The development of a seismic risk reduction procedure for the prioritization of low cost, load bearing masonry buildings

by

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Declaration

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Summary

The Western Cape is one of the most seismically active regions in South Africa. It features geological properties which can develop earthquakes as large as 6.87 on the Richter scale. This poses a serious threat to all of the buildings that are currently located within this region.

A recent study has found that typical three-storey Unreinforced Masonry (URM) buildings in the Cape Town area shows a high probability of failure or damage if subjected to such a large earthquake. Many of these buildings can be found in an area of Cape Town called the Cape Flats, housing approximately 11 000 individuals. The structural integrity of these buildings are of concern to engineers since it houses a number of individuals.

The purpose of the study was to develop a risk assessment procedure that could be used to assess low-rise multi-storey (2, 3 and 4 storeys) URM buildings in order to determine where the risk of earthquake related damage would be the highest. The risk assessment procedure compared various characteristics regarding the buildings, residents, seismic attributes of the region and the recovery capability of the residents.

The result, in the form of a risk rating, enabled the buildings to be prioritized according to their seismic risk. The aim was to develop a comparative model which could be applied to a range of buildings, indicating where the impact of an earthquake would be greatest. This result could then be used for further remedial action (such as retrofitting) where it is needed the most.

The risk assessment procedure used an Earthquake Risk Assessment Model (ERAM) which was specifically developed to assess the earthquake risk of each building with the use of 26 factors. These factors would each be individually scored and through the ERAM model would produce a risk rating. The buildings' can then be ranked (prioritized) according to it's risk rating to determine where remedial actions or procedures are needed first.

Opsomming

Die Wes-Kaap is een van die mees seismiese aktiewe streke in Suid-Afrika. Dit bevat geologiese eienskappe wat aardbewings met groottes van 6,87 op die Richterskaal kan laat ontwikkel (1 in 475 jaar herhaal periode). Dit hou 'n bedreiging vir baie die geboue wat tans in hierdie streek geleë is.

'n Onlangse studie het bevind dat tipiese drie-verdieping lasdraende steengeboue in die omgewing van Kaapstad 'n hoë waarskynlikheid van faling of skade toon as dit blootgestel word aan 'n groot aardbewing. Baie van hierdie geboue kan gevind word in 'n gebied van Kaapstad genaamd die Kaapse Vlakte, wat vir ongeveer 11 000 individue behuising bied. Die strukturele integriteit van hierdie geboue is van belang aangesien dit 'n groot aantal individue huisves.

Die doel van die studie was om 'n risiko-evaluerings proses te ontwikkel wat gebruik kan word om multi-verdieping (2, 3 en 4 verdiepings) lasdraende steengeboue te evalueer ten opsigte van aardbewing verwante skade. Die risiko-evaluering proses vergelyk verskeie kenmerke van die geboue, die inwoners, seismiese eienskappe van die streek en die vermoë van die inwoners om terug te keer na hul alledaagse leefstyl.

Die resultaat is in die vorm van 'n risiko-gradering, wat die gebruiker in staat stel om die geboue te prioritiseer volgens hul aardbewings risiko. Die doel was om 'n vergelykende model te ontwikkel wat toegepas kan word om 'n verskeidenheid van geboue te evalueer, en aan te dui waar die impak van 'n aardbewing die grootste sal wees. Hierdie resultaat kan dan gebruik word vir verdere remediërende optrede of prosedures soos versterkings.

Die risiko-evaluerings proses gebruik 'n "Earthquake Risk Assessment Model" (ERAM) wat spesifiek ontwikkel is om die aardbewings-risiko van elke gebou te evalueer met die gebruik van 26 faktore. Hierdie faktore word elkeen individueel beoordeel en 'n risiko-gradering word verkry met behulp van die ERAM model. Die geboue kan dan geprioritiseer word volgens elkeen se risiko-gradering om te bepaal waar daar remediërende optrede nodig is.

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"Try not to become a man of success. Rather become a man of value." - Albert Einstein

Contents

List of Figures

List of Tables

Abbreviations and Acronyms

ATC	Applied Technology Center
CAPRA	Central American Probabilistic Risk Assessment
CGS	Council for Geoscience
CM	Confined Masonry
CRU	Community Residential Units
DSHA	Deterministic Seismic Hazard Assessment
EDRI	Earthquake Disaster Risk Index
ERAM	Earthquake Risk Assessment Model
FEMA	Federal Emergency Management Agency
Hazus	Hazard United States software
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Assessment
P-SHARP	Probabilistic Seismic Hazard Assessment and Risk Program
QUAKELOSS	Earthquake loss estimation
RM	Reinforced Masonry
SABS	South African Bureau of Standards
SANS	South African National Standards Bureau
SANSN	South African National Seismological Network
UN	United Nations
UNISDR	United Nations International Strategy for Disaster Reduction
URM	Unreinforced Masonry
USGEIC	United States Geological Earthquake Information Center
USGS	United States Geological Survey
WAPMERR	World Agency of Planetary Monitoring and Earthquake Risk Reduction
WWSSN	World Wide Standard Seismograph Network

Chapter 1

Introduction

Earthquakes are natural phenomena which have been recorded as early as 464 B.C. (Armijo *et al.*, 1991). The United States Geological Survey (2014a) has determined that an average of 1 444 469 earthquakes occur around the world annually, causing damage on a widespread scale. Seismologists have long been studying the effects of earthquakes, yet the forecasting of earthquakes remain a challenging endeavour. Earthquakes have been found to be random events, occurring unexpectedly over periods of days, months, years or even centuries (Gardner and Knopoff, 1974). This was the case for the Haiti earthquake which unexpectedly occurred in 2010. A Richter magnitude 7 earthquake occurred at 16:53, causing widespread damage in the capital city of Port-au-Prince. Kolbe *et al.* (2010) estimates that 158 679 people died as a result of the event, making it one of the deadliest natural disasters recorded. The earthquake also caused major damage to the infrastructure of the capital, disrupting the efforts of emergency services. The unpredictable nature of earthquakes give rise to the problem of human vulnerability. If it is not addressed pre-emptively, it may have the potential for dire consequences.

1.1 Background to Research

The United Nations International Strategy for Disaster Reduction (UNISDR, 2010) states that more than 780 000 people have lost their lives due to natural disasters during the period 2000 to 2010. The cost of these disasters amount to \$ 960 billion for this period. It furthermore declares that nearly 60 percent of people killed by disasters, died because of earthquake related injuries. These are appalling statistics which affect humans all around the world every day. It sketches the context for a problem where earthquakes claim thousands of lives each year.

It is well known that earthquakes have been prevalent since the earliest of times, and will certainly be ever present in the future as well. This fact poses two discussion points: 1. how have humans in the past reacted to the effects of earthquakes and 2. how will humans in the future, being aware of its presence, react to earthquakes?

There has been a policy shift in structural engineering over the past 30 years to introduce the use of seismic loading codes and seismic construction practices world wide. South Africa introduced its first seismic loading code in 1989 (SABS 0160), with a revised version in 2010 (SANS 10160: Part 4). The UNISDR was created in December 1999 as part of the United Nations Secretariat. It was tasked with ensuring the implementation of the International Strategy for Disaster Reduction. The strategy entailed a major shift from the traditional emphasis of disaster response to disaster reduction, and in effect seeks to promote a "culture of prevention" (UNISDR, 2014). The movement of the past 30 years has been promoting proactive engineering and decision making, instead of sustaining reactive response towards natural disasters. Despite these innovations, a number of shortcomings still remain when addressing natural disasters.

The Western Cape province is one of the most seismically active regions in South Africa (Kijko *et al.*, 2002). Earthquakes with a magnitude of up to 6.87 can be expected for the region of Cape Town (AON Benfield, 2010). In 1969, a 6.3 Richter magnitude earthquake occurred in Tulbagh in the Western Cape. It is the most destructive earthquake to occur in South African history, causing an estimated $ 24 million (at 2002 currency rates) in property damage and 9 fatalities (Kijko *et al.*, 2002). Due to the low population density, damage would have been significantly more if the earthquake had occurred within Cape Town. During the time period 1809 - 2014, a total of ten earthquakes were registered in the southern part of the Western Cape, each with a Richter magnitude exceeding 5.0. This suggests that earthquakes of a moderate magnitude regularly occur within this region.

It is often quoted in newspapers, journals or at conferences that "*Earthquakes don't kill people, buildings do*" (UNOPS, 2013). This suggests that the well-being of an individual is dependent on two features: 1. the size of the earthquake itself and 2. the building in which an individual resides. Looking at residential buildings, Sivaraja (2014) has found that Unreinforced Masonry (URM) buildings are the most common type of structures used for housing purposes all around the world. It is also widely used in South Africa, including in seismically active regions within the Western Cape. Two to four storey URM buildings are a common sight in the city of Cape Town and the surrounding areas, such as the Cape Flats. These buildings were built prior to the introduction of the South African seismic loading code (SABS 0160:1989). URM buildings are popular for a number of reasons, providing advantages such as low cost, good thermal insulation, durability and good compressive strength (Van der Kolf, 2014). All of these features make these buildings a common feature in residential areas. There is however great uncertainty whether these structures were designed for seismic action, whether they meet the current design provisions and whether these structures are able to resist moderate intensity earthquakes.

Van der Kolf (2014) investigated whether a typical three-storey URM building, found in the Cape Flats, could resist a moderately sized earthquake (0.15g, 5.5 on Richterscale). In his study he found that the buildings showed a high probability of failure or damage, to the extent where the structural safety was deemed to be compromised. Indeed this finding is supported by international trends. The Federal Emergency Management Agency (FEMA) of the United States, states that:

> "*...this building type is typically the most seismically vulnerable category of construction in a community, and it is by far the most common type of building to be singled out for voluntary or mandatory seismic risk reduction programs in the United States*" (ATC, 2009).

These considerations suggest that masonry construction displays conflicting properties. Its low cost, good thermal properties, durability, good compressive strength and ease of construction is contrasted with poor seismic performance. Owners choose to build URM buildings because of the good characteristics it is associated with. Due to the scarcity of earthquakes, the owners often neglect the influence of a possible future earthquake.

In addition, the multi-storey URM buildings in the Cape Flats provide residence for over 11 000 individuals. The buildings are owned, serviced and maintained by the Department of Human Settlements of the Western Cape. These buildings date back to the apartheid era, which lasted from 1948 to 1994. The buildings were originally constructed to provide accommodation for migrant workers and were called "migrant hostels". These buildings have since been transformed into dormitories that provide accommodation to individuals (and families) that qualify for residence. The individuals are often from previously disadvantaged ethnic groups and need a monthly income between R800 and R3500 to qualify for residence (City of Cape Town, 2012*a*).

The City of Cape Town, in cooperation with Aurecon South Africa (Pty) Ltd, recently launched a programme to renovate these buildings. The programme is called the Community Residence Units (CRU) Refurbishment Programme which is aimed at building new rental stock and refurbishing the existing higher density stock (Boshoff, 2011). The project is not aimed at risk reduction but rather renovation. This study will attempt to accomplish the first step in reducing the seismic risk of these buildings.

1.2 Problem Statement

The background discussed above outlines the context for a problem with potential financial and safety concerns. From the discussion it is clear that a great number of 2, 3 and 4 storey URM buildings exist in a region of Cape Town called the Cape Flats. In engineering it is generally known that URM buildings are the most seismically vulnerable category of construction (Tomazevic, 1999). The buildings were built before the introduction of the South African seismic loading code (SABS 0160) in 1989 and there is great uncertainty whether these structures were designed for seismic actions and whether they meet current design provisions. Van der Kolf (2014) found that the buildings are at risk of failure or damage, to the extent where the structure can be unsafe for use. The City of Cape Town is responsible for maintaining and leasing these buildings to individuals from previously disadvantaged ethnic groups. For individuals to qualify, they need to have a monthly income of between R800 and R3500. This places them in one of the lowest income groups that exists. It is estimated that 11 000 individuals reside in these buildings. The City of Cape Town is currently busy with a refurbishing project which aims to renovate all of these buildings.

In addition to this, seismologists have estimated that the city of Cape Town is located in a region vulnerable to low- to moderate seismicity. Earthquakes with a Richter magnitude of up to 6.87 can therefore be expected for this region (AON Benfield, 2010). Earthquakes were found to be the most hazardous natural disaster, claiming 60% of all natural disaster related casualties (UNISDR, 2010).

When combining all of the details from above, it is clear to see that this is a situation that needs to be addressed. The following paragraph provides a description of an approach to address this situation.

1.3 Purpose of the Study

The purpose of the study was to develop a risk assessment procedure that could assess multi-storey (2, 3 and 4 storeys) URM buildings in Cape Town in order to determine where the risk of seismic damage would be the highest. The risk assessment procedure had to include various characteristics regarding the buildings, residents, seismic attributes of the region and the recovery capability of the residents. The characteristics that might be relevant is seismic hazard, the exposure of the building, the exposure of the individuals in the building and lastly the response capability by emergency personnel. The result, in the form of a risk rating, would enable the buildings to be prioritized according to their seismic risk. The aim is to develop a comparative model which can be applied to a range of buildings, indicating where the impact of an earthquake would be greatest. The results could be applied for various purposes, including prioritizing the buildings for seismic risk reduction measures (retrofitting of buildings) or used for disaster management planning.

It must be emphasized however that the focus of the study is to develop a risk assessment procedure, rather than to develop and implement the procedure. The time and resource constraints of the study only allows for the development of a seismic risk identification process; the full implementation of the procedure is recommended as a follow-up study.

1.4 Research Objectives

The primary objective of the study is:

1. To develop a model that could be used to prioritize the seismic risk of low cost, load bearing masonry buildings.

The following secondary objectives need to be accomplished, in order for the primary objective to be fulfilled:

(a) Determine the model structure and layout that will be used to prioritize the buildings with.

(b) Identify the hierarchy of factors, which together form the conceptual Earthquake Risk Assessment Model (ERAM).

(c) Identify the importance/weighting of each factor. This is necessary for the mathematical combinations of the model.

(d) Establish a suitable risk rating for each factor.

(e) Validate the model to prove that it is useful and of an acceptable standard.

1.5 Thesis Statement

In light of the above (problem statement and research objectives), the thesis of this work is to develop a procedure for assessing and prioritizing the seismic risk of low cost, multi-storey URM buildings. The procedure has to assess each building individually on various characteristics in order to evaluate its seismic performance. The procedure also has to account for the residents living in the building, their social circumstances and recovery capability after an earthquake. A seismic risk rating will then be assigned to each building, according to which it can be prioritized.

1.6 Significance of Research

This research may have wide-ranging theoretical and practical applications. Regarding the practical significance, the research will:

1. Develop a procedure to assess the earthquake risk of URM buildings, addressing the problem statement and research objectives as outlined above.

Regarding the theoretical significance of the research, the research will:

1. Identify the local factors that influence the seismic risk of multi-storey URM buildings and their residents.
2. Identify the importance and priority of each of these factors.
3. Identify a rating scale which can be used to measure the state/condition of the local factors.

Further significance of the research may include:

1. Assess seismic risk of multi-storey URM buildings for local government agencies (City of Cape Town for example).
2. Data from the study can be used for further disaster management research such as follow-up research and earthquake disaster planning or analysis of scenarios for disaster management agencies.

1.7 Scope and Limitations

This study aims to develop a seismic risk prioritization procedure which, to the best of the author's knowledge, is one of the first of its kind in South Africa. It focusses on laying the ground work for a procedure based on scientific principles. It does however not aim to develop a risk assessment procedure with an absolute value. Instead, the aim is to develop a functional model for comparison purposes.

In order to simplify the study, one type of building was chosen to be assessed. The focus is therefore only on the "migrant hostels". There were various reasons for this:

1. The buildings were built during the same era with similar designs, construction techniques and construction materials. One can therefore generalize the structural behaviour of these buildings.
2. Van der Kolf (2014) already modelled the structural behaviour of this type of building to earthquakes, finding that these buildings are at risk of failure.
3. Once developed, the model can be expanded to include other types of buildings
4. 11 000 individuals live in these buildings
5. The individuals living in the building are from a low income group
6. This type of building has been identified by the (ATC, 2002) as one of the most vulnerable housing structures to an earthquake

An additional limitation includes access to existing data. The study deals with numerous methodological and data issues, shifting the focus of the study from absolute accuracy to functionality. It is also important to keep in mind that one has to work with available data. If no data is available for a certain characteristic, then there simply is no way to quantify the characteristic. This will be discussed later on.

Lastly, validating the model would prove to be difficult. The ideal validation of the model would be to investigate the effects of an earthquake after it has occurred. This is however not practical. Therefore, another validation technique was found for the model. It will be discussed in Chapter 9.

1.8 Chapter Overview

The following overview contains a brief summary of each chapter of the thesis.

Chapter 1

The first chapter serves as an introduction to the study. It presents the background and rationale for conducting the research. It outlines the research problem, purpose and objectives. The research methodology is discussed with the thesis statement and scope and limitations sections. The chapter concludes with the research development process presented in Figure 1.1.

Chapter 2

Chapter 2, 3 and 4 include a comprehensive literature review. The literature review starts with a general introduction to earthquakes. It then focusses on earthquakes in South Africa and narrows to earthquakes in Cape Town. It concludes with the Probabilistic Seismic Hazard Analysis (PSHA) that has been compiled for South Africa.

Chapter 3

The third chapter discusses the vulnerabilities of URM buildings to earthquakes. It mentions all of the characteristics that have been identified by previous authors, highlighting the vulnerabilities of this housing type. The chapter also discusses the history of multi-storey URM buildings that will be investigated. It makes reference to the parties who own, maintain and live in these buildings.

Chapter 4

This chapter discusses the existing research that has been conducted to address the problem statement. Specific reference is made to disaster risk reduction techniques of previous researchers.

Chapter 5

The fifth chapter defines the research design and methodology. This chapter presents and discusses the entire investigation methodology. It outlines the steps for developing the ERAM model, and quantifies the scientific principles on which it is based.

Chapter 6

The sixth chapter proceeds to present and discuss the development of the ERAM model. It starts with stating some general challenges of developing the model. It further defines the model structure and identifies factors that will be used by the model.

The chapter is concerned with identifying and explaining the choice of factors, identifying weights of factors and identifying indicators for factors. The chapter concludes with the completed ERAM model, which will be used to address the problem statement and to fulfil research objectives.

Chapter 7

Chapter 7 is where the weight of each factor is identified. This was done by two methods: a study of the literature and an industry survey. The chapter proceeds to discuss the survey. Indicators are lastly defined, which will be the mechanisms that will provide a score for each factor.

Chapter 8

This chapter illustrates briefly the implementation of a fictitious example of the ERAM. The example is intended to illustrate the implementation of the model and how it works.

Chapter 9

Chapter 8 discusses how the ERAM model was validated. It critically evaluates the model and give suggestions for improvement.

Chapter 10

This is the final chapter and provides a summary of the main conclusions derived from the entire development process. It concludes with recommendations which can be implemented in future research.

Figure 1.1 illustrates the research development process.

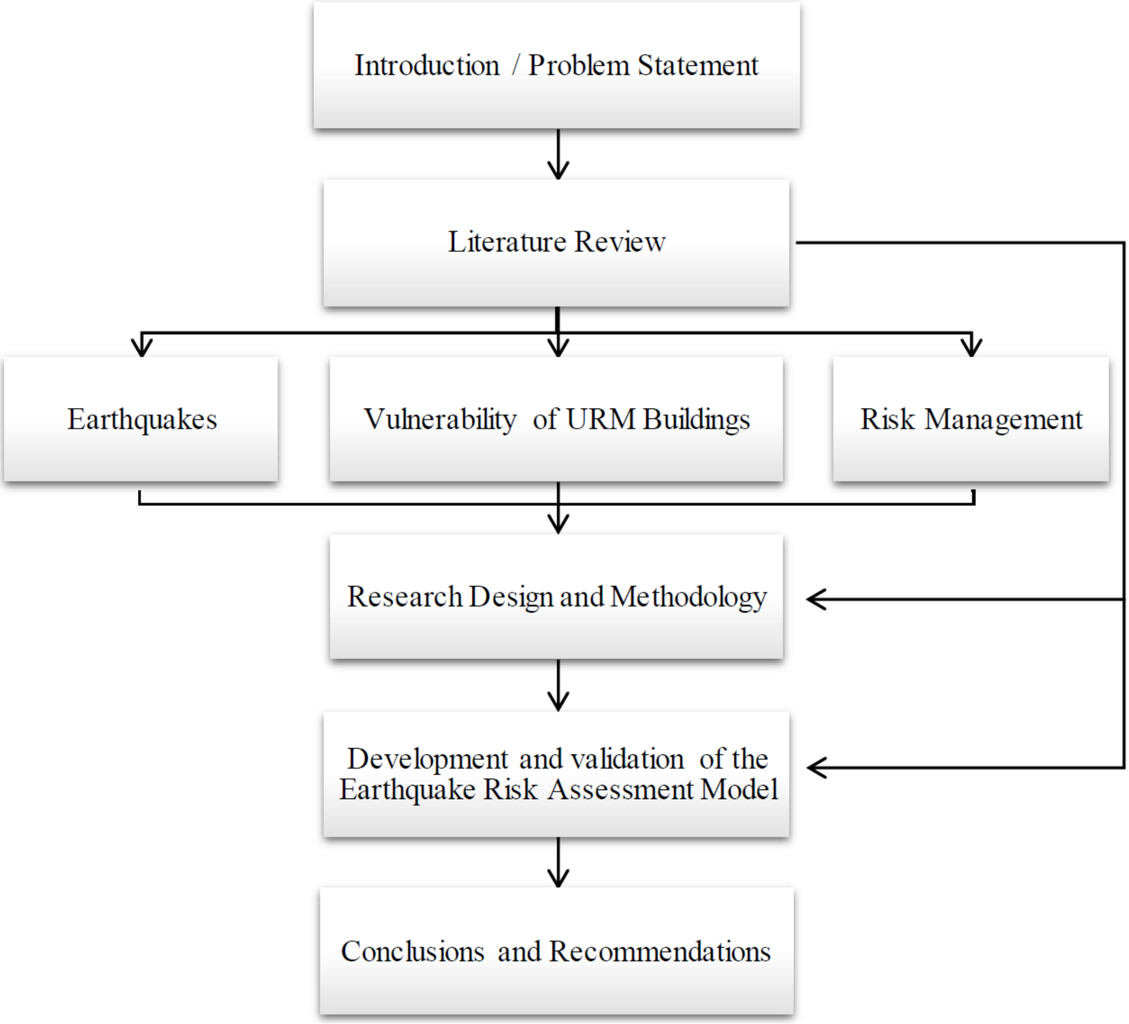

Figure 1.1: The research development process

Chapter 2

Earthquakes as Natural Hazards

2.1 Introduction

The following three chapters will provide relevant background to the research. Chapter 2 focuses earthquakes as natural hazards. It discusses the earthquake history of South Africa and narrows the scope to specifically focus on the earthquake history of Cape Town. Chapter 3 examines the vulnerability that URM buildings have to earthquakes. It highlights the factors which affect the building vulnerability. It further goes on to discuss the URM buildings that were focussed on during the study, providing a background to their historic and current uses. Chapter 4 concludes by examining the different disaster risk assessment techniques available to evaluate the consequences of an earthquake with. All three chapters discuss the relevant terminology and concepts which were used further on in the study.

2.2 Hazards

The objective of this section is to provide the necessary terminology and background for understanding the proceeding sections relating to earthquakes. This section focuses specifically on the definition of a hazard, the different types of hazards that can typically be found, how hazard classification works and the interaction between various hazards. These aspects are specifically discussed to indicate the importance of holistically viewing the interactions between natural hazards. In previous research, hazards are often discussed in an isolated context and the interaction amongst other hazards are neglected or not taken into account.

2.2.1 Definition

The word “hazard” is a broadly defined term which may take on several meanings. The Oxford English Dictionary (2013) supplies 15 different definitions to the word, making it clear that the meaning of the word can be misconceived if it is not applied in the right context. Specifically relating to disaster management, the most applicable definition can be found from the United Nations International Strategy for Disaster Reduction (UNISDR) terminology. It defines "hazard" as "*A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation*" (UNISDR, 2004). All hazards can be classified into one of two main categories, namely natural hazards or human induced hazards. The classification is based upon the source which generates the hazard.

2.2.2 Natural Hazards

A natural hazard is a physically damaging event or phenomenon that is caused by extraneous natural forces. These natural forces range from physical, chemical, electromagnetic and biological origins. Natural hazards can in turn be subdivided into three categories namely (Sorensen *et al.*, 2006):

- Geophysical hazards
- Hydrometeorological hazards
- Biological hazards

Geophysical hazards relate to all geological features of the earth that pose a hazard. Such features include the shape of the earth's surface, gravitational forces, magnetic fields, and plate tectonics. These features often combine to generate hazardous events such as an earthquake, volcanic eruption, sinkhole or a landslide.

Hydrometeorological hazards are processes of atmospheric, hydrological or oceanographic nature. Most of these hazards are extremes since they are not distinctive events but rather the consequence of entering the low or high end of climate variation (Rougier *et al.*, 2013). Examples of these hazards include extreme precipitation, tsunami's, heat waves, droughts, blizzards, cyclonic storms, tornados, climate change and magnetic storms.

Lastly biological hazards refer to biological substances that threaten the functioning of living organisms. This type of hazard is characterised by the outbreak of epidemic diseases or infections. Humans are usually considered to be the primary focus for the hazard. Examples include organisms such as bacteria and viruses which causes disease.

2.2.3 Anthropogenic Hazards

An anthropogenic hazard, or a human induced hazard, is a threat which was created directly or indirectly by humans. Anthropogenic refers to an event which is brought about with an element of human intent, negligence or error (Oxford English Dictionary, 2013). Since the study will involve an investigation into an earthquake hazard and contributing hazards, not much investigation will be done on these types of hazards. Examples of anthropogenic hazards are environmental degradation, crime, civil disorder, terrorism, war, structural collapse and hazardous materials.

Table 2.1 displays the different types of hazards as it was discussed above. It is interesting to note that no current relationship exists between natural hazards and anthropogenic hazards. This relationship is hard to define since natural hazards often occur at random and may vary in magnitude. Anthropogenic hazards are much the same since they are also highly unpredictable events which occurs at random locations. The difference however is that anthropogenic hazards are induced by humans usually who intend to cause harm at a point in a society that is the most vulnerable.

As a developing country, South Africa has a shortage of funds to conduct research on natural hazards. Couple the aforementioned effects to this and it is easy to see why research on natural hazards in South Africa are often overlooked. Viewing this matter from a different perspective, this shortage creates great opportunities for individuals to investigate the potential local effects of natural hazards.

Table 2.1: Different types of natural and anthropogenic hazards

Natural Hazards			**Anthropogenic Hazards**
Geophysical	*Hydrometeorological*	*Biological*	*Environmental degradation*
Earthquake	Extreme precipitation	Diseases	Crime
Volcanic eruption	Heat wave		Civil disorder
Sinkhole	Drought		Terrorism
Landslide	Cyclonic storm		War
	Tornado		Structural collapse
	Climate change		Hazardous material
	Magnetic storm		

2.2.4 Interactions between Natural Hazards

Hazards do not always occur in isolation. It sometimes happens that given the right conditions, one hazard can trigger the generation of another hazard. These secondary hazards are called collateral hazards, since they were triggered by a primary hazard and now their effect runs parallel with that of the primary hazard. Figure 2.1 depicts the interaction diagram used by Morales (2002) to display the interactions amongst natural hazards. A suitable example to describe collateral hazards would be for that of an earthquake or drought. Assuming the right conditions exist, the occurrence of an earthquake can act as a trigger for the generation of secondary hazards such as landslides, tsunamis, fire or soil liquefaction. Similarly the presence of a drought can facilitate the start of a fire. These events are therefore called collateral hazards since they were generated by a primary hazard and now their effect runs parallel to the primary hazard. Figure 2.1 also depicts the possible interactions between some of the other hazards mentioned earlier.

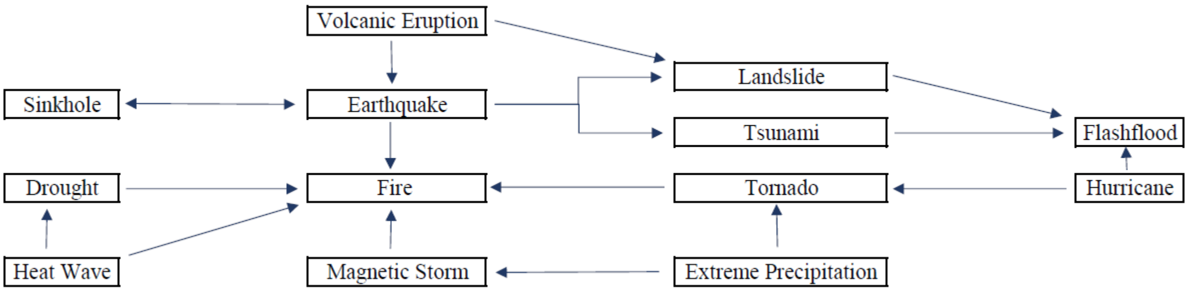

Figure 2.1: Possible interactions between different types of natural hazards

It is important to consider the possible interactions between natural hazards. Researchers often neglect the effects of collateral hazards while investigating the specific effects of a single hazard. This remark was emphasized after soil liquefaction caused extensive damage in the Niigata and Alaskan earthquakes of 1964 (Davidson and Shah, 1997). More recently the Great Hanshin earthquake of 1995 caused substantial damage. The earthquake triggered lateral soil spreading, a form of soil liquefaction. The combined economic effect of the earthquake and lateral soil spreading was estimated to be $ 170 billion at the time (Jiang *et al.*, 2013).

