and if the predicted death toll is more than ten people, the parameters of the lower table will be used shown in Table 4.4 (2) (All results of model1).

Next, looking at the inundation depth, the ○ mark in Figure 4.16 is a result of multiple regression analyses on all data of the target areas and calculation of the death toll in the 500 m grid by Eq. (4.3). As also discussed above, multiple regression analysis using Eq. (4.3) was performed using all data. Next, only data with of observed inundation depth more than 4m were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. The result of calculating the death toll with the result of inundation depth < 4 m and the result of inundation depth ≧ 4 m is the ■ mark in Figure 4.16.

Ea (○), *Ea* (■) and *Ea* (■) represent the average prediction error using Eq. (4.4), and *Eac* (×) represents it using Eq. (2.1). The death toll calculated by the proposed model was much lower than the prediction error calculated by Eq. (2.1) as shown in table in Figure 4.15 and Figure 4.16. Death toll calculated by the proposed model is 1,861 people, on the other hand, death toll took into account of interview data in Iwate Prefecture by Iwate Nippo is 6,204 people. Necrology by Iwate prefectural police was 4,419 people.

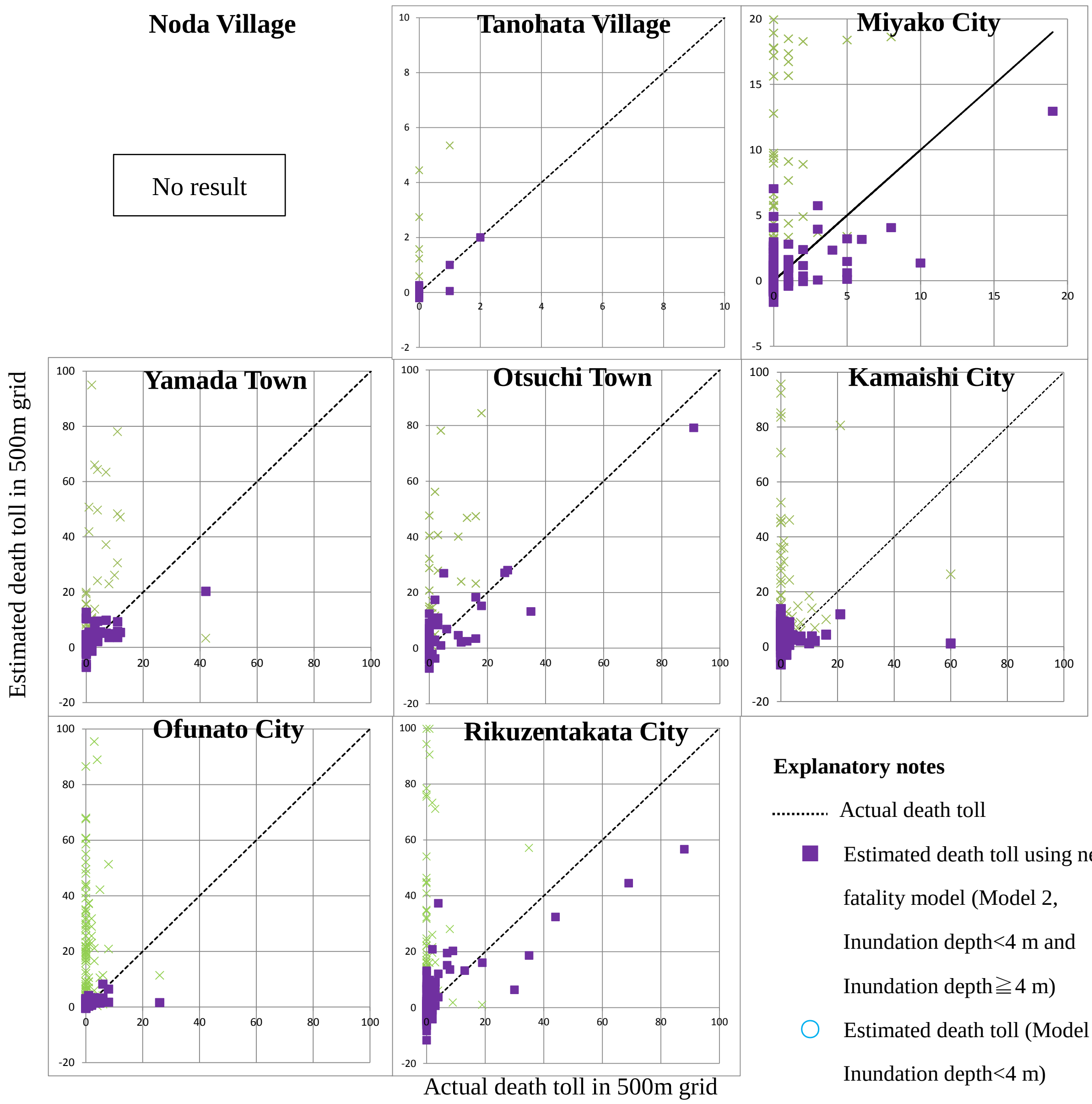


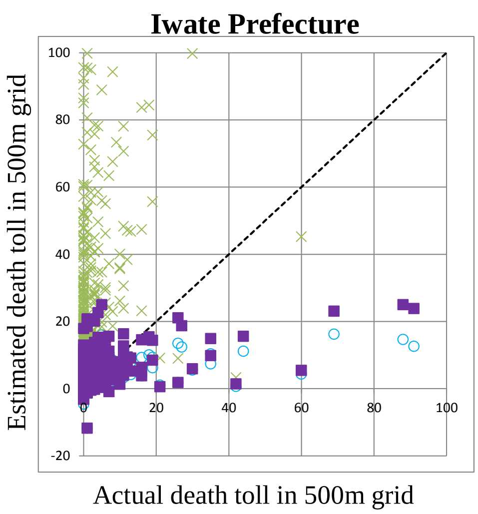


Average prediction error

	Ea(○)	Ea(■)	Eac(×)
Noda Village	0.34	—	14.48
Tanohata Village	0.35	—	33.96
Miyako City	1.09	1.01	13.7
Yamada Town	2.85	1.86	19.02
Otsuchi Town	5.36	4.78	33.11
Kamaishi City	3.16	2.27	26.81
Ofunato City	1.1	0.92	26.39
Rikuzentakata City	4.07	3.28	40.17
Iwate Prefecture	2.9	2.33	27.58

Figure 4.15: Correlation between actual death toll and estimated death toll using Eq. (4.3) in Iwate Prefecture (Model 1)





Average prediction error

	Ea(○)	Ea(■)	Eac(×)	Ea(■)
Noda Village	0.34	—	14.48	—
Tanohata Village	0.35	—	33.96	1.89
Miyako City	1.09	1.01	13.7	1.13
Yamada Town	2.85	1.86	19.02	3.25
Otsuchi Town	5.36	4.78	33.11	5.16
Kamaishi City	3.16	2.27	26.81	4.27
Ofunato City	1.1	0.92	26.39	1.08
Rikuzentakata City	4.07	3.28	40.17	4.17
Iwate Prefecture	2.9	2.33	27.58	3.04

Figure 4.16: Correlation between actual death toll and estimated death toll using Eq. (4.3) in Iwate Prefecture (Model 2)

Table 4.4 (1): Results of coefficient in Iwate Prefecture

	Noda Village					**Tanohata Village**				
Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)		Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.003435	0.00158	2.178	0.061	+	-0.00062	0.0035	-0.180	0.861	
Average inundation depth	-0.032930	0.05615	-0.587	0.574		0.07405	0.0673	1.100	0.300	
Average evacuation distance	-0.000142	0.00133	-0.107	0.918		0.00023	0.0036	0.064	0.951	
Average intercept	-0.057990	0.08870	-0.654	0.532		0.00480	0.0030	1.622	0.139	
Average wavelength	0.000003	0.00001	0.306	0.767		-0.00002	0.0001	-0.334	0.746	
Average damping ratio	0.149800	0.38980	0.384	0.711		-0.38910	0.5759	-0.676	0.516	
Gender(men)	0.005178	0.03133	0.165	0.873		0.00794	0.0550	0.145	0.888	
Age(over 65 years old)	0.001688	0.01457	0.116	0.911		-0.00567	0.0137	-0.413	0.689	
Intercept	0.116100	1.43900	0.081	0.938		0.04861	3.6620	0.013	0.990	

	Miyako City					**Yamada Town**				
Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)		Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.00302	0.00082	3.662	0.000	***	0.00668	0.0035	1.923	0.060	+
Average inundation depth	0.04891	0.05554	0.881	0.381		0.29680	0.3005	0.988	0.328	
Average evacuation distance	-0.00069	0.00169	-0.410	0.682		0.00355	0.0077	0.459	0.648	
Average intercept	-0.00003	0.00032	-0.106	0.916		0.00383	0.0052	0.734	0.467	
Average wavelength	0.00024	0.00004	5.320	0.000	***	-0.00001	0.0001	-0.112	0.912	
Average damping ratio	0.40860	0.49020	0.834	0.407		0.73940	1.6440	0.450	0.655	
Gender(men)	-0.01878	0.02228	-0.843	0.401		0.05980	0.1471	0.406	0.686	
Age(over 65 years old)	0.00054	0.00896	0.061	0.952		-0.07766	0.0589	-1.320	0.193	
Intercept	0.37030	1.21300	0.305	0.761		-0.88410	8.2660	-0.107	0.915	

	Otsuchi Town					**Kamaishi City**				
Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)		Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.0170	0.0055	3.072	0.004	**	0.0112	0.0046	2.402	0.019	*
Average inundation depth	0.4109	0.4395	0.935	0.356		0.0122	0.2160	0.056	0.955	
Average evacuation distance	-0.0115	0.0102	-1.124	0.269		0.0009	0.0044	0.207	0.836	
Average intercept	0.1369	0.2369	0.578	0.567		-0.0862	0.0795	-1.085	0.282	
Average wavelength	0.0027	0.0019	1.395	0.172		-0.0006	0.0034	-0.191	0.849	
Average damping ratio	1.2486	0.1661	7.517	0.000	***	-0.5265	0.2862	-1.840	0.070	+
Gender(men)	0.0837	0.1200	0.698	0.490		0.0969	0.1063	0.911	0.366	
Age(over 65 years old)	0.0021	0.0823	0.025	0.980		-0.0215	0.0635	-0.339	0.736	
Intercept	-6.2544	7.3727	-0.848	0.402		-2.6009	5.6539	-0.460	0.647	

*** P<0.001, **P<0.01, *P<0.05, +P<0.1

Table 4.4 (2): Results of coefficient in Iwate Prefecture

Ofunato City

Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.00299	0.0012	2.543	0.012	*
Average inundation depth	-0.03874	0.0593	-0.653	0.515	
Average evacuation distance	0.00206	0.0025	0.834	0.406	
Average intercept	-0.00146	0.0006	-2.540	0.012	*
Average wavelength	-0.00003	0.0001	-0.212	0.832	
Average damping ratio	-0.00046	0.0066	-0.071	0.944	
Gender(men)	-0.01081	0.0262	-0.412	0.681	
Age(over 65 years old)	0.01490	0.0165	0.902	0.369	
Intercept	0.33660	1.4790	0.228	0.820	

Rikuzentakata City

Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.0539	0.0053	10.123	<2e-16	***
Average inundation depth	0.0116	0.1952	0.059	0.953	
Average evacuation distance	0.0060	0.0046	1.286	0.201	
Average intercept	0.0741	0.1513	0.490	0.625	
Average wavelength	-0.0005	0.0005	-1.007	0.316	
Average damping ratio	0.2077	0.0791	2.626	0.010	**
Gender(men)	0.0514	0.0699	0.735	0.464	
Age(over 65 years old)	-0.0393	0.0455	-0.864	0.390	
Intercept	-6.4757	4.5474	-1.424	0.157	

Iwate Prefecture (8 municipalities)

Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.0136	0.00141	9.690	<2e-16	***
Average inundation depth	0.2225	0.07348	3.028	0.003	**
Average evacuation	0.0059	0.00203	2.925	0.004	**
Avearge intercept	0.0004	0.00085	0.420	0.674	
Average wavelength	0.0000	0.00005	0.057	0.954	
Average damping ratio	0.0368	0.01752	2.099	0.036	*
Gender(men)	0.0058	0.03261	0.178	0.858	
Age(over 65 years old)	0.0026	0.01772	0.145	0.885	
Intercept	-2.8500	1.76800	-1.612	0.108	

All results of model 1 (result of D≦10 and result of D>10)

		a1	a2	a3	a4	a5	a6	a7	a8	C
		Population	Inundation depth	Evacuation distance	Intercept by ARMA model	Wavelength	Damping ratio	Gender	Age	Intercept
Noda Village	D≦10	0.0034 +	-0.0329	-0.0001	-0.0580	0.000003	0.1498	0.0052	0.0017	0.1161
	D > 10	-	-	-	-	-	-	-	-	-
Tanohata Village	D≦10	-0.0006	0.0741	0.0002	0.0048	-0.000022	-0.3891	0.0079	-0.0057	0.0486
	D > 10	-	-	-	-	-	-	-	-	-
Miyako City	D≦10	0.0030***	0.04891	-0.00069	-0.00003	0.0002***	0.40860	-0.01878	0.00054	0.37030
	D > 10	-	-	-	-	-	-	-	-	19.0000
Yamada Town	D≦10	0.00668 +	0.29680	0.00355	0.00383	-0.00001	0.73940	0.05980	-0.07766	-0.88410
	D > 10	-	-	0.0066	-0.7277	-	-5.9545	-	-0.8579	50.4891
Otuchi Town	D≦10	0.0170**	0.4109	-0.0115	0.1369	0.0027	1.2486***	0.0837	0.0021	-6.2544
	D > 10	-	0.1737	1.5226	-35.1922	0.0423	1.3349	24.2927	19.9664	-1796.1794
Kamaishi City	D≦10	0.0112*	0.0122	0.0009	-0.0862	-0.000646	-0.5265 +	0.0969	-0.0215	-2.6009
	D > 10	-	-	-0.0640	-4.2113	-	-2.5844	-	-0.7722	94.6208
Ofunato City	D≦10	0.00298*	-0.03874	0.00206	-0.00146 *	-0.00003	-0.00046	-0.01081	0.01490	0.33660
	D > 10	-	-	-	-	-	-	-	-	26
Rikuzentakata City	D≦10	0.0539***	0.0116	0.0060	0.0741	-0.0005	0.2077**	0.0514	-0.0393	-6.4757
	D > 10	-	-793.11	12.45	-93.56	-11.75	-15.03	-	378.89	-5315.57
Iwate Prefecture	D≦10	0.01364***	0.2225**	0.0059**	0.0004	0.0000	0.0368*	0.0058	0.0026	-2.8500
	D > 10	0.0248 +	0.5629	0.0633	-0.9568 *	-0.0002	0.9986***	3.324*	0.2180	-164.2000 +

*** P<0.001, **P<0.01, *P<0.05, +P<0.1

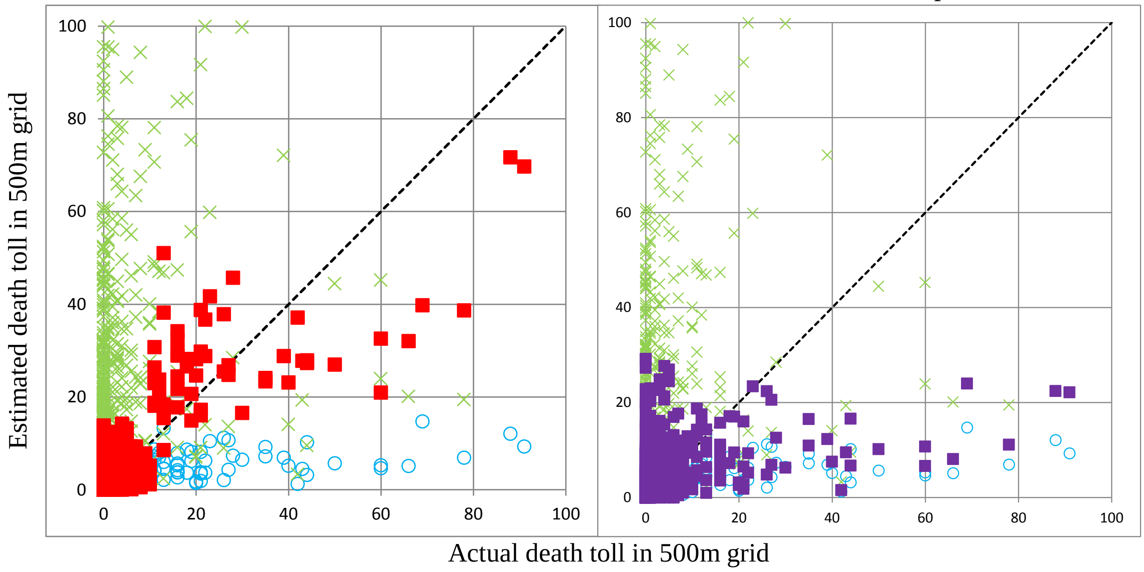
4.5.3 Fukushima and Iwate Prefectures combined

The results of whole areas (data in Fukushima and Iwate Prefectures combined) are shown in Figure 4.17. In addition, the death toll (○ mark and ■ mark) in the 500 m grid calculated by using the proposed model and the death toll (× marks) in the 500 m grid calculated by Eq. (4.3) are shown in Figure 4.17. First of all, the ○ mark in Figure 4.17 is a result of multiple regression analyses on all data of the target areas and calculation of the death toll in the 500 m grid by Eq. (4.3). It can be seen that the predicted value is capped at about ten fatalities in any region same as the result of Fukushima and Iwate Prefectures. The reason is that the data on more than ten fatalities is not sufficient, or there is the tendency of the occurrence of fatality to differ depending on the circumstances. Therefore, only data with estimated fatalities of more than ten people were extracted in each region, and multiple regression analysis using Eq. (4.3) was performed. Finally, the result of calculating the death toll with the result of $D \leqq 10$ and the result of $D>10$ is the ■ mark in Figure 4.17. The result is shown in the table in Figure 4.17. Hence, if the estimated death toll is ten people or less, the parameters of the left side (Results of $D \leqq 10$) table are used, and if the predicted death toll is more than ten people, the parameters of the right side table (Results of $D>10$) will be used shown in table in Figure 4.17. In addition, although explanatory variables having p-values exceeding the assumed significance level are scattered over the table, when this method looks at the whole event, six explanatory variables, including geographical factors among the nine explanatory variables, are judged as significant and the target area is only 12 samples (municipalities).

The table in Figure 4.17 shows the average prediction error, *Ea* (○), *Ea* (■) and *Ea* (■) represent the average prediction error using Eq. (4.4), and *Eac* (×) represents it using Eq. (2.1). Here understood that the death toll calculated by the proposed model in this thesis was much lower than the prediction error calculated by Eq. (2.1).

The result of calculating the death toll with the result of inundation depth< 4 m and the result of inundation depth≧4 m is the ■ mark in Figure 4.17. From the results of focusing on inundation depth, it can calculate results similar to the results for the number of deaths by looking at prediction errors. However, right side figure in Figure 4.17 shows that the result is not so good.

Fukushima and Iwate Prefectures combined



Result of D ≦ 10 / **Result of D > 10**

Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)		Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.01018	0.00115	8.831	<2e-16	***	0.02007	0.01082	1.855	0.07005	+
Average inundation depth	0.26400	0.06547	4.032	0.0001	***	-0.13010	0.80950	-0.161	0.8730	
Average evacuation distance	0.00616	0.00124	4.978	0.0000	***	0.01791	0.01391	1.288	0.2043	
Avearge intercept	0.00021	0.00092	0.226	0.8212		-0.46610	0.39910	-1.168	0.2488	
Average wavelength	0.00001	0.00003	0.378	0.7054		-0.00046	0.00063	-0.734	0.4664	
Average damping ratio	0.00080	0.00147	0.548	0.5837		0.86090	0.26470	3.252	0.0022	**
Gender(men)	-0.00485	0.01098	-0.442	0.6589		1.54000	0.84790	1.816	0.0759	+
Age(over 65 years old)	0.00694	0.00937	0.742	0.4586		-0.02937	0.04782	-0.614	0.5422	
Intercept	-1.70900	0.82830	-2.063	0.0393	*	-56.71000	41.47000	-1.368	0.1781	

Result of Inundation depth <4m / **Result of Inundation depth ≧4m**

Explanatory variables	Estimate	Std. Error	t value	Pr(>|t|)		Estimate	Std. Error	t value	Pr(>|t|)	
Population	0.01018	0.00115	8.831	<2e-16	***	0.02367	0.00230	10.312	<2e-16	***
Average inundation depth	0.26400	0.06547	4.032	0.0001	***	-0.00649	0.13090	-0.05	0.9605	
Average evacuation distance	0.00616	0.00124	4.978	0.0000	***	0.00838	0.00198	4.233	0.0000	***
Avearge intercept	0.00021	0.00092	0.226	0.8212		0.00270	0.00161	1.673	0.0950	+
Average wavelength	0.00001	0.00003	0.378	0.7054		0.00002	0.00004	0.41	0.6816	
Average damping ratio	0.00080	0.00147	0.548	0.5837		0.07991	0.03946	2.025	0.0434	*
Gender(men)	-0.00485	0.01098	-0.442	0.6589		0.00115	0.01565	0.073	0.9415	
Age(over 65 years old)	0.00694	0.00937	0.742	0.4586		0.00350	0.01456	0.24	0.8103	
Intercept	-1.70900	0.82830	-2.063	0.0393	*	-1.92500	1.61700	-1.191	0.2344	

*** P<0.001, **P<0.01, *P<0.05, + P<0.1

Average prediction error

	Ea (○)	Ea (■)	Ea (■)	Eac (×)
The whole area	3.14	2.65	3.98	21.47

Explanatory notes

·········· Actual death toll

■ Estimated death toll using new fatality model (result of D≦10 and result of D > 10)

■ Estimated death toll using new fatality model (Inundation depth < 4m and Inundation depth≧4)

○ Estimated death toll using the result of multiple regression analysis on all data of the target areas

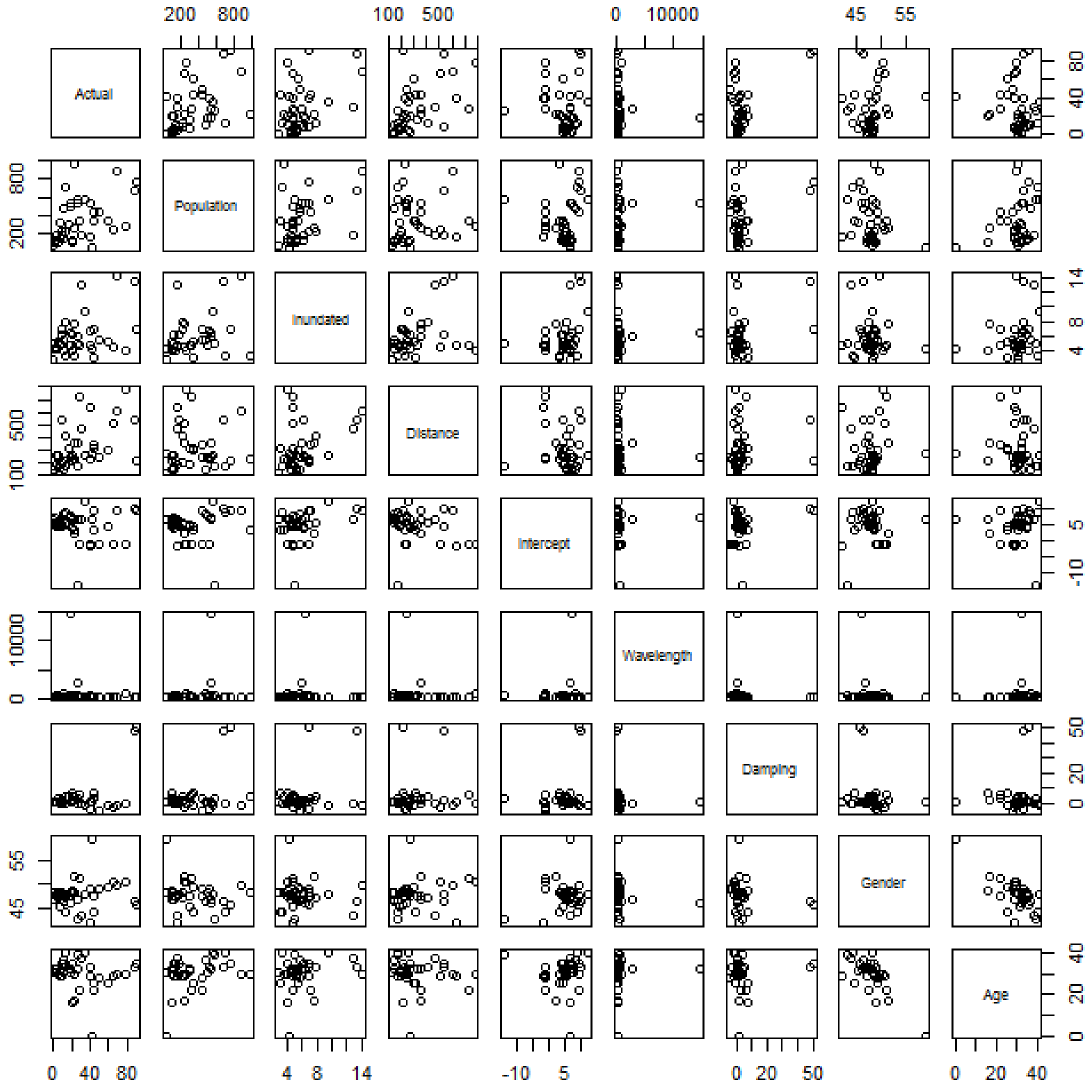
× Estimated death toll using equation of Central Disaster Management Council (Eq.(2.1))

Figure 4.17: Correlation between actual death toll and estimated death toll using Eq. (4.3) as the whole area

4.6 Discussions

4.6.1 Accuracy of the model

To improve the accuracy and precision of the above method, this thesis also sought to predict fatalities by other methods and analyze them. The current data are defined as Dataset 1. The data contain a large number of grids where fatalities did not occur, and it is conceivable that the weight of the grid number to the death number is different. Therefore, to solve the problem, the median values (population before the event, inundation depth, evacuation distance, intercept by ARMA model, wavelength, damping ratio, percentage of men and percentage of people over 65 years old in each 500 m grid) for each death toll are determined and this data are defined as Dataset 2.



Explanatory notes

Actual (death), Population, Median inundation depth (m), Median evacuation distance (m), Median intercept by ARMA model, Median wavelength, Median damping ratio, Percentage of men and Percentage of people over 65 years old

Figure 4.18: Scatter plot using Dataset 2

In terms of Dataset 2, a scatter plot matrix with two variables on one screen is written using the dead toll and the statistical software of eight variables shown in Figure 4.18. This is a scatter plot. The diagram shows that the relationship between the number of death, population, inundation depth and evacuation distance have a linear distribution.

A general approach for the estimation of loss due to natural disasters in Japan, among the human damage rate against the tsunami, there are equations which are divided into an area where people save their lives by evacuation actions and areas where fatality occurs during evacuation. According to the prediction method of human damage caused by the tsunami in Kochi Prefecture, whether people take an evacuation behavior or not is judged from “when all people evacuate immediately after the earthquake”, “when the ratio of early evacuees is high (telling for evacuation)”, “when the ratio of people is high”, “when early evacuees are low” and “numerical values reflecting evacuation in Kochi Prefecture at the time of the 2011 Great East Japan earthquake” are set and incorporated into the formula [20]. However, in this thesis, the evacuation rate does not consider. Therefore, this section rebuilt the proposed models and organizes them from Eq. (4.5) and Eq. (4.6) below and Table 4.5 shows outline of the model.

1. Previous models have been obtained so far by multiple regression analysis (Objective variable= Death toll)

$$D = a_1P + a_2x_1 + a_3x_2 + a_4x_3 + a_5x_4 + a_6x_5 + a_7x_6 + a_8x_7 + \mathrm{C} \tag{4.5}$$

where *D*, *P*, x_1, x_2, x_3, x_4, x_5, x_6 and x_7 are death toll in 500 m grid, population before the event, average inundation depth (m), average evacuation distance (m), average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old in each 500 m grid, respectively.

2. Improved version : The method is a multiple regression analysis, but changed the objective variable to fatality rate (Objective variable= Fatality rate)

$$D/p = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6 + a_7x_7 + \mathrm{C} \tag{4.6}$$

where *D*, *P*, x_1, x_2, x_3, x_4, x_5, x_6 and x_7 are death toll in 500 m grid, population of 500 m grid before the event, average inundation depth (m), average evacuation distance (m), average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old in each 500m grid, respectively.

As with the previous methods, the result is calculating death toll with the result of D≦10 and the result of D>10 focusing on the number of deaths. Furthermore, when death toll or death rate calculated using the formula becomes negative, it is defined as 0. As a result, this thesis adopted the fatality model of tsunami disaster with average prediction error result shown in Table 4.6. From this analysis, model 1 performed smaller average prediction error than model 2 and model 3. The results shown in Table 4.7 represents contribution ratio of model 1, model 2 and model 3. It was confirmed that the parameters with less influence were in the regression equation. However, here restates when this method looks at the whole event, six explanatory variables, including geographical factors among the nine explanatory variables, were judged as significant and the target area is only 12 samples (municipalities) as shown in Figure 4.17. Therefore, this thesis is proceed with the validation of the model using eight parameters: population of 500 m grid before the event, average inundation depth, average evacuation distance, average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old in each 500 m grid.