For this study it will be important to include all collateral hazards which have the potential of causing injury, loss, damage or disruption to society. This will not only give a holistic view for approaching the risk assessment of an earthquake but also account for collateral effects which are often overseen.

2.3 Earthquakes: In General

2.3.1 Formation of Earthquakes

The earth consists of numerous different layers called the lithosphere, asthenosphere, mesosphere, outer core and inner core. The lithosphere is the outer most layer of the earth. The plate tectonics theory (Tarbuck and Lutgens, 2013) describes the lithosphere as the outer layer of the earth that is divided into seven separate and distinct tectonic plates. The asthenosphere is located beneath the lithosphere and has visco-elastic characteristics. The tectonic plates of the lithosphere can be said to "float" on top of the asthenosphere. The boundaries between tectonic plates are called fault lines or faults. Movement of tectonic plates take place at these fault lines. Figure 2.2 indicates the seven primary tectonic plates of the lithosphere, separated by fault lines where plate movement takes place.

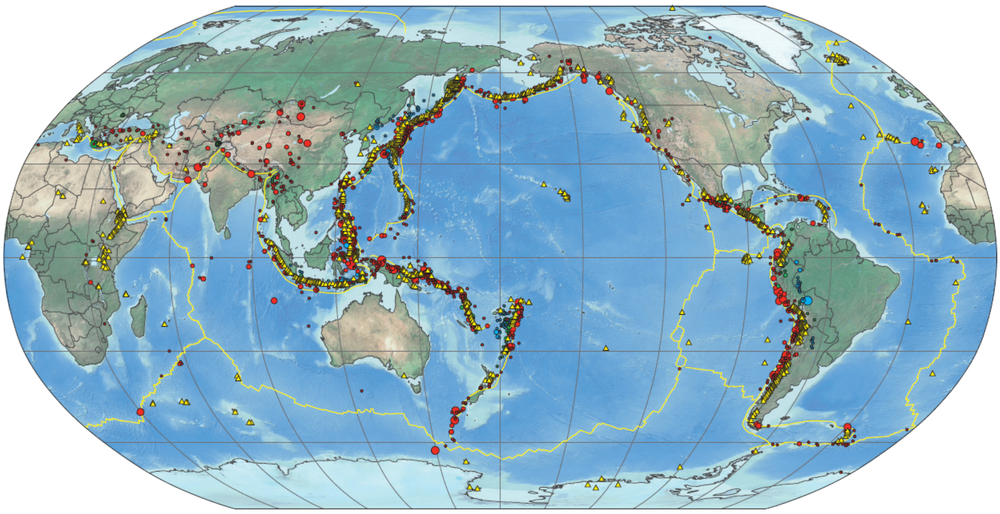

Figure 2.2: Seven primary tectonic plates of the earth (United States Geological Survey, 2014b)

Complex interactions in the earth's core and mesosphere, such as the convection of magma, produces energy dissipation through the asthenospheric layer. This energy dissipation then causes strain energy to build up at the tectonic plate boundaries, until the resistance at these boundaries are overcome. This phenomenon is called plate slippage. As the plates slip relative to one another, friction between the plate boundaries generate seismic waves. These seismic energy waves then travel to and along the surface of the earth causing movement of the ground. Humans observe the movement of the ground and call this an earthquake.

The location on a fault where the plate movement occurred is termed the focus or hypocenter. The epicenter is the location on the surface of the earth which is above the focus point. The characteristics of an earthquake is influenced by the type of fault region. Three general fault mechanisms exists which influence an earthquake. Strike-slip faults occur where two tectonic plates are sliding horizontally past each other. Normal faults occur when two plates move apart from each other. Thrust faults occur where a basaltic (heavy) plate subducts below a continental plate (Tarbuck and Lutgens, 2013).

Earthquakes can be characterized by the type of ground motion, displacement measured at the earth's surface and the frequency of the seismic waves. Instruments that measure seismic waves are called seismometers. These meters are sensitive instruments that measure the vertical displacement of the surface of the earth. The type of ground motion, frequency and displacement of the seismic waves can be deducted from the recordings of seismometers.

2.3.2 Measurement of Earthquakes

Two methods of earthquake measurement exist namely magnitude scales and intensity scales. Magnitude scales rely on the measurement of energy released during an earthquake, whereas intensity scales use arbitrary rankings based on observed effects by an earthquake. Two common measurement scales in use is the Richter scale (magnitude scale) and Mercalli scale (intensity scale).

The magnitude of most earthquakes measured is represented on a Richter scale. This scale was invented 1934 by Charles F. Richter, and uses the amplitude of the largest seismic wave recorded during an earthquake to calculate the magnitude. The magnitude is obtained by taking the logarithm of the largest seismic wave measured by a seismometer and adjusting it according to the distance from the epicenter of the earthquake (Saradj, 2007).

The Mercalli scale was invented in 1902 by Giuseppe Mercalli. The scale uses the observations of people who experienced the earthquake to estimate the intensity. The method has since been modified and is currently called the Modified Mercalli intensity (MMI) scale. The scale uses twelve degrees according to which an earthquake can be classified. Appendix A presents a comparison between the Richter scale and the corresponding Modified Mercalli intensity scale (Saradj, 2007).

2.3.3 Location of Earthquakes

The US Geological Earthquake Information Center (USGEIC) estimates 1 400 000 earthquakes occur around the world annually (United States Geological Survey, 2014a). Much of these earthquakes go undetected due to their small magnitudes and remote location. Research shows that 90% of all devastating earthquakes occur at fault lines between tectonic plates (Alabi *et al.*, 2013). Figure 2.2 shows the different tectonic plates for the earth and earthquakes with a magnitude greater than 6 (United States Geological Survey, 2014b). Indicators in red show earthquake magnitudes subsequent to 1964 and yellow indicators show earthquake magnitudes prior to 1964.

According to the MMI scale earthquakes with an intensity of III can be felt by most people (Saradj, 2007). According to the data gathered by the USGEIC, 144 000 earthquakes annually exceed an MMI intensity of III, which translates into 10.3% of all earthquakes.

2.3.4 Types of Earthquakes

Not all earthquakes are caused by the movement of tectonic plates. There exists other mechanisms by which an earthquake can also be generated. These mechanisms include volcanic activity, collapse of underground chambers and explosions. These mechanism were excluded from the scope of the study since it was not relevant in the study area.

2.4 Earthquakes in South Africa

2.4.1 Formation of Earthquakes

South Africa is generally not considered a country that is prone to earthquakes. Research has shown that South Africa experiences low to moderate seismicity compared to other international countries (Ntsuku, 2013). Looking at the countries' geography, South Africa is located at the southern most tip of Africa. The continent of Africa is centrally located on the African tectonic plate, as seen in Figure 2.3.

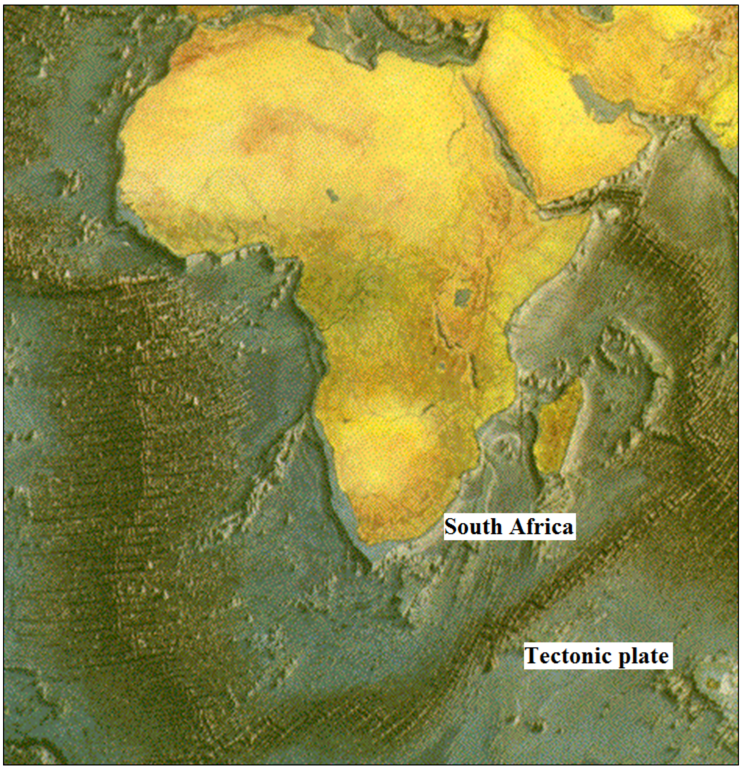

Figure 2.3: African tectonic plate (Combrinck, 2013)

In Figure 2.3 it can therefore be seen that South Africa is not located close to any plate boundary. The question then arises why the country can experience low to moderate seismic events if the closest plate boundary is located approximately 2000 km away.

Singh *et al.* (2009) has found that intraplate fault lines and mining activities are the two most general earthquake generation mechanisms in South Africa. Intraplate fault lines do not occur near tectonic plate boundaries but rather along faults in the stable interior of the tectonic plates. These faults formed due to ancient failed rifts in the earth's surface where the lithospheric layer experienced decompression forces. The intraplate fault lines present a local weakness in the lithosphere that can slip if enough regional tectonic strain is accumulated. Researchers theorize but still do not understand the exact cause of intraplate earthquakes, which can make the process of hazard quantification much more demanding (Monroe *et al.*, 2007).

The second general earthquake generation mechanism in South Africa is from mining activities (Singh *et al.*, 2009). These activities may include controlled explosive detonation or the collapse of underground tunnels and chambers. South Africa is a country which is famous for its abundance of mineral resources. In order to extract these underground resources, mining companies often use the method of controlled explosive detonation to obtain these resources. Controlled explosive detonation is an old and effective method for extracting minerals, but also complicates the matter of earthquake monitoring. Individuals now have to distinguish between natural earthquakes and explosion tremors when analyzing seismometers (Singh *et al.*, 2009).

2.4.2 History of Earthquakes

Historic records show that certain regions in South Africa are particularly vulnerable to severe earthquakes. Two examples of this is the Tulbagh earthquake in 1969 and the Stilfontein earthquake in 1976. The Tulbagh earthquake occurred on 26 September 1969 with a Richter magnitude registering 6.3. This is one of the largest earthquakes experienced in South Africa to date. The earthquake was felt all over the Western Cape. Buildings in the area suffered serious damage estimated at $ 24 million (2002 currency rates). Damage to buildings ranged from total destruction for aged and poorly constructed buildings to considerable cracks in ordinary buildings. The earthquake claimed nine fatalities with many more reported injuries (Kijko *et al.*, 2002). The cause of the earthquake was related to intraplate activity.

Another severe earthquake occured on 9 March 2005 near the town of Stilfontein. The earthquake registered a Richter magnitude of 5.3. The earthquake is known for being the largest mining induced earthquake to date. Several buildings of the town were damaged. 58 people were injured by the earthquake and two fatalities were recorded (Linzer *et al.*, 2007). Figure 2.4 shows damage caused to buildings by the earthquake.

Table 2.2 describes all the earthquakes occurring in South Africa which exceeded a Richter magnitude of 5.5.

Figure 2.4: Damage to buildings after Stilfontein earthquake (Linzer *et al.*, 2007)

Table 2.2: Earthquake history of South Africa (Singh *et al.*, 2009)

Date	**Region**	**Magnitude**	**Intensity**
4/12/1809	Cape Town	6.3	VIII
2/6/1811	Cape Town	5.7	VII
20/2/1912	Koffiefontein	6.2	VII
31/10/1919	Swaziland	6.3	VIII
31/12/1932	Cape St. Lucia	6.3	VIII
1/11/1942	Port Shepstone	5.5	VII
30/9/1950	Namaqualand	5.5	VI
1/5/1953	Namaqualand	5.8	VII
13/4/1957	Zastron District	5.5	VI
12/1/1968	Uitenhage	5.5	VI
29/9/1969	Tulbagh	6.3	VIII
21/2/1979	Northern Cape	5.8	VII

2.4.3 Measurement of Earthquakes

Earthquakes in South Africa are monitored by the Seismology Unit of the Council for Geoscience (CGS). The council manages all of the geoscientific activities within South Africa. This includes (South African Council for Geoscience, 2012*a*):

- Geoscience surveying
- Water resource evaluation and preservation
- Mineral identification and development
- Environmental and chemical geohazards
- Engineering geoscience and physical geohazards

The Seismology Unit regularly conducts geoscience and physical hazard assessments for projects in South Africa. This includes assessments for major projects relating to buildings, dams, bridges, power plants and nuclear facilities. A seismic hazard analysis is used to estimate the possible ground motion that can be expected at a location over the lifetime of a structure. This analysis will then be used for the design, safety evaluation or loss estimation by engineers. Such an analysis is conducted by either deterministic- or probabilistic methods. The Seismology Unit collects and analyses data from 28 seismic stations located throughout South Africa. The 28 stations together form the South African National Seismological Network (SANSN). This information is used for hazard assessments. Figure 2.5 presents the positions of the South African National Seismological Network where seismic stations are located.

2.4.4 Location

Figure 2.6 shows the distribution of earthquakes for South Africa during the period of 1809 to June 2008. The earthquakes displayed all exceed a Richter magnitude of 3. According to the South African National Seismological Database more than 27 000 earthquakes were recorded for the country during this period.

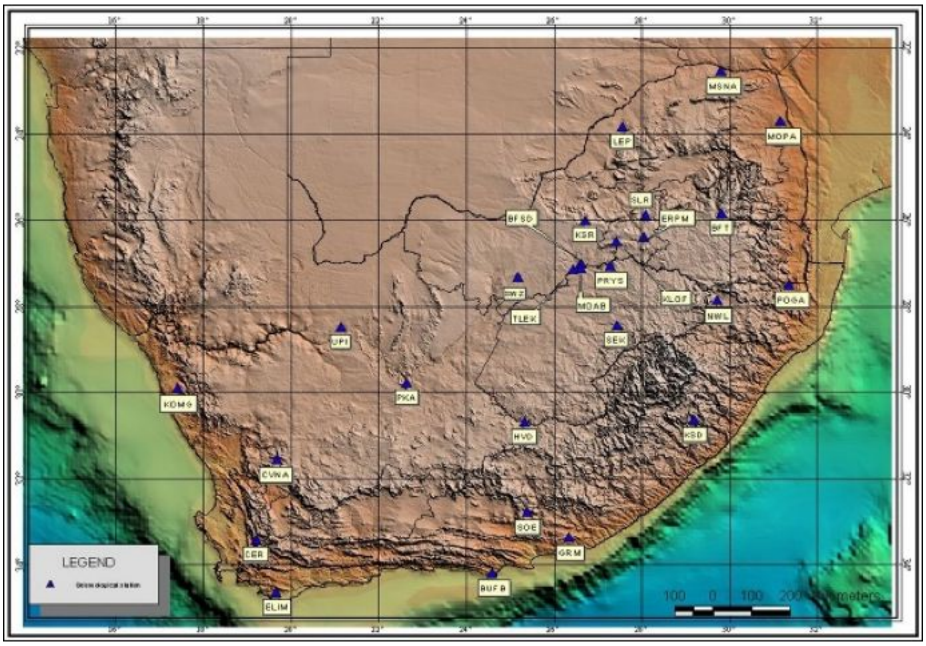

Figure 2.5: SANSN where seismic stations are located

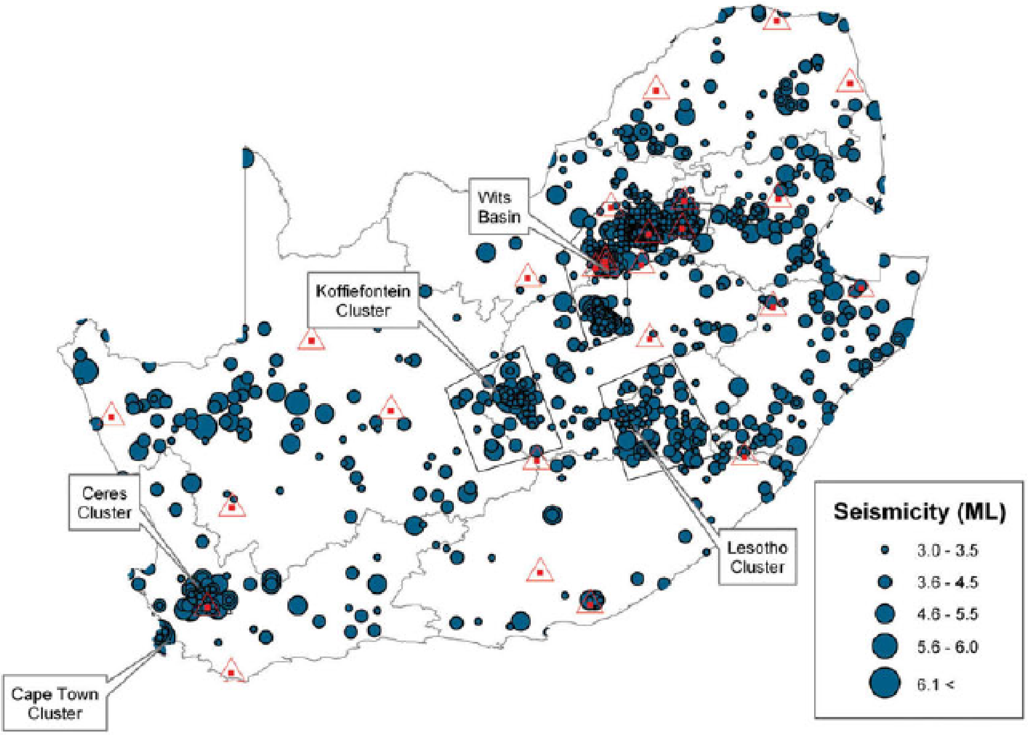

Figure 2.6: Earthquakes in South Africa for the period 1809 until 2008. The seismic station are represented by red triangles (Singh *et al.*, 2009)

Figure 2.6 also displays clusters of seismic activity. Fernandez and Guzman (1979) first identified these patterns according to its generation mechanism, in specific natural or mining induced earthquakes. The notable clusters are:

- Historical earthquakes in the Cape Town area (fault)
- Ceres cluster (fault)
- Koffiefontein cluster
- Lesotho cluster
- Witwatersrand cluster (mining induced)

Figure 2.6 therefore displays the distribution and cause of earthquakes in South Africa.

2.5 Earthquakes in Cape Town

2.5.1 History of Earthquakes in the Region

The earthquake history of Cape Town is recorded as far back as 1809. For the period of 1809 to 1971, a total of eight earthquakes were recorded by public observations. Since the introduction of seismic stations in the Western Cape in 1971, earthquakes could for the first time be recorded with specialized equipment (South African Council for Geoscience, 2012*b*). Their characteristics could now be used in conjunction with paleoseismic evidence to identify possible earthquake prone regions within the South Western Cape. The introduction of seismic stations in the Western Cape can be considered a breakthrough, as much of the earthquake data recorded before this time can be considered incomplete, vague and often erroneous (Hartnady, 2004).

According to Hartnady (2004) the largest historical earthquake that Cape Town has experienced occurred on 4 December 1809. Observations by the public established that the epicenter of the event was approximately 20 - 30 km from the current city center. Sources reported the complete destruction of some farmhouses and the spurting of muddy water out of fountains during the earthquakes. The latter is a vibration induced liquefaction phenomenon also associated with the presence of seismic activity. Sources disagree about the magnitude of the event. Fernandez and Guzman (1979) calculated the magnitude for the earthquake as 6.5, whereas Singh *et al.* (2009) found the magnitude to be 6.3. Estimating the magnitude of the earthquake between 6.3 to 6.5, this is still found to be the largest magnitude for the city. Other notable earthquakes in the region of Cape Town are classified in Table 2.3.

Table 2.3: Earthquake history of the Western Cape, exceeding a Richter magnitude 5 (Singh *et al.*, 2009)

Date	**Region**	**Magnitude**	**Intensity**
4/12/1809	Cape Town	6.3	VIII
2/6/1811	Cape Town	5.7	VII
19/6/1811	Cape Town	5	VI
14/8/1857	Western Cape	5	VI
13/9/1899	Cape Town	5	VI
9/10/1921	Tulbagh	5	VI
27/8/1963	Worcester-Ceres	5	VI
29/9/1969	Tulbagh	6.3	VIII
2/3/1977	South Western Cape	5.3	VI
31/10/1991	Ceres	5	VI

2.5.2 Historic Effects of Earthquakes

The Tulbagh earthquake of 26 September 1969 is known as South Africa's most destructive earthquake to date, occurring only 100km from Cape Town (Kijko *et al.*, 2002). Severe damage was inflicted to buildings in the towns of Tulbagh, Wolseley, Ceres and Prince Alfred Hamlet. Moderate damage was reported in further towns such as Saron, Gouda, Hermon and Worcester, whereas buildings in Stellenbosch suffered a light degree of damage.

The magnitude of the Tulbagh earthquake remains debatable, since the introduction of seismic stations in the region only followed much later. An estimate of the earthquake was made by using observations from the public. A maximum MMI of VIII was observed in the northern part of Tulbagh. Kijko *et al.* (2002) used this observation to calculate the Peak Ground Acceleration (PGA) for the event, assuming that the epicenter was located 25km from Tulbagh. It was found that the earthquake most likely had a Richter magnitude of 6.3 and a PGA of 0.22g. The focus of the earthquake was calculated to be at a depth of 10km, along the Saron - Groenhof lineament. The event was followed by numerous aftershocks, of which the largest measured a Richter magnitude of 5.7 on 14 April 1970.

Impacts of the Tulbagh earthquake ranged from physical, economical, psychological and environmental effects to secondary effects such as service disruptions and homelessness. Eyewitness accounts in a regional newspaper reported falling rocks in the mountains during the event (Die Burger, 1989). These rock collisions acted as sources of ignition for starting fires. Other sources reported that during the event people emerged from their homes, moving over broken glass and fallen plaster. The old age home of Waveren House was completely destroyed, but by chance happened to be completely empty because of the school holidays. After the event the church, school, municipal complex, magistrate's court, town hall and police offices had to be rebuilt in Ceres due to the damage incurred. This illustrates the destructive force of an earthquake. Figures 2.7, 2.8 and 2.9 illustrate the damage the Tulbagh earthquake caused.

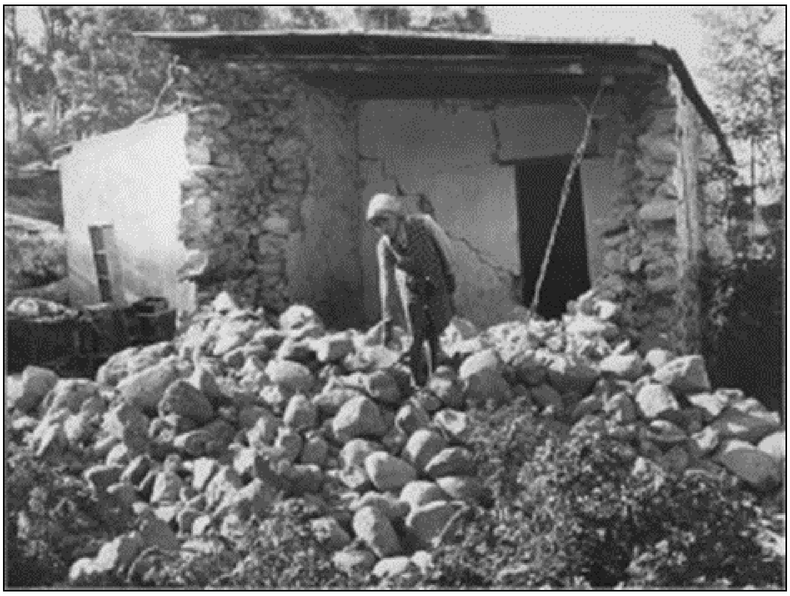

Figure 2.7: Damaged masonry building in the Tulbagh region. Note the natural construction materials that were used (Die Burger, 1989).

Figure 2.8: A heavily damaged masonry building in the Tulbagh (Thompson, 2012).

According to Kijko *et al.* (2002), large seismic events occurring within 300km of a structure, should be of engineering interest. The Tulbagh earthquake should therefore not be considered as a separate incident, since the town of Tulbagh is located only 121 km from Cape

Figure 2.9: Veldfires close to Wolseley, as a result of the earthquake (Die Burger, 1989).

Town. Any seismic activity occurring within this region will therefore certainly be of great engineering interest for buildings situated within Cape Town.

2.5.3 The Formation of Earthquakes

As discussed earlier, earthquakes in South Africa are usually generated by two mechanisms: fault movement and mining activities. Due to the absence of mining activities in the South Western Cape the predominant generation mechanism will be movement at fault lines located within the continental plate. Figure 2.10 displays the epicenters for all earthquakes recorded in the South Western Cape from 1801 to 1993.

As it can be seen in both Figure 2.6 and Figure 2.10, two clusters can be identified in the South Western Cape where earthquakes are generated. This is close to the town of Ceres and near city of Cape Town. Research shows that these regions' seismic activities are generated at two separate faults. Focusing on the city of Cape Town, investigations prior to the construction of the Koeberg nuclear power station in 1984 revealed a local intraplate fault, located approximately 8 km offshore from the site of the power station. Located beneath the Milnerton area, the fault is also named the Milnerton fault. On land the fault extends across the Milnerton and Cape Flats regions in a northwesterly to southeasterly direction. Figure 2.11 displays the location of the fault beneath Cape Town.

2.5.4 Measurement of Earthquakes

Any earthquakes, aftershocks or tremors in the Western Cape are measured by means of two seismic stations. These stations have been in operation since 1971 and are located near the towns of Ceres and Elim which is located close to Cape Town. Figure 2.5 shows these locations relative to Cape Town. The two stations form part of the SANSN network of 28 seismic stations, which the CGS utilizes for monitoring national seismic activity.

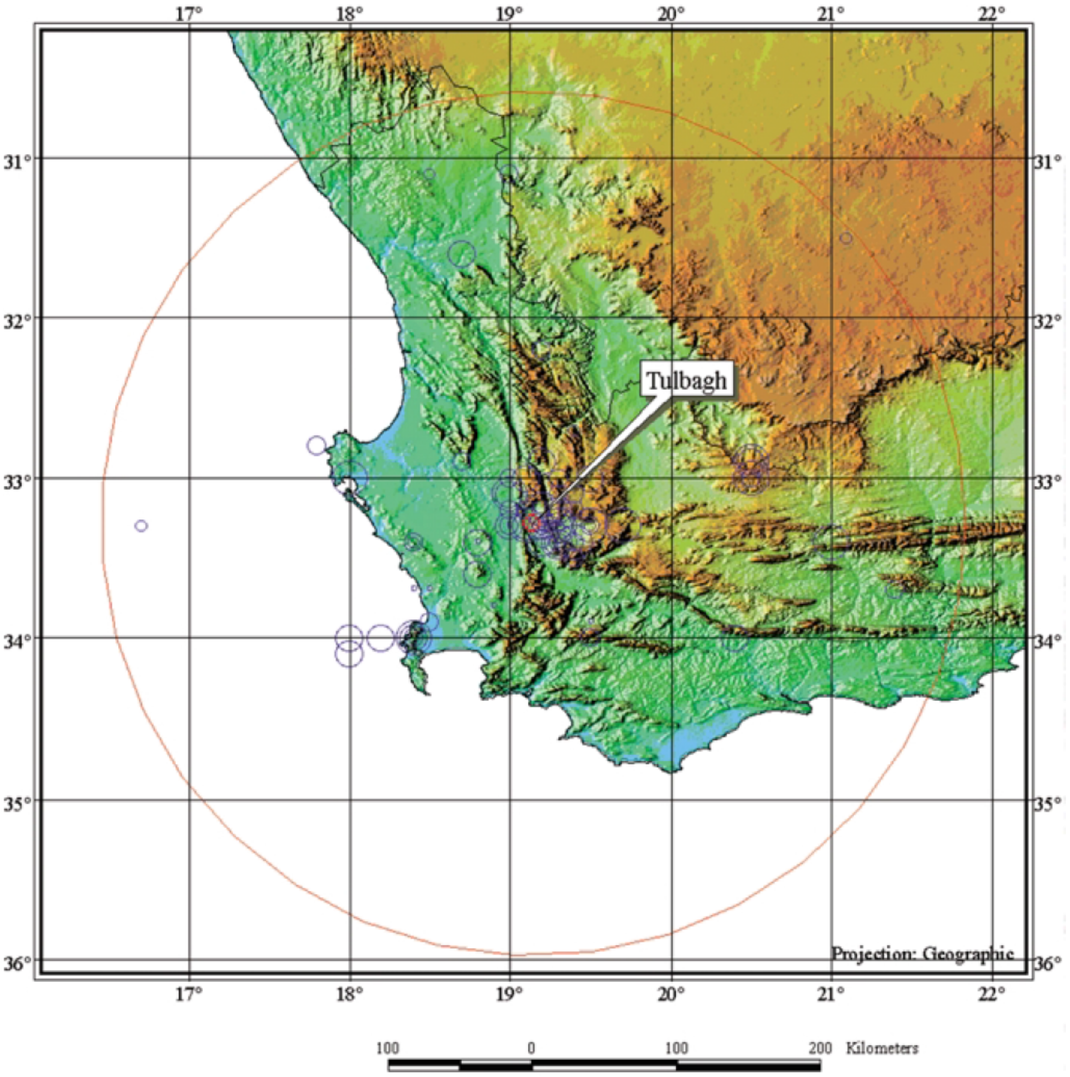

Figure 2.10: Seismicity recorded for the South Western Cape, 1801-1993 (Kijko *et al.*, 2002)

2.5.5 South African Hazard Map

The varying geographical properties in South Africa create regions with different earthquake characteristics. The SABS 0160 (1989) document was the first attempt to illustrate all of these properties. Figure 2.12 illustrates this attempt, where "g" represents the gravity acceleration with a 10% probability of exceedance in 50 years.

More recently, the Council for Geoscience (2003) performed a probabilistic seismic hazard assessment, mapping the probabilistic peak ground acceleration for South Africa. Figure 2.13 illustrates the peak ground acceleration with a 10% probability of exceedance in 50 years. It should be noted that the contour format in Figure 2.13 is not presented on a flat earth surface. The contours may therefore be slightly out of position.

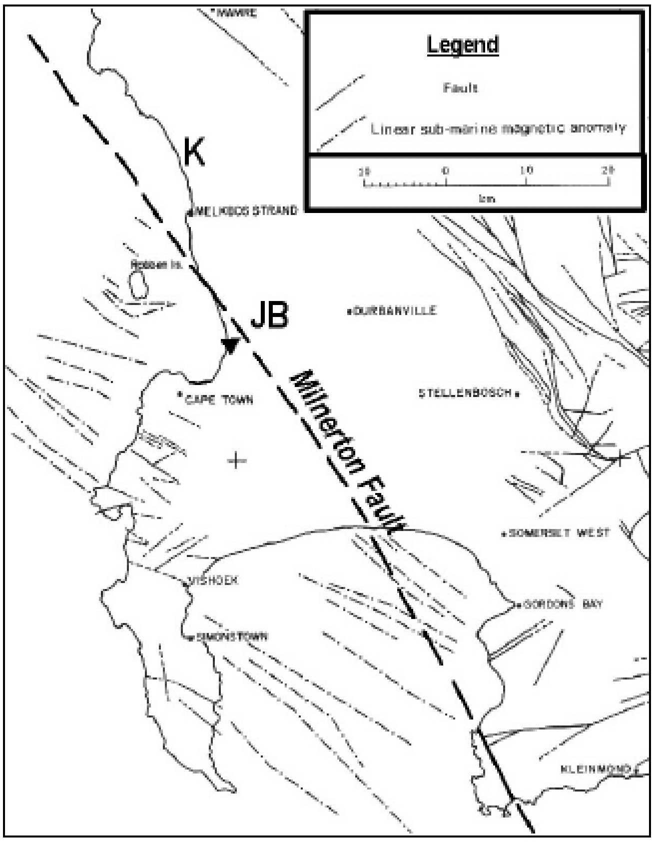

Figure 2.11: Milnerton fault location beneath Cape Town (Hartnady, 2004)

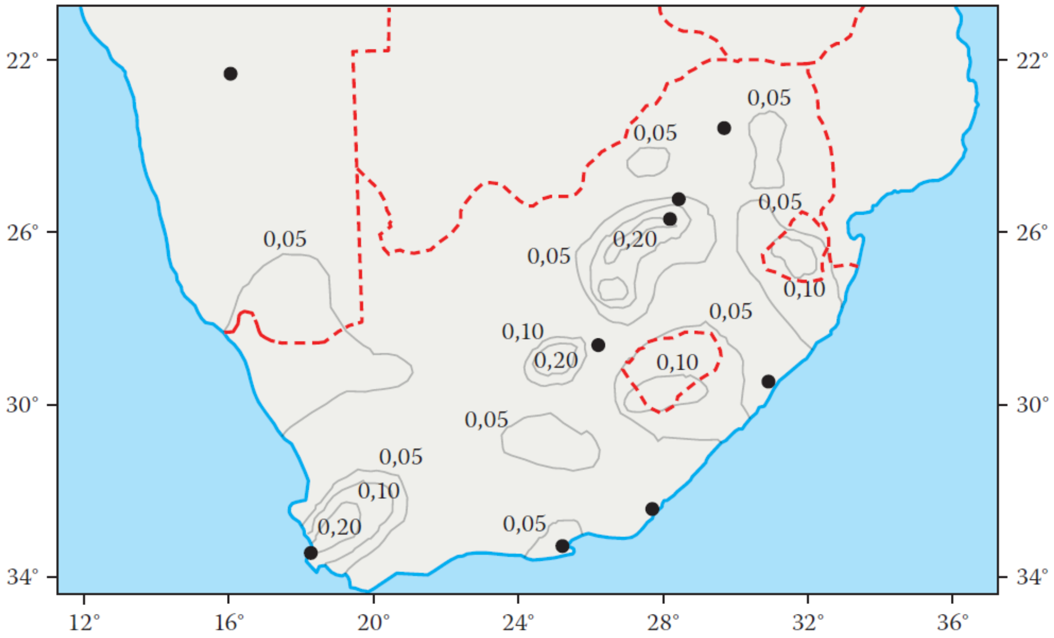

Figure 2.12: Seismic hazard map from SABS 0160 (1989) showing the peak ground acceleration in g (gravity acceleration) with 10% probability of exceedance in 50 years (Wium, 2010)

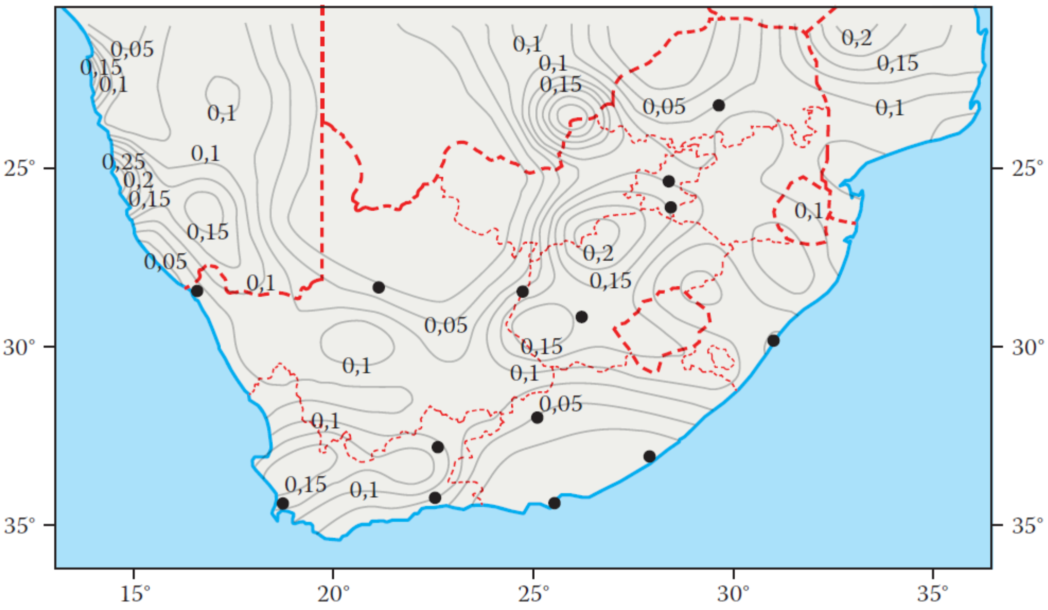

Figure 2.13: Seismic hazard map from SABS 0160 (1989) showing peak ground acceleration in g (gravity acceleration) with 10% probability of exceedance in 50 years (contours are slightly out of position)(Wium, 2010)

2.6 Conclusion

This chapter focused on earthquakes as natural hazards. It discussed the process of earthquake formations as well as the earthquake history of South Africa. It further narrowed the scope to specifically focus on the earthquake history of the South Western Cape and Cape Town.

Chapter 3

Vulnerability of URM Buildings to Earthquakes

3.1 Introduction

This chapter aims to investigate the effects of earthquakes on URM buildings. The chapter discusses the different types of masonry buildings that exist. It also outlines the factors that affect a buildings' vulnerability. The specific buildings that will be focussed on in the remainder this study is lastly described.

3.2 Damage in Buildings

Earthquakes can cause many different types of damage in buildings. The Federal Emergency Management Agency (FEMA) classifies damage to buildings into two possible categories, namely structural and non-structural damage (ATC, 2002). Even though damage is divided up into two categories, both types of damage may be seen as hazardous to the residents of the building. Structural damage refers to the degradation of the building's structural support systems such as the vertical- or lateral force resisting systems. Non-structural damage refers to any damage that does not affect the integrity of the structural support system of the building. Examples of non-structural damage may be chimneys collapsing, household objects falling, windows breaking or falling insulation panels.

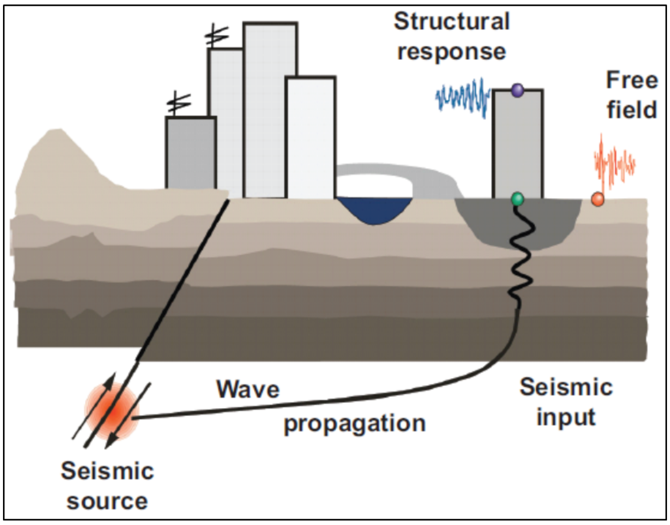

Figure 3.1: Seismic actions on buildings (Dazio, 2013)

Predicting the damage following an earthquake is a complex matter that often depends on various characteristics of the building. These properties include the structural type, age, configuration and construction materials of the building. Additionally the geologic conditions of the site or the proximity of adjacent buildings may also have an influence. Figure 3.1 illustrates how a seismic source affects a building.

Not all buildings respond to an earthquake equally. Due to the unpredictable nature of an earthquake, a building may either be thrown from side to side (lateral movement) or up and down (vertical movement). In order for a structure to successfully resist this movement, the building should at least be able to resist a force at upper most floor which equals its mass and the imposed acceleration, according to Newton's law. Therefore a tall, heavy building will be subject to a greater force than a single storey, lightweight building. Figure 3.2 illustrates this phenomenon. If the building cannot resist these forces the structural components will be damaged and collapse may occur.

The damage incurred to a building is not only related to the characteristics of the building but to a large extent also to the duration and severity of the earthquake. Previous research has found that earthquakes with Richter magnitudes of less than 5 rarely cause any significant damage to buildings, since the duration and acceleration levels are relatively small (Singh *et al.*, 2009).

In addition to the damage caused by ground shaking, a building may also experience damage due to hitting adjacent buildings, degradation of the foundations due to poor subsoil conditions or the development of collateral hazards such as landslides, fires, tsunamis etc. as discussed in Chapter 2.

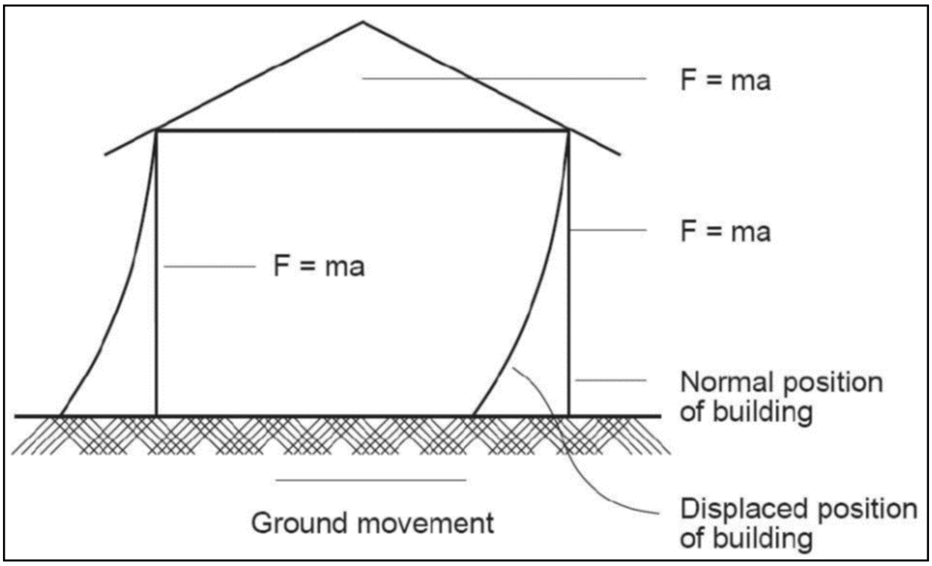

Figure 3.2: Failure mechanism of a URM building (ISET, 1986)

It is generally accepted that the further a site is from the epicentre of an earthquake, the less sever the motion of the ground. Close to an epicentre the ground motion often tends to be violent and rapid whereas further away the motion could be portrayed more as swaying. The geologic conditions of a site can also have a significant influence on the amplitude of an earthquake. Soft and loose soils tend to amplify the ground motion and create a resonance effect, making the shaking last longer.

As mentioned earlier, each building will behave differently to ground shaking. This is due to the inherent set of characteristics of each building. These characteristics also contribute to a building's vibrational characteristics. This is largely dependent on the height and structural type of a building. As with buildings, each earthquake in turn also possesses its own vibrational characteristics. These indicators are dependent on the geology of the site, distance from the earthquake epicentre, magnitude and severity of the earthquake and lastly the type and site of the earthquake mechanism.

3.3 Masonry Buildings

Masonry has long been an effective construction material. The Oxford English Dictionary (2013) defines *masonry* either as *"...brickwork executed by a mason"* or *"composed or built of masonry"*. Here there exists two different definitions to the word. In South Africa it is generally accepted that "masonry" refers to the use of brick- or block units to construct buildings. These units conventionally exist of either clay or concrete. In the second instance the use of the word refers to the composition of a structure. In structural engineering a building erected with these units will be referred to as a masonry structure. With this distinction made, the same convention will apply to this study. When there is being referred to "masonry" there will be referred to a construction material. If "masonry building" is used, it will refer to the structural composition of the building as a whole.

3.4 Masonry Construction Systems

Construction with masonry remains one of the most popular and durable techniques in South Africa. This style of construction offers numerous advantages such as fire resistance, good thermal qualities, acoustic resistance and great design flexibility. Construction with masonry is also favoured worldwide. A great deal of masonry construction systems exist due to traditional and engineering designs. Concerning masonry buildings, there are in general three types of structural systems that exist in these buildings, namely unreinforced masonry (URM), confined masonry (CM) and reinforced masonry (RM) (Tomazevic, 1999).

Tomazevic (1999) and other previous studies found that each of these construction systems behave differently when subjected to seismic loading. Where unreinforced, plain masonry represents a non-ductile structural material, confined- and especially reinforced masonry have been found to offer structural systems of improved strength and ductility.

An URM building is a type of building that makes use of load bearing walls to transfer vertical and lateral loads. These loads are imposed upon the building by either the building's own weight or external forces that are applied to the building. The study focuses only on URM and the focus will therefore only be on URM buildings.

3.5 Factors Affecting a Buildings' Vulnerability

From an engineering perspective, ISET (1986) states that there are four properties which determines the vulnerability of a building:

- The structural configuration
- Lateral strength
- Adequate stiffness
- Sufficient ductility

Here follows a discussion on each of these properties.

3.5.1 Structural Configuration

3.5.1.1 Structural Design

A building typically comprises of structural and non-structural elements. Examples of structural elements include columns, walls, floors, roofs, beams, girders etc. The structural performance of any building typically depends on these structural elements.

Structural elements are those elements of the building that help to support the horizontal and vertical forces acting on it. There are basically two types of structural framing possible to withstand gravity and seismic loads, namely load bearing wall construction and framed construction. This study will only focus on load bearing wall construction (URM buildings).

Non-structural elements are those elements of buildings that are connected to a structural system but without a load carrying capability. Although these elements are not designed to carry loads, most of the non-structural elements do have some load carrying capacity. Examples of non-structural elements include varieties of different architectural, mechanical, electrical components and other house contents. According to the response to earthquake motion and in order to assess their damage, these elements are classified into two classes: acceleration sensitive elements and drift sensitive elements. Acceleration sensitive elements are caused by floor acceleration whereas drift sensitive elements are influenced by inter-storey drift.

3.5.1.2 Shape of the Building

The symmetry and regularity of a building is an important feature when planning and designing it. Asymmetry of a building can lead to torsional forces being developed during an earthquake, which is considered to be unsafe. Rectangular shapes behave better during an earthquake than shapes with any projections. The damage in long buildings may also be severe. This property will be discussed further when the ERAM model is developed in Chapter 6 (Gulati, 2006).

3.5.1.3 Number of Storeys

The height of a building is one of the most important elements in a building's configuration. The higher a building, the greater the relative displacement at the top of the building. In tall buildings the horizontal movement of floors during an earthquake is large.

3.5.1.4 Other Buildings' Proximity

The separation distance between buildings is an important factor for preventing buildings from pounding against each other in case of a seismic event. The separation distance can be treated like expansion joints or it may be filled or covered with a weak material, which would easily crush and crumble during earthquake shaking. Such separation may be considered in larger buildings since it may not be convenient in small buildings.

Multi-storey buildings swing according to their own natural frequency during an earthquake. The probable displacement of a building can be obtained from a structural analysis with finite element analysis software. The minimum separation distance between two buildings should be 4 % of the height of the buildings - this is based on with the assumption that most structures will not drift more than 2 % during the occurrence of an earthquake (ATC, 1998).

3.5.1.5 Lateral Strength

The lateral strength of a building is the maximum lateral force that it can resist, to the extent that the damage induced in it does not result in collapse. The lateral force largely depends upon the total weight of the structure and stiffness of the building (IAEE, 1986). The larger the stiffness for given mass, the shorter the fundamental period of vibration of the structure will be. The inertia forces are proportional to the mass of the building and only that part of the loading action that possesses mass will give rise to seismic force on the building. The lighter the material, the smaller the seismic force will be.

Buildings that have fewer columns or walls in a particular storey or with unusually tall storeys tend to have severe damage in that storey, or may even collapse. Buildings with an open ground storey intended for parking are more prone to collapse or were severely damaged. This is called the "soft storey" phenomenon.

3.5.1.6 Building Stiffness

As mentioned before, the taller a building, the longer its natural period tends to be. But the height of a building is also related to another important structural characteristic: building flexibility. Taller buildings tend to be more flexible than short buildings (Bachmann, 2003). The stiffness greatly affects the building's uptake of earthquake generated force. This factor is comprise of two factors namely the building height and construction materials, which play an important role in the stiffness of the building.

3.5.1.7 Ductility

Ductility is the ability of a building to undergo deformation and bending under severe seismic activity even after yielding. Different individual buildings shaken by the same earthquake respond differently. It is more desirable for a building to sustain a limited amount of deformation than for it to suffer a complete failure and collapse. The ductility of a structure is therefore one of the most important factors that affects its seismic performance. The building should possess enough ductility to withstand the size and types of earthquakes it is likely to experience during its lifetime (Dazio, 2013).

3.5.1.8 Foundation

The last important factor relates to the foundation of the building. Buildings which are structurally able to withstand earthquakes sometimes fail due to an inadequate foundation design. Tilting, cracking and failure of the structures may result from soil liquefaction and differential settlement of the foundation. Certain types of foundations are more susceptible to damage than others. For example, isolated footings of columns are likely to be subjected to differential settlement, particularly where the supporting ground consists of different or soft types of soil. Mixed types of foundations within the same building may also lead to damage due to differential settlement. Buildings can be constructed on firm and soft soils but it will be dangerous to build them on weak soils. Therefore appropriate soil investigations should be carried out to establish the allowable bearing capacity and nature of soil. Figure 3.3 illustrates this concept. Weak soils must be avoided or compacted to improve them so as to qualify as firm or soft (Gulati, 2006).

Figure 3.3: An overturned multi-storey residential building during the 1999 Taiwan earthquake (Bachmann, 2003)

3.6 Community Residential Units Program in Cape Town

The Community Residential Units (CRU) programme promotes the provision of secure, rental occupation for individuals in lower income classes. A large part of the buildings for the CRU programme consists of URM buildings (formerly “migrant hostels”) and were chosen to be the structures that will be focussed on in the study (see Chapter 1). The programme, previously called the Human Settlements Redevelopment programme, dates back to 1999 (National Treasury, 2001). The present CRU programme was approved in December 2006 by the South African Minister of Housing, Dr. Lindiwe Sisulu (Department of Housing, 2006). The programme nationally consists of 2000 public hostels and 200 000 residential units owned by provincial governments and municipalities (GCIS, 2011).

The programme aims to target low income individuals and households that are unable to enter the formal private rental and social housing market. Criteria for such an application includes (Pienaar, 2010):

- Existing residents and households in public housing that qualifies for government subsidies
- Displaced individuals from informal settlement upgrading, emergency housing and evictions
- Individuals or households earning a monthly income between R800 to R3500
- Individuals from previously disadvantaged- or aged groups

The CRU programme obtains its funding from the South African National Housing Fund. The properties will usually be in the possession of either the provincial government or the local municipality. Considering the case of the city of Cape Town, the property is owned, serviced and maintained by the local municipality (Cape Town Human Settlements Directorate, 2006).

The Cape Town municipality possesses 43 500 diverse rental units: 21 000 of which are homeownership dwellings, 11 000 hostel beds and 11 old-age complexes. The history of the CRU hostels dates back to the apartheid era, which lasted from 1948 to 1994. The hostels were originally constructed to provide accommodation for the 15 000 to 20 000 contracted migrant workers, but has since been transformed into dormitories that provide accommodation to families. These buildings are currently very old, in a state of disrepair and extremely overcrowded (City of Cape Town, 2012*b*).

The CRU hostels in Cape Town were not built in the same period. Clusters of hostels were built during the apartheid era as the need for accommodation emerged. The buildings therefore show different characteristics regarding design, layout, construction methods and materials used. In light of the differences between the clusters of hostels, two similarities can be found namely the use of the South African Bureau of Standards (SABS) structural design standards and the classification of the buildings as URM buildings.

3.7 Relevance to Study

All of the factors in mentioned in 3.5 are relevant for the CRU buildings mentioned above. Van der Kolf (2014) outlined that the typical layout and ductility of these buildings made it brittle. The buildings' height often exceeding design criteria. Lateral strength is not provided in these buildings and the long shape of the buildings make them vulnerable to damage or failure.

3.8 Conclusion

This chapter described the effects that earthquakes have on URM buildings. It outlines the different types of masonry buildings that exist. It also describes the factors that affect a building's vulnerability. The CRU masonry buildings that will be focussed on in this study were described in the last section.

Chapter 4

Earthquake Risk Assessment

4.1 Introduction

This chapter discusses several different risk assessment approaches that have been developed to date (by others). The chapter firstly defines risk management and the components it comprises of. It further discusses the popular earthquake loss estimation models, arriving at the model that is going to be used for this study.

4.2 General Procedure for Risk Assessment

The UNISDR (2007) defines the term *risk assessment* as *"a methodology to determine the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend."* The general principles of risk assessment and the common tools applied for analysing risk in disaster management are based on common concepts as presented in the ISO (2009), UNISDR (2005) and CSA (1991) documents. The main parts of risk assessment and the basic terminology used are indicated in Figure 4.1.

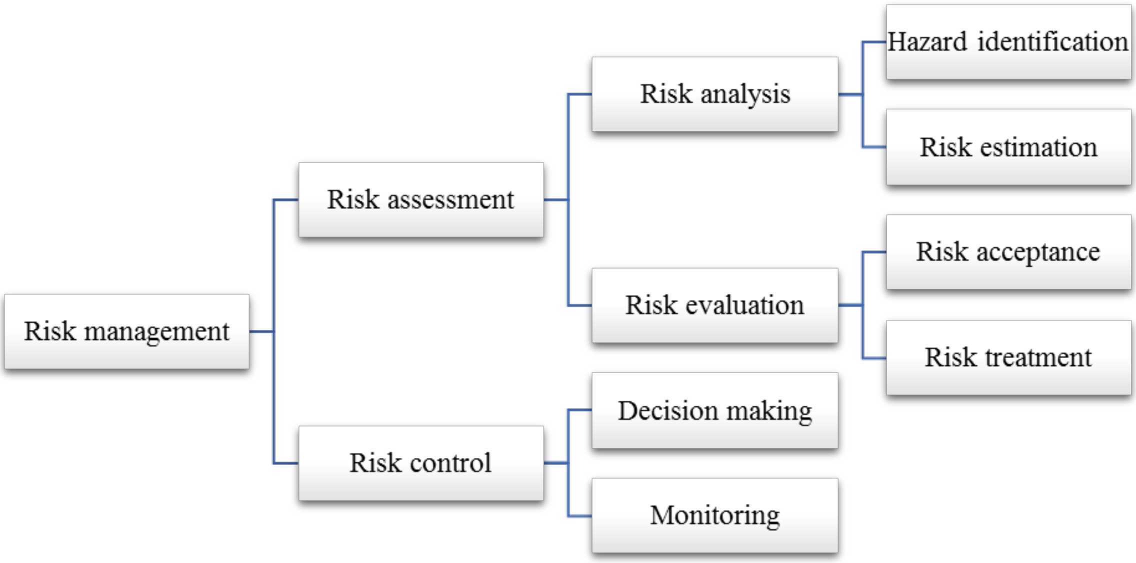

Figure 4.1: A framework for risk management (adopted from CSA (1991))

It follows from Figure 4.1 that risk assessment is an important part of risk management as a whole. Risk assessment in general comprises of two components, namely risk analysis and risk evaluation. In this study a risk analysis consists of the systematic identification of hazards as well as estimating the risk potential. Risk evaluation is the process that is used to compare risk analysis results with risk criteria (or thresholds) in order to determine whether or not a specified level of risk is acceptable or should require treatment.

Risk can mathematically be expressed as a function of the following components (Louw, 2007):

$$\mathrm{R} = f(\mathrm{H}, \mathrm{V}, \mathrm{CC}, \mathrm{E}, \mathrm{R}, \ldots) \tag{4.2.1}$$

where:

H - Hazard
V - Vulnerability
CC - Coping Capacity
E - Exposure
R - Resilience

The precise mathematical relationship between the variables is however unknown, although many agree on a basic equation where (Villagrán de León, 2006):

$$Risk = Hazard \times Vulnerability \tag{4.2.2}$$

Here *Hazard* refers to the consequences following a certain event and *Vulnerability* refers to the likelihood of such an event. This can consequently be rewritten to state:

$$Risk = \text{Consequence related to event} \times \text{Likelihood of event} \tag{4.2.3}$$

In this study an event tree will be utilized to calculate the risk of a number of different characteristics of a building (event trees are discussed later on in section 5.3.1). The consequence that is associated with a certain risk level will be represented by the weight that is assigned to each branch of the event tree. Weights indicate the branches that may have the largest influence (consequences). Similarly, each branch will be scored a likelihood rating. This rating will act as a measurement for the likelihood of that branch occurring. The outcome of combining these two factors will then represent the risk of each branch of the event tree (Ostrom and Wilhelmsen, 2012). Section 5.3 deliberates on the methodology that was used for the study, along with the mathematical combinations (section 5.3.7) where the risk formula is used.

It is the intention of the study to deliver a risk rating that is quantitative of nature. This will enable the user to compare buildings by using the risk score. The units of measurement for consequence will be a percentage that contributes to the overall risk. The likelihood of an event happening to each branch will be assigned a score between 0 and 1. When these two factors are combined according to Formula 4.2.3, it will produce a quantitative result which can be compared to other results.