Table 4.5: Outline of the model

Method		Objective variable =Death toll	Objective variable =Fatality rate
Multiple regression analysis	Dataset 1	Model1	-
	Dataset 2	Model2	Model3

Table 4.6: Average prediction error

	Objective variable= Death toll	Objective variable= Fatality rate	Central Disaster Management Council
	Multiple regression analysis	Multiple regression analysis	
Dataset 2	Model 2 10.47 people	Model 3 7.41% (19.28 people)	48.13 people

Table 4.7: Contribution ratio of model 1, model 2 and model 3

	Model 1		Model 2		Model 3
	Contribution (D≦=10)	Contribution (D>10)	Contribution (D≦=10)	Contribution (D>10)	Contribution
Population	0.508%	94.873%	0.060%	0.023%	-
Average inundation depth	13.186%	0.034%	1.780%	0.976%	0.489%
Average evacuation distance	0.307%	0.218%	0.084%	0.058%	0.029%
Average intercept by ARMA model	0.010%	0.03%	1.252%	0.690%	0.765%
Average wavelength	0.001%	0.780%	0.001%	0.001%	0.0001%
Average damping ratio	0.040%	1.440%	1.366%	1.050%	0.385%
Gender (men)	0.242%	2.576%	2.125%	2.095%	4.107%
Age (over 65 years old)	0.347%	0.049%	0.702%	0.012%	2.860%
Intercept	85.358%	94.873%	92.630%	95.095%	91.365%

4.6.2 Relationship between topography and fatality model

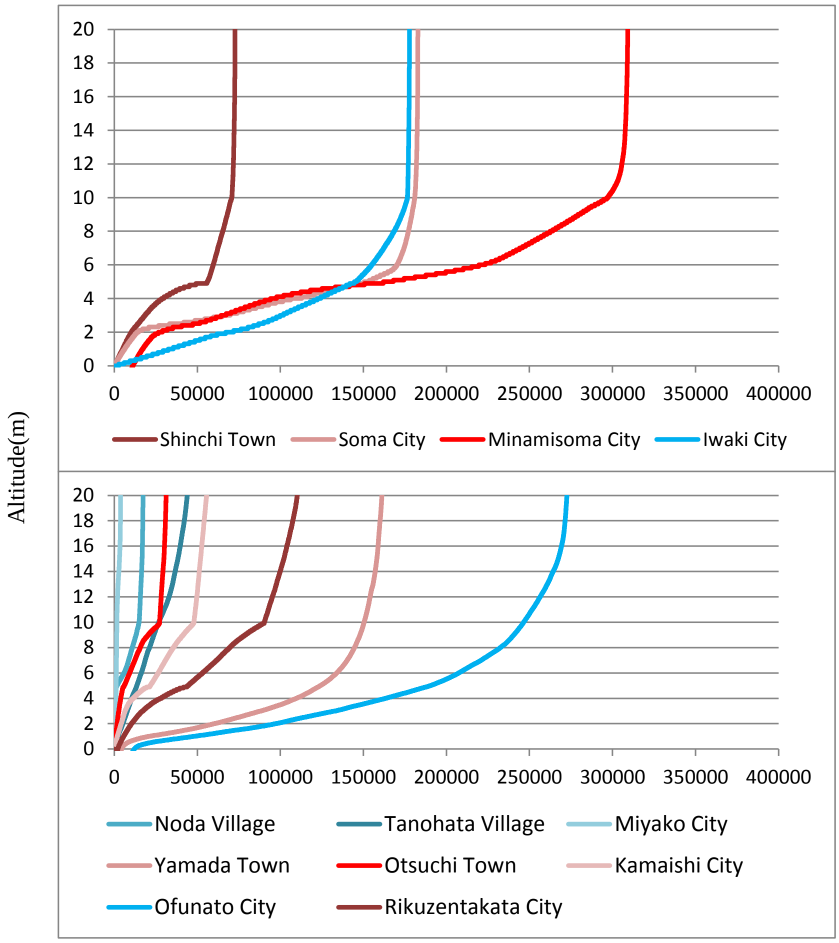
Furthermore, from the above results, there were differences in the fatality model depending on the region. As a cause of this difference, a topographical difference might be considered. Here this section discusses in detail the effect of the topography in the case study area.

(1) Methods

Geographical feature of each small region was assumed to be represented using a number of altitude data. This section used the figure (same results as Figure 3.10) shown in Figure 4.19, the vertical axis refers to the altitude and the horizontal axis refers to the altitude data number. The altitude data number is a number that are arranged in ascending order all the altitude data of inundated area in each small region, in ascending order of altitude numbering. Therefore, the topography was flat when the inclination is small throughout the chart. On the other hand, if the slope of the graph was large, it was considered that the change in the altitude of the inundated area of the small region was severely, it meant that the topography was steep.

(2) Results and Discussions

The fatalities in 500m grid could be evaluated with new explanatory variables including elevation and distance of evacuation route, intercept by ARMA model, wavelength and damping ratio only by inputting population, inundation depth, road network data, elevation data at prefectural or regional level. It has become possible to predict human damage with an expression incorporating index that can express the situation of region concretely. Hence, the fatality is estimated by using the fatality model shown in Figure 4.19, Table 4.3 (1) and (2), Table 4.4 (1) and (2) and Table in Figure 4.17 for each geographical feature in each area at the prefecture level and municipal level. Based on the results, this thesis could propose a prediction method that can estimate human damage to other areas looking at the altitude distribution in inundated area.



Reordering in ascending order altitude in the region

Explanatory notes

(Color gradient) Fatality Rate in region is over 1%

(Color gradient) Fatality Rate in region is less than 1%

Figure 4.19: Relationship between altitude distribution and fatality rate

4.6.3 Human behavior after the tsunami based on the data of Iwate Nippo

The data obtained by the interview survey of Iwate Nippo includes information on the location where the earthquake occurred, the behavior after and during earthquake. It is meaningful data that we can learn about the behavior of the fatality. Therefore, based on the data described here, this section analyzes the behavior tendency after the earthquake.

(1) Methods

Human behavior after the earthquake was classified in Table 4.8 to analyze by age group and gender. Human behavior categories 2, 3 and 4 represent the main reasons for physical reasons or a case in which they could not escaped by social roles or went to rescue someone. Human behavior categories 5 and 6 represent a case that people took an evacuation action but they could not save. The social factors in the table include cases where they could not escape due to health reasons, cases where they could not move due to work, nursing care, etc.

(2) Results and Discussions

The ratio of unknown actions after the earthquake accounts for nearly half of all data (excluding Kamaishi City) from the result of Table 4.9. Therefore, this thesis analyzed except for those whose behavior after the earthquake is unknown. The human behavioral classifications in Figure 4.20 and Figure 4.21 are as shown in Table 4.8. In Figure 4.20 and Figure 4.21, the red bar to yellow bar (human behavior category 1 to 3) showed people could not evacuate and the light blue bar to blue bar (human behavior category 5 and 6) represented people took an evacuation action but they lost their lives. More than 70% of people in any regions did not evacuate except for Yamada Town. Figure 4.21 shows the result of arranging and using the data on whether did evacuate to safe place or not. As a result of Figure 4.21, although there are some variations, it is understood that more than 80% of people are not able to evacuate.

There are many people who did not evacuate as age goes up in Table 4.10 and Figure 4.22. It can be seen that the percentage of elderly people aged 75 years or older is high even in the case that people could not evacuate because of the health problems. In addition, it can be seen that the percentage of those who were evacuated for social reasons or who took action to go to help others is more frequent for 19-44 years old and 45-64 years old. In addition, in terms of people who were on the way to evacuate and evacuated safe place inundated, the proportion increases as the age goes up. This section investigated the difference in evacuation behavior in gender, but there was no noticeable difference (Figure 4.23). According to some reports, there were differences about the influence of gender on evacuation behavior and the difference between male and female fatalities in the 2004 Indian Ocean Earthquake and Tsunami. Therefore, this thesis considered the age and gender is one of the indexes which are caused fatality.

Table 4.8: Behavior classification after the earthquake

Number of category	Color	Behavior classification after the earthquake
0		Unknown
1		Did not evacuate
2		Could not evacuate because of the health problems
3		Could not evacuate because of work issue
4		Rescue family and neighbor
5		On the way to evacuate
6		Safe place inundated

Table 4.9: Behavior classification after the earthquake by municipalities

Number of category	Noda Village	Tanohata Village	Miyako City	Yamda Town	Otsuchi Town	Kamaishi City	Ofunato City	Rikuzentakata City
0	75.0%	85.7%	47.7%	62.9%	61.0%	39.4%	50.4%	63.7%
1	0.0%	14.3%	25.7%	12.6%	23.9%	29.0%	26.0%	12.0%
2	0.0%	0.0%	7.3%	6.9%	4.6%	10.4%	18.9%	3.4%
3	0.0%	0.0%	4.6%	2.9%	2.3%	3.2%	0.0%	8.1%
4	25.0%	0.0%	1.8%	2.9%	1.3%	0.5%	0.8%	1.8%
5	0.0%	0.0%	11.0%	9.7%	5.6%	9.5%	2.4%	5.7%
6	0.0%	0.0%	1.8%	2.3%	1.3%	8.1%	1.6%	5.2%

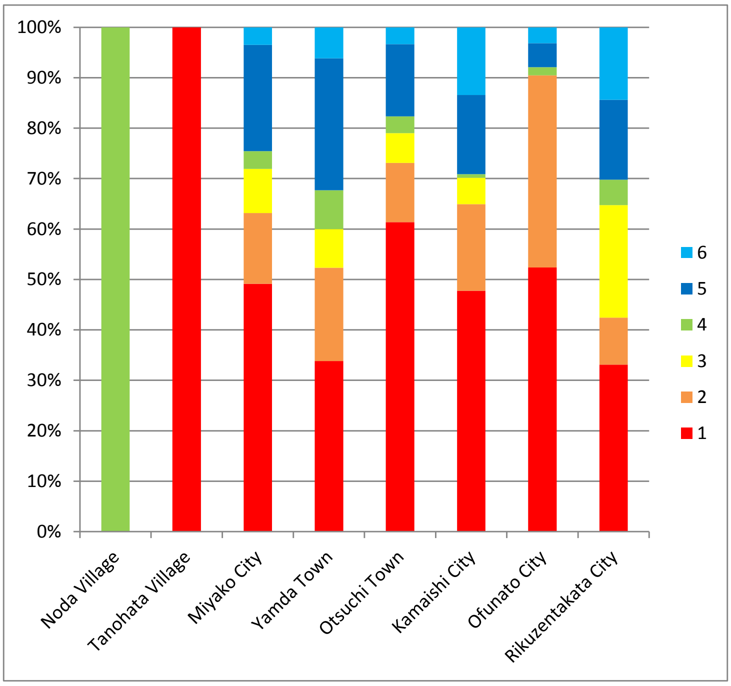


Figure 4.20: Behavior classification after the earthquake by municipalities (without non-respondent)

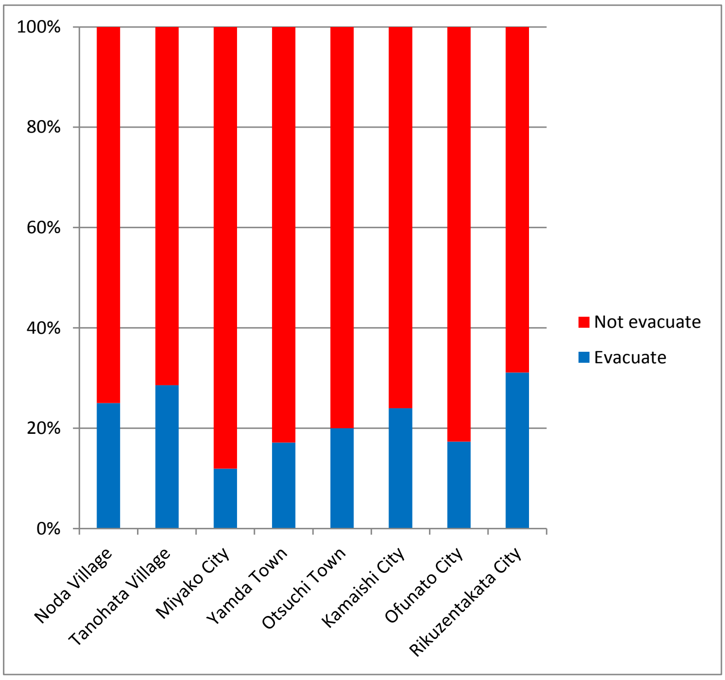
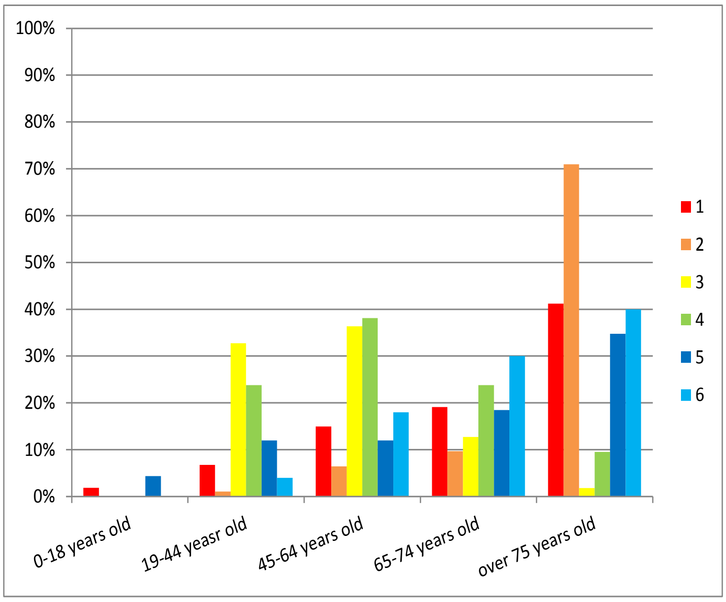


Figure 4.21: Evacuation behaviors after the earthquake

Table 4.10: Behavior classification after the earthquake by age (without non-respondent)

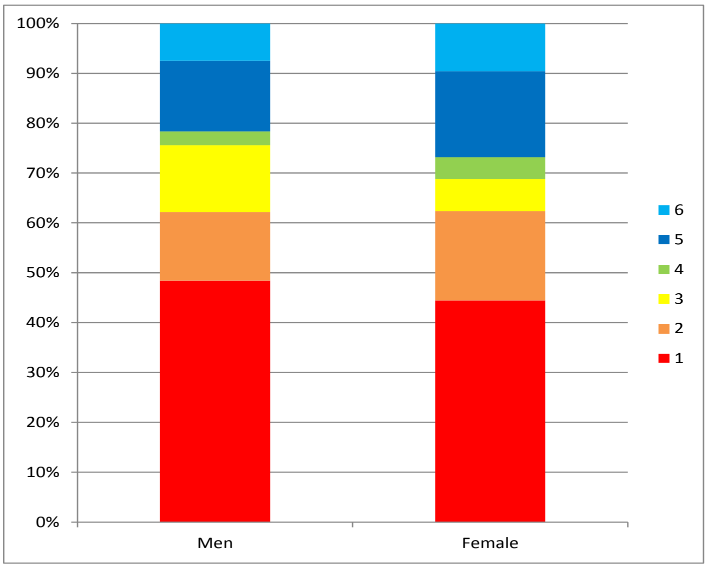
Number of category	1	2	3	4	5	6
0-18 years old	1.9%	0.0%	0.0%	0.0%	4.3%	0.0%
19-44 yeasr old	6.7%	1.1%	32.7%	23.8%	12.0%	4.0%
45-64 years old	15.0%	6.5%	36.4%	38.1%	12.0%	18.0%
65-74 years old	19.1%	9.7%	12.7%	23.8%	18.5%	30.0%
over 75 years old	41.2%	71.0%	1.8%	9.5%	34.8%	40.0%
unknown	16.1%	11.8%	16.4%	4.8%	18.5%	8.0%



Number of category	Behavior classification after the earthquake
1	Did not evacuate
2	Could not evacuate because of the health problems
3	Could not evacuate because of work issue
4	Rescue family and neighbor
5	On the way to evacuate
6	Safe place inundated

Figure 4.22: Behavior classification after the earthquake by age (without non-respondent)

.