4.3 Existing Research on Earthquake Risk Assessment

Research in earthquake disaster risk assessment can be dated as far back as 1968 (Cornell, 1968). To date earthquake risk assessment endeavors have generally taken on one of two forms, either as Probabilistic Seismic Hazard Assessments or as Deterministic Seismic Hazard Assessments. There also exists modern variations of these assessments which are called Earthquake Loss Estimation Tools. Each of these methods vary considerably from the other, requiring different input parameters and manipulation techniques. The following discussion highlights the motive, use, deficiencies and effectiveness of these different risk assessment models.

4.3.1 Probabilistic Seismic Hazard Assessments

The development of Probabilistic Seismic Hazard Assessments (PSHA's) started in 1968 by providing a methodology for mapping the expected levels of ground shaking at the site of an engineering project (Cornell, 1968). The ground shaking is then incorporated into a methodology to estimate physical losses resulting from an earthquake. This is also called probabilistic earthquake loss estimation modelling. Barbat *et al.* (2006) have conducted extensive research and numerous studies involving PSHA models for large metropolitan areas, including Mexico City, Bogota and Barcelona. The implementation of probabilistic earthquake loss modelling involves extensive efforts of data collection and processing. The disadvantage of such models are that they often require comprehensive databases of technical information. An example of this is a study conducted for Barcelona which used a housing database of 69 000 buildings, of which 91% of all buildings were completely characterized (Barbat *et al.*, 2006). The method calculates physical losses resulting from a seismic event in the form of damage to buildings, debris, injuries, deaths and economic losses. The method calculates the losses for a specific site, which can be aggregated for larger regions. Popular PSHA models for loss estimation include the HAZUS methodology created by the Federal Emergency Management Agency (FEMA) and the CAPRA methodology which is used in South American countries such as Colombia, Peru, Panama and Venezuela.

4.3.2 Deterministic Seismic Hazard Assessments

Deterministic Seismic Hazard Assessments (DSHA) function similarly to PSHA's. Both methods calculate the physical losses resulting from a seismic event. The difference lies in the selection of earthquake characteristics. DSHA's rely on the selection of historical events that occurred within a region or a similar tectonic region elsewhere. This is why the method is also sometimes referred to as earthquake damage scenarios. Earthquakes that are considered should represent the most extreme ground movement scenario for a region. It should be noted that this method can only be used in cases and regions where the tectonic features are well investigated, recorded and experiences frequent seismic activities. These shortcomings limit the use of this method, however earthquake damage scenarios are much simpler to implement than PSHA's (Lee *et al.*, 2003).

4.3.3 The Earthquake Disaster Risk Index

The Earthquake Disaster Risk Index (EDRI) is a method that differs fundamentally from the other risk assessment methods. Where deterministic and probabilistic methods strive to calculate risk on an absolute basis, the EDRI assesses the relative risk levels associated with earthquake disasters. The EDRI does not seek to measure seismic risk on an absolute scale, but rather comparatively. Any absolute definition of disaster risk (e.g. number of deaths, injuries, damaged buildings, economic loss etc.) neglects factors contributing to earthquake disaster risk (Cockburn and Tesfamariam, 2012). Measuring risk on an absolute scale may be appealing, but this is not currently possible since no units exist by which to measure seismic risk. Such factors include socio-economic, political, cultural and emergency response contexts. Instead the EDRI is concerned with providing information about factors that come together to create seismic risk. The seismic risk within large cities or metropolitan areas are then compared to other evaluated regions to describe the varying degrees of an expected impact. The method is therefore said to be not only a function of the physical impact an earthquake has, but also the capacity of an affected site or community to sustain that impact.

The advantage of the EDRI method is that it represents a holistic and multi-disciplinary approach to seismic risk assessment. It aims to piece together work by role players such as geologists, structural engineers, social scientists, emergency response planners and economists in a holistic, multidisciplinary effort to interpret the implications on a greater scale. The method focuses on the characteristics of a city to help determine the seismic risk. These characteristics could be of any type: geological, structural, economic, social, political, cultural etc. as long as it contributes to the seismic risk.

4.4 Earthquake Loss Estimation Software Tools

An extensive body of research, tools and applications exist that deals with the aspects of loss estimation methodologies. These methodologies all require an inventory of buildings and locations where the ground shaking distribution can be determined. Daniell (2009) has provided a comprehensive comparison between different earthquake loss estimation software packages, in terms of their applicability regions, exposure resolution (district, city, regional, country), hazard (deterministic predicted, deterministic observed, probabilistic), vulnerability type (analytical, empirical, socio-economic). The following four models and software tools are most commonly used:

- The HAZUS software (United States)
- The QUAKELOSS software (South Africa)
- The Central American Probabilistic Risk Assessment software (CAPRA) (Central- and South America)
- The EDRI software (United States and Canada)

Here follows a discussion on each of the named software tools.

4.4.1 HAZUS software

HAZUS was developed by FEMA for the prediction and mitigation of losses due to earthquakes, hurricanes and floods (Whitman *et al.*, 1997; Kircher *et al.*, 2006). The package is intended for U.S. applications only and includes federally collected data by default. The inventory is classed based on 36 different types of building based on construction standards and material as well as size and building use. HAZUS-MH MR2 version, released in 2006, includes the capability for rapid post-event loss assessment.

4.4.2 QUAKELOSS software

QUAKELOSS is a computer tool for estimating human loss and building damage due to earthquakes. It was developed by the staff of the Extreme Situations Research Center in Moscow. An earlier version of this program and data set is called EXTREMUM (Larionov *et al.*, 2000). QUAKELOSS software is used by the World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) to provide real-time estimates of deaths and injuries caused by earthquakes around the world. The building inventory incorporates data from two million structures throughout the world.

4.4.3 CAPRA software

The CAPRA (Probabilistic Risk Assessment) Program is an initiative that aims to strengthen the institutional capacity for assessing, understanding and communicating disaster risk, with the ultimate goal of integrating disaster risk information into development policies and programs. The software functions on a GIS platform which executes different scenarios to show risk prone areas. Under the CAPRA Program, government institutions and other agencies partner with the World Bank to address specific development challenges and meet disaster risk information needs through hands-on practical training and other complementary services(Anderson, 2008).

4.5 Proposed Model for Assessing Seismic Risk in Cape Town

The most appropriate model framework for assessing the seismic risk of URM buildings in Cape Town was determined to be that of the EDRI model. This decision was based on multiple criteria such as the recent trends in seismic risk assessment literature, capabilities of each model, factors that are taken into account and the computation effort required. A recent study of seismic risk evaluation literature reveals that the use of hierarchical models (such as EDRI) to assess risk is gaining popularity (Roberts *et al.*, 2009). The reason for this is that loss estimation models are data intensive and require a wide range of experts. To optimize the resource allocation for risk assessment, Tesfamaraim and Saatcioglu (2008) called for the use of hierarchical models such as the EDRI to give an overall overview of how risk is distributed. Figure 4.2 displays the different characteristics that the EDRI incorporates.

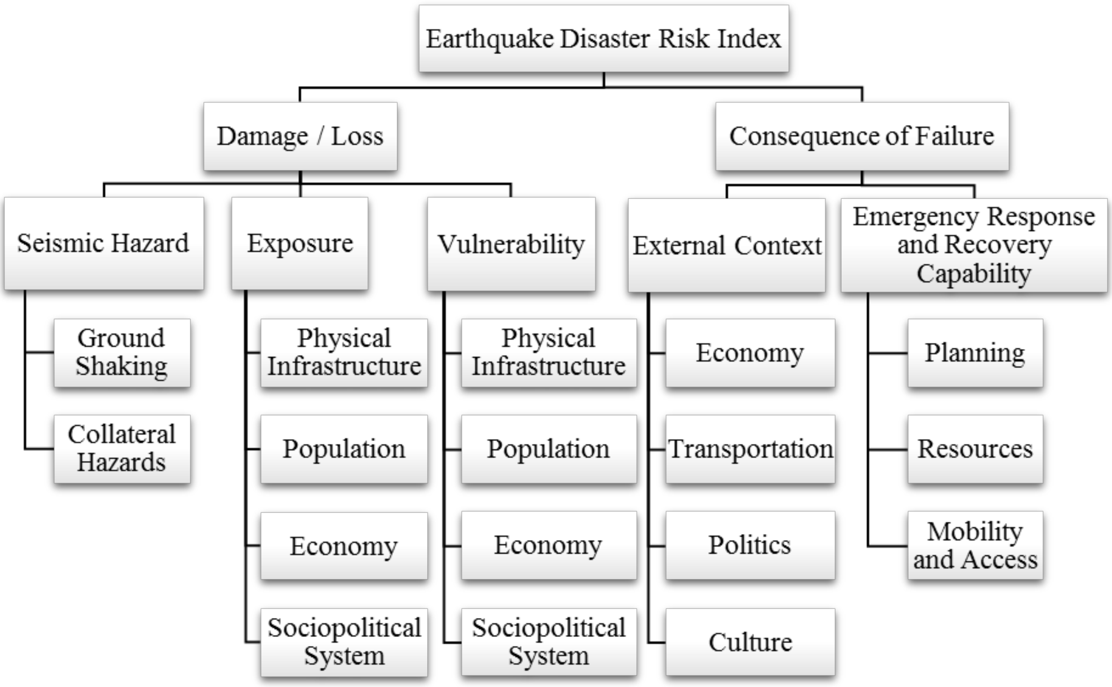

Figure 4.2: Conceptual framework of EDRI for assessing seismic risk

Davidson and Shah (1997) first developed the EDRI model to assess the seismic risk between urban cities of the world. Since then the methodology has been adapted and used in similar studies. An example of this is to highlight which cities in a region requires a further detailed loss estimation analysis (Cockburn and Tesfamariam, 2012). The methodology has been applied and adapted to many other cases (e.g. Granger (2003); Cutter *et al.* (2008); Sica *et al.* (2002); Zobin and Ventura-Ramírez (2004)).

In this case it would also be inappropriate to apply a deterministic methodology since the region of Cape Town rarely experiences seismic activity. Only ten notable earthquakes were recorded for the South Western Cape for the period of 1908 to 2009 (Singh *et al.*, 2009). The observation period is too short and incompletely documented to base a deterministic methodology on. Before the installation of modern seismic stations in South Africa in 1971, the recordings of earthquakes were obtained from public observations which were often subjective and erroneous.

4.6 Opportunities for Further Research in Seismic Risk Assessment

The field of seismic risk assessment has advanced considerably over the last 20 years. This is due to the efforts of individuals and organizations to develop a comprehensive methodology that describes seismic risk by considering different contexts. There are however still a lot of opportunities regarding seismic risk assessment and its implementation. An example of this is the development of Geographic Information Systems (GIS) software to evaluate seismic risk. Not only does this give the researcher additional processing capacity but it also establishes a spatial representation illustrating where risk is located and what intensity that would be associated with it. This will not be attempted in this study due to the enormity and complexity of such a project, but will be of great benefit to the disaster management community of South Africa and Africa. Locally, a similar attempt by the Council for Geoscience has produced the Probabilistic Seismic Hazard and Risk Program (P-SHARP) that models the probabilistic earthquake magnitudes that can be expected around South Africa. This however is an initial attempt and does not model the risk to the communities associated with a seismic event.

4.7 Research on the EDRI Model

While loss estimation models estimate the expected impact of future earthquakes (eg. deaths, injuries, damaged buildings, economic loss), the EDRI aims to assess the risk of earthquake disaster. The economic, social, political, and cultural context of the earthquake hazard, therefore, plays a critical role. As it was described, disaster is a function of not only the physical impact of an earthquake, but also the capacity of the affected city to sustain that impact, and the implications of the impact to the city and to world affairs. The EDRI model will be discussed in greater detail in Chapters 5 and 6.

4.8 Conclusion

This chapter discussed several different risk assessment approaches that have been developed to date. It firstly defined risk management and the components it comprised of. It further discussed the popular earthquake loss estimation models currently in use, arriving at the model that is going to be used for this study.

Chapter 5

Research Design and Methodology

5.1 Scope of Chapter

The Research Design and Methodology chapter describes the systematic, theoretical analysis of the methods that were applied in the research. It provides credibility to the data and methods that were used to develop the ERAM. The model that will be developed in this research is called ERAM, which closely resembles the EDRI model in the previous chapter. This will be discussed later on. Figure 5.1 outlines the sections that are discussed in the chapter.

The Research Design section (5.2) outlines the overall approach that was followed to solve the research statement. It discusses the motivation for using the approach, the shortcomings and the means through which the shortcomings were addressed.

The Methodology section (5.3) refers to the detailed procedures of the overall approach. It essentially discusses the step by step procedures that were used to develop ERAM. The Model Structure of the study was the first to be defined (section 5.3.1). It discusses the choice of model, while identifying strengths and weaknesses to motivate its use.

Research Instruments (section 5.3.2) outlines the measurement devices that were used, followed by the Data section (5.3.3) which discusses the sources and validity of data the model had to use. The process of Factor Identification (section 5.3.4) then details the means and criteria for selecting input parameters for the model.

Section 5.3.5 discusses how the model structure was combined with the identified factors to form the Conceptual Framework. The process of determining Factor Weights (section 5.3.6) is then described, followed by the Mathematical Combination (5.3.7) for the model. All of the steps above constitute the methodology of ERAM. They will be discussed below.

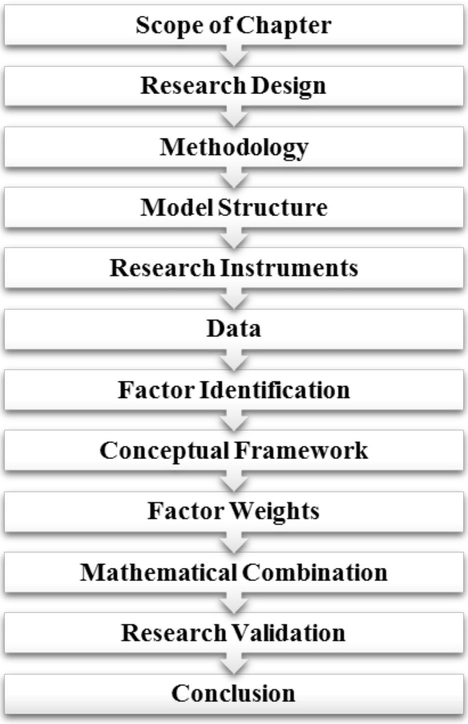

Figure 5.1: Chapter 5 outline

5.2 Research Design

The following is a discussion of the choice of research design for the study. A thorough review is made regarding the characteristics of the chosen research design: this includes the strengths, weaknesses, means of addressing the research shortcomings and lastly the application of the model in the context of the study. In this study, distinction is made between the meaning of the words *research design* and *methodology*. The word *research design* refers to the overall approach that was taken to test the thesis statement. The word *methodology* refers to the detailed procedures of the research design. A clear distinction should be made between the two words since they have very different meanings in this document.

5.2.1 Technique

It was decided that in order to fulfil the research objectives, a quantitative research model should be used. Quantitative research is defined as *"an inquiry into a human problem, based on the testing of a hypothesis or a theory composed of variables."* It is measured with numbers and analysed with statistical procedures, in order to determine whether the hypothesis or theory holds true" (Creswell, 1994). Burns and Grove (1989) similarly defines it as *"A formal, objective, systematic process in which numerical data is used to obtain information about the world."* It is perceived as 'objective' in nature. Quantitative data is not abstract; it is hard and reliable; measurements of tangible and countable features of the world (Bouma and Atkinson, 1995). The use of a quantitative research design as a research strategy is motivated throughout this section.

Quantitative research is generally selected if:

- One wants to find facts about a question or attribute
- When the researcher wants to collect factual evidence and study the relationship between these facts in order to test a particular theory or hypothesis
- To examine the relationships among variables or attributes
- If one wants to determine the cause-and-effect interactions between variables or attributes

The research method usually starts with the collection of data that is meant to represent a condition or a state in the real world. The data is then manipulated by some statistical method to provide a meaningful result. This information is then used to come to a conclusion regarding an event or situation in the real world from which the original data was collected.

This research design forms part of a collection of standard research designs that are used internationally (Hofstee, 2006). However, in order to create a starting point, one should first start with the research objectives. It was stated in section 1.4 that the objectives for the research were to:

1. Create an earthquake risk assessment model that is applicable to unreinforced masonry buildings. The model should calculate the risk pertaining to each building and its residents in the case of a large, severe earthquake. The model was to be created by studying literature and current trends within the field of risk management.
2. Implement the earthquake risk assessment model.
3. Validate the model by obtaining feedback from academic, public and private professionals. In doing so, it can be determined whether or not, and to what extent, the risk assessment model would improve decision making, strategic planning and capacity building endeavours.

Quantitative research seeks to understand the facts that contribute to a phenomenon while not regarding the subjective state of a situation or condition. The research method regards reality, experience and situations as quantifiable. What is not measurable is not worth of being reported. If something is measurable and can be validated, then that object/situation can be generalized to all populations that are similar to that which was studied.

The choice of research design was therefore based on multiple criteria, of which the main considerations were the application in similar studies as well as the strengths and weaknesses of the design method (sections 5.2.2, 5.2.3 and 5.2.4). The researcher also discusses the means of addressing the shortcomings of quantitative research, with specific reference to this study (section 5.2.4).

5.2.2 Application in Similar Studies

A study of the literature has revealed that there exist a multiple of similar studies internationally. Work done by Davidson and Shah (1997), Cockburn and Tesfamariam (2012), Granger (2003) and Birkmann (2007) have been identified to potentially have the most contributing value to this study. All of these studies have the same research design, which makes applying them in this study beneficial.

The strengths and weaknesses of a quantitative research design should also be identified to fully support why a specific design is chosen. This will be discussed in the following sections.

5.2.3 Strengths of Quantitative Research

Quantitative research has many distinctive qualities. It is widely used in the field of engineering and also in similar risk assessment studies. The advantages of quantitative research design as it applies to this study follows below (adapted from Johnson and Onwuegbuzie (2004) and Borrego *et al.* (2009)):

- Quantitative research tests and validates already existing theories about how and why phenomena occur. This means that the research can be replicated, analysed and compared with similar studies.
- The data is precise and numerical, which allows for greater objectivity in the study.
- The researcher may construct a situation that eliminates the influence of many variables, allowing one to more credibly establish cause-and-effect relationships.
- Useful for a large study, involving a great number of objects that have to be observed.
- Summarizes information from a vast range of sources and facilitates comparisons across different categories.
- Helps to observe changes over time by using quantitative indicators.

- Research bias is more likely to be avoided due to researcher keeping a distance from results.
- Easier to compile data that is numerical, unlike an opinion or common sense answer.

5.2.4 Weaknesses of Quantitative Research

A quantitative model attempts to capture the essence of a process by identifying key variables and then creating a representation of it. The largest disadvantage to using such a model is that in reality, the model is always a simplification of the reality. The other disadvantages that scholars have identified for this design include (adapted from Velez (2009) and Johnson and Onwuegbuzie (2004)):

- The work of previous researchers do not occur in the same environment as this study. These methods might therefore deliver different results than expected.
- The subjective nature of the researchers' decisions are not accounted for throughout the stages of the research process.
- When duplicating the methods of other researchers, local factors that contribute to the result can be overlooked.
- The numerical results of a quantitative design provide a limited description rather than a detailed narrative.
- Preset answers that are used in quantitative design does not always necessarily reflect how people feel about a subject.
- Quantitative research is more costly than qualitative research.
- Numbers may change often, and to take this into account computations have to be done more often to balance out the change in numbers.
- Data that is used has to be refined first to a usable format.
- The design ignores some human elements.
- The larger the sample, the more time it takes to collect data.
- The larger the sample, the more time it takes to analyse the data and results.
- A quantitative method may sometimes be technically difficult to read and understand for average readers of educational journals.

5.2.5 Motivation for Quantitative Approach

The motivation for a quantitative approach is due to the speed and ease with which precise information can be obtained. The data analysis is less time consuming and one can track the changes that occur over time. Previous studies were shown to also use a quantitative approach, which more likely avoids user bias.

5.3 Methodology

This section discusses the procedures that were followed to implement the research design (that was chosen in 5.2.1). To obtain a credible conclusion, the development of a quantitative earthquake risk assessment model necessitates the collection of accurate and reliable data and statistically analyse it. It is due to this process that the methodology can be broken up into four sections: research instruments, data, model development and mathematical combination. The following is a discussion of all four these sections and the manner in which they were implemented.

5.3.1 Model Structure

The model configuration comprises of a decision tree layout, due to some important advantages it provides. Holicky (2009) mentions that decision trees have been specifically developed to analyze risk. Influences of the environment and of human activities can easily be considered simultaneously, which is favourable for this type of study. Furthermore, it can be easily understood by inexperienced individuals, creating a very effective communication means between experts and the general public.

This type of model configuration can also be used to complete a multiple-criteria decision analysis (Yang and Xu, 2002). This is a form of analysis that considers the effects of multiple criteria in a decision-making environment. Whether in a decision analysis or risk-based assessment, there are typically multiple conflicting influences that need to be taken into account in the evaluation process.

A decision tree is defined as a logical diagram for representing a number of influences that can lead to a certain condition. When establishing such a model, the objectives of the risk analysis always constitute the starting point (Yang and Xu, 2002). From this point onward, possible influences can be identified which affects the condition of the object/phenomenon under investigation. In this study factors represented the influences that were identified to contribute to the overall objectives. Sub-factors are factors which contribute to the influence of a factor. A factor can be considered to be an independent variable if it does not influence another factor, but more on this in section 5.3.4. The selection of factors, sub-factors and indicators for the model are discussed in the following sections.

5.3.2 Research Instruments

The term *research instrument* is described as *"a device which responds to a physical quantity or phenomenon, by measuring it"* (Hofstee, 2006). Multiple research instruments exist that may be used in quantitative research. Examples include questionnaires, personal interviews or sampling from a population. The research instrument should be chosen so that it accurately and reliably measures the data which will be used in the mathematical combination. This study will utilize two types of research instruments, namely questionnaires (that gather data from experts) and statistical data (obtainable from census survey data).

5.3.2.1 Definition of an Indicator

An *indicator* is a device that measures a physical condition or state, as it is in the real world. It has a wide range of applications in the fields of sociology, politics, business, science and engineering. In these fields an indicator usually represents a scalar measurement that enables the researcher to see the progress towards intended outputs, outcomes, goals and objectives. It is often related to measuring the quantity of something, rather then its quality. For this study an **indicator** will represent the **risk score of each sub-factor** that was identified.

5.3.2.2 Purpose of Indicators

The rationale for using indicators in the study is the following:

- it measures the physical condition or state of an object or phenomenon
- it represents the numerical measurement of a single objects condition or state
- it indicates change over a time period
- it indicates the efficiency of an decision or effect

5.3.2.3 Indicator Selection Criteria

The selection of indicators for the model should proceed in a way that is rational and reliable, since the outcome of the results depends largely on the accuracy and consistency of the data that were obtained. If the indicators were found to be unreliable, it may ultimately result in erroneous results. It should therefore be emphasized that the choice of indicators play an important role. The indicators should be chosen according to a protocol and standards set out in previous literature. Birkmann (2006) set out a list of standard criteria according to which indicators should be chosen. This criteria states that an indicator should be:

- Measurable
- Relevant
- Policy-relevant
- Measure specific key-elements
- Analytically and statistically sound
- Understandable
- Easy to interpret
- Be sensitive to the underlying phenomenon
- Valid and accurate
- Reproduceable
- Based on available data
- Data comparability
- Of appropriate scope
- Cost effective

5.3.2.4 Indicator Selection Process

Birkmann (2006) developed a standard procedure to identify indicators. This is illustrated in Figure 5.2. The process starts with defining the objectives for the study. This was done in Chapter 1. Next an appropriate framework was chosen to fulfil the research objectives. This was discussed in the research design section (5.2 above). Birkmann further specifies that a set of selection criteria be identified according to which the indicators should be chosen. This is discussed in the previous section 5.3.2.3, based on the indicator selection criteria. The next few steps were an iterative process which aimed to identify any potential indicators, to choose a final indicator set, to assess their accessibility and to validate and then start again by removing any indicators which were inconsistent with the selection criteria identified earlier. The choice of indicators is discussed in the subsequent chapter, Chapter 6, along with the model layout, factors and assigned weightings.

5.3.3 Data

The subsequent section relates to the validity of the data that the indicators collect. This is followed by a listing of the strengths and weaknesses of the data, and why this is so important.

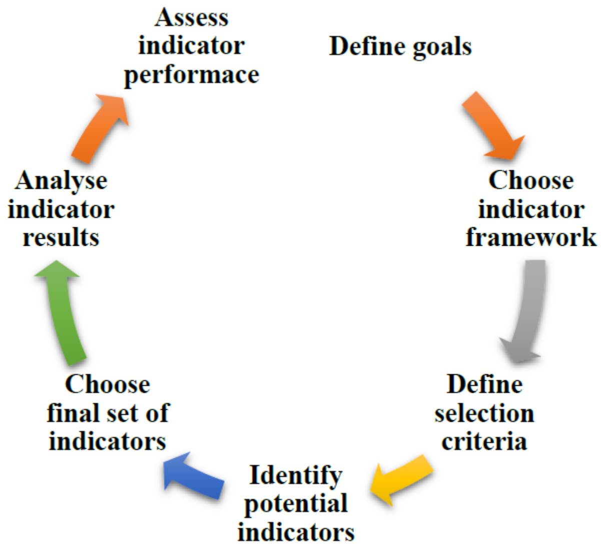

Figure 5.2: Development process of indicators. Adapted from Birkmann (2006).

5.3.3.1 Sources of Data

The following sources have been identified that could potentially contribute data to the model:

- Statistics South Africa
- South African National Standards (Building Codes)
- The Department of Human Settlements
- World Health Organization
- United Nations International Strategy for Disaster Reduction
- Visual Inspection
- FEMA handbooks

General indicator values for the South Africa, its provinces and municipalities can be obtained from the Statistics South Africa website (beta2.statssa.gov.za). AfriGIS has also developed an interactive and online GIS program that is based on data from the 2011 census (www.census2011.co.za). It displays census data per province, municipality, ward and sub-place. This greatly aids the data gathering process which has to do with collecting data from different wards that buildings are located in.

5.3.3.2 Strengths

The following are strengths of numerical indicators:

- Greater objectivity when measuring data
- Greater accuracy of data
- It summarizes the physical condition of something
- Research can be repeated and compared
- It avoids personal bias

5.3.3.3 Weaknesses

The following are weaknesses of numerical indicators:

- It collects a much narrower dataset
- Results are limited since they provide numerical results
- Preset answers do not necessarily replicate how people feel

Caution should be taken with the data from visual inspections, in order to:

- Avoid researcher bias
- Establish the appropriate measurement criteria
- Ensure measurements are carried out correctly

5.3.4 Factor Identification

A factor can be described as an influence that contributes to earthquake risk. The process of identifying factors follows after suitable indicators were chosen. Two groups exist according to which a factor can be classified: principal factors and sub-factors. Here follows a discussion defining the identification of both types of factors.

5.3.4.1 Principal Factors

A principal factor is one of the main factors which contribute to the earthquake risk of an individual. It comprises of other sub-factors, which if combined together, form the influence of the principal factor. A principal factor is therefore in essence a collective term which describes the combined influences of its sub-factors. This mechanism is better described at the hand of an example. It is evident that one of the principal factors of ERAM would be the seismic hazard. The term seismic hazard may however comprise of other sub-influences such as ground shaking and secondary events which are triggered by the ground movement (soil liquefaction or fires). The term seismic hazard is therefore the main description of a collection of other events.

The factors of the model were identified from the literature. The literature discussed in Chapter 4 refers to previous studies in the same field of research. From this literature study the factors were chosen, omitting factors which were not applicable (or site specific).

5.3.4.2 Sub-Factors

A sub-factor is a component of a principal factor. The combined effect of all of the sub-factors describe the effect of the principal factors. The lowest order factor is assigned an indicator to measure the physical condition of the factor. To return to the example of the seismic hazard, one can consider the ground shaking and secondary effects of ground shaking both as sub-factors. The secondary effects category can then in turn be subdivided again into soil liquefaction and the possibility of a fire.

It is important to note at this point that the connection between an indicator and a factor should be accurately described. The purpose of the model was to define a structure whereby earthquake risk can be calculated. The purpose of the principal factors were to group together factors with similar influences. Furthermore the purpose of sub-factors were to identify any events or phenomena that could have an impact on the earthquake risk of individuals. Lastly, an indicator was used as a mechanism that makes a measurement of the event or situation that the sub-factor describes. Figure 5.3 describes functioning of the model.

Sometimes a situation may arise where a factor can be identified, but no measurable indicator exists to measure the state of the factor. An example of this may be the property damage that an individual experiences. Considerable effort has gone into researching the behavioural characteristics of different types of buildings. There however exists no measurement device which can estimate the monetary loss of damage to an individuals furniture, appliances etc. Such a factor therefore has no potential indicators and was omitted from the model.