Number of category	Behavior classification after the earthquake
6	Safe place inundated
5	On the way to evacuate
4	Rescue family and neighbor
3	Could not evacuate because of work issue
2	Could not evacuate because of the health problems
1	Did not evacuate

Figure 4.23: Evacuation behaviors after the earthquake by gender

Through analyzes of Chapter 4, this thesis also considers the features of human behavior to influence geographical factors when people evacuate. In other words, it is considered that children, elderly people who are week to the disaster, and need assistance. For example, according to the event in the 2011 Great East Japan Earthquake and Tsunami [21], in a certain area, 585 people were registered among 1,213 registered persons in the inundated area. However, 88 registrants died and this is 15% of registrants. Furthermore, it states that it is necessary to sufficiently examine whether factors such as disaster type have a large influence or factors such as coastal area, river, steep slope or residential area, as a geographical factor to people who are week to the disaster.

4.7 Summary

Previous analysis focused on the number of death and inundation depth. As a result, this thesis adopted the fatality model of tsunami disaster with good average prediction error result. Finally, the proposed models are summarized below. The model could be improved through the above analysis.

Result of model 1 using Dataset 1

D≦10

$$D = 0.0102P + 0.2640x_1 + 0.0062x_2 + 0.0002x_3 + 0.00001x_4 + 0.0008x_5 - 0.0049x_6 + 0.0069x_7 - 1.7090 \quad (4.8)$$

D>10

$$D = 0.0200P - 0.1301x_1 + 0.01791x_2 - 0.4661x_3 - 0.0005x_4 + 0.8609x_5 + 1.5400x_6 - 0.0294x_7 - 56.7100 \quad (4.9)$$

Result of model 2 using Dataset 2

D≦10

$$D = 0.0385P + 1.1440x_1 + 0.0543x_2 - 0.8048x_3 - 0.0004x_4 + 0.8782x_5 + 1.3660x_6 - 0.4513x_7 - 59.5400 \quad (4.10)$$

D>10

$$D = 0.0204P + 0.8511x_1 + 0.0507x_2 - 0.6018x_3 - 0.0006x_4 + 0.9154x_5 + 1.8270x_6 + 0.0104x_7 - 82.9200 \quad (4.11)$$

where D, P, $x_1, x_2, x_3, x_4, x_5, x_6$ and x_7 are death toll in 500 m grid, population of 500 m grid before the event, average inundation depth (m), average evacuation distance (m), average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old in each 500 m grid, respectively.

It should be noted that both Fukushima and Iwate Prefectures do not analyze using the data of where the people actually died. Hence, it is different situation from the actual disaster damage. Based on these facts, this thesis tests these above equations (Eq. (4.8), Eq. (4.9), Eq. (4.10) and Eq. (4.11)) in the coastal area of Miyagi Prefecture and some districts in Indonesia, which was damaged by the 2011 Great East Japan Earthquake and Tsunami and by the 2004 Indian Ocean Tsunami in Chapter 5.

References

[1] H. Tsubokawa (1992) "Insurance Rate Making Methodology for Natural Hazards", *Journal of Geography* 101(6), pp.528-538 (in Japanese)

[2] K. Irikura (2007) "Elucidation and prediction of natural phenomenon as a disaster factor- Predictive research for earthquake disaster mitigation as an example", Vol.12, No.11, pp.13-17 (in Japanese)

[3] D. P.Aldrich and Y. Sawada (2015) "The physical and social determinants of mortality in the 3.11 tsunami" , *Social Science & Medicine 124*, pp. 66-75

[4] D. Alexander (2012) "Models of Social Vulnerability to Disasters", *RCCS Annual Review*, 4, pp.22-40

[5] Y. Yamashita and M. Mikami (2013) "Problems and analyses of social damage in tsunami-stricken area: A case study of Noda Village", *Journal Global Environmental Research* (in Japanese)

[6] M. Yoshino (2013) "Injury to human beings caused by the tsunami of the Great East Japan Earthquake",Chikyu Kankyo, *Association of International Research Initiatives for Environmental Studies*, Vol.18, No.1, pp. 13-22 (in Japanese)

[7] Y. Ohta (2010) "Characterization of Casualties and Health Consequences in Earthquake" *Mizutami International Symposium on Earthquake Casualties and Hearth Consequences*, 15-16 November, Mizutani, Gifu, Japan, pp.13-16

[8] H. Ochi, T. Nishihata, T. Tamura, K. Takimono and F. Miura (2005) "Influence of Human Age in Tsunami Evacuation", *Institute of Social Safety Science*, No.17, pp39-42 (in Japanese)

[9] N. Y. Yun and M. Hamada (2015) "Evacuation Behavior and Fatality Rate during the 2011 Tohoku-Oki Earthquake and Tsunami", *Earthquake Spectra*, Vol. 31, No.3, pp.1237-1265

[10] S. Doocy, A. Rofi, C. Moodie, E. Spring, S. Bradley, G. Burnham and C. Robinson (2006) "Tsunami mortality in aceh Province, Indonesia", *Bulletin of the World Health Organization*, 85 (2)

[11] K. Ginige, D. Amaratunga and R. Haigh (2009) "Mainstreaming gender in disaster reduction: why and how?", *Disaster Prevention and Management*, Vol. 18, No. 1

[12] J. M. Bateman and B. Edwards (2002) "Gender and evacuation: A closer look at why women are more likely to evacuate for hurricanes." *Nat. Hazards Rev*.,3 (3), pp. 107–117

[13] T. Charnkol and Y. Tanaboriboon (2006) "Tsunami Evacuation Behavior Analysis –One Step of Transportation Disaster Response-", *IATSS Research*, Vol. 30, Issue 2, pp.83-96

[14] N. Dash and H. Gladwin (2007) "Evacuation Decision Making and Behavioral Responses : Individual and Household", *Natural Hazards Review*, Vol. 8, Issue 3

[15] K. Toki, T. Sato, J. Kiyono and J. Wakabayashi (1985) "Attenuation of Simulated Peak Accelerations

Taking into Account Fault Extent and Rupture Process", Disaster Prevention Research Institute, Kyoto University 28B-2, pp.1-11 (in Japanese)

[16] M. Kanai and T. Katada (2013) "The Effect of Lessons to Survive from Tsunamis; Actual Conditions at the Great East Japan Earthquake in Kamaishi City", *Japan Society for Disaster Information Studies*, No.11,pp.114-124 (in Japanese)

[17] Report of Nagoya University, report of the 2004 Indian Ocean Tsunami V, Available: http://www.seis.nagoyau.ac.jp/INFO/sumatra/sumatra_report_5.pdf. Last Accessed: 16th February, 2015

[18] T. Aoki (2017) "Analysis of factors causing death in the Great East Japan Earthquake based on Iwate Nippo Interview data", Bachelor's degree thesis, Department of Civil Engineering, Gifu University (in Japanese)

[19] Central Disaster Management Council Report. (2011) "Report of a special investigation meeting on earthquake and tsunami countermeasures lessons from the 2011 Great East Japan Earthquake", Available: http://www.bousai.go.jp/kaigirep/chousakai/tohokukyokun/pdf/sankou.pdf. Last Accessed: 2nd November, 2017 (in Japanese)

[20] Materials of calculation method for damage assumption in Kochi Prefecture Available:http://www.pref.kochi.lg.jp/soshiki/010201/files/2013051500465/2013051500465_www_pref_kochi_lg_jp_uploaded_attachment_95462.pdf. Last Accessed: 2nd November, 2017 (in Japanese)

[21] Report on the study meeting on evacuation support for people who need assistance in the event of a disaster (2013) Available:http://www.bousai.go.jp/taisaku/hisaisyagyousei/youengosya/h24_kentoukai/houkokusyo.pdf. Last Accessed: 2nd November, 2017 (in Japanese)

Chapter 5

Testing the fatality model for tsunami disasters

This thesis presented a new fatality model with explanatory variables including elevation and distance of evacuation route, intercept by ARMA model, wavelength and damping ratio simply by inputting population, inundation depth, road network data and elevation data. The model should be tested in other areas. This section focuses on two areas: one is Miyagi Prefecture affected by a tsunami during the 2011 Great East Japan Earthquake and Tsunami in Japan, and the other is Banda Aceh affected by the 2004 Indian Ocean Tsunami in Indonesia. The proposed mode is adapted to areas where data on the number of fatalities are available. The validity of the model is discussed in this section.

5.1 Case study in Miyagi Prefecture, the 2011 Great East Japan Earthquake and Tsunami

5.1.1 Location of case study area

A lot of deaths occurred in Miyagi Prefecture during the 2011 Great East Japan Earthquake and Tsunami. However, detailed information on fatalities could not be obtained because of data situation. Therefore, using the information of the 2010 Japanese National Census and inundated area, the number of deaths in the 500 m grid was calculated in the same way as the analysis where fatalities did not occur in the Section 3.3.2, and then the number of deaths in each region was calculated.

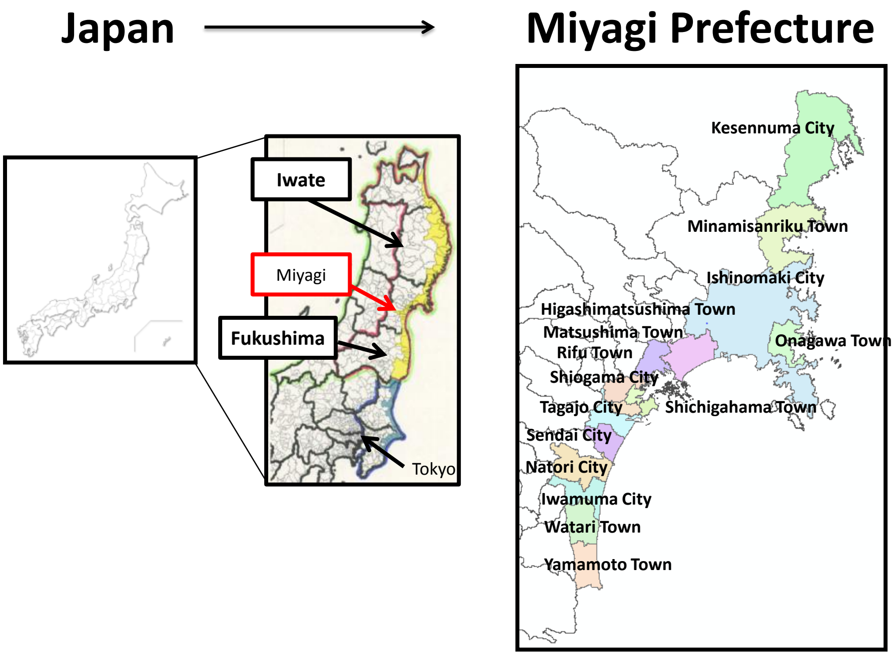


Figure 5.1: Location of the case study area in Miyagi Prefecture

The target areas were 15 municipalities: Kesennuma City, Minamisanriku Town, Higashimatsushima City, Onagawa Town, Ishinomaki City, Matsushima Town, Rifu Town, Shiogama City, Tagajo City, Natori City, Iwanuma City, Shichigahama Town, Watari Town, Yamamoto Town and Sendai City in Miyagi Prefecture shown in Figure 5.1.

5.1.2 Methods

This section used ArcGIS (ESRI) for the spatial analysis to analyze the causes of human damage, and used ArcGIS Network Analyst for the analysis of evacuation routes as well as the analysis in Chapter 3 and Chapter 4. The analysis was based on data that have been published on the website to date. The datasets used are as follows: (1) the 2010 Population Census of Miyagi Prefecture, (2) necrology by the Miyagi prefectural police by the end of March, 2012, (3) the inundated area map by the MLIT, (4) the inundated area 5m mesh by the Reconstruction Support Survey Archive, (5) road center lines from MLIT and (6) the foundation map – information digital – elevation model 10m – by the Geospatial Information Authority of Japan.

The processes are shown below. The actual number of deaths in the inundated area is used for the result obtained by analysis in Chapter 3.

Step D1. Calculating the population in the inundated area using the 2010 population census.

Step D2. Extracting the area that overlaps the inundated area and the 2010 population census. A center of gravity point was then determined for a 500 m grid cut by the inundated area polygon and defined as a start point. This step subsequently involved the extraction of the points that overlap the inundation area and the road network (the point on the road exiting the inundated area was determined as the goal point). It should be noted that there are several points where the center of gravity is set outside the inundated area because of the analysis on ArcGIS.

Step D3. Organizing the inundation depth of the center of gravity point from the MLIT information.

Step D4. Calculating the distance and elevation from the center of gravity point to the non-inundated areas through the road network using ArcGIS Network Analyst.

Step D5. For the evacuation route, using an altitude model of 10 m mesh to extract the altitude's distribution.

Step D6. Organizing the age and gender of each grid according to the 2010 population census.

Step D7. Evaluating the fatalities in the 500 m grid with new explanatory variables including elevation and distance of evacuation route, intercept by ARMA model, wavelength and damping ratio only by inputting population, inundation depth, road network data and elevation data obtained from the above steps.