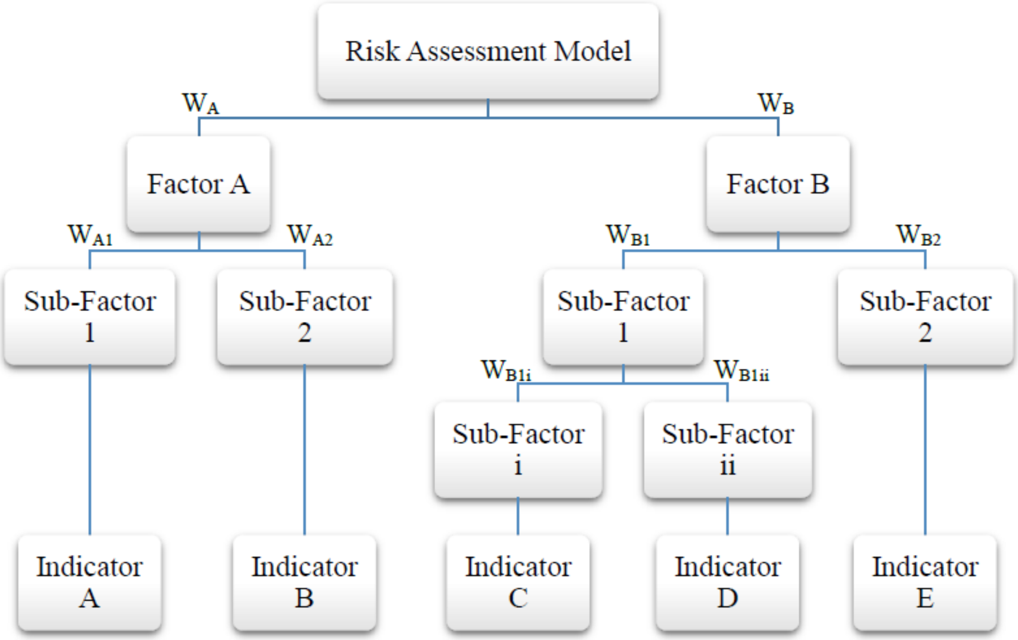

Figure 5.3: An example of a risk assessment model showing the relationship between principal factors, sub-factors, indicators and factor weights (illustrated by W_i and explained in subsequent sections)

5.3.5 Conceptual Framework

Figure 5.4 shows the conceptual framework for assessing the earthquake risk. Cockburn and Tesfamariam (2012) hypothesized that two important features contribute towards earthquake risk: the damage/loss a community suffers or the capability of a community to sustain an impact and recover from it. The damage/loss to a community feature represents the short term or immediate hazards that threatens individuals. The capability of a community to sustain and recover from an impact feature focuses on the medium to long term effects of an earthquake.

Three principal factors were identified for the damage/loss to a community group: the Seismic Hazard, Exposure and Vulnerability of the Building and lastly the Exposure and Vulnerability of the Residents (Davidson and Shah, 1997). Two principal factors were identified for the community impact group: Emergency Planning and Recovery Capability factors. Each of these factors can be broken into more specific factors. For each of the factors, appropriate indicators were then chosen.

5.3.6 Factor Weights

A weight is an estimated value that is added to a factor to indicate the importance of the factor compared to other factors in the group. The purpose of assigning a weight is to prioritize which factors contribute the most towards the result of the model.

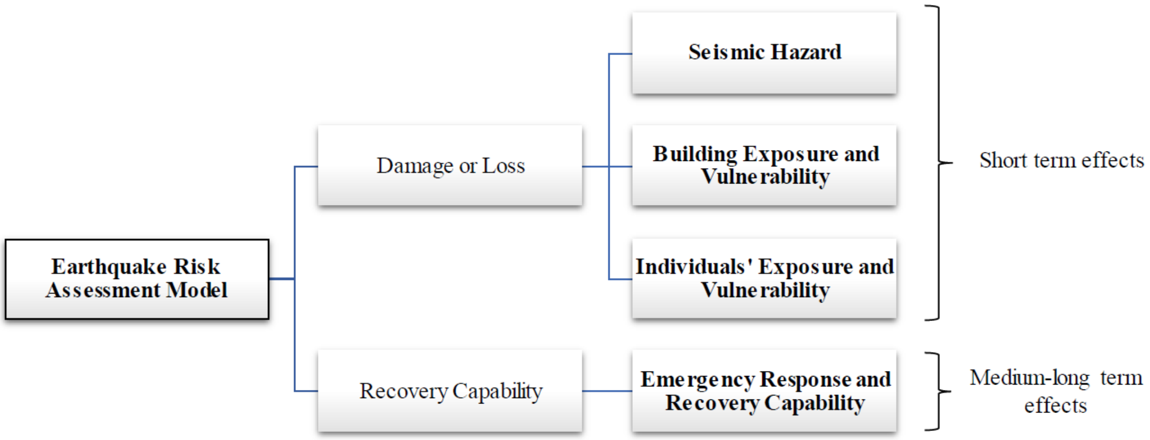

Figure 5.4: Conceptual framework for creating the earthquake risk assessment model.

The use of weights has its advantages and disadvantages. One of the largest disadvantages to using weighted factors is certainly that no "correct" set of weights exists a priori. Although there is no "correct" weights, the industry survey for this research helped with the estimation of these weights. The best weights represented the most accurate contribution of each factor to the overall earthquake risk assessment. The most appropriate technique for determining the weight values would be the one that produced the best weight values, while still meeting the indicator criteria as it was set out in section 5.3.2.3.

The weights were established by two methods: either from studying previous literature or by an industry survey (subjective assessments). Existing weights were obtained from a study of the literature. The other weights which could not be identified, were determined with an industry survey of disaster management professionals. Chapter 6 discusses the weights that were identified, where they were identified from and which techniques were employed to obtain the weights.

5.3.7 Mathematical Combination

Chapter 4 describes the approach used by Davidson and Shah (1997) to determine the earthquake risk. Based upon that rationale, the linear combination techniques provides the best method for mathematically combining the principal factors, sub-factors and indicators. The equation for the model is therefore:

$$ERAM = W_S.S + W_B.B + W_I.I + W_E.E \tag{5.3.1}$$

where

$$S = W_{S1}.x_{S1} + W_{S2}.x_{S2} + W_{S3}.x_{S3} + W_{S4}.x_{S4} + W_{S5}.x_{S5} \tag{5.3.2}$$

$$B = W_{B1}.x_{B1} + W_{B2}.x_{B2} + W_{B3}.x_{B3} + W_{B4}.x_{B4} + ... + W_{B7}.x_{B7} \tag{5.3.3}$$

$$I = W_{I1}.x_{I1} + W_{I2}.x_{I2} + W_{I3}.x_{I3} \tag{5.3.4}$$

$$E = W_{E1}.x_{E1} + W_{E2}.x_{E2} + W_{E3}.x_{E3} + W_{E4}.x_{E4} + ... + W_{E12}.x_{E12} \tag{5.3.5}$$

where S, B, I and E are values of Seismic Hazard, Building Exposure and Vulnerability, Individuals' Exposure and Vulnerability, Emergency Planning and Recovery Capability; x_i refers to the score values of the indicators and W_i are the weights associated with each factor.

5.4 Limitations

The methodology was designed to be as complete as possible, though there still are some important limitations which prevent this from being the case. One of the first issues regards the weights that are used in the model. Two techniques are used in this study for obtaining the weightings: literature study or subjective assessment. Obtaining weights from the literature can be useful since the weightings have been established a priori, however it should be kept in mind that the work by previous researchers was not conducted in the same environment. The weights obtained from literature are therefore more accurate. Obtaining weights from literature can limit the results of the study. Subjective assessments tend to be more subjective in nature, however this technique is only used where there is no available information. This said, it is the most accurate method of estimating weights in the absence of information and is therefore justifiable.

Another key issue which limits the results of the study is the availability of data. In order for the earthquake risk assessment model to function perfectly, it requires a database of site specific data to be used in the analysis. Building characteristics, subsoil conditions and data pertaining to the residents of each building is needed to obtain accurate results from the model. One of the reasons why this study is conducted is to cast light on the relationships between the factors and to enhance the availability of data from which disaster risk reduction research can be conducted.

Describing the vulnerability of masonry buildings can sometimes be difficult due to the large variation of design practices that exist. This certainly limits the accuracy of the results. In order to increase the accuracy of the model, further research should be conducted on these masonry designs. These investigations are however costly and resource intensive, and justify the use of existing literature in this study.

Lastly there are some immeasurable factors which influence the earthquake risk of an individual. These include the social and political circumstances which influence the individuals. There exists no measurement device which can measure the level of influence of this factor. This is a disadvantage that is associated with a quantitative research design. In light of the discussion above based on the advantages of a quantitative research design, it was accepted that this issue would sometimes arise if a quantitative research design was chosen.

5.5 Ethical Considerations

Ethical considerations were accounted for when designing the industry survey. The scientific nature of the research entails that there were minor ethical issues to be addressed, especially when issuing the questionnaires to individuals that were not affiliated with the university. The purpose of the survey was to validate the earthquake risk assessment model. The survey involved sending out questionnaires to specialists from various backgrounds (academic, public and private).

The possible ethical problems that were identified for this study include:

- Use of an individual's particulars in the research document (name and surname)
- Disclosure of confidential information to researcher
- Conducting interviews during work hours of institution

A specific procedure was implemented in the questionnaire development process to address the problems mentioned above.

The questionnaires included a cover letter with a brief summary of the purpose of the research, purpose of the survey, details of the researcher, name of the institution where research was conducted at and details of the supervisor. A letter of consent was also included to obtain permission for the survey. If the participant agreed to this, the letter of consent was stored in a safe facility which was only accessible by the researcher or study supervisor.

More information on this can be found in section 7.3. The departmental ethics committee of the Department of Civil Engineering approved this procedure. Proof of the approval can be found in Appendix B or at the department secretary.

5.6 Conclusion

The Research Design and Methodology chapter summarises the theoretical analysis of the methods that were applied.

The Research Design section (5.2) outlined the overall approach that was followed to solve the research statement. It discussed the motive for using the approach, the shortcomings and by what means the shortcomings were addressed.

The Methodology section (5.3) referred to the procedures that were used to develop the ERAM. It essentially discusses the step by step procedures that were used to develop the ERAM. The Model Structure of the study was the first to be defined (section 5.3.1). It discussed the choice of model, while identifying strengths and weaknesses to motivate its use.

Research Instruments (section 5.3.2) outlines what measurement devices were used, followed by the Data section (5.3.3) which discussed the sources and validity of data. The process of Factor Identification (section 5.3.4) then detailed the means and criteria for selecting factors for the model.

Section 5.3.5 discussed how the model structure was combined with the identified factors to form the Conceptual Framework. The process of determining Factor Weights (section 5.3.6) was then described, followed by the Mathematical Combinations (5.3.7). The Limitations section (5.4) discussed the limitations to developing the model whereas the Ethical Considerations (section 5.5) discussed the manner of approaching the industry survey in an ethically correct way.

Chapter 6

Earthquake Risk Assessment Model

6.1 Scope of Chapter

The following three chapters (6, 7 and 8) describe the development of the Earthquake Risk Assessment Model (ERAM). The ERAM will enable the researcher to evaluate the seismic risk of a multi-storey, load bearing masonry building. This forms part of the primary research objective, which is to develop a procedure for prioritizing the seismic risk reduction of low cost, load bearing masonry buildings.

Figure 6.1 illustrates the chapter outline and the components that will be discussed. All of these components were used to develop the ERAM.

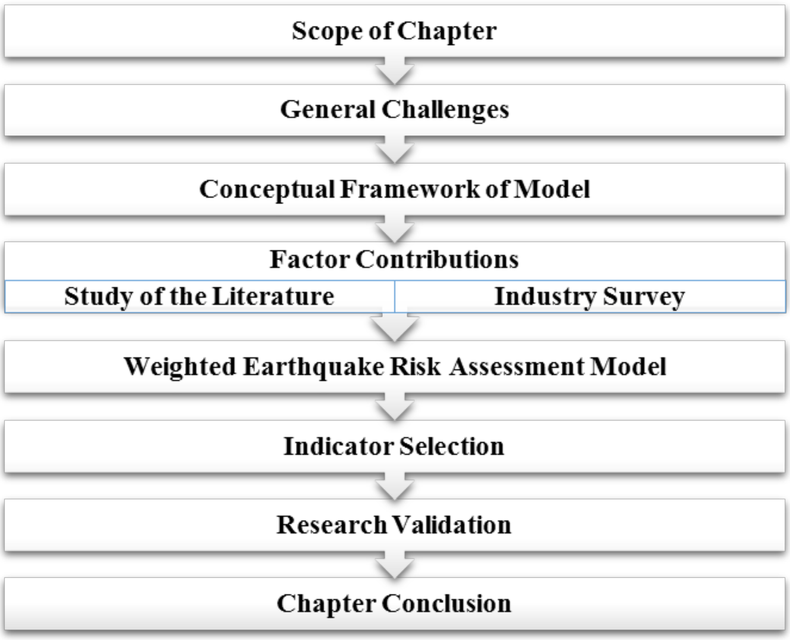

Figure 6.1: Chapter 6 outline

Chapter 6 starts with a brief discussion regarding some of the general challenges that were faced while developing the ERAM (section 6.2). This is followed by the actual starting point for the model, the conceptual framework (section 6.3). Here factors were identified for the model which contributes to earthquake risk. In order to differentiate between the importance of each of these factors, the researcher then had to determine a weight for each factor. The weights were determined by either a literature study or by a survey of the industry, and are discussed in Chapter 7.

After obtaining the weights, the weighted ERAM was developed (section 7.5). This was established with the help of the conceptual model and factor weights. The model needed an indicator for each factor, which were determined in section 7.6. The last step was to validate whether the weights obtained for the model were realistic when compared to other research (Chapter 9).

Here follows a discussion on the general challenges that were faced when constructing the ERAM. The discussion clarifies some general problems that were identified and the approaches used to avoid these problems.

6.2 Challenges of Developing Model

The search for factors that contribute to earthquake risk is challenging for a number of reasons. Firstly, earthquake risk is a broadly defined term. The factors may span a range of disciplines such as geology, engineering, economics, emergency management, political- and social relations. Care should therefore be taken to identify the appropriate contribution each field makes towards earthquake risk.

Secondly, the above mentioned activities interact with each other. These interactions can be seen as a complex web connecting each activity with another. The researcher should attempt to remove factors from this web so that they are mutually exclusive. Care should also be taken not to double count or omit factors from the framework.

Factors were further not chosen to be too specific or too general. When choosing factors one has to bear in mind that each factor must contribute towards the objective of the model. The situation may arise where factors are chosen to be too specific and the model may become unnecessarily complicated. When defining a factor too generally, it may become difficult to see how the earthquake risk is affected.

Finally, it was not always possible to separate or mutually exclude factors from each other. The best that could be done was to acknowledge this difficulty and define factors in a way to avoid this or to rather focus on the principal effect of each factor. To overcome all of the above mentioned challenges, the author sought to include factors that contribute significantly to earthquake risk and varied from one building to another, so that each building may have had a different risk ranking, if compared.

6.3 Conceptual Framework

A conceptual framework is a tool that is used to distinguish and organize ideas. In this case, a conceptual framework was created to distinguish between some of the main influences which affects the earthquake risk of an individual. These influences (principal factors) were then disaggregated into further contributing components (sub-factors).

Fortunately, the idea of ERAM is not a new one. Research by Davidson and Shah (1997) identified four principal factors that have an influence on the earthquake risk, namely:

- Seismic Hazard
- Building Exposure and Vulnerability
- Individuals' Exposure and Vulnerability
- Emergency Response and Recovery Capability

Cockburn and Tesfamariam (2012) took this further by grouping the *Seismic Hazard*, *Building Exposure and Vulnerability* and an *Individuals' Exposure and Vulnerability* together, since it represents the damage or loss that a community experiences in the short-term. Similarly, the *Emergency Response and Recovery Capability* factor represents the medium- to long-term capability of a community to recover from such a disaster. Figure 6.2 illustrates the conceptual framework that was created for this study.

Following is a discussion of each factor that was mentioned above. This includes the sub-factors, which were also identified for each principal factor. All of these factors were identified following the procedure set out in the Factor Identification (section 5.3.4).

6.3.1 Seismic Hazard Factor

The Seismic Hazard factor represents the geophysical phenomena that may impose harm upon a building. This includes ground shaking, the soil conditions of the foundation, as well as multiple secondary (collateral) effects. Collateral hazards are hazards that are initiated by the ground movement (primary action) of an earthquake. This includes the susceptibility of soil for liquefaction and the probability of fire in the buildings.

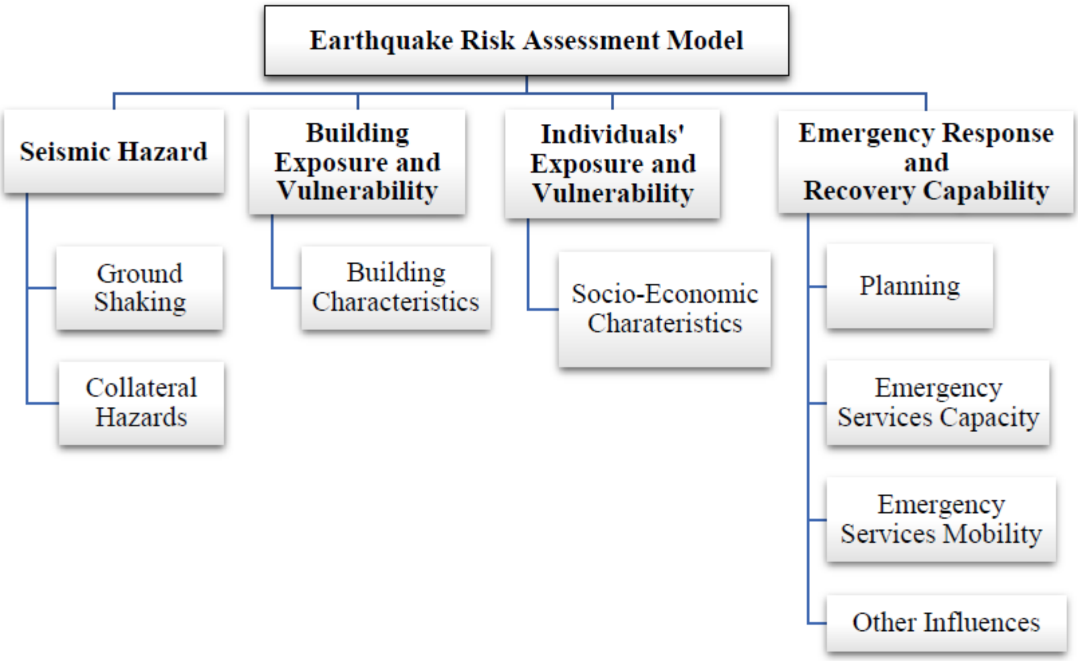

Figure 6.2: Conceptual framework for ERAM.

It is notable that for earthquakes the ground shaking and foundation soil conditions directly influence a building. Soil liquefaction and fires follow straight after an earthquake, which categorises it as secondary actions.

6.3.1.1 Ground Shaking

Ground shaking is the most important component of the Seismic Hazard factor, since it is directly responsible for the majority of damage that is inflicted. It is also an important component since other secondary hazards (soil liquefaction and fires) are triggered by a large enough level of ground shaking and suitable conditions.

The characteristics that describe ground shaking include the amplitude, frequency and duration. Amplitude is the most commonly used measuring unit, and is expressed in terms of acceleration (peak ground acceleration, PGA, or spectral acceleration, S_a) or intensity (Modified Mercalli Intensity, MMI) (Schmid and Slejko, 2009).

As mentioned in section 4.3.1, Probabilistic Seismic Hazard Assessments (PSHA) can be used to identify probabilistic ground movement. PSHA's use PGA to incorporate two equally important characteristics into a single parameter, namely the expected magnitude of ground shaking for a specified future time period. Using this to investigate a short time period shows how frequent ground shaking occurs, while investigating a longer time period conveys how strong the ground shaking could potentially be.

Probabilistically determined ground shaking depends on:

1. The location of the earthquake, recurrence patterns and maximum magnitudes of historic earthquakes within the region.
2. The attenuation relationships of the soil and the topography of the region, which describe the way ground motion changes as it travels from the source of the earthquake to the site.
3. The ability of the soil at the site to amplify or reduce the ground shaking. Topography and fault direction have been identified as additional characteristics of PSHA's, however have not been included in PSHA's yet.

The choice of time period will define a time horizon for the ERAM model. If the level of ground shaking with a one-year return period was used in the Seismic Hazard factor, the hazard for many buildings would be close to zero. There is however an enormous difference between a small chance of an earthquake and no chance of an earthquake. By using the magnitude of ground shaking for a five hundred year return period, the ERAM model addresses the seismic hazard in areas of low seismicity. It also represents the most commonly sized earthquakes in engineering, seismology and disaster management. Design codes typically use an earthquake magnitude with 475 year return periods for no-collapse design criteria, which is equivalent to a 10% probability of exceedance for an earthquake with return period of 50 years (SANS 10160 Part 4, 2009). These are reasonable time horizons for engineers and disaster management specialists.

6.3.1.2 Liquefaction Susceptibility of Soil

"Soil liquefaction is a phenomenon in which soil changes from a firm material into a viscous semi-liquid material" (Gere and Shah, 1984). It generally occurs with sandy soils that are saturated and then subjected to vibrations. The vibrations tends to compact and decrease the volume of the soil. If no drainage occurs, then the decrease in soil volume results in an increase in pore water pressure. This pressure then builds up to the point at which it is equal to the overburden pressure of the soil, and the effective stress becomes zero. The soil then loses its bonding strength and the soil develops a liquefied state (Seed *et al.*, 1991; Bray, 2002).

Soil liquefaction can cause minor- to moderate levels of structural damage to buildings. As described above, when soil liquefies, it loses its bearing strength which causes buildings and other structures to sink. Often the structures remain intact, however are tilted or settled deeper. Buildings are usually repaired through complex foundation raising and replacement procedures. Liquefaction can cause damage to underground service infrastructure, like causing pipes or septic tanks to float to the surface of the ground. Other infrastructure such as roads and railroad tracks can also suffer damage. The settling of soil also causes discontinuities in the roads/tracks, which imposes great harm to unaware users. Soil liquefaction has received much attention lately after causing severe damage during the Hanshin (Japan) earthquake of 1995.

The liquefaction potential of an area is determined by its soil characteristics, intensity of ground shaking and water table depth. Soil liquefaction often occurs in sandy soils that is saturated in water, and shouldn't be underestimated. This is especially applicable to the Cape Flats region where buildings are built on sandy soils with high water tables in the winter.

6.3.1.3 Fire

Fires that break out following an earthquake can be extremely destructive since there may be many simultaneous ignitions and the capability of any emergency services may be impaired. This impairment may be due to multiple earthquake related issues such as damaged water supply systems, the unavailability of fire extinguishing personnel or restricted mobility due to debris filled and/or damaged roads.

Two components govern the fire hazard: the amount of potential ignition sources and the material which fuels the fire. Potential ignition sources include gas line breaks, overturned heaters, electrical shortages and the ignition of flammable liquids. How the fire spreads depends on the fuel (wooden furniture, building contents, building construction materials etc.), the weather conditions (humidity, temperature, wind speed and wind direction) and the capability of emergency services to suppress the fire. Fire suppression can be considered both as part of Seismic Hazard (ignition due seismic activity) or Emergency Response and Recovery Capability factor (fire suppression capability of emergency personnel). In order to avoid double counting, it has been included in the Emergency Response and Recovery factor discussion. The argument to this is that fire suppression is an activity that is carried out to reduce the impact of a fire, whereas fire following an earthquake is a consequence of an earthquake.

6.3.2 Building Exposure and Vulnerability Factor

The Building Exposure and Vulnerability factor describes the characteristics of a building. The characteristics that were identified to assess the vulnerability of a building includes: the building age, building storeys and structural system, vertical irregularities, plan irregularities, post-seismic code retrofitting and the proximity of the buildings to each other.

These characteristics were obtained from the *Rapid Visual Screening of Buildings for Potential Seismic Hazards* handbook (ATC, 2009). The FEMA issued this handbook to assist emergency agencies around the United States in rapidly screening which buildings need more investigating for seismic vulnerability. The following is a discussion of each characteristic that was identified to assess a buildings risk.

6.3.2.1 Building Age

The age of the building is one of the most important factors to consider when determining the vulnerability of a building. This study will consider only unreinforced masonry buildings that were built before 1989. This is important, since the South African seismic loading code, the SABS 0160, was first introduced in 1989 (Wium, 2010). This compelled engineers to design and construct buildings in seismically active regions to resist the effect of probabilistic ground motions. This age constraint implies that the minimum age of any building considered for this research is 25 years old, which makes these buildings worthy of being investigated.

6.3.2.2 Building Storeys

Another important factor is the amount of storeys of a building. The ATC (2002) states that the height of a structure is related to the amount of damage it may sustain. Tall buildings may experience considerably stronger and longer durations of shaking than shorter buildings of the same type. The introduction of the SABS 0160 (1989) brought about changes in design criteria for reinforced masonry buildings. SANS 10160 Part 4 (2009), the current seismic loading code, states that for reinforced masonry buildings above 3 storeys, specialist literature should be consulted or the Eurocode (EN 2004-1 (2004)) should be used. This limits the height that most modern masonry buildings are typically designed for.

6.3.2.3 Vertical Irregularities

A vertical irregularity is a location in the building where a physical discontinuity occurs in the vertical configuration. This is a region where the stiffness between the discontinuous parts often differ. Examples of vertical irregularities include buildings with setbacks, hillside buildings and buildings with soft storeys. Figure 6.3 illustrates the three different types of vertical irregularities, where the arrows indicate the particular locations of concern.

6.3.2.4 Plan Irregularities

Plan irregularities are much the same as vertical irregularities, except that the discontinuities occur within the plan view. Buildings that have plan irregularities are subject to greater twisting forces (torsion) about the vertical axis. Unreinforced masonry buildings are especially vulnerable to torsional forces. Damage at connections may significantly reduce the capacity of vertical load-bearing elements, leading to partial or total collapse. Figure 6.4

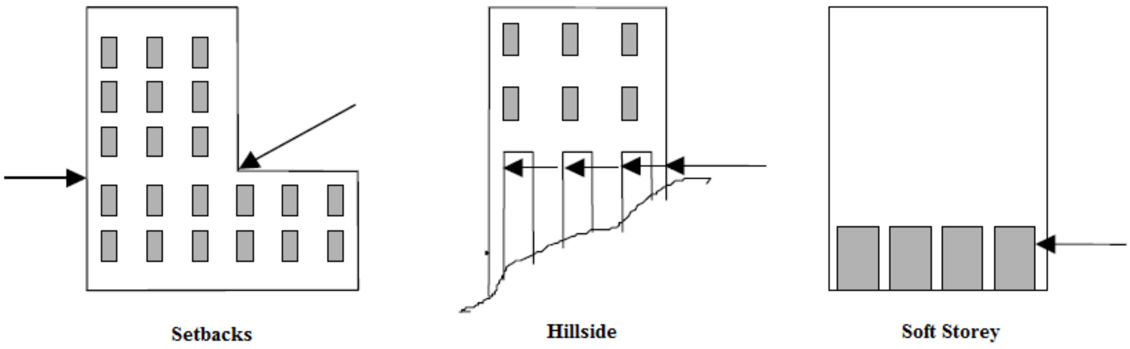

Figure 6.3: Elevation views showing vertical irregularities (ATC, 2002)

illustrates various different types of plan irregularities, where the arrows indicate possible areas of damage.

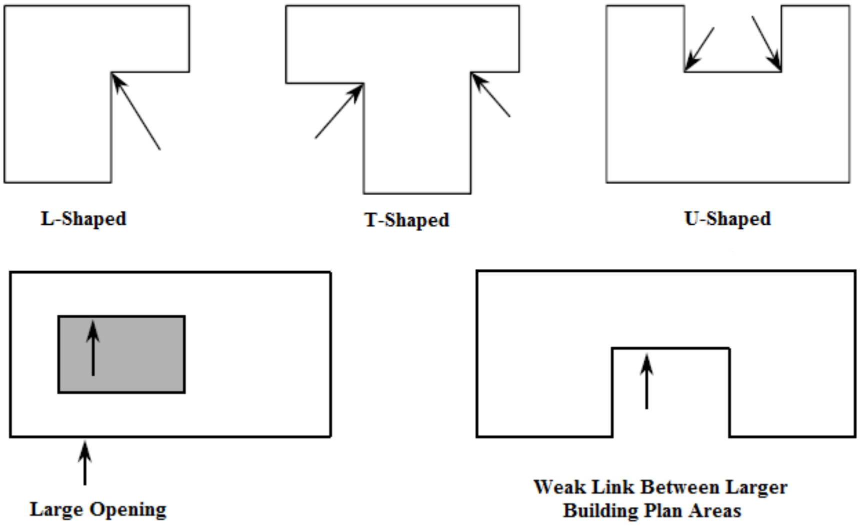

Figure 6.4: Plan views showing various plan irregularities (ATC, 2002)

6.3.2.5 Post-Seismic Code Retrofitting

Post-seismic code retrofitting refers to masonry buildings that have been reinforced after it was constructed. This would have followed after the introduction of the SABS 0160 (1989) and later SANS 10160 Part 4 (2009) codes. The code requires engineers to take into account seismic forces when designing a building in a seismically active region. This is an important factor, since these masonry buildings are now retrofitted against any major damage such as partial- or total collapse. The buildings are however still vulnerable to minor- or moderate levels of damage, such as walls cracking, windows breaking or plaster peeling off.

6.3.2.6 Proximity of Buildings

The proximity of buildings factor refers to the effect that one building may have on another, free-standing building. This is important in situations where buildings are located relatively close to each other or where a building has its own movement joints. Agarwal *et al.* (2007) identified the pounding of buildings in close proximity as a potential threat to the structural integrity of the building. This also included the partial- or full collapse of one building, that could affect another free-standing building.

6.3.3 Individuals' Exposure and Vulnerability Factor

The Individuals' Exposure and Vulnerability factor describes the characteristics of the individuals living within a building. The three describing characteristics: Population Density, Vulnerable Groups and Income Per Person all aim to identify possible factors which influence either the resilience of the individuals in the short term or the coping capacity (medium- to long-term effects) long after the event. Here follows a description of each factor that has been identified by Davidson and Shah (1997) and Cockburn and Tesfamariam (2012).

6.3.3.1 Population Density

The Population Density measures the number of individuals living in a building. The less individuals living in the building, the lower the risk of any injuries or deaths. Similarly, the more individuals living in the building, the greater the risk of harm. Buildings that are therefore overpopulated show a much greater potential for harm, since the effective evacuation, treatment and recovery of individuals are impeded by the vast number of injured individuals.

Population density is a characteristic that is mentioned twice in the model. This is due to it playing various roles in the event of a disaster. When an earthquake strikes, the number of individuals within a building will to a large extent determine how many injuries or deaths occur. Similarly, the population density will also influence the evacuation time, treatment capacity and ability of the residents to recover from such a disaster long after. The population density is therefore also mentioned under the Emergency Response and Recovery Capability parameter as a characteristic that plays a role in treatment- and recovery time.

6.3.3.2 Vulnerable Groups

Research has shown that young individuals (less than 4 years old), old (65 years or older), sick, disabled or pregnant are more vulnerable to natural disasters. Blaikie *et al.* (2004) mentions that *"studies of disaster casualties have indicated that the young and the old are often most at risk. They are, for example, less mobile (capable of evacuation), more dependent, have less resistance to disease, and often command fewer resources."*

Blaikie *et al.* (2004) therefore mentions important characteristics, since it could have an effect on a person's ability to escape from a collapsing structure, recover from an injury or survive in times of hardship, long after an earthquake. In this study the Vulnerable Groups factor will be measured by the proportion of individuals who are younger than 4 years and older than 65 years old, since it is difficult to predict how many sick or pregnant individuals are present in a building. One can obtain information for disabled persons from national census data, however this was omitted in this study.

6.3.3.3 Economic Vulnerability

Economic Vulnerability accounts for the fact that individuals who are struggling financially before an earthquake, or are poor or unemployed, will struggle to recover from their losses after an earthquake. The financial loss these individuals will experience, will be greater than for wealthy individuals. All types of individuals will be affected, however the influence on the life quality of poorer individuals will be much greater. This factor will be represented as a generalization of each individuals' income, or income per capita. The higher the income, the quicker the recovery from losses. Similarly, the lower the income, the slower the recovery from losses during an earthquake.

6.3.4 Emergency Response and Recovery Capability Factor

The Emergency Response and Recovery Capability factor describes two particulars: firstly, the capability of the emergency services to respond to a disaster and secondly, the ability of affected individuals to recover from a disaster. When assessing the capability of the emergency services, one has to take into account the response measures already in place to cope with a disaster as well as the mobility and capacity of emergency services to respond. When assessing the recovery capability of individuals, one has to assess how effectively and efficiently the residents of a building can respond and recover from medium- and long-term impacts of an earthquake. Below is a discussion on some of the aspects that Davidson and Shah (1997) identified, that may influence this factor.

6.3.4.1 Emergency Planning

This aspect describes the quality of plans and procedures developed (before the earthquake) to aid individuals with effective emergency response and recovery. The plans should be organizational, establishing the roles and responsibilities of each party involved. It should indicate what should be done, how, when and who should do it.

A city's historical experience with previous earthquakes may also influence the degree of planning of a society. In areas of frequent earthquakes, seismic building regulations, evacuation procedures and emergency plans may be well documented. This may differ in regions where earthquakes rarely occur, such as the Haiti earthquake disaster of 2010.

6.3.4.2 Emergency Services Capacity

This aspect relates to the mobility, capability and capacity of the emergency services after a disaster has occurred. Due to the vast amount of emergency services offered, it was decided to focus on fire extinguishing- and medical services, since these are the two most important emergency services.

Factors which have been identified to play a role in the mobility, capability and capacity of fire services are:

1. Number of fire personnel available to the public
2. Distance to nearest fire station

Factors which have been identified to play a role in the mobility, capability and capacity of medical services are (Cockburn and Tesfamariam, 2012):

1. Capacity of hospitals to population of public
2. Number of doctors available to the public
3. Distance to nearest hospital

6.3.4.3 Other Factors

Other miscellaneous factors which have been identified to play a role in emergency response and recovery capability, includes (Davidson and Shah, 1997):

1. The population density
2. Number of individuals dependent on residents
3. Communication pathways such as landline telephone, cellphone, radio or TV

The population density of a building is a very important factor. It has already been mentioned in section 6.3.3 since the amount of people within a building will not only affect the number and severity of injuries, but also the emergency treatment capability and recovery speed of these individuals.

Another factor which influences the recovery capability of an individual is the number of individuals they have to financially support. This may include a spouse, elders, family members, children or friends. This study will only focus on children that are dependent on their parents, since this is the only parameter that can be obtained from census data. Unemployment may be a good indicator of dependants that have to be supported, since these individuals of have little to no income to live from. The omission of this factor underestimates the recovery capability of a community and can have an affect on the results.

Lastly communication pathways have also been identified as manners to improve the recovery speed (Underwood, 2010). Devices such as a telephone, cellphone, radio or TV may assist in communicating valuable information during times of need. The development in society is such that each individual at least has access to one of the above mentioned communication devices.

6.3.5 Factors Not Implemented

Although many factors were considered for the model, some were found to be unsuitable for use. This was the case when a factor did not adhere to the selection criteria that was specified in section 5.3.2.3. Table 6.1 displays some of the factors that were considered worthy of implementing, though found to be inappropriate or outside the scope of this study.

Table 6.1: Factors not implemented in ERAM.

Principal Factor	**Sub-Factor**
Seismic Hazard	Tsunami potential
	Landslide potential
	Apartment vacancy rate
Building Exposure and Vulnerability	Construction quality
	Construction materials
Individuals' Exposure and Vulnerability	Socio-economic development speed
	Proportion of residents insured
	Overturning objects
Emergency Response and Recovery Capability	Per Capita GDP growth
	Extreme weather indicator
	Critical infrastructure condition
	City layout indicator

The effects of a tsunami (or seiche) must not be ruled out, however was not implemented in the model due to the lack of expertise involved.

Similarly, the potential of a landslide must not be ruled out. It was not considered for this study since the study of landslides is a complex field and the site where these buildings are located is relatively flat (Dai *et al.*, 2002).

The apartment vacancy rate was identified as a good indicator on how many apartments are vacant in a building, but was not chosen since it is very difficult to determine the vacancy rate without a physical inspection. It is assumed for this study that the buildings are 100% populated, overestimating the risk of injuries.

Factors not considered for the Building Exposure and Vulnerability were the masonry quality. Van der Kolf (2014) found that the masonry quality will to a large extent influence the ability of a load bearing structure to withstand a moderate intensity earthquake. These factors were found to be very difficult to determine since the buildings considered for the study are at least 25 years old and differ in age, and it is very difficult to determine the composition or state of the masonry used in a building.

The socio-economic development speed indicates the tempo of social and economic development in a society. Indicators to this include the life expectancy, literacy and levels of employment. This factor was not chosen since no indicators exist which can determine factors for each building.

The proportion of the individuals insured may also affect recovery capability and speed. It was omitted due to this study being applied to individuals living in low cost housing (R800 - R3500 income gap) and the majority of the residents not being able to afford any insurance. It is also a very difficult factor to obtain information for, since there exists multiple insurance institutions from which the data have to be collected.

The per capita Gross Domestic Profit (GDP) growth (which differs from GDP) represents the economic growth per person. This is an excellent indicator to represent the economic growth and recovery capability of an individual, though no statistic currently exists which shows the GDP distribution within a city. According to data obtained from the national census, only generalized figures exists for cities as a whole in South Africa.

The extreme weather indicator indicates the probability of extreme weather occurring over a city, reducing the mobility of emergency services. This factor was omitted because extreme weather events (with exception to tornado's) often occur over a city as a whole, and not within one particular region. The possibility of a tornado can be ruled out, since there is a very small possibility that it can occur in conjunction with a earthquake of 475 year return period. The Mannenberg tornado (1999) is an example of such an event of late.

The condition of critical infrastructure such as bridges, water distribution- and treatment facilities or energy distribution networks has a large influence in the mobility of the emergency services and recovery capability of individuals, though was omitted due to it being a vast field of its own. This also includes water supply- or gas lines which influences the fire suppression capacity.

The following factors could also be considered, though not implemented due to a shortage of indicators:

1. Critical infrastructure (bridges, water treatment facilities, hospitals etc.)
2. Electricity distribution networks
3. Gas distribution networks
4. Public transport
5. Unemployment of individuals
6. Layout of city
7. Value of building
8. Value of building contents

6.3.6 Conceptual Model

The conceptual model was constructed from all of the factors that were identified in section 6.3. Table 6.2 summarises all 26 factors that were chosen. These were grouped together according to which category it belonged.

Figure 6.5 uses a decision tree to illustrate the conceptual model for determining earthquake risk. The figure illustrates that for each principal factor there exists multiple sub-factors which can influence it. Similarly, the principal factors in turn have an influence on the earthquake risk, which is the desired outcome. The connecting lines are paths which indicate the relationships between factors, and will be used to mathematically combine all of the factors.

All of the principal factors that were used in the ERAM (shown in Figure 6.5) were obtained from a study that was conducted Davidson and Shah (1997). The subsequent sub-factors were developed by the author as part of this study. Each of the current sub-factors were independently chosen, with the factors that were not implemented stated in section 6.3.5 (and reasons why it was not implemented). Chapter 7 will investigate the relationships between all of the sub-factors that the author identified by issuing a survey.

Table 6.2: Factors identified for the conceptual ERAM model.

Principal Factors	**Sub-Factors**
Seismic Hazard	PGA 500 year return period Soil conditions Liquefaction susceptibility Fire
Building Exposure & Vulnerability	Building age Building storeys Vertical irregularity Plan irregularity Post-code retrofitting Falling hazards Buildings' proximity
Individuals' Exposure & Vulnerability	Population density Percentage of population aged 0-4 or 65+ Per capita GDP
Emergency Response and Recovery Capability	Emergency planning indicator Number of hospitals per 100 000 people Number of doctors per 100 000 people Number of firemen per 100 000 people Distance to nearest hospital Distance to nearest fire station Population density Individuals dependency Access to landline Access to cellphone Access to radio Access to TV

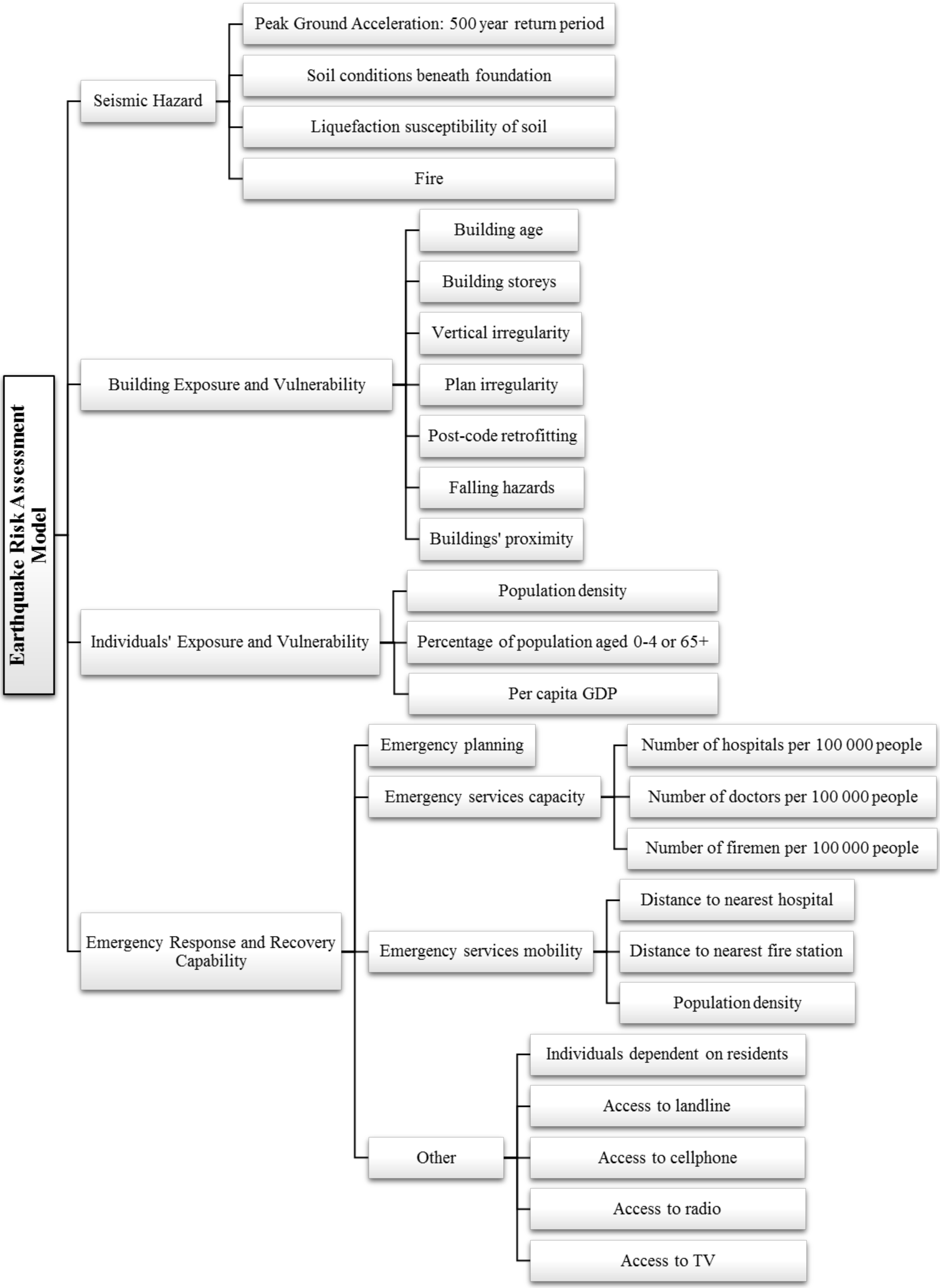

Figure 6.5: Conceptual configuration of ERAM.

Having established the configuration of the model, one can now start to determine the importance of each factor. This is important since it indicates the contribution that each factor makes in a group. Consequently, the following step will discuss the procedure that was followed to determine the importance of each factor.

6.4 Conclusion

Chapter 6 started with a brief discussion regarding some of the general challenges that were faced while developing the ERAM model (section 6.2). This is followed by the actual starting point for the model, the conceptual framework (section 6.3). Four principal factors were identified which contribute to earthquake risk: Seismic Hazard (section 6.3.1), Building Exposure and Vulnerability (section 6.3.2), Individuals' Exposure and Vulnerability Factor (section 6.3.3) and lastly Emergency Response and Recovery Capability (section 6.3.4). For each of these groups subsequent sub-factors were identified, and reasons were supplied why some factors were not chosen. All of the factors from above were compiled together to form the conceptual model, as illustrated in section 6.3.6.

Chapter 7

Factor Importances

7.1 Introduction

The next phase in completing the ERAM model required that the contribution of each factor be determined. This was very important for three reasons. Firstly, it enabled the author to distinguish between the contributions that each factor had to the higher-ranking factor. Secondly, one could now differentiate between the factors that played a significant/insignificant role in determining the earthquake risk. Lastly this was an important component for mathematically combining all of the factors and determining the end result, the earthquake risk.

This study relied on two methods to obtain the factor contributions: previous research (section 7.2) and the use of an industry survey (section 7.3). The first method refers to a study of the existing literature. It was used to gain information that was already available. This was however not the only method to be used. Due to the nature of the study, not all of the information could be obtained using historical research. Other research often had a very different and limited scope, and the availability of the information was restricted. A survey was therefore implemented as a second data gathering method, to fill the gap of missing data. Below follows the results from these two methods.

The results from the survey was discussed (section 7.4) and integrated into what was called the weighted Earthquake Risk Assessment Model which is discussed in section 7.5. The last step to completing the model was developing an indicator for each sub-factor (section 7.6).

7.2 Study of the Literature

The idea of ERAM is not a new one. An increase in disaster risk reduction research over the past 15 years has seen the development of multiple risk assessment methods. By studying this literature the author gained valuable insight into the work of others. Davidson and Shah

(1997) in particular, also identified five principal factors, four of which are used in this study. The fifth factor for External Influences has been omitted from this study, since it could not be defined in the context of the study.

Davidson and Shah (1997) established the importance of factors through the use of a industry survey. It was posted to professionals working in the seismic- and disaster management fields. This information was obtained and utilized (Appendix C) so that the effect of the External Influences factor was removed. After removing the factor, the weights were normalized so that the sum of the weights again produced 100%. The contribution of each principal factor could now be obtained, and are displayed in Figure 7.1.

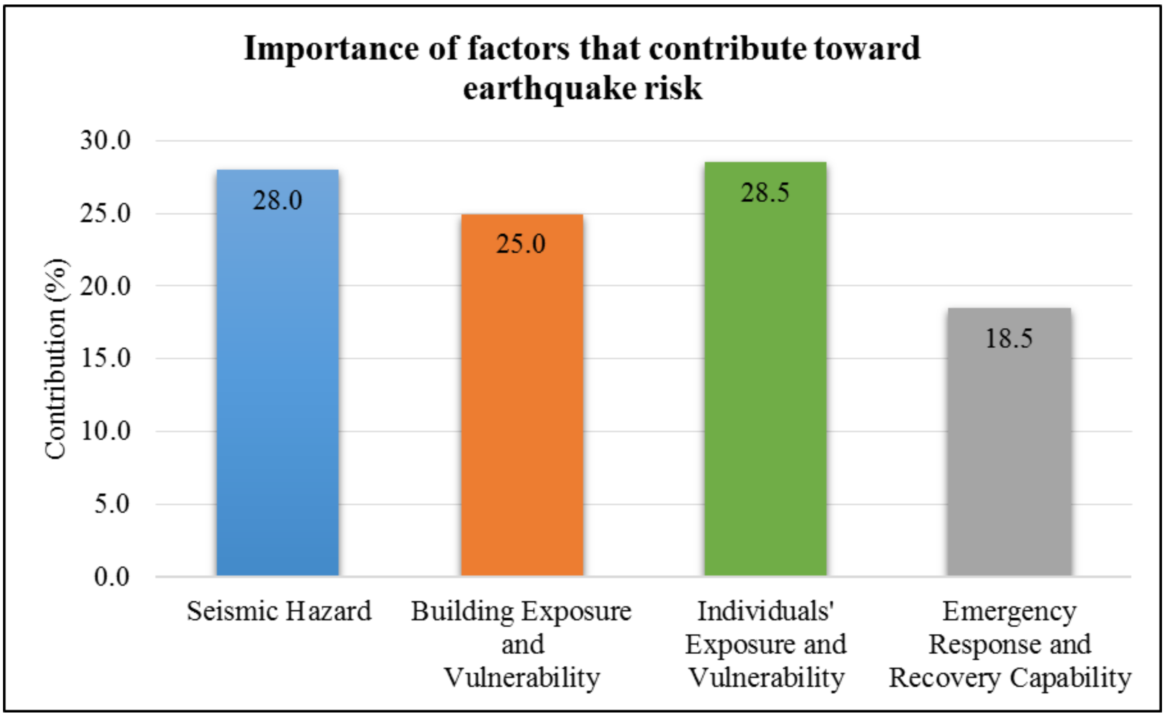

Figure 7.1: Relative importance of each principal factor (Cockburn and Tesfamariam, 2012).

Experts indicated that the Exposure and Vulnerability of Individuals (28.5%) contributed the most towards the overall earthquake risk. This was logical, since the primary aim of the model was to calculate the well-being and safety of the individuals. Secondly, the Seismic Hazard (28%) was identified to be a large threat while the Exposure of the Building (25%) and the Emergency Measures (18.5%) were rated marginally less important. This indicated that experts rated the emergency treatment and recovery process as having a slightly smaller effect when compared to the other principal factors.

7.3 Industry Survey

The problem that arose with defining the factors of ERAM, was that there were in some cases simply no evidence of weights for the factors. This meant that the researcher had no theoretical foundation to distinguish the factor contributions from one another. The use of a survey was therefore chosen as the best solution to fill this knowledge gap. By obtaining the subjective assessments of professionals within the South African disaster management industry, a good estimation could be obtained to distinguish these factors with. The following sections will discuss how the survey was used to attain these importances.

7.3.1 Survey Objectives

The primary aim of the survey was to fill the knowledge gap needed to make the ERAM function. Second to this, one could also use the results of the survey to investigate the interrelationship between the different factors. The questionnaire therefore had to act as a communication means between industry professionals and the researcher; to collect data from participants in a standardized way. Having established the primary and secondary aim of the survey, the researcher identified a number of objectives for completing the survey. The objectives were:

1. Formally introduce the participant to the research, the researcher and the research institution
2. Communicate the purpose of the questionnaire: to establish the importance of a number of identified factors that contribute to earthquake risk
3. Obtain the subjective assessment of each participant's perception on the importance of each factor, compared to the other factors
4. Keep the layout as simplistic and relevant as possible, not to confuse the participant
5. Keep the survey as objective as possible; avoiding any subjective aspects which may influence the results

7.3.2 Survey Content

The questionnaire was designed to facilitate the objective assessment of each factor. In addition to this, the questionnaire objectives provided the guidelines according to which it had to be created. It consisted of a cover page, introduction letter, definitions section, remarks section and lastly the questionnaire itself.

The cover page of the questionnaire was created to give the reader a first glance of what would follow: the title of the research, the research institution, the relevant department or division, and lastly the particulars of the author. This was followed by an introduction letter, introducing the participant to the researcher, his/her research topic, purpose of the questionnaire and details of the researcher and his supervisor. The definitions section was designed to familiarize the participant with the terminology that was used in the questionnaire (and in the study). The remarks section explained how the questionnaire worked, including how to correctly answer it.

After having communicated all of the necessary information, the actual questionnaire followed last. This comprised of a table which grouped together all of the sub-factors, according to their principal factor. The respondent then had to assign a weight between 1 and 10 to each sub-factor, according to how important it was in the group. The most important sub-factor(s) had to be assigned a weight of 10, and all of the other factors had to be scored relative to this score. An example of such a procedure was also attached, to aid the participant if any uncertainty arose. The participant also had the opportunity to identify any factors which may have been omitted from the study, and include this for future reference. The participants were lastly asked to supply their particulars, should they want a copy of the results.

7.3.3 Survey Distribution

The questionnaires were distributed to a selected group of earthquake- and disaster management experts. The input of the professionals were highly regarded since they were well qualified and/or experienced in the field. Eleven participants were sent the questionnaire, a copy of which is included in Appendix D. Figure 7.1 below contains the details of the participants.

Participants with a range of different backgrounds, capabilities and level of involvement (in disaster management) were chosen to take part in the survey. This was done in order to avoid possible bias when completing the questionnaire. It could however be possible that some bias still exists due to participants from the same organization are of the same opinions, and may therefore bias the results. The participants background ranged from academics, state owned services and independent consulting services. One of the participants were of international origin while the rest were all of South African origin.

Table 7.1: Details of survey participants and fields of involvement within disaster management

Participant	Occupation	Organization	Involvement in Disaster Management	Origin	Survey Returned
1	Director	University of Cape Town	Disaster management research	South African	Yes
2	Full time researcher	University of Cape Town	Disaster risk researcher	South African	Yes
3	Technical director	Aurecon Group	Disaster management assessments and projects	South African	No
4	Senior risk management consultant	Aurecon Group	Risk and resilience management	South African	No
5	Project officer	CT Disaster Management Centre	Disaster officer: projects	South African	Yes
6	Manager	West Coast Disaster Management	Disaster and risk management	South African	No
7	Senior disaster officer	Overstrand Disaster Management	Senior disaster officer	South African	No
8	Manager	Disaster Management Solutions	Disaster risk manager	South African	No
9	Disaster management director	Western Cape Government	Facilitate disaster management and fire brigade services	South African	No
10	Professor at Faculty of Civil Engineering	University of Algiers, Algeria	Disaster management courses	International	Yes
11	Deputy director	CT Disaster Management Centre	Disaster risk reduction	South African	No

7.3.4 Survey Feedback

During a sixteen week period, four of eleven questionnaires were returned from the industry professionals. This represented a response rate of 36%. This was a low response rate, considering that it is generally accepted that a response rate of 60% represents adequate feedback for a survey (Richardson, 2005). The low response rate for the survey could be due many reasons. The most likely reasons were identified to be:

1. Participant never received questionnaire
2. Participant received questionnaire, but did not find it important
3. Lack of an incentive demotivated participation
4. Participant uncomfortable with questionnaire; questions out of field of knowledge
5. Participants were too busy
6. Participant did not understand questionnaire and failed to complete it
7. Any combination of the above mentioned reasons

The number of questionnaires returned certainly plays a large role in in the results of a data analysis. The more feedback, the higher the accuracy of the data analysis, and less chance of biased data. Similarly, little feedback can lead to inaccurate data which is biased. From this description one would think that the survey feedback for this study would tend to be inaccurate and/or biased. This was however not found to be the case. It was found (in later discussions) in the correspondence that the professionals provided, to a great extent, showed a large consensus amongst them on the importance of the factors. This consensus therefore provided a mechanism by which to prove that the data was sufficiently accurate and relatively free of bias.

Table 7.2 summarizes responses for the survey. As requested, each participant completed the questionnaire by rating the importance of each factor. Two statistical parameters were then used to describe the survey ratings with, namely the arithmetic mean (or average) and standard deviation. The average score ($\bar{x}$) for each factor was then calculated (Montgomery and Runger, 2010):

$$\bar{x} = \frac{\sum\limits_{i=1}^{N} x_i}{N} \tag{7.3.1}$$

The standard deviation (σ) was calculated:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{7.3.2}$$

The standard deviation measures the dispersion of a set of data from its mean. The more the spread of the data, the higher the deviation. Similarly, the lower the spread of the data, the lower the dispersion of data. The standard deviation of each data set was calculated to give the researcher an idea of how far the typical values were from the mean of the data set. Table 7.2 shows that the standard deviation for all of the factors ranged between 0 and 1.58. This means that for some factors the industry professionals completely agreed on the score for a factor, whereas for other factors the spread of data about the mean was 1.58. This spread was significant, however seemed to suggest that the industry professionals could not precisely agree on the influence of the factor. The following section discusses the survey results. Each group of sub-factors is discussed separately, identifying the most important and least important factor(s), the spread of the data and importance of the other factors.

Table 7.2: Summary of survey data, as obtained from industry professionals.

Principal Factors	**Sub-Factors**	**Respondents**				**Average**	**Standard Deviation**
		1	**2**	**3**	**4**		
Seismic Hazard	PGA 500 year return period	10	10	10	10	10	0.00
	Soil conditions	5.5	3	4.5	6	4.75	1.15
	Liquefaction susceptibility	6	5	5	6	5.5	0.50
	Fire	4	4	6	5	4.75	0.83
Building Exposure & Vulnerability	Building age	8	7	7	8	7.5	0.50
	Building storeys	9	10	10	10	9.75	0.43
	Vertical irregularity	6	7	6	6	6.25	0.43
	Plan irregularity	5.5	6	5	5	5.375	0.41
	Post-code retrofitting	10	10	9	9	9.5	0.50
	Falling hazards	6	5	3.5	5	4.875	0.89
	Buildings' proximity	4	6	5	3.5	4.625	0.96
Individuals' Exposure & Vulnerability	Population density	10	10	10	10	10	0.00
	Percentage of population aged 0-4 or 65+	9	8	9	9	8.75	0.43
	Per capita GDP	7	6	7	8	7	0.71
Emergency Response and Recovery Capability	Emergency Planning indicator	9	8	8	8	8.25	0.43
	Number of hospitals per 100 000 people	10	10	10	10	10	0.00
	Number of doctors per 100 000 people	9	10	10	10	9.75	0.43
	Number of firemen per 100 000 people	9	8	9	9	8.75	0.43
	Distance to nearest hospital	6	9	5	7	6.75	1.48
	Distance to nearest fire station	6	9	5	7	6.75	1.48
	Population density	5	7	8	4	6	1.58
	Individuals dependency	5	4	7	3.5	4.875	1.34
	Access to landline	2.5	3	6	5	4.125	1.43
	Access to cellphone	2.5	3	6	5	4.125	1.43
	Access to radio	4	2	4.5	4	3.625	0.96
	Access to TV	4	2	4.5	4	3.625	0.96

7.3.5 Survey Results

7.3.5.1 Seismic Hazard Results

Figure 7.2 illustrates the importance of the factors as it was rated by the industry professionals. As expected the Peak Ground Acceleration factors for the 500 year return period had the highest importance (40.0%), whereas the factors for Fire (19.0%), Soil Conditions (19.0%) and Soil Liquefaction Susceptibility (22.0%) were determined to have only a minor influence. It should noted that these values were all normalized, and amount to 100%.