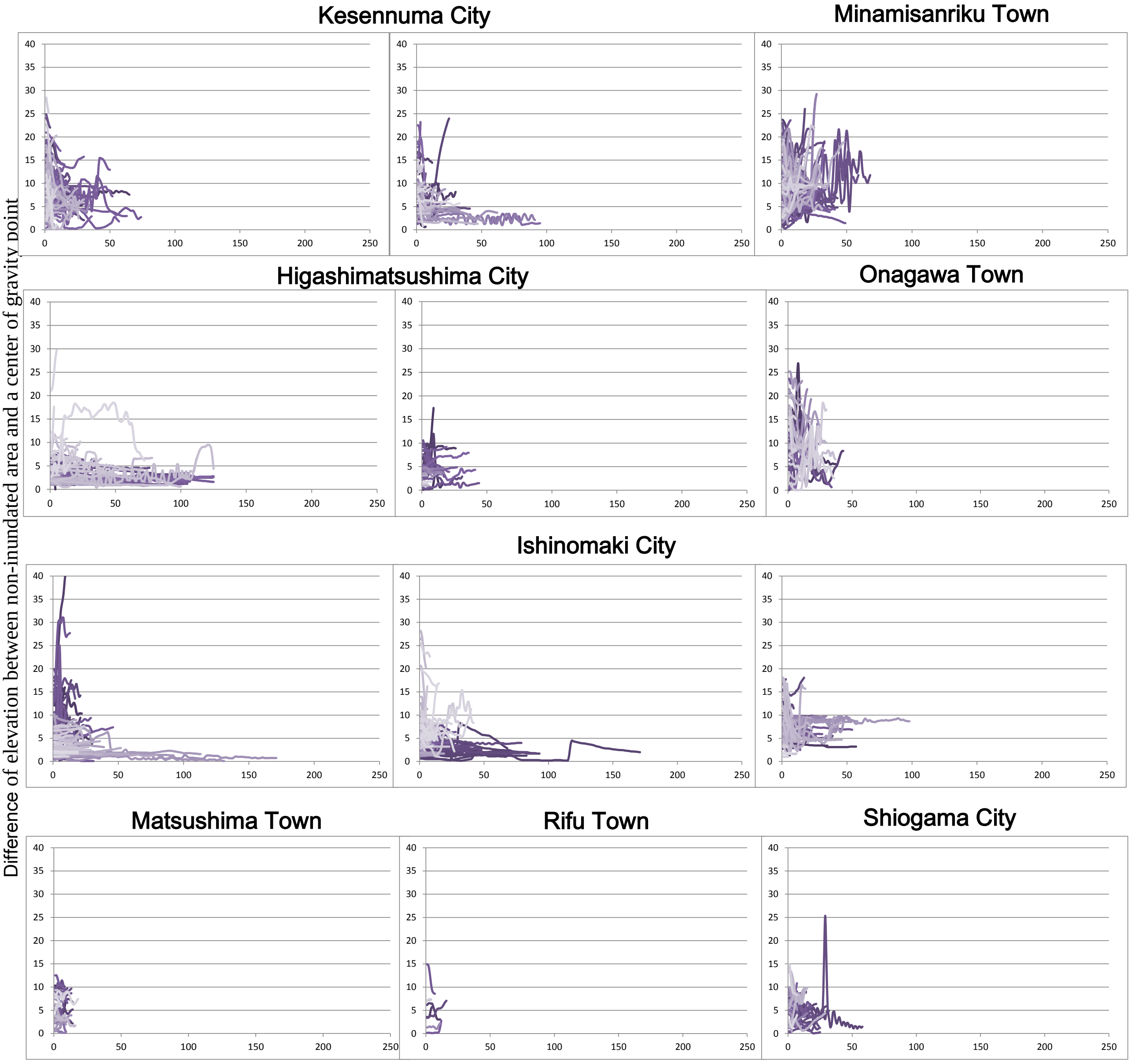
Step D8. Calculating the death toll per grid and then determining the sum of death tolls for each municipality using Eq. (4.8) to Eq. (4.11).

Table5.1: Number of deaths and grids in Miyagi Prefecture

	Death toll in inundated area	Grids
Sendai City	662	203
Ishinomaki City	3,127	671
Shiogama City	48	75
Kesennuma City	951	347
Natori City	873	229
Tagajo City	112	104
Iwanuma City	151	176
Higashimatsushima City	1,023	285
Watari Town	285	129
Yamamoto Town	601	107
Matsushima Town	14	53
Shichigahama Town	89	80
Rifu Town	10	12
Onagawa Town	511	82
Minamisanriku Town	538	175

5.1.3 Results

These are the results of the detailed altitude distribution in Miyagi Prefecture shown in Figure 5.2 (1) and Figure 5.2 (2). Each line in figure shows each evacuation route. Especially, the evacuation distance in Sendai City is longer than that in other areas. In other words, the evacuation distance from the coast to a safe place is long and Sendai City is situated in a flatland. Moreover, it is understood that the altitude is low in municipalities other than Kesennuma City and Minamisanriku Town compared with Fukushima Prefecture and Iwate Prefecture. That is, one of the reasons why the death toll in Miyagi Prefecture was high is its topographical features. The altitude from the coast to a safe location is low and it is likely to be easily caught by the tsunami, even if it escaped direct impact.



Distance to the non-inundated area (×10m)

Figure 5.2 (1): Altitude distribution in Miyagi Prefecture

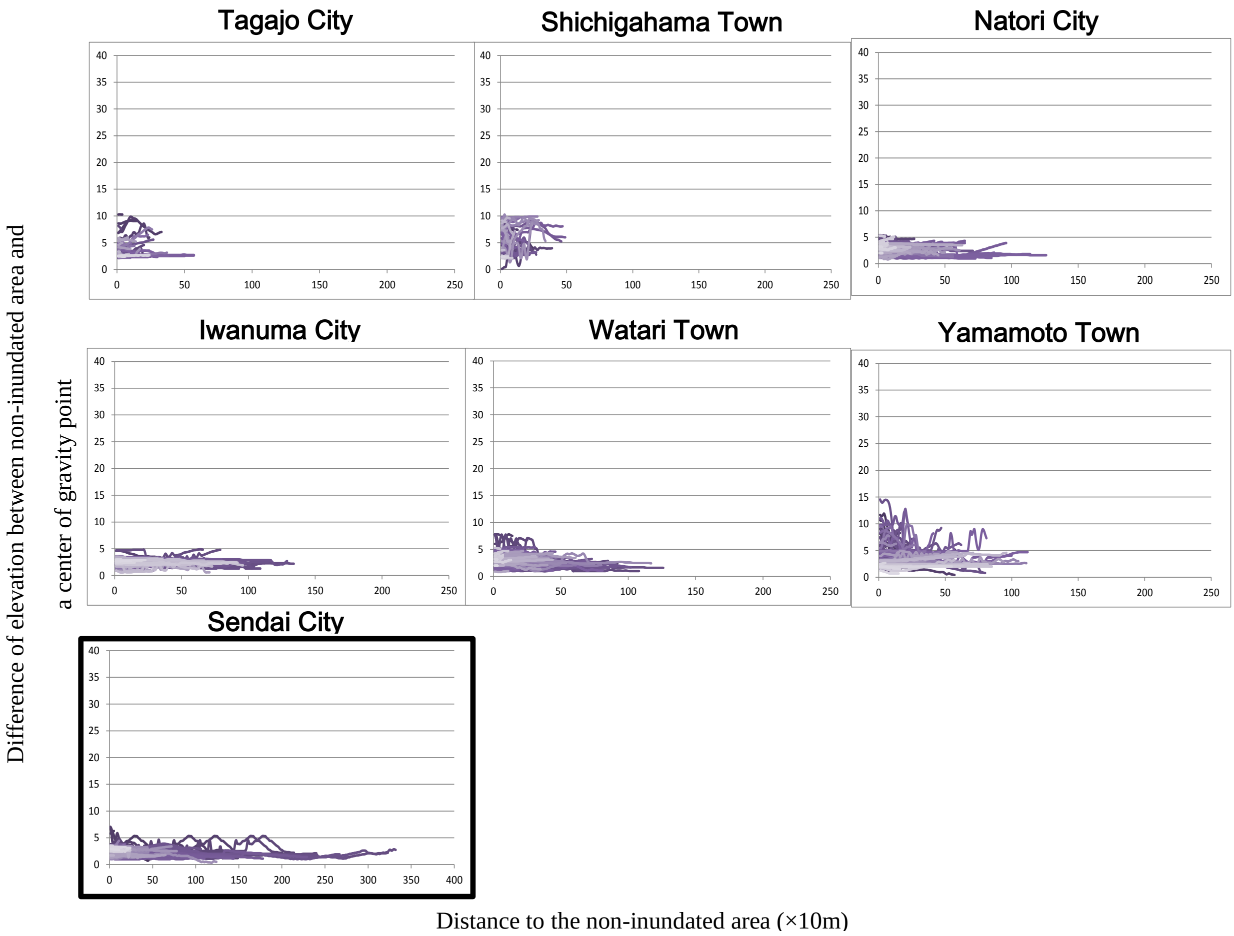
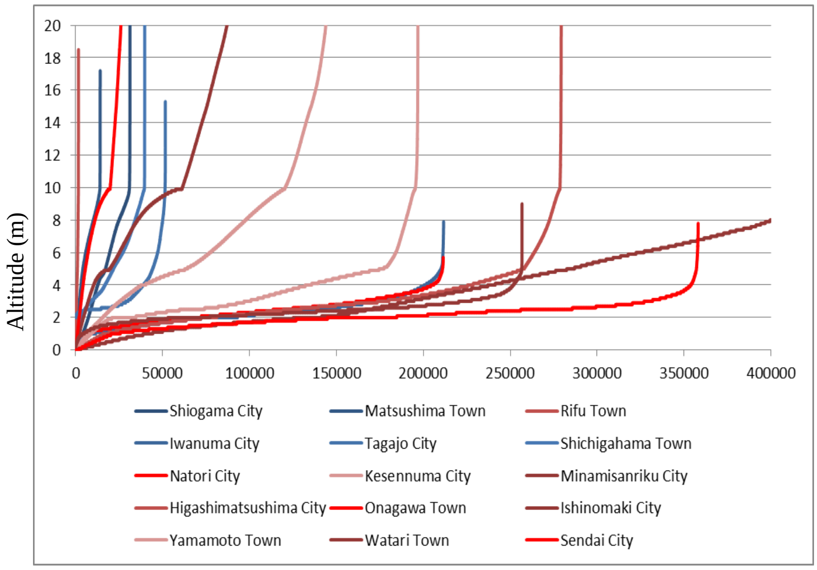


Figure 5.2 (2): Altitude distribution in Miyagi Prefecture (The maximum value is shown on the horizontal axis in 250m. However, in graphs with thick frames, the maximum value depends on each result.)

This thesis considered the influence of the terrain, focusing on regional classification by terrain in Miyagi Prefecture. Figure 5.3 shows the relationship between elevation distribution in the inundated areas and an elevation model (10 m) of the inundated areas. Therefore, the horizontal axis shows a reordering, in ascending order, of the altitude of the region, and the vertical axis shows the altitude. Here, the horizontal axis represents the elevation characteristics of the inundated area in the “regional classification by terrain” not a specific cross-sectional view. As with Fukushima Prefecture and Iwate Prefecture, the fatality rate tended to be high in all regions of Miyagi Prefecture and it is higher in areas with flat altitude distributions than areas with steep altitude distributions.

The population, average inundation depth, average evacuation distance, average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old in each grid were all calculated based on data from each municipality. The processes were the same in Chapter 4. The result is shown in Table 5.2 and Figure 5.4. The values for Onagawa Town and Natori City are not listed in Table 5.2 because accurate inundation depth data could not be obtained. The estimated death toll in each municipality was calculated using Eq. (4.8) to Eq. (4.11). The death toll (■ mark and ○ mark) in each municipality in Miyagi Prefecture was calculated using the proposed model from Eq. (4.8) and Eq. (4.9) and the death toll (× marks) calculated by Eq. (2.1). The results are shown in Figure 5.4. Eq. (4.10) and Eq. (4.11) were applied, but it did not fit well. Therefore, the results of the proposed model using Eq. (4.8) and Eq. (4.9) were shown in Figure 5.4. The average prediction error in each municipality was 293 people in the case of using Eq. (4.8) and 435 people in the case of using Eq. (4.8) and Eq. (4.9). The average prediction error in each municipality of the Central Disaster Management Council in Japan was 1,156 people. Therefore, The death toll (■ mark and ○ mark) shows good accuracy compared with the fatality equation used by the Central Disaster Management Council in Japan.