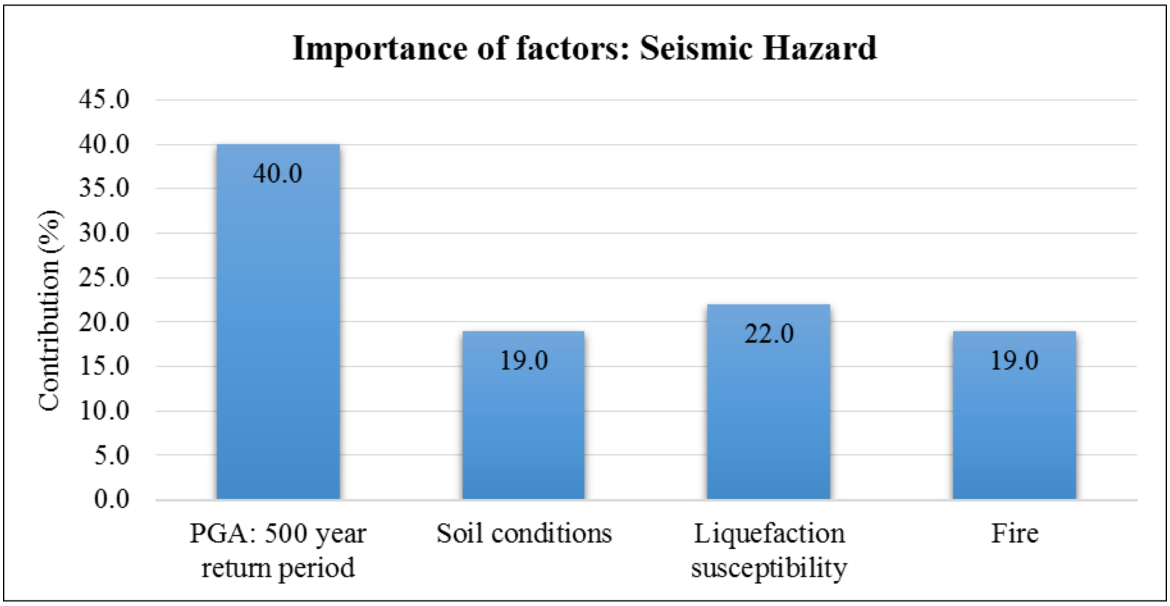

Figure 7.2: Importance of the Seismic Hazard factors, as determined by industry professionals.

Concerning the spread of data, or standard deviation, the professionals seemed to all agree on the importance of most factors. Here $\sigma \leq 1.0$ represented an acceptable spread of data (10%), and $\sigma = 2.0$ a wide spread (20%). The professionals seemed to show agreement towards the importance allocated to the Peak Ground Acceleration-, Soil Liquefaction- and Fire factors. They did show some slight differing opinion about the Soil Conditions factor ($\sigma = 1.15$). The differing importance ratings were inevitable, since the questionnaire conveyed the subjective assessments of different individuals working in the disaster management field.

7.3.5.2 Building Exposure and Vulnerability

Figure 7.3 illustrates the importance of factors for the Building Exposure and Vulnerability factor. It consists of 7 different sub-factors. The Building Storeys (20.4%) factor was established to have the largest effect. This came as no surprise, since the ATC (2009) outlined this as one of the components that contributes to damage in unreinforced masonry buildings. It states that the height of a building is related to the amount of damage it may sustain. Consequently, the higher the building is, the larger the potential for earthquake induced damage. Post-Seismic Code Retrofitting (19.8%) was rated to also have a significant influence. When reinforcing an existing building, the buildings' structural behaviour is altered to withstand the seismic forces. The possibility of damage to the building then greatly decreases, lowering the risk of any injuries the residents can sustain.

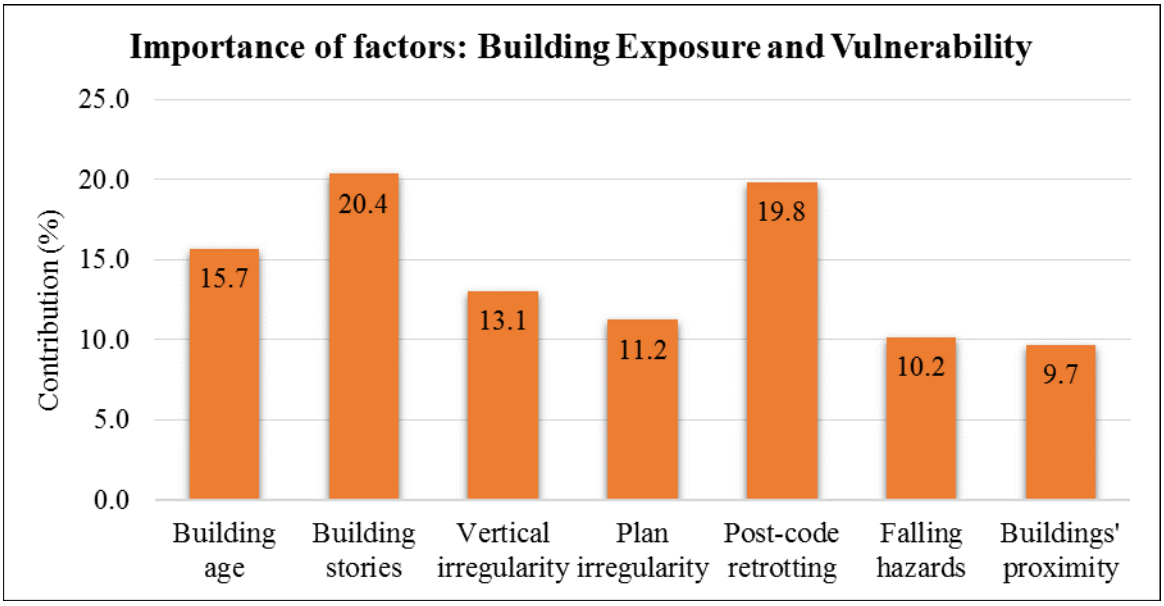

Figure 7.3: Importance of the Building Exposure and Vulnerability factors, as determined by industry professionals.

In contrast to that which were mentioned above, the Buildings' Proximity- (9.7%) and Falling Hazard (10.2%) factors were rated to be the least important. These two factors are dependant on the structural integrity of the building and whether the building actually featured any of these components (chimneys, cladding etc.). If, for example, an unreinforced masonry building proved to show little out-of-plane behaviour during excitation, the chance of a load bearing wall collapsing would be small. This in turn could also have an effect on elements such as the building cladding and chimneys, or other buildings that are in close proximity. This is possible, though not very common. This is why these two factors were chosen to have the least importance.

The ratings supplied by industry participants showed very little variation. The standard deviation for factors ranged from 0.41 to 0.96, with $\sigma \leq 1.0$. This seemed to confirm that a consensus exists among the professionals on the importance of each of these factors.

7.3.5.3 Individuals’ Exposure and Vulnerability

Figure 7.4 depicts the factor importances for the Individuals’ Exposure and Vulnerability factor. The Population Density (38.8%) was identified to contribute the most to the Individuals’ Exposure and Vulnerability group. Second was the proportion of the residents which belonged to a vulnerable group (persons aged 0-4 or 65+ years), with 34.0% contribution. The income per person (Per Capita GDP factor, 27.2%) was rated to have the smallest contribution of the three factors.

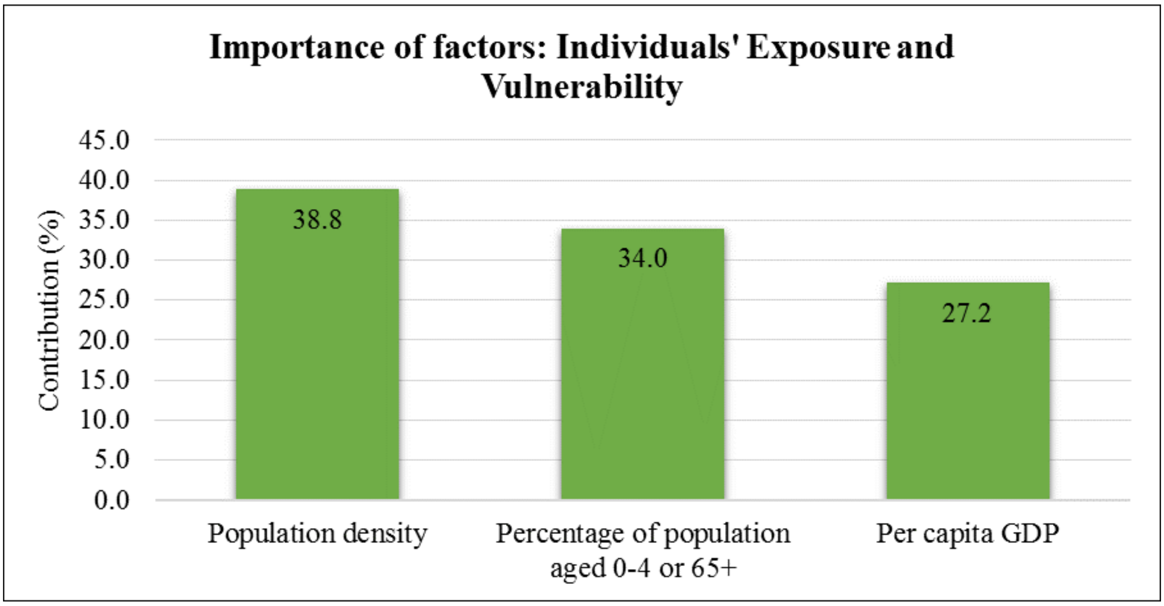

Figure 7.4: Importance of the Individuals’ Exposure and Vulnerability factors, as determined by industry professionals.

The disaster management professionals also reached a consensus with the factor ratings. The Population Density was scored to be the most influential ($\sigma = 0$), whereas the Vulnerable Groups- ($\sigma = 0.43$) and Income Per Person factors ($\sigma = 0.71$) showed some differing opinion. This was however, still within a 10% margin ($\sigma = 1.0$).

Put in perspective, this result showed that the exposure of the residents during an earthquake, mattered the most. This was illustrated by the high ratings for the Population Density- and Proportion of Vulnerable Residents factors. In contrast to this, the Income Per Person factor (which was a recovery indicator) showed that the income of a person seemed like a less important attribute when considering the well-being of the building residents.

7.3.5.4 Emergency Response and Recovery Capability

The Emergency Response and Recovery Capability factor consisted of various sub-factors, to which experts had differing opinions. The Number of Hospitals factor (13.1%) was rated the most important, with the Number of Doctors- and Firemen factors (12.7% and 11.4%) rated second and third. Factors with the lowest ratings included Access to Radio/TV (4.7%) and Access to Landline Telephone/Cellphone (5.4%).

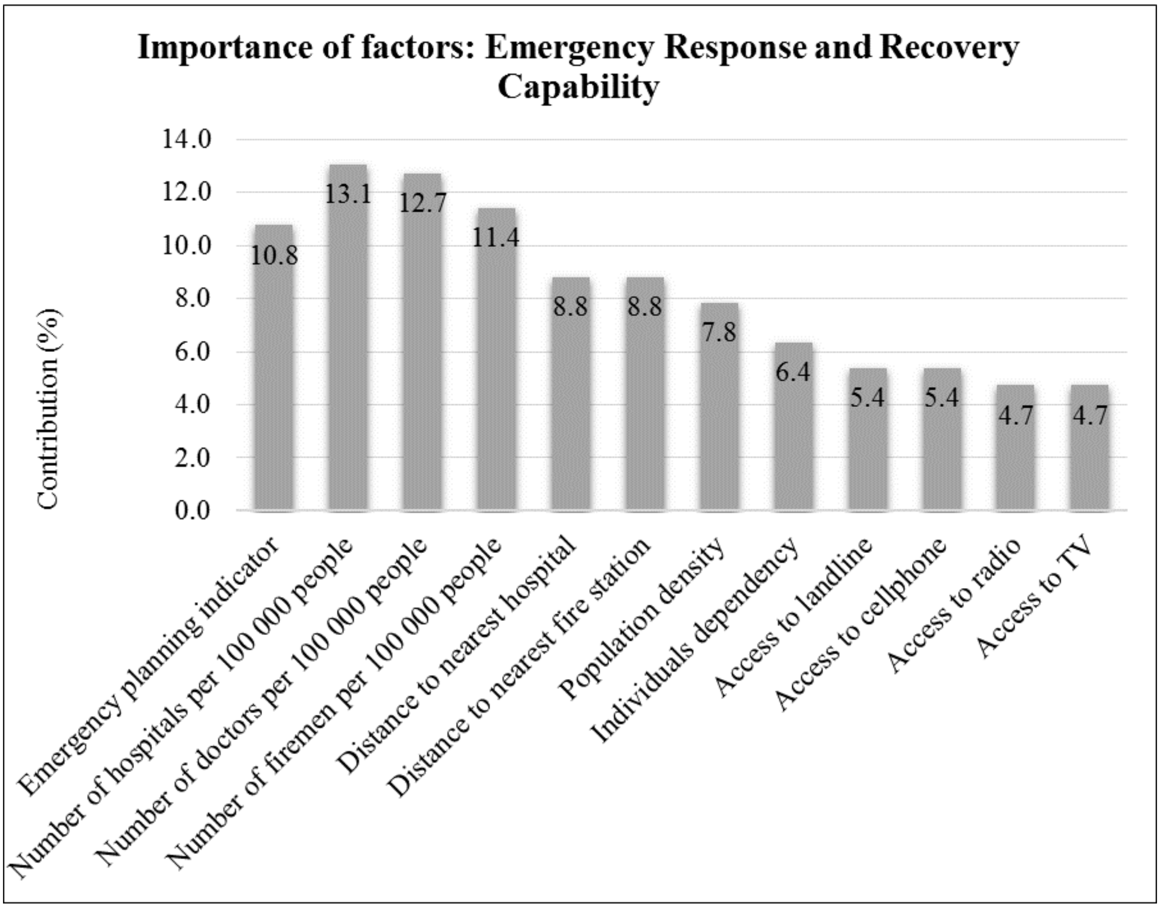

Figure 7.5: Importance of the Emergency Response and Recovery Capability factors, as determined by industry professionals.

The professionals did however differ in opinion on the importance of some of these factors (see Table 7.2). The factors that showed some form of variation were:

- Distance to Nearest Hospital ($\sigma = 1.48$)
- Distance to Nearest Fire Station ($\sigma = 1.48$)
- Population Density ($\sigma = 1.58$)
- Individuals Dependency ($\sigma = 1.34$)
- Access to Landline Telephone/Cellphone ($\sigma = 1.43$)

An interesting observation from this result was that the factors which had to to with the short term emergency relief were rated higher than the factors which had to do with the medium- to long term recovery capability of the residents. It can therefore be deducted from this result that the short term relief measures (number of hospitals-, doctors- or firemen, distance to hospital or fire station) play a bigger role in the well-being and recovery of the residents. This might have something to do with the fact that humans tend to discount hazards and consequences that are further into the future.

7.3.5.5 Overall Importances

After finding all of the relationships amongst the sub-factors, the next step was to mathematically combine the weightings of the principal- and sub-factors. This was done to compare the contribution of each sub-factor in the whole model. This combination is important for two reasons: 1. each factor's contribution can now be compared globally, that is to say, compared to sub-factors from other principal factor groups, and 2. the most and least important factors of the ERAM model could now be identified.

Table 7.3 contains the overall importance of each sub-factor. This was obtained by multiplying the principal factor weight with the weight of the sub-factor, as given by Equation 7.3.3.

$$\text{Overall Importance} = \text{Principal Factor Weight} \times \text{Sub-Factor Weight} \tag{7.3.3}$$

The overall importance unit is a percentage of the total contribution to the ERAM model. Therefore all of the contributions from all of the factors amount to 100%. Figure 7.3 illustrates these importances (as in Table 7.3) as per principal factor group.

From Table 7.3 and Figure 7.7 it is clear that there are five factors which have the largest influence in the ERAM model. These are the Peak Ground Acceleration for a 500 year return period, Liquefaction susceptibility of a building, Population Density, Percentage of Vulnerable Group Population and Per Capita GDP of each individual. In Figure 7.7 they

Table 7.3: Overall importance of each sub-factor in ERAM

Principal Factors	**Sub-Factors**	**Weight Name**	**Weight Value**
Seismic Hazard	PGA: 500 year return period	W_{S1}	11.20*
	Soil conditions	W_{S2}	5.32
	Liquefaction susceptibility	W_{S3}	6.16*
	Fire	W_{S4}	5.32
Building Exposure & Vulnerability	Building age	W_{B1}	3.93
	Building storeys	W_{B2}	5.10
	Vertical irregularity	W_{B3}	3.28
	Plan irregularity	W_{B4}	2.80
	Post-code retrofitting	W_{B5}	4.95
	Falling hazards	W_{B6}	2.55
	Buildings' proximity	W_{B7}	2.43
Individuals' Exposure & Vulnerability	Population density	W_{I1}	11.06*
	% of population aged 0-4 or 65+	W_{I2}	9.69*
	Per capita GDP	W_{I3}	7.75*
Emergency Response and Recovery Capability	Emergency planning indicator	W_{E1}	2.00
	Num. of hospitals per 100 000 people	W_{E2}	2.42
	Num. of doctors per 100 000 people	W_{E3}	2.35
	Num. of firemen per 100 000 people	W_{E4}	2.11
	Distance to nearest hospital	W_{E5}	1.63
	Distance to nearest fire station	W_{E6}	1.63
	Population density	W_{E7}	1.44
	Individuals dependency	W_{E8}	1.18
	Access to landline	W_{E9}	1.00
	Access to cellphone	W_{E10}	1.00
	Access to radio	W_{E11}	0.87
	Access to TV	W_{E12}	0.87
	Total		**100**

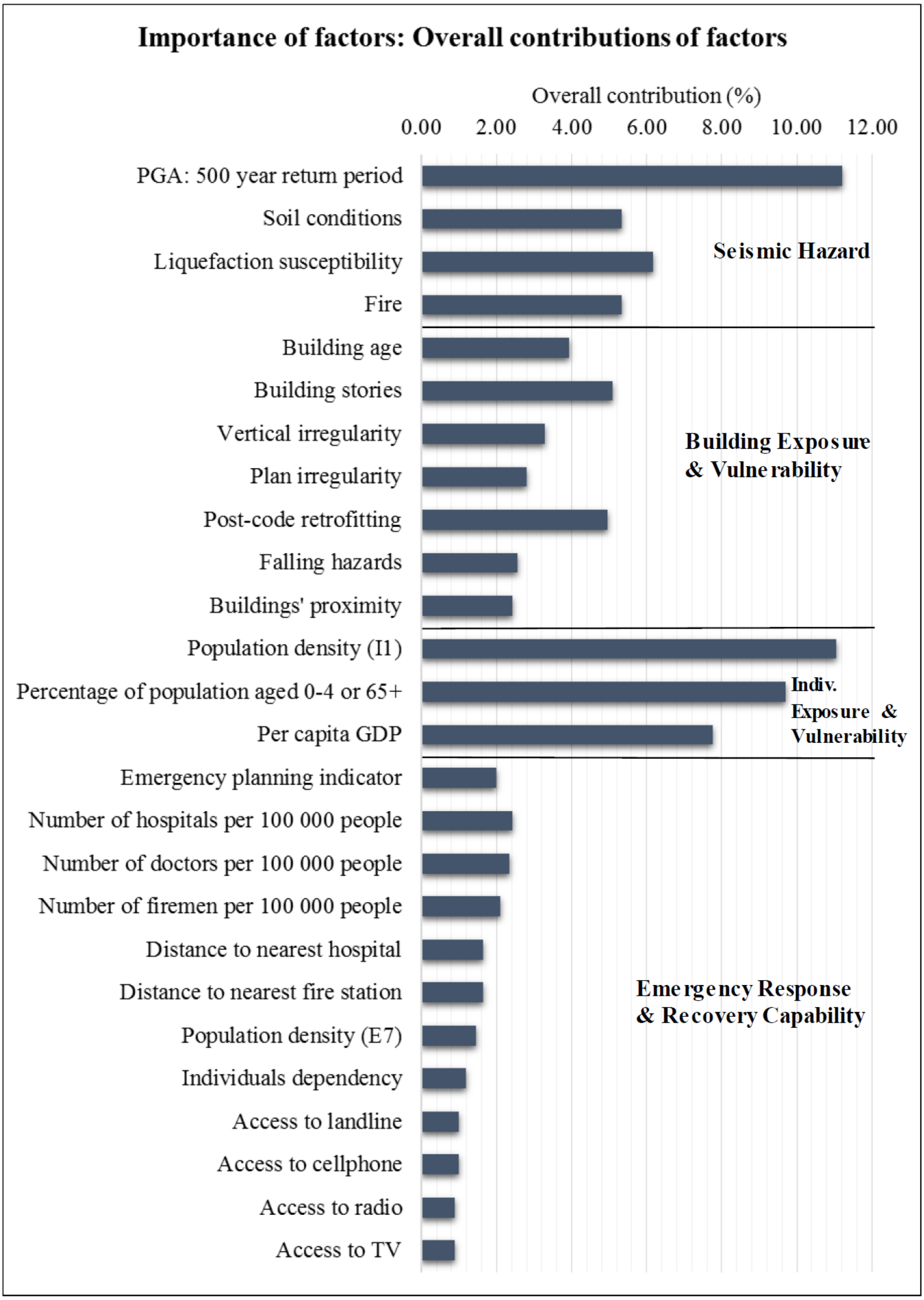

Figure 7.6: Overall importance of each sub-factor in ERAM

are indicated with an asterisk symbol (*). Together these five factors comprise 45.86% of the ERAM model. They therefore have a big effect on the outcome of the model, controlling to a large extent the outcome of the model. The other 21 factors make up the other 54.14%.

In contrast to this, the Individuals' Dependency, Access to Landline Telephone, -Cellphone, -Radio and -Television factors were identified to be the least contributing factors. Together they were determined to contribute 4.9% to the model. This is a very small effect, and will have a very minor effect on the outcome of the model. These are also the factors with the least agreement between respondents of the survey. This means that the lack of agreement is of little importance.

The following section discusses the survey shortcomings and recommendations that were highlighted by the industry professionals. It states all of the comments that the participants made, which will help to improve future surveys of this type.

7.3.5.6 Shortcomings in Survey

The questionnaire provided an opportunity where the participants could recommend any additions/changes to the questionnaire. One specific participant suggested the following:

> *"In my point of view, the weight cannot be just a number, as it depends strongly on the various conditions, as for instance, for the soil conditions, it depends on whether the soil is a rock, firm or alluvions (site effect), etc. It is important to take into account in the analysis of several scenarios."*

This comment was certainly true. Assigning a value to a condition does not always accurately describe the full extent of the state/condition of a parameter (as discussed in section 5.2.4). It is however the only, and best way up to date to approach this issue. It was stated in the methodology that with this decision, one would have to to endure the consequences of using a quantitative model.

The questionnaire was also scrutinized for:

> *"...the predominant conditions of the materials as well as bracing are important, and could have been included."*

This referred to the construction material a building comprised of and structural characteristics such as lateral bracing. The aim of this specific study was to prioritize the strengthening of unreinforced masonry buildings. Here the material and structural configuration were common between all of the buildings. One could therefore not prioritize the risk of buildings according to their structural configuration or based on their construction materials.

Another comment was:

> *"Horizontal and vertical wall linkages (chaining) should have been included to avoid off plan collapse."*

This comment was out of the scope of the study. The main idea behind the research was to develop a procedure where the influence of a number of different influential parameters (on a masonry building) were to be evaluated on a holistic level. Buildings with higher combined ratings, were seen to be more risk prone than other (lower rated) buildings. These buildings were then identified for seismic improvements (retrofitting). This comment was aimed at particular details and would certainly be included in an in depth structural study of these buildings.

Overall the comments received from the survey participants were useful and relevant. These comments are however also discussed throughout the model development process (sections 5.2.4 and refscopelimitations).

7.4 Interpretation of Survey Results

The results of the survey may have far reaching, beneficial findings for disaster management research. The industry survey not only provided information which was useful for this study, but also for any future research which is relevant to the work conducted here. Table 7.4 shows the ranked importances of each factor, as it was determined above. Figure 7.7 gives a better illustration of the weight of each factor, with the results ranked from highest to lowest weighted factors.

It has come to light that the following factors contribute the most to the earthquake risk of individuals. They are, in order of importance:

1. Peak ground acceleration of for earthquake with a return period of 500 years (11.2%)
2. Population density of building (11.1%)
3. Percentage of vulnerable population groups (9.7%)
4. Per capita GDP income of individuals (7.75%)
5. Liquefaction susceptibility of a building (6.16%)

As mentioned before, the contributions of these seven factors collectively comprise 45.86% of the ERAM model. They are therefore not only the most influential factors for decision

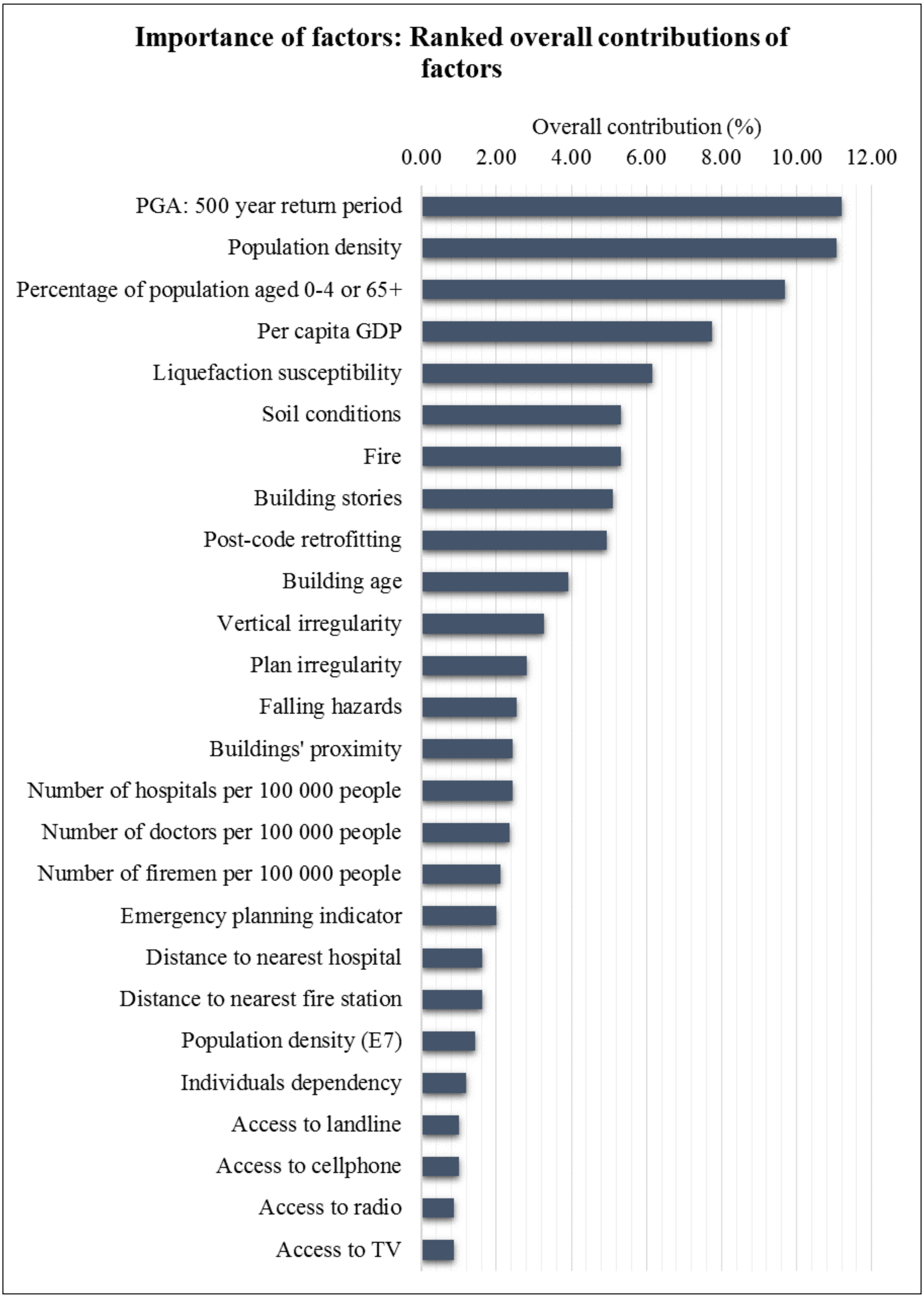

Figure 7.7: Ranked overall contribution of each factor

Table 7.4: Ranked overall contribution of each factor

Sub-Factors	**Weight Name**	**Weight Value**
PGA: 500 year return period	W_{S2}	11.20
Population density	W_{I1}	11.06
Percentage of population aged 0-4 or 65+	W_{I2}	9.69
Per capita GDP	W_{I3}	7.75
Liquefaction susceptibility	W_{S4}	6.16
Soil conditions	W_{S3}	5.32
Fire	W_{S5}	5.32
Building stories	W_{B2}	5.10
Post-code retrofitting	W_{B5}	4.95
Building age	W_{B1}	3.93
Vertical irregularity	W_{B3}	3.28
Plan irregularity	W_{B4}	2.80
Falling hazards	W_{B6}	2.55
Buildings' proximity	W_{B7}	2.43
Number of hospitals per 100 000 people	W_{E2}	2.42
Number of doctors per 100 000 people	W_{E3}	2.35
Number of firemen per 100 000 people	W_{E4}	2.11
Emergency planning indicator	W_{E1}	2.00
Distance to nearest hospital	W_{E5}	1.63
Distance to nearest fire station	W_{E6}	1.63
Population density	W_{E7}	1.44
Individuals dependency	W_{E8}	1.18
Access to landline	W_{E9}	1.00
Access to cellphone	W_{E10}	1.00
Access to radio	W_{E11}	0.87
Access to TV	W_{E12}	0.87
Total		**100.00**

making, but also the factors which (when combined) govern the outcome of the ERAM model to a large extent.