Reordering in ascending order altitude in the region

Explanatory notes

(Color gradient) Fatality Rate in region is over 1% (Color gradient) Fatality Rate in region is less than 1%

Figure 5.3: Relationship between altitude distribution and fatality rate

Table5.2: Results in Miyagi Prefecture

	Death toll in inundated area	Estimated death toll	Estimated death toll	Estimated death toll using equation of Central Disaster Management Council
		Eq. (4.8)	Eq.(4.8) and Eq.(4.9)	Eq. (2.1)
Kesennuma City	951	654	905	4,831
Minamisanriku Town	538	315	354	5,060
Higashimatsushima City	1,023	703	1,268	1,282
Onagawa Town	511	–	–	–
Ishinomaki City	3,127	1,876	4,371	5,799
Matsushima Town	14	28	28	40
Rifu Town	10	35	35	–
Shiogama City	48	242	560	352
Tagajo City	112	578	1,412	1,539
Natori City	873	–	–	–
Iwanuma City	151	375	375	493
Shichigahama Town	89	204	265	1,198
Watari Town	285	366	366	502
Yamamoto Town	601	298	298	519
Sendai City	662	946	2,276	853

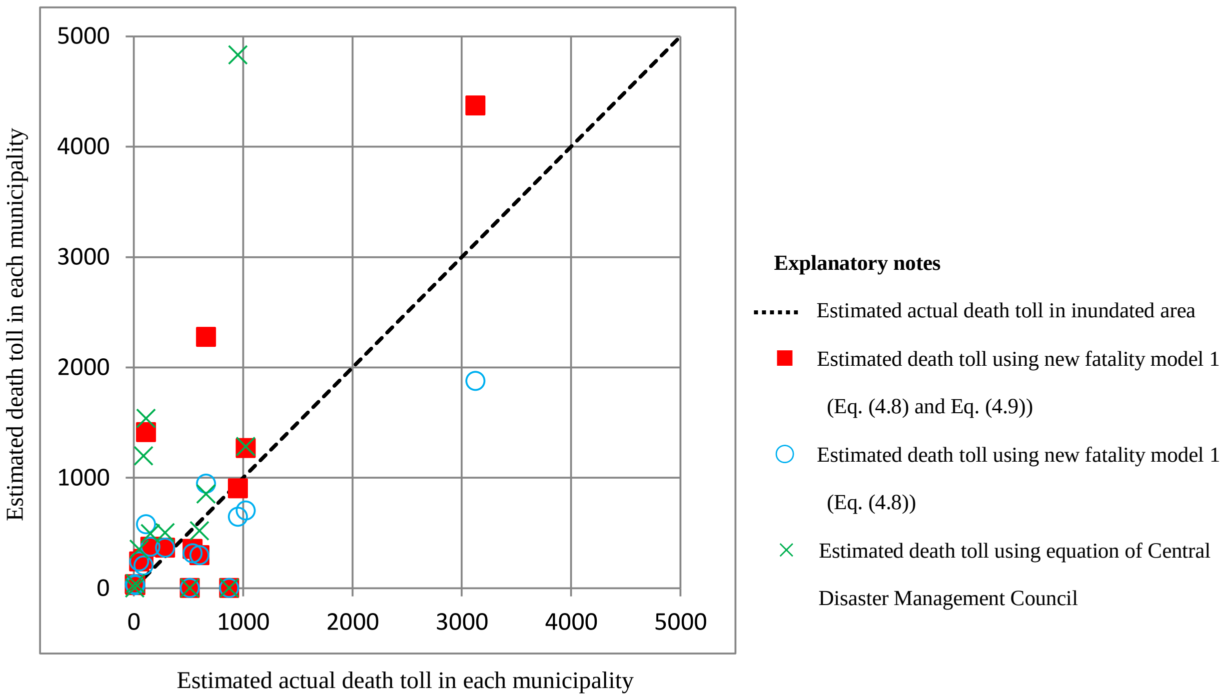


Figure 5.4: Correlation between actual death toll and estimated death toll using Eq. (4.8) and Eq. (4.9) in Miyagi Prefecture

5.2 Case study in Banda Aceh, Indonesia, the 2004 Indian Ocean Tsunami

5.2.1 Introduction

The huge tsunami in Sumatra happened at around 8 am (Indonesia Standard Time) on December 26, 2004. The tsunami has happened with 165,708 deaths from the EM-DAT database [1] or 227,899 deaths from historical tsunami database from National Centers for Environmental Information, the Global Historical Tsunami Database (NGDC) [2]. Thus, accurate values have not been confirmed. The tsunami accompanying the earthquake caused serious damage in Indonesia and other coastal areas of the Indian Ocean. The greatest damage was in the island of the Sumatra, Indonesia and the coastal area was destroyed due to the strong vibration and sudden large tsunami. The first wave of the tsunami was struck approximately 15 min after the earthquake. The maximum tsunami height hit near the resident was 48.9 m measured on the peninsula about 20 km southern of Banda Aceh [3]. Imamura [4] said that instant judgment and late evacuation have meant the difference between life and death in the past disasters. In reality, it may be difficult to perform evacuation actions and safely reach evacuation sites. The 2004 Indian Ocean Tsunami showed the difficulty of evacuation. Marchand *et al.* [5] explain that differences topographical features and population density will affect the impact of a tsunami as well as physical and socioeconomic factors. They collected data in Banda Aceh, Calang, Samatiga and Lhoksumaweh in Indonesia. Based on the analysis of the 2004 Indian Ocean Tsunami, the percentage of houses destroyed was close to 100% if the inundation depth was approximately 1.5 m. In terms of the relationship between casualties and inundation depth, the casualties were low for an inundation depth of up to 1.5 m. If the inundation depth was above 4 m, the casualty rates were more than 80%. They noted that the correlation coefficient between inundation depth and percentage of casualties was 0.82, however, the correlation between percentage of permanent housing and casualties was 0.32. From this result, inundation depth was a highly significant variable related to the cause of death. The most affected area was Aceh Province in Indonesia, which suffered 129,775 deaths, 38,786 missing people and 504,518 tsunami-displaced persons. Doocy *et al.* [6] noted that *"the continued development of mortality estimation methods can provide insight for impact estimation in future disasters where population data and resources are scarce"*. Umitsu and Takahashi [7] considered the characteristics of physical damage and human damage focusing on the regional difference of the topographic condition and tsunami condition. They analyzed the flat area in Banda Aceh City. Banda Aceh has an alluvial lowland consisting of alluvial plains and coastal plains. Compared with Meuraxa and Kutaraja in the western part of the city, they found that deaths and missing person were remarkably low in the districts of Kuta Alam and Syiah Kuala located in the eastern part although at the same distance from the coast.

In terms of gender and age-specific death rates, significant differences in mortality rate were recognized by age rather than gender, regardless of the degree of damage. Hence, the mortality rate was low at the age of 20 to 30 and it was high at ages of more than 60 and less than 10. They also stated that the damage of the tsunami was basically related to the distance from the coast. Another paper of Doocy *et al.* [8], they investigated the tsunami mortality rate and injury as well as the surviving displaced population in Aceh, Indonesia based on a questionnaire. They gave the questionnaire to displaced populations identified by local authorities in Meulaboh, Aceh Jaya, Aceh Besar and Lhoksumawe. The highest mortality rate was 23.6% in the Aceh Jaya district on the west coast. In Banda Aceh/Aceh Besar crude mortality was 22.9%. When the results focused on age-specific mortality rate, the highest mortality was among older people, more than 70 years old, as well as the youngest children (0-9 years old). They said that females suffered greater losses than men in all survey areas. According the results, females were 1.44 times as likely to die in the tsunami. In terms of the characteristics of topography, the Banda Aceh/Aceh Besar area is alluvial flood plain and has a relatively slow elevation. The reason was thought to be that men were fishing far at sea or working in the fields in agricultural areas. Regarding the physical ability, women and young children could not stand on their feet as well against the huge tsunami wave. Additionally, Iemura *et al.* [9] [10] mainly distributed a questionnaire survey consisting of multiple choice and write-in questions with 12 questions. The aim of study was to provide information about the disaster and the effects of such a huge earthquake and tsunami. Of the respondents, 75-90 % expected that they survived because they had run away just after the big earthquake happened. Another result shows the tsunami awareness of people is low. Koshimura *et al.* [11] explained that data on vulnerability constructed from Banda Aceh may not be applicable to tsunami vulnerability studies in other areas and tsunami scenarios. This is because *"vulnerabilities should include the multitude of uncertain sources, such as hydrodynamic features of tsunami inundation flow, structural characteristics and site conditions*". Therefore, when applying the current vulnerability function to use other regions and countries, it is necessary to use it carefully.

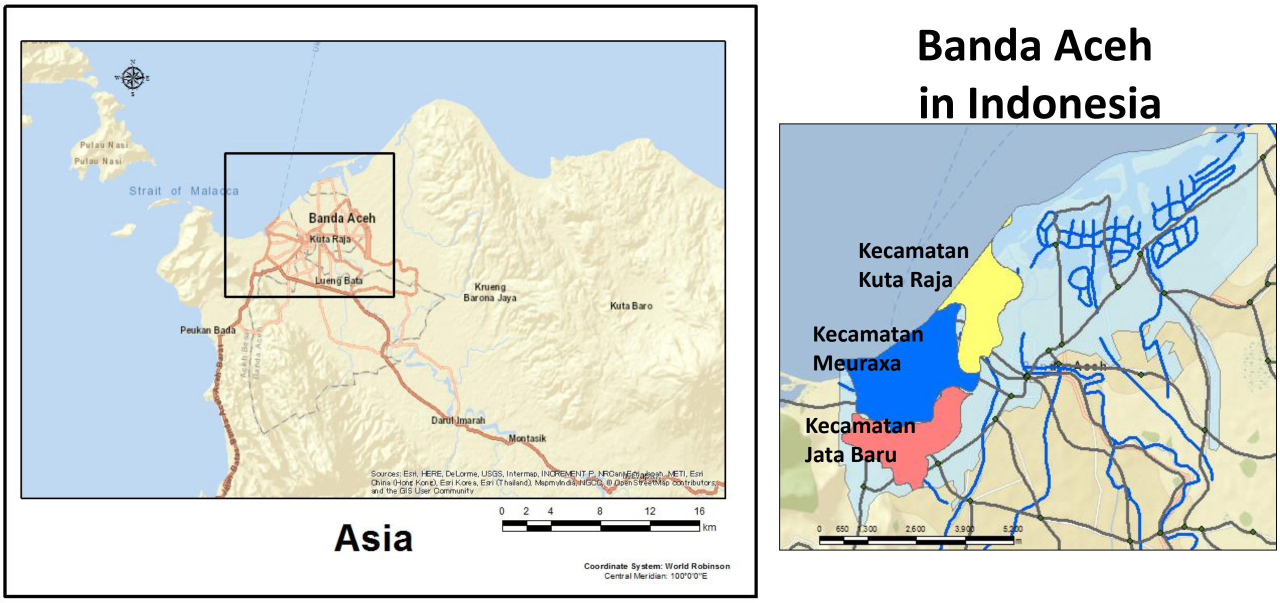


Figure 5.5: Location of the case study area in Banda Aceh

5.2.2 Methods

The new model that resulted from Fukushima Prefecture and Iwate Prefecture is adapted to the 2004 Indian Ocean Tsunami. The target areas were three districts shown in Figure 5.5: Kecamatan Kuta Raja, Kecamatan Meuraxa and Kecamatan Jata Baru in Banda Aceh obtained the number of deaths by the Japan International Cooperation Agency (JICA) report. The analysis is based on data that have been published on the website to date. The datasets used are as follows: (1) the information about the 2004 Indian Ocean Tsunami by the JICA report [12], (2) the elevation model for Banda Aceh is from ALOS World 3D – 30m – by the Japan Aerospace Exploration Agency (JAXA) [13], (3) population data [12] and (4) gender data [12] and population composition [14]. The procedure follows Step D above and the number of deaths and grids is shown in Table 5.3.

Table5.3: Number of deaths and grids in Banda Aceh

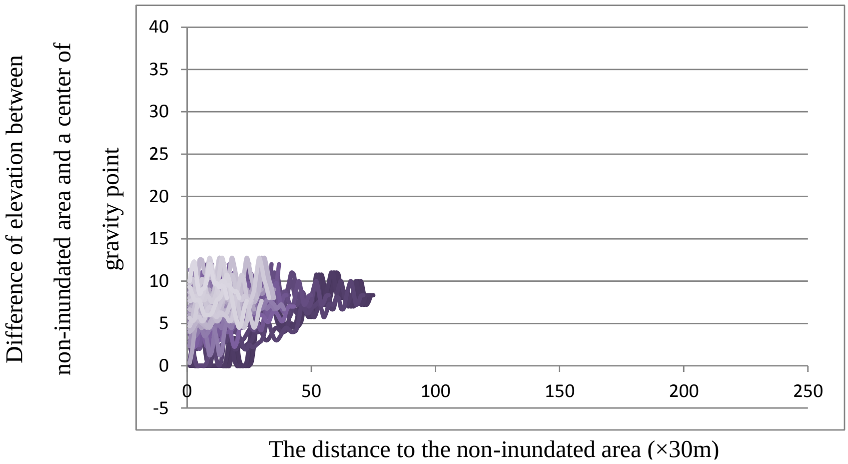
	Population	Death toll	Fatality Rate	Death of one grid	Grids of fatality
Kuta Raja	20,217	13,707	67.8%	2,285	6
Meuraxa	31,218	21,679	69.4%	1,807	12
Jata Baru	22,005	7,470	33.9%	498	15

5.2.3 Results

Figure 5.6 is the results of the detail altitude distribution in three districts in Banda Aceh. As a general trend, the altitude is low and the evacuation distance to a safe place is long. In terms of the influence of the terrain, it focused on regional classification by terrain in Banda Aceh, Indonesia. It shows the relationship between elevation distribution in the inundated areas and an elevation model (30 m) of the inundated areas. Figure 5.7 indicated the geographical features in Banda Aceh. The horizontal axis shows a reordering, in ascending order, of the altitude of the region, and the vertical axis shows the altitude. Here, the horizontal axis represents the altitude characteristics of the inundated area in the "regional classification by terrain" not a specific cross-sectional view. In terms of estimating fatality of the 2004 Indian Ocean Tsunami, the actual death toll of Kecamatan (district) level and the death toll calculated by Eq. (2.1) were shown in Table 5.4.

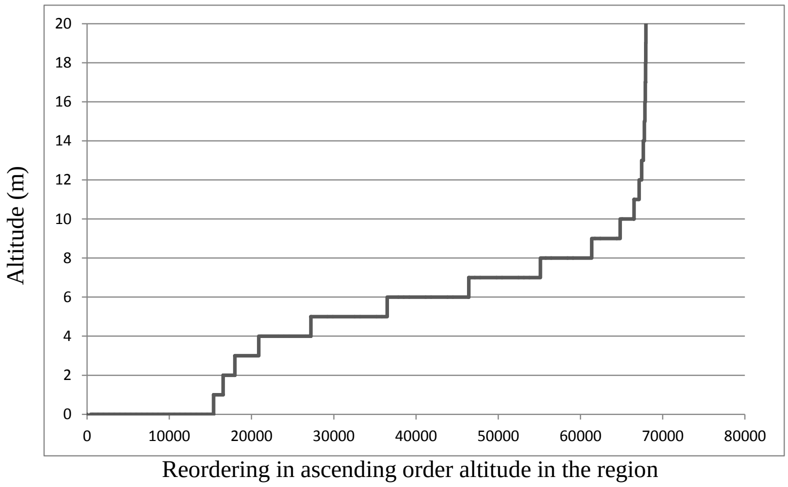
Table 5.4: Detail results in Banda Aceh

	Population	Death toll in inundated area	Estimated death toll	Estimated death toll	Estimated death toll using equation of Central Disaster Management Council
			Eq. (4.8)	Eq.(4.8) and Eq.(4.9)	Eq. (2.1)
Kuta Raja	20,217	13,707	293	815	2,909
Meuraxa	31,218	21,679	499	1,495	2,132
Jaya Baru	22,005	7,470	360	1,148	2,955



Source: Elevation model for Banda Aceh is from ALOS World 3D ©JAXA

Figure 5.6: Altitude distribution in three districts in Banda Aceh



Source: Elevation model for Banda Aceh is from ALOS World 3D ©JAXA

Figure 5.7: Altitude distribution in the inundated area in Banda Aceh

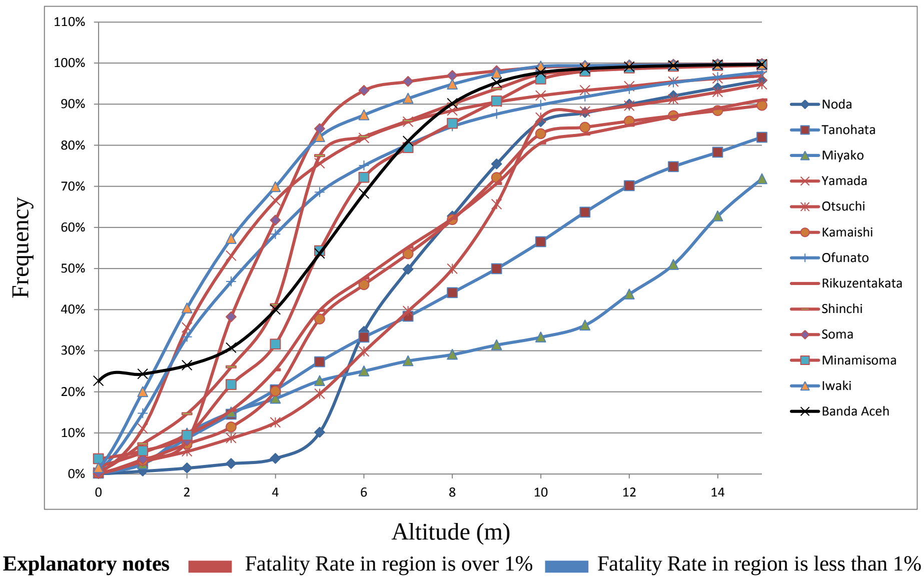


Figure 5.8: Relationship between altitude distribution and frequency in Fukushima Prefecture, Iwate Prefecture and Banda Aceh

5.3 Discussions

Although the proposed model could be applied to Miyagi Prefecture, it was not fitted for Indonesia. First, this section focused on geographical features. The formula calculated in Shinchi Town, Kamaishi City and Rikuzentakada City was applied to the three districts because the geographical trend was similar. However, none of the formulas could be applied successfully. Thus, this section devised a method to grasp topographical features shown in Figure 5.8. The horizontal axis shows the altitude, and the vertical axis shows the cumulative frequency of the number of points per altitude. As a result, clearly for Banda Aceh the trends would be different. The proportion of the altitude of 0 m is 20%, and the area trends to have a topography where the plain continues beyond Japan. However, there are other differences than geographical features. This thesis investigated the reason for using disaster risk for the earthquake index provide by UNDP [15] as well as the differences between the 2011 Great East Japan Earthquake and Tsunami and the 2004 Indian Ocean Tsunami using the framework of "environment surrounding human society in the event a natural disaster" established in Chapter 4 [12-25]. Physical exposure in terms of percentage of population, shown in Table 5.5, was significantly different. In terms of Table 5.6 (1) and Table 5.6 (2), compared with the 2011 Great East Japan Earthquake and Tsunami, the percentage of men was large, and the percentage of people over 65 years old was low, which means that there were fewer deaths than in the 2011 Great East Japan Earthquake and Tsunami. However, the evacuation distance was significantly longer in Banda Aceh. Regarding disaster prevention measures, there was no warning sign in Banda Aceh. The proposed fatality model took into account the following three factors: tsunami characteristics, geographical features and demographic components. Therefore, the regional differences were among the factors that caused human damage. According to Figure 4.9, Table 5.6 (1) and Table 5.6 (2), there were some significant influences on the fatality model as well as significant differences in the situations between Japan and overseas. In the case of the 2004 Indian Ocean Tsunami, the experience of the past tsunamis, the degree of knowledge about natural disasters and tsunamis, and the information provided by the national and local government that could not be expressed by this model were significant influences on human damages.

Table 5.5: UNDP Disaster Risk for Earthquake

		Japan	Indonesia
Average number of events per year	Event per year	1.14	1.62
Number of people killed per year	Killed per year	281.29	193.24
Average number of people killed per million inhabitants	Killed per million	2.31	1.04
Average physical exposure per year	People per year	30,855,862	16,601,764
Physical exposure in percentage of population	%	25.39	8.8
Relative Vulnerability	Killed per million exposed	9.12	11.85
Percentage of Urban growth (as average for 3-year period)	%	0.02	0.15

Source: Statistical Annex Disaster Risk Index Table, http://www.undp.or.jp/publications/pdf/RDR_ES_J.pdf

Table 5.6 (1): Differences between the 2011 Great East Japan Earthquake and the 2004 Indian Ocean Tsunami

	2011 Great East Japan Earthquake and Tsunami			2004 Indian Ocean Tsunami
	Iwate Prefecture	Miyagi Prefecture	Fukushima Prefecture	Banda Aceh
Population	11,889 (Inundated area)	337,533 (Inundated area)	84,950 (Inundated area)	69,764
Percentage of men	47.7%	48.6%	48.5%	55.6%
Percentage of people over 65years old	27.1%	22.4%	25%	5%
Death	5,136 (whole area)	10,563 (whole area)	3,762 (whole area)	42,856
Inundation depth	Average 5.6m	Average 3.1m	Average 2.5m	Average 5.8m
Evacuation distance	Average 167.3m	Average 270.4m	Average 249.2m	Average 2197.2m
Geography	Complexity coast lines	Relatively flat	Relatively flat	Flat
Environmental characteristics				
Building structure	Average 2 stories	Average 2 stories	Average 2 stories	Lower than Japan
Embankment	○	○	○	Embankment as a measure against the flood of the Aceh River
Vulnerable people's facilities	28 welfare facilities and 23 educational facilities	47 welfare facilities and 9 elementary schools	2 welfare facilities and 1 primary school	Not sure
Natural disaster characteristics				
Arrival times of tsunamis	15 min after the earthquake			15-30 min after the earthquake
Culture				
Religion	74% (Shinto)	78%(Shinto)	53%(Buddhist)	Following Islamic law
Experience	1993 Showa Sanriku Tsunami			1907 Tsunami
Social capital	Not sure	Not sure	Not sure	Not sure(Kinship systems is strong)
Local industry				
Industry	Fishing industry	Fishing industry	Fishing industry	Fishing industry
Tourist	Not sure	Not sure	Not sure	about 500 people
Education				
Drill	○	○	○	×
Knowledge	Higher than Indonesia	Higher than Indonesia	Higher than Indonesia	Low
Community linkages	Not sure	Not sure	Not sure	High

Table 5.6 (2): Differences between the 2011 Great East Japan Earthquake and the 2004 Indian Ocean Tsunami

	2011 Great East Japan Earthquake and Tsunami			2004 Indian Ocean Tsunami
	Iwate Prefecture	Miyagi Prefecture	Fukushima Prefecture	Banda Aceh
Emergency plan	○	○	○	Not sure
Provided information				
Hazard map	○	○	○	×
Warning sign	○	○	○	×
Early warning system	○	○	○	×

5.4 Summary

The proposed model expresses actual fatalities with good accuracy compared with the fatality equation used by the Central Disaster Management Council in Japan in the case of Miyagi Prefecture in the 2011 Great East Japan Earthquake and Tsunami. The fatalities in the 500m grid were evaluated with new explanatory variables including the elevation and distance of the evacuation route, the intercept by ARMA model, the wavelength and the damping ratio by inputting only population, inundation depth, road network data, and elevation data.

The differences between the 2011 Great East Japan Earthquake and Tsunami and the 2004 Indian Ocean Tsunami were compared in Chapter 5. Among past tsunami disasters occurred in the world, this thesis also tested the proposed model using the 1933 Showa Sanriku Tsunami and the 2009 American Samoa Tsunami. However, the proposed model did not fit these past tsunami disasters because the quality and quantity of data were inadequate. Regarding the 2009 American Samoa, Shibayama *et al.* [26] reported that the first tsunami hit 5 m at the coastal area in the Samoa islands about 20 min after the earthquake happened. A 9 m tsunami hit American Samoa. Residents in coastal areas felt a sense of danger because the waves were different than usual. They evacuated to a safe site. Shibayama noted that the deaths were few. Nevertheless people got the tsunami warning, they evacuated, and they knew the danger of the tsunami and the importance of evacuating to a safe place. Moreover the community was extremely strong in Samoa. Okal *et al.* [27] explained that the Pacific Tsunami Warning Center issued a tsunami warning 16 min after the earthquake happened. However the tsunami occurred between 15 to 20 min after the earthquake, it is considered that some areas caught the waring in time, but some areas did not. In American Samoa, residents spread warning information using bells when cyclones occur. Because of the strong community system, people help each other during natural disasters. Further, human casualties could be reduced as people recognized the danger of a tsunami. However, in Upolo, people could not evacuate successfully due to the evacuation distance was long. Moreover there were few signs warn of the tsunami. That is why human damage by happened. People in Upolo stated that it is important to spread information and knowledge about natural disasters and to prepare for such natural disasters.

This chapter confirmed factors causing human damage in tsunami disasters by focusing on demographic components, evacuation distance, whether there are warning issues or not, and whether people have knowledge of natural disasters by analyzing the data of the 2011 Great East Japan Earthquake and Tsunami, the 2004 Indian Ocean Tsunami and the 2009 American Samoa Tsunami. However, the parameters that cannot be expressed by this model, such as the experience of past tsunamis, the degree of knowledge about natural disasters such as tsunamis, and whether information has been provided by the country or local government or not, have relevance to human damage. That is, it is considered that the difference in regions will become an important factor. However, although factors globally show remarkable differences, analysis results indicate the age, gender and evacuation distance are factors that can be incorporated in the proposed model. Therefore, a minimum international standard model for predicting fatalities could be constructed.

References

[1] EM-DAT website (2017) Available: http://www.emdat.be/. Last Accessed:30th September, 2017

[2] NGDC/WDS Global Historical Tsunami Database, Available: https://www.ngdc.noaa.gov/hazard/tsu_db.shtml. Last Accessed: 2nd November, 2017

[3] Y. Kawata (2005) Sumatra-Andaman islands Earthquake of 26 December 2004, Annuals of disas. Prev. Inst., Kyoto Univ., No.48 (in Japanese)

[4] F. Imamura (2005) "Devastating Damage due to the 2004 Sumatora Earthquake Tsunami –Lessons for Japan-", PROCEEDINGS OF CIVIL ENGINEERING IN THE OCEAN, Vol. 21, pp. 31-37(in Japanese)

[5] M. Marchand, J. Buurman, A. Pribadi and A. Kurniawan (2009) "Damage and casualties modelling as part of a vulnerability assessment for tsunami hazards: a case study from Aceh Indonesia", Journal of Flood Risk Management 2, pp.120-131

[6] S. Doocy, Y. Gorokhovich, G. Burnham, D. Balk and C. Robinson (2007) "Tsunami Mortality Estimates and Vulnerability Mapping in Aceh, Indonesia", American Journal of Public Health, Vo. 97, No.S1

[7] M.Umitsu and M. Takahashi (2007) "Geo-environmental Features in the damages of the 2004 Indian Ocean Tsunami in/around Banda Aceh, Indonesia", E-journal GEO, Vol.2 (3), pp.121-131 (in Japanese)

[8] S. Doocy, A. Rofi, C. Moodie, E. Spring, S. Bradley, G. Burnham and C. Robinson (2006) "Tsunami mortality in a Aceh Province, Indonesia", Bulletin of the World Health Organization, 85 (2)

[9] H. Iemura, Y. Takahashi, M. H. Pradono, P. Sukamdo and Rudi Kurniawan (2006) "Earthquake and tsunami questionnaires in Banda Aceh and surrounding areas", Disaster Prevention and Management", Vol. 15, No.1, pp.21-30

[10] H. Iemura, M. H. Pradono, A. bin Husen, T. Jauhari, and M. Sugimoto (2008) "Information dissemination for reality-based tsunami disaster education", The 14th World Conference on Earthquake Engineering, October 12-17, Beijing, China

[11] S. Koshimura, T. Oie, H. Yanagisawa and F. Imamura (2009) "Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia", Coastal Engineering Journal, Vol. 51, No. 3, pp.243–273

[12] Japan International Cooperation Agency. (2005) "The study on the urgent rehabilitation and reconstruction support program for Aceh Province and affected areas in north Sumatra (urgent rehabilitation and reconstruction plan for Banda Aceh City) in the Republic of Indonesia : final report(1);Vol.2. Main report." Available : http://open_jicareport.jica.go.jp/pdf/11802741_04.pdf

[13] ALOS World 3D – 30m – by the Japan Aerospace Exploration Agency (JAXA). (2016) Available:

http://www.eorc.jaxa.jp/ALOS/aw3d30/index_j.htm. (in Japanese)

[14] Institute of Social Science, The University of Tokyo, "Labor market and social security system in Indonesia", Available : http://web.iss.u-tokyo.ac.jp/gov/research/asia_ch12_indonesia.pdf Last Accessed: 2nd November, 2017 (in Japanese)

[15] Statistical Annex Disaster Risk Index Table, http://www.undp.or.jp/publications/pdf/RDR_ES_J.pdf. Last Accessed: 4tn January, 2018 (in Japanese)

[16] Statistics of Japan, e-Stat, http://www.e-stat.go.jp/SG1/estat/List.do?lid=000001084274. Last Accessed: 4tn January, 2018 (in Japanese)

[17] City Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (2017) "About the result of a survey of damage by the Great East Japan Earthquake (the 156th report), Retrieved September 8, 2017" Available: http://www.fdma.go.jp/bn/higaihou/pdf/jishin/156.pdf. Last Accessed: 4tn January, 2018 (in Japanese)

[18] E. E. Webb (2009) "Re-mapping the 2004 Boxing Day Tsunami Inundation in the Banda Aceh Region with Attention to Probable Sea Level Rise", Bachelor of Arts degree from Carleton College, Northfield, Minnesota, Available:https://www.carleton.edu/departments/geol/Resources/comps/CompsPDFfiles/2009/webbe_2009.pdf. Last Accessed: 4tn January, 2018

[19] T. Oie, S. Koshimura, H. Yanagisawa and F. Imamura (2006) "Tsunami flooding analysis and damage assessment in the Banda Aceh city area by the 2004 Indian Ocean tsunami", Proceedings of Coastal Engineering, Japan Society of Civil Engineers, Vol. 53, pp.221-225, Available: http://www.tsunami.civil.tohoku.ac.jp/hokusai2/staff-students/oie/Kaikou_Oie_2006.pdf. Last Accessed: 4tn January, 2018 (in Japanese)

[20] T. Tobita, S. Iai, B. Chairullah and W. Asper (2005),"Damage to earth structures after the 2004 Sumatra-Andaman, Indonesia, Earthquake", Proceedings of Earthquake Engineering Symposium, Japan Society of Civil Engineers Available: http://library.jsce.or.jp/jsce/open/00578/2005/28-0211.pdf. Last Accessed: 4tn January, 2018

[21] Point data of welfare facilities and school by National Land Numerical Information download service, Available: http://nlftp.mlit.go.jp/ksj/. Last Accessed: 1st November, 2017 (in Japanese)

[22] Statistics of Japan, e-Stat , Religion data (2011) Available: http://www.mext.go.jp/b_menu/toukei/chousa07/shuukyou/1262852.htm. Last Accessed: 4tn January, 2018 (in Japanese)

[23] Ministry of Education, Culture, Sports, Science and Technology, Japan, Religious Statistics Survey Available: http://www.mext.go.jp/b_menu/toukei/chousa07/shuukyou/gaiyou/chousa/1262860.htm. Last

Accessed: 4tn January, 2018

[24] International Recovery Platform (2012) “Indian Ocean Tsunami 2004:Recovery in Banda Aceh”, Available:http://www.recoveryplatform.org/assets/recoverycases_reports/RECOVERY%20STATUS%20REPORT%20ACEH%20JAN15.pdf. Last Accessed: 4tn January, 2018

[25] Statistics Indonesia, Available:https://www.bps.go.id/subject/16/pariwisata.html#subjekViewTab3. Last Accessed: 4tn January, 2018

[26] T. Shibayama, T. Mikaki, R. Matsumaru, H. Takagi, F. Latu (2010) “Field Survey and Analysis of Tsunami Disaster in the Samoan Islands”, *Coastal Engineering/ Journal of Japan Society of Civil Engineers*, Ser. B2, Vol. 66, Issue 1, pp. 1376-1380 (in Japanese)

[27] E. A. Okal, H. M. Fritz, C. E. Synolakis, J. C. Borrero, R. Weiss, P. J. Lynett, V. V. Titov, S. Foteinis, B. E. Jaffe, P. L.-F. Liu and I-chi Chan (2010) “ Field Survey of the Samoa Tsunami of 29 September 2009” *Seismological Research Letters*, Vol. 81, No. 4, pp. 577-591

Chapter 6

Conclusion

This research proposed a fatality model taking into account the following three factors: tsunami characteristics, geographical features and demographic components. New explanatory variables have been developed based on the analysis of the 2011 Great East Japan Earthquake and Tsunami. These explanatory variables indicate local features such as the distance and elevation trend of evacuation routes. Characteristics of the distance and elevation trend of evacuation routes were analyzed focusing on Fukushima Prefecture, Iwate Prefecture and Miyagi Prefecture in Japan and Kecamatan (district in English) Kuta Raja, Kecamatan Meuraxa and Kecamatan Jata Baru in Indonesia. Additionally, social factors such as age and gender that affect evacuation decision making were considered.

Chapter 2 summarized the past literature. It was essential to identify what research had already been conducted regarding fatality models and damage analysis of natural disasters. Previous fatality models and damage analysis of past natural disasters, especially earthquakes, tsunamis and floods were explained. There were tsunami inundation prediction simulation methods and building damage prediction methods implemented by national and local governments in Japan and throughout the world. Alongside there was little research regarding a model that included social factors. Natural disasters reflect strong regional characteristics and a fatality model constructed in a certain region is not necessarily directly applicable to other regions. Besides, each country faces different natural disasters, each country has different disaster prevention plans and there are differences in culture, risk perception and human behavior. Society needs a global fatality model for estimating fatalities using the same criteria.

Chapter 3 summarized the detailed analysis of factors causing human damage (fatality rate, geographical features, evacuation distance, evacuation distance and human damage and inundation depth). To briefly summarize, the fatality rate of elderly people was high. It was found that flat areas had a higher fatality rate than those where the elevation distribution from the coastal line had a steep slope. Furthermore, in terms of evacuation distance, the fact that evacuations were delayed despite the evacuation route being short is a reason for people not being able to escape (because they thought they were safe). In terms of inundation depth, although each region is different, the death rate tends to rise when the depth of flooding exceeds 2 m.

Chapter 4 explained the method for constructing a fatality model. First, using GIS, the inundation zone was divided into two areas, the area where deaths occurred and the area where there were no fatalities. Second, the distance and elevation from a deceased' address to the non-inundated areas through the road network were calculated. Third, the distance and elevation, which are characteristics of evacuation routes were converted into numerals by an autoregressive moving average model (ARMA). This thesis determined the wavelength

(L) and the damping ratio (h) of a single degree of freedom system that express the smoothness of the evacuation routes. This thesis carried out multiple regression analyses against eight explanatory variables: population, average inundation depth, average evacuation distance, average intercept by ARMA model, average wavelength, average damping ratio, percentage of men and percentage of people over 65 years old. The objective variable was the number of deaths in each 500 m grid. Fatalities in 500 m grid was evaluated with new explanatory variables including elevation and distance of evacuation route, intercept by ARMA model, wavelength and damping ratio only by inputting population, inundation depth, road network data and elevation data. The average prediction error was defined to evaluate how much difference exists between the actual death toll and the estimated death toll. The proposed model expressed actual fatality with good accuracy compared with the fatality equation used by the Central Disaster Management Council in Japan. This thesis confirmed that the death toll calculated by the proposed model was much lower than the prediction error calculated by Eq. (2.1). The equation of the Central Disaster Management Council assumed the number of deaths to be about 2,700 in the affected area, but in reality, 7.6 times as many deaths occurred. The formula proposed here is thought to be able to evaluate the death toll with a higher degree of accuracy than the formula of the Central Disaster Council.

This is proposed as a fatality model at national level.

D≦10
$$D = 0.0102P + 0.2640x_1 + 0.0062x_2 + 0.0002x_3 + 0.00001x_4 + 0.0008x_5 - 0.00049x_6 + 0.0069x_7 - 1.7090 \quad (6.1)$$

D>10
$$D = 0.0200P - 0.1301x_1 + 0.01791x_2 - 0.4661x_3 - 0.0005x_4 + 0.8609x_5 + 1.5400x_6 - 0.0294x_7 - 56.7100 \quad (6.2)$$

Moreover, this chapter summarized construction of a globally applicable human damage model for natural disasters (earthquakes, tsunamis and flooding) based on past studies. It showed the differences between Japan and overseas in terms of the human damage caused by natural disasters. The environment surrounding human society in the event of a natural disaster classified what is a significant influence on the fatality model, significant differences in situations between Japan and overseas and the difficulty of obtaining a data.

In Chapter 5, the testing of the fatality model during tsunami disasters was presented. The target areas were Miyagi Prefecture affected by the 2011 Great East Japan Earthquake and Tsunami and Kecamatan Kuta Raja, Kecamatan Meuraxa and Kecamatan Jata Baru in Indonesia affected by the 2004 Indian Ocean Tsunami. Although the proposed model could be applied to Miyagi Prefecture, it was not suitable for Indonesia. Therefore, the regional difference was one of the factors that influence human damage. According to Figure 4.9, Table 5.6 (1) and Table 5.6 (2), there were some significant influences in the fatality model as well as significant differences in situation between Japan and overseas. In the case of the 2004 Indian Ocean Tsunami, altitude distribution was significantly different than in Japan. Experience of past tsunamis, the degree of knowledge about natural disasters and tsunamis, and the information provided by national and local governments which could not be expressed by this model were significant influences on human damage. However, fatalities in 500 m grid could be evaluated with new explanatory variables including elevation and distance of the evacuation route, intercept by ARMA model, wavelength and damping ratio only by inputting population, inundation depth, road network data and elevation data at a prefectural or regional level by focusing on tsunami characteristics, geographical features and demographic components. It was possible to predict human damage with an expression incorporating an index that can express the situation of a region. Hence, fatalities were estimated using the fatality model shown in Figure 4.19, Table 4.3 (1) and (2), Table 4.4 (1) and (2) and table in Figure 4.17 for each topographic feature in each area at the prefecture level and municipal level.

Finally, this thesis conducted detailed analysis of factors causing fatalities by tsunami based on the 2011 Great East Japan Earthquake and Tsunami. New fatality model for the estimation of loss of life due to tsunamis was proposed. The proposed model expresses actual fatality with good accuracy compared with the fatality equation used by the Central Disaster Management Council in Japan. Fatalities in the 500m grid were evaluated with new explanatory variables including the elevation and distance of the evacuation route, intercept by ARMA model, wavelength and damping ratio. This thesis analyzed the elevation and distance of evacuation routes which previous research has not taken into account. This thesis could evaluate fatalities using new explanatory variables simply by inputting population, inundation depth, road network date, and elevation data. The fatality model could evaluate deaths at the national level, prefecture level, and municipality level. The result of this thesis will give new worldwide criteria to estimate human damage for future tsunami events. Furthermore this fatality model can help in communicating risk to local communities and in disaster management and it can take into account the characteristics of a region.

6.1 Limitations

Analyzing the mechanism of human damage and developing a fatality model greatly depends on the quality and quantity of data. Moreover, the contents and precision of the analysis are examined carefully. From the viewpoint of data quality, it is desirable to utilize detailed data provided by disaster affected municipality, but in reality, it is difficult to obtain such data on all areas. Hence, this thesis used publicly released data as much as possible, so that a similar analysis can be done for future disasters. However, it is conceivable that more detailed information will be analyzed and the data will be updated as time passes after disaster. Therefore, it is also necessary to proceed with the analysis while checking for the updated data. Additionally, regarding similar analyses overseas, it is difficult to imagine that detailed data will always exist, like in Japan. In the future, when constructing a human damage model, it will be necessary to construct one that can be evaluated by applying published information without requiring information.

Ordinarily, to explain the human damage caused by a tsunami, this thesis would analyze the location where a person was at the time of the tsunami, where a person was caught up in the tsunami, and how to evacuate to a safe place. However, this analysis was based on the deceased’s address. This thesis assumed that all residents died at home and constructed a regression equation based on the results obtained from the above analysis. However, in reality, not everyone died at home. Therefore, it is necessary to take into account that the number estimated may be different from the actual number of dead. Moreover, the 2010 population census used in this thesis is the resident population; that is, it is equivalent to the nighttime rather than the daytime population. However, since the 2011 Great East Japan Tsunami actually occurred during the daytime, the mortality rate should be calculated by using the daytime population. Moreover, coastal areas damaged by the 2004 Indian Ocean Tsunami have beaches. It is thought that many people died there, but it should be noted that tourists' data is not included in this proposed model.

6.2 Recommendation

Regarding similar analyses overseas, it is difficult to imagine that detailed data will always exist, as in Japan. We need to use open license programs such as Open Street Map which is a project aimed at creating free geographical information data. In terms of the elevation data, we can use the data provided by JAXA for places all over the world. In the future, when constructing a human damage model, it will be necessary to construct one that can be evaluated by applying published information without requiring additional information. Ease of use and quality are required for any model of a disaster. Moreover, more cases of tsunami damage need to be examined when adapting this model to other regions. The analysis of big data has progressed and the mutual relationship between peoples is becoming apparent. Therefore, if we analyze human behavior by using these data, it can be utilized for evacuation behavior and the fatality model at the time of a disaster.

Appendix 1: Results of questionnaire in Rye, UK

A1.1 Numbers responded

1. Have you been affected by flooding?	Numbers responded
Yes	13
No	70
3. What kind of information would you like to have during a flood? Please tick all appropriate answer(s)	
What is happening to the nearby rivers?	62.65%
What is happening to the local infrastructure?	24.10%
The extent of flooding (location)?	48.19%
Where are the shelters?	25.30%
When would the flood waters arrive?	34.94%
Safety information about family and friends	25.30%
Other : please specify	3.61%
4. Have you registered for the Flood Warning Direct Service?	
Yes	27
No	56
5. When would you consider evacuating ?	
When informed by Authorities	50
When the river is above the bank	7
When flood water reaches my home	18
When flood water rises to a metre in my home	1
I do not evacuate	5
Other : please specify	1
Spoilt vote	1
6. What transportation would you use to evacuate during a flood ?	
Walk / Wade	13
Bicycle	3
Motorbike	9
A motor vehicle with four wheels (e.g. Car, Truck, Van)	44
Boat	5
Other : please specify	4
No answer	3
Spoilt vote	2
7. Where would you evacuate to during a flood?	
High ground	27
An official evacuation centre	16
Friend's house	27
I would not evacuate	9
Other : please specify	0
Spoilt vote	4

A1.2 Numbers responded

8. If you were not at home, to which location would you evacuate?	Numbers responded
Go back to my home	15
Go to my friend's house	30
Go to official evacuation centre	18
Go to place of work	2
Go to place related to education (School, University)	0
Go in search of family or friends	14
Go to somebody's rescue	2
Other : please specify	1
Spoilt vote	1
9. How far is your home from a safe location away from any flood?	
0-100m	6
100-200m	3
200-300m	3
300-400m	11
400-500m	13
500-1km	13
over 1 km	12
Not sure	21
Spoilt vote	1
10. Once you decide to evacuate, how long do you think it would take you to get the necessary items together and leave the property?	
0-5mins	6
5-10mins	0
10-20mins	12
20-30mins	15
over 30 mis	36
Not sure	13
Spoilt vote	1
11. Have you ever discussed evacuation with family members or friends (for example agreed on meeting points in case of separation)?	
Yes	19
No	49
Not sure	14
Spoilt vote	1
12. Do you have any neighbours who would be vulnerable during a flood? (i.e. disabled people, elderly people)	
Yes	48
No	18
Not sure	16
Spoilt vote	1
16. Do you have flood risk insurance?	
Yes	54
No	25
Not sure	2
Spoilt vote	2

Appendix 2: Human behavior after the tsunami based on the data of Iwate Nippo

A2.1 Behavior classification after the earthquake

Number of category	Color	Behavior classification after the earthquake
0	(grey)	Unknown
1	(red)	Did not evacuate
2	(orange)	Could not evacuate because of the health problems
3	(yellow)	Could not evacuate because of work issue
4	(green)	Rescue family and neighbor
5	(blue)	On the way to evacuate
6	(light blue)	Safe place inundated

A2.2 Data of Evacuation behaviors after the earthquake

	Noda Village	Tanohata Village	Miyako City	Yamada Town	Otsuchi Town	Kamaishi City	Ofunato City	Rikuzentakata City
Evacuate	1	2	13	30	61	53	22	119
Not evacuate	3	5	96	145	244	168	105	264

	Noda Village	Tanohata Village	Miyako City	Yamada Town	Otsuchi Town	Kamaishi City	Ofunato City	Rikuzentakata City
Evacuate	25.0%	28.6%	11.9%	17.1%	20.0%	24.0%	17.3%	31.1%
Not evacuate	75.0%	71.4%	88.1%	82.9%	80.0%	76.0%	82.7%	68.9%

A2.3 Data of Evacuation behaviors after the earthquake by gender

	1	2	3	4	5	6
Men	123	35	34	7	36	19
Female	144	58	21	14	56	31

	1	2	3	4	5	6
Men	48.4%	13.8%	13.4%	2.8%	14.2%	7.5%
Female	44.4%	17.9%	6.5%	4.3%	17.3%	9.6%