To put it differently, these five factors (which represent 19% of all the factors) together influence 45.86% of the outcome of the ERAM model. They could therefore be described as the group of factors which governs the outcome of the model. The other 21 factors (81% of factors) only influence 54.14% of the model outcome. In theory therefore, if the influence of these factors were reduced or removed, it will greatly affect the safety of an individual living in a multi-storey, unreinforced masonry building. This is in reality however, not always the case. Humans often have very little or even no control over these influences. An example of this is the peak ground acceleration for a 500 year (probabilistically expected) earthquake, for which no mechanism currently exists by which to control, reduce or even predict the severity of such an earthquake.

It is also worthy to note at this point that there seems to be a tendency where factors, which have an immediate effect during an earthquake, were rated a higher score. This was supported by the high ratings of the Population Density-, Percentage Vulnerable Groups-, 500 year PGA factors. These factors all resemble the number of people in a building, the composition (how many vulnerable residents) and the intensity of the ground movement.

On the other hand, factors which had to do with medium- to long term recovery process were rated a lower score. The number of hospitals, doctors or firemen were rated to be the 16^{th}, 17^{th} and 18^{th} important factors (out of 27). This is not rated very high, and seems to support this reasoning. One can therefore argue that experts regard the short term effects of an earthquake (to play a larger role in the well-being of an individual) more important than the medium- to long term effects, which influences the recovery rate of individuals.

Lastly, the factors which have the least potential for influence was determined to be (in descending order):

1. Number of individuals dependent on residents (1.2%)
2. Access to landline telephone (1.0%)
3. Access to cellphone (1.0%)
4. Access to radio (0.9%)
5. Access to television (0.9%)

Most of these factors have to do with either the recovery capability in the medium- to long term or a communication means which informs the individuals. These factors together have a 4.9% influence on the model, which is relatively small compared to the importance of other factors. Interestingly, emergency response and recovery capability is rated to play a relatively small role when compared to other principal factors. It could be possible that experts view the short term effect of earthquakes as having the biggest impact, and the emergency response and recovery capability as being less important. Put this another way: the experts view is that that most of the injuries/losses are expected to occur during the ground movement of the earthquake. They expect very little casualties after the earthquake. This added extra weight to the preventative measures discussed earlier. It certainly sounds logical, however one should remember that without the assistance of emergency services, the number of injuries/casualties would be much higher. The emergency response and recovery capability factor still comprises 18.5% of all the principal factors, and should not be neglected for its small (but still meaningful) contribution.

It is also interesting to that the factors which were scored the least, were the factors of which the experts opinions seemed to differ. This indicated that although the opinions that differed did not matter since their contribution was small compared to other factors. It may also imply a lack of understanding the significance of the factors.

7.5 Weighted Earthquake Risk Assessment Model

Finally, after obtaining all the necessary weightings and establishing the quantitative relationship between factors, the weighted ERAM model was developed. Figure 7.8 displays the weighted ERAM model. The model is the same as it was defined in section 6.3.6, except that now each factor was assigned an importance (weight).

In the figure, the importance for the sub-factors were all assigned to the left of the sub-factor label. The weights for a set of sub-factors all amount to one. Similarly, the importance of each principal factor can be found below the principal factor label. The weights of all four principal factors also amount to one.

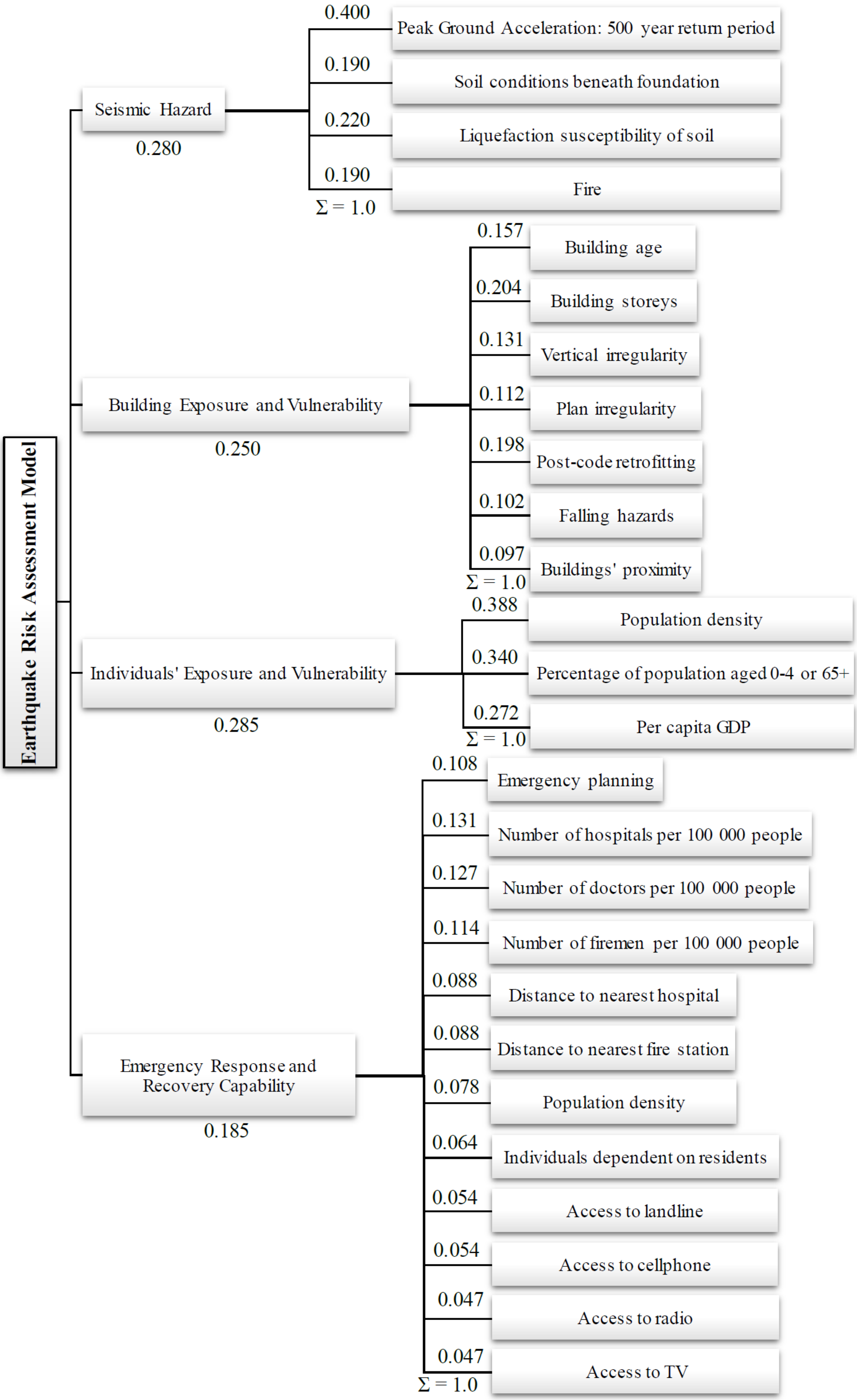

Figure 7.8: Weighted Earthquake Risk Assessment Model

The last step in configuring the model comprises of selecting the risk rating scales. Here each sub-factor has to be assigned a risk rating scale that measures the state/condition of it. The following section discusses the scales and the reasoning it was based on.

7.6 Indicator Development

An indicator is an instrument that is used to measure the current state (or condition) of something in the real world. This measurement is made on a risk scale which was developed for each indicator. This quantitative measurement is then used in the ERAM model to determine the overall earthquake risk rating of a masonry building (by using mathematical combinations mentioned in section 5.3.7). Refer back to Figure 5.3 for an illustration of the principal factors, sub-factors and indicators.

Risk scales were developed for each indicator to indicate the risk level. The indicator score for each indicator ranged between 0 and 1. These scores were assigned through three possible methods: linear scaling, census data or boolean arguments. Linear scaling comprised of the indicator scores which increased incrementally and formed uniform categories of risk. Census data could be inserted, as long as it was normalized to a maximum possible score of 1. Boolean arguments represented “Yes/No”. A “Yes” answer was awarded an indicator score of 1 and “No” answer was awarded a 0 score.

It is very important at this stage to note the reasoning behind assigning indicator scores. The ERAM model was created to prioritize the earthquake risk of multi-storey buildings. The model therefore had to compare buildings of similar nature. The scores that were developed for each indicator is therefore a relative and comparative measure. This is best explained at the hand of an example.

Building A has 2 storeys and building B has 3 storeys. As mentioned earlier, the aim of the ERAM model is to prioritize these buildings according to their earthquake risk. The earthquake risk of building B is higher than building A, due to literature discussed earlier. It can therefore be said building B has a relatively higher earthquake risk to building A. Here the indicator scores does not matter as much, as long as the indicator score of building B is higher than building A (relative scale).

As mentioned above, indicator values can range between 0 and 1 depending on the risk scale that is used. A value of one represents the maximum value whereas zero represents the lowest value. It was reasoned that a higher score would indicate a higher probability of damage and injury to an individual living in a building and a lower score would indicate a lower probability of harm. The risk of harm or loss to an individual is therefore higher in a building with a higher indicator score. This thought process formed the basis of the indicator scoring approach and is used from here on further in the document.

The development of indicators in this study represented the probability or likelihood of an event occurring. The probability of this event is however not described in absolute probabilistic terms, but rather risk rating scores. These risk scores were only constructed in order to compare different situations with one another.

The risk scores that were assigned to each indicator thus did not represent a probability but rather a comparative score. The indicators were developed by the author and was intended to represent a relative scoring mechanism rather than an absolute value.

The indicator scores are represented by the symbol x_{ij} where i represents principal factor abbreviation and j the sub-factor number. The sections below describe the methods that were used to develop the indicator scoring scales.

7.6.1 Seismic Hazard

7.6.1.1 PGA 500 year return period

The Peak Ground Acceleration factor represents the magnitude of the expected ground acceleration of an earthquake. A Probabilistic Seismic Hazard Assessment (PSHA) estimates (and maps) the probable ground acceleration values at different geographical regions. In South Africa the Council for Geoscience publishes this information. The indicator score for this sub-factor was calculated according to equation 7.6.1:

$$x_{S1} = \frac{\text{PGA 500 year return period (m/s}^2\text{)}}{\text{Maximum PGA for region (m/s}^2\text{)}} \tag{7.6.1}$$

In equation 7.6.1, “PGA 500 year return period” represents the 500 year PGA value for the location where a building is located (in m/s^2). The bottom term represents the maximum PGA value that was determined by a PSHA for the region. The rating of the indicator can be best explained with the use of an example.

Consider a building located at a certain location with an expected 500 year PGA of 0.19g (where g = 9.81 m/s^2). The maximum probable acceleration at the location was determined to be 0.29g. This value was obtained from a PGA versus return period graph, which is determined by a PSHA. The indicator score for this sub-factor will therefore be equal to 0.66 (out of a possible 1).

Table 7.5: Indicator symbols

Principal Factors	Sub-Factors	Indicator Symbol
Seismic Hazard	PGA: 500 year return period	x_{S1}
	Soil conditions	x_{S2}
	Liquefaction susceptibility	x_{S3}
	Fire	x_{S4}
Building Exposure & Vulnerability	Building age	x_{B1}
	Building stories	x_{B2}
	Vertical irregularity	x_{B3}
	Plan irregularity	x_{B4}
	Post-code retrofitting	x_{B5}
	Falling hazards	x_{B6}
	Buildings' proximity	x_{B7}
Individuals' Exposure & Vulnerability	Population density	x_{I1}
	Percentage of population aged 0-4 or 65+	x_{I2}
	Per capita GDP	x_{I3}
Emergency Response & Recovery Capability	Emergency planning indicator	x_{E1}
	Number of hospitals per 100 000 people	x_{E2}
	Number of doctors per 100 000 people	x_{E3}
	Number of firemen per 100 000 people	x_{E4}
	Distance to nearest hospital	x_{E5}
	Distance to nearest fire station	x_{E6}
	Population density	x_{E7}
	Individuals dependency	x_{E8}
	Access to landline	x_{E9}
	Access to cellphone	x_{E10}
	Access to radio	x_{E11}
	Access to TV	x_{E12}

7.6.1.2 Soil Conditions Beneath Foundation

The indicator scores for this sub-factor was based on the ground condition values from SANS 10160 Part 4 (2009). Table 7.6 illustrates the corresponding indicator score for each ground type, as it was determined in the SANS 10160 Part 4 (2009) documentation. The indicator values are based on the normalized acceleration values of each ground type, and there is therefore a lower bound of 0.76 as it appears in SANS 10160 Part 4 (2009).

Table 7.7 below describes each ground type and the associated parameters that are used to classify it. A general stratigraphic description is given of each ground type and the characteristics of each ground type for the Standard Penetration Test (N_{SPT}).

Table 7.6: Indicator score for each ground type

SANS 10160-4 Ground Types	Indicator Score
4	1
3	0.88
2	0.91
1	0.76

Table 7.7: Description of each ground type and parameters (SANS 10160 Part 4, 2009)

Ground Type	Description	Parameter N_{SPT} (blows/30cm)
1	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	-
2	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterized by a gradual increase of mechanical properties with depth	>50
3	Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters	15 - 50
4	Deposits of loose-to-medium cohesion-less soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	<15

7.6.1.3 Liquefaction Susceptibility of Soil

The liquefaction susceptibility of soil is a complex subject. There are many variables that contribute to the effect, and for the case of simplicity it was decided to use the classifications as set out by Youd and Perkins (1978). These classifications can be found in Table E.1 in Appendix E.1.

Table 7.8: Risk categories and indicator scores for soil liquefaction susceptibility factor

Soil Categories	Indicator Score
None	0
Very low	0.2
Low	0.4
Moderate	0.6
High	0.8
Very high	1

The first step is to start with Table E.1 and identify the indicator category. With the liquefaction category established, one can now refer to Table 7.8 to obtain the indicator score. The indicator score will then be used for earthquake risk calculations (in the ERAM model).

The indicator scores were chosen according to a linear scale, increasing in uniform increments. Six risk categories were developed. It is important to remember that the indicator scores were a relative measure, not absolute. The indicator score therefore did not matter greatly, as long as it represented the risk level relative to that of other buildings.

7.6.1.4 Fire

This factor represent the fire hazard that can occur during an earthquake. The indicator is based on statistical data, which can be obtained from the most recent census survey. It measures the proportion of individuals that use fuel other than electricity (gas, paraffin, wood, coal etc.) to generate light, heat or for cooking. Table 7.9 displays the indicator selection categories, the different classification groups (obtained from census data) and lastly the score which is assigned to each indicator category (used in ERAM).

Six uniform risk categories were chosen to represent different levels of fire risk. The process would start with obtaining the percentage of alternative energy sources that residents use from census data. This information was then used to classify the building into a category in Table 7.9. The score for the indicator could now be obtained depending on the category.

Table 7.9: Selection categories and indicator scores for fire after an earthquake

Alternative Energy Sources (%)	**Indicator Score**
0	0
1 - 20	0.2
21 - 40	0.4
41 - 60	0.6
61 - 80	0.8
81 - 100	1

7.6.2 Building Exposure and Vulnerability

The indicator scores for this group can mostly be established by visual inspection, with exception for the building age. Here follows the details of the scoring that was used for each indicator.

7.6.2.1 Building Age

As already mentioned before, the age of a building plays a very important role in its structural behaviour and performance. Five age categories were developed to score the building age with. Table 7.10 shows the age categories with the score allocated to each category. The age categories starts with a 0 to 19 year group. It is assumed that buildings in this category are structurally safe because it was built after the introduction of the SABS 0160. From this value a building's score increases uniformly until 50 years of age, when it reaches a maximum score of 1.

Table 7.10: Building age categories and indicator scores

Building Age (Years)	Indicator Score
0 - 19	0.2
20 - 29	0.4
30 - 39	0.6
40 - 49	0.8
50 +	1

7.6.2.2 Building Storeys

It has been proven earlier that the taller a building, the more damage it may sustain during an earthquake (section 6.3.2.2). Table 7.11 shows the scores for buildings with different storeys. Note that the study only applies to multi-storey URM masonry buildings, therefore only buildings with 2, 3 or 4 storeys were selected. The indicator scores were based on the minimum sum of the cross sectional area of horizontal shear walls provision, based in Appendix B of SANS 10160-4 (2010). It states that:

"The minimum sum of cross sectional area of horizontal shear walls, in each direction, as a percentage of the total floor area per storey must be 2,5 % for 2 storey buildings and 5 % for 3 storey buildings."

Using this as a starting point, the indicator scores were assigned knowing that a 3 storey buildings would require twice the cross sectional horizontal shear area than a 2 storey building. This was extrapolated to obtain an indicator score for 4+ storey buildings. In research conducted by Van der Kolf (2014), it was concluded that a typical 3 storey masonry building was inadequately designed to resist a moderate intensity earthquake. The value for a 3 storey building was therefore used as a basis to calculate the scores for 2- and 4 storey buildings.

Table 7.11: Indicator score allocation for buildings with different storeys

Building Storeys	Indicator Score
2	0.5
3	0.75
≥ 4	1

7.6.2.3 Buildings' Proximity

This factor measures the possibility of earthquake induced pounding between adjacent buildings. The indicator measures the distance between adjacent buildings as a function of building height. This is similar to the approach used in SANS 10160 Part 4 (2009). Van der Kolf (2014) found that the period of a typical three storey unreinforced masonry building is less than 0.7 seconds, which can be used to characterise the movement of a masonry building. If the distance between buildings exceeds 0.05h, no pounding would occur (SANS 10160 Part 4, 2009). Tabel 7.12 illustrates how scores should be assigned for this indicator. Scores between the boundary conditions should be interpolated. The symbol 'h' represents the building height.

Table 7.12: Distance classifications for the buildings' proximity scoring

Buildings' Proximity	**Indicator Score**
0 (buildings together)	1
>0.05 h	0

7.6.2.4 Other Building Indicators

Other building factors such as Vertical Irregularities, Plan Irregularities, Post Seismic Code Retrofitting or Falling Hazards could be determined with boolean "Yes/No" answers. For the definitions of these factors, refer back to section 6.3.2. Table 7.13 indicates the scores for each choice. An answer of "Yes" was awarded a score of 1 with a "No" answer representing a score of 0. This was based on a "Yes" answer that would influence the ERAM model and a "No" answer that would not influence it (hence the value 0).

Table 7.13: Other building indicator scores

Factor Description	**Indicator Criteria**	**Indicator Score**
Vertical irregularity	Yes	1
	No	0
Plan irregularity	Yes	1
	No	0
Post seismic code retrofitting	Yes	1
	No	0
Falling hazards	Yes	1
	No	0

7.6.3 Individuals' Exposure and Vulnerability

7.6.3.1 Population Density

The indicator measuring the Population Density is given by equation 7.6.2. Here the actual population density is given as a proportion of the population density that the building was designed for. This is called the building occupancy rate. Using Table 7.14, the indicator score (x_{I1} and x_{E7}) can be obtained by finding the corresponding building occupancy rate.

$$\text{Building occupancy rate} = \frac{\text{Actual population density of building}}{\text{Building design capacity}} \tag{7.6.2}$$

Table 7.14: Indicator scores for different building occupancy rates

Building Occupancy Rate	**Indicator Score**
0	0
0.5	0.25
1	0.5
1.5	0.75
2+	1

The building occupancy rate was divided into five categories. If the building was filled to its designed population density, it would be represented with a score of 0.5. The indicator score then either increased or decreased as the building occupancy rate increased or decreased. A maximum building occupancy limit of 2 was imposed, which scored all of the higher occupancy rates a score of one. The values for other indicator scores can be obtained from linear interpolation. The motivation for the choice was based on the building occupancy classifications as in the SABS 0400-1990.

7.6.3.2 Percentage of Population Aged 0-4 and 65+

The Vulnerable Groups indicator (x_{I2}) represented the group of vulnerable individuals which may suffer more harm from an earthquake. This indicator can be directly obtained from the data of the most recent census survey. The census data represents a statistic out of 100, which is normalized to a score out of one for the indicator.

7.6.3.3 Per Capita GDP

The Per Capita GDP indicator measured the income levels of the individuals living in a building. Equation 7.6.3 displays how the indicator score was calculated. It measured the income of the residents against the national average income per person.

$$x_{I3} = 1 - \frac{\text{Per capita GDP income of residents}}{\text{National average per capita GDP income}} \tag{7.6.3}$$

This study focuses on individuals in the R 800 to R 3500 income group (per person per month). The World Bank estimates the national income of South Africa (per capita per month) to be R 6188 (World Bank, 2014). The score of this indicator will therefore range between 0.47 and 0.88, which is acceptable because it is smaller than 1.

7.6.4 Emergency Response and Recovery Capability

7.6.4.1 Emergency Planning

The emergency planning indicator (x_{E1}) indicates the state of emergency planning and preparedness of a region. The indicator is rated on a scale from 0 to 1, based on the preparedness of local authorities to a large-scale earthquake disaster. This indicator is scored 0 if the building is located in a region with disaster management facilities. A score of 1 should be assigned if no disaster management facilities exist in the region of the building. A score of 0 indicates (low likelihood of damage) that disaster planning does exist for a region whereas 1 indicates (high likelihood of damage) no disaster planning for a region. This method of scoring the indicators was used because no emergency planning indicators exist in South Africa to evaluate the different levels of planning. This was therefore chosen to be the most appropriate alternative of rating the emergency planning and preparedness measures.

7.6.4.2 Emergency Services Capacity

The emergency services capacity indicators measure the number of hospitals, doctors and firemen available to assist individuals. The indicator scores are based on equations 7.6.4, 7.6.5 and 7.6.6. Here an indicator is assigned a score based on the capacity of the emergency services.

$$x_{E2} = 1 - \frac{\text{Number of hospitals per 100 000 people}}{\text{Largest number of hospitals per 100 000 people (in sample group)}} \tag{7.6.4}$$

$$x_{E3} = 1 - \frac{\text{Number of doctors per 100 000 people}}{\text{Largest number of doctors per 100 000 people (in sample group)}} \tag{7.6.5}$$

$$x_{E4} = 1 - \frac{\text{Number of firemen per 100 000 people}}{\text{Largest number of firemen per 100 000 people (in sample group)}} \tag{7.6.6}$$

Equations 7.6.4, 7.6.5 and 7.6.6 were developed to assign a score of 1 to the building which would have the lowest emergency services capacity. The scores for all the other buildings in the sample group will range between 0 and 1. The scores are assigned on a comparative scale, finding the building with the lowest capacity and assigning a maximum value of 1 to it.

It should be noted that these equations are based on the existence of a sample group. A sample group is here defined as a group with two or more buildings. This is needed in order to identify the building with the worst score and assign the maximum value of 1 to it. All of the other buildings are then organized a score of between 0 and 1 accordingly.

7.6.4.3 Emergency Services Mobility

The emergency services mobility indicators measures the distance from a building to the closest hospital or fire station. The indicator scores are based on equations 7.6.7 and 7.6.8. Here an indicator is assigned a score based on the building (in the sample group) that is located the furthest away from the facility.

$$x_{I1} = \frac{\text{Distance from building to hospital (km)}}{\text{Distance from furthest building (in sample group) to hospital (km)}} \tag{7.6.7}$$

$$x_{I2} = \frac{\text{Distance from building to fire station (km)}}{\text{Distance from furthest building (in sample group) to fire station (km)}} \tag{7.6.8}$$

Equations 7.6.7 and 7.6.8 were developed to assign a score of 1 to the building the furthest away from an emergency facility. Subsequently the scores for all the other buildings in the sample group will range between 0 and 1.

It should be noted that these equations are based on: 1. the existence of a sample group and 2. the use absolute values. A sample group is here defined as data for two or more buildings. Secondly, the equations are based on absolute distances. For example, consider building A to be 2km from hospital X and building B to be 3km from hospital Y. The indicator score for building A will then be $2/3 = 0.67$ and for building B will be $3/3 = 1$. This example shows that the equations does not differentiate between different hospitals or fire stations, but only accounts for the absolute distance to the closest facility.

7.6.4.4 Other Indicators

The last five indicators (x_{E8-12}) were based on statistics that could be obtained from the most recent census survey. The individuals dependent on residents- (x_{E8}) and access to land-line/cellphone/radio/TV indicators (x_{E9-12}) were chosen because information for it could be obtained from census statistics. The final scores for all of these indicators can be obtained by subtracting the census score from the largest possible rating of one. Again, this was done to ensure that lower rated scores (which indicates poorer performance) is represented by a higher final score than a higher rated performance score.

7.7 Conclusion

This chapter outlined the two methods which were used to obtain the factor weights with namely with a study of the literature (section 7.2) and an industry survey (section 7.3). The results of the survey was discussed (section 7.4) and integrated into a weighted Earthquake Risk Assessment Model. Indicators were lastly developed for each sub-factor to assign a risk score to each sub-factor's condition/state (section 7.6).

Chapter 8

Example of Implementation

This chapter illustrates briefly the implementation of a fictitious example of the ERAM. It was developed to prioritize URM buildings according to their seismic risk. The example is intended to illustrate the implementation of the model and how it works. It makes use of three buildings with different properties.

8.1 Step 1: Data Collection

Table 8.1 displays the data that was collected of the three buildings. The data was obtained from the sources (as it was mentioned Data Collection, section 5.3.3).

Table 8.1: Data obtained for each building from sources

Description	**Building A**	**Building B**	**Building C**	**Sources**
Peak Ground Acceleration: 500 years	6.2 m\s^2	6.4 m\s^2	6.3 m\s^2	Council for Geoscience
Maximum Peak Ground Acceleration of region	6.7 m\s^2	6.8 m\s^2	6.7 m\s^2	Council for Geoscience
Ground types	3	4	4	SANS 10160-4
Liquefaction susceptibility of sedimentary deposits	Very Low	Low	Low	Appendix D
Alternative energy source use	21%	12.40%	8%	Statistics South Africa
Building age	35 years	42 years	28 years	City of Cape Town
Building storeys	2	3	4	City of Cape Town
Buildings' proximity	50cm	20cm	60cm	City of Cape Town
Buildings' height (h)	6.4m	9.6m	12.8m	
Vertical irregularity	No	No	No	City of Cape Town
Plan irregularity	No	No	No	City of Cape Town
Post seismic code retrofitting	No	No	No	City of Cape Town
Falling hazards	Yes	No	No	Visual inspection
Actual population density of building (persons)	48	48	80	Visual inspection
Building design capacity (persons)	32	48	64	City of Cape Town
Percentage of population aged 0-4 and 65+	10%	6%	8.10%	Statistics South Africa
Per capita GDP income of residents	R 3000	R 2400	R 1200	Statistics South Africa
National average per capita GDP income	R 6188	R 6188	R 6188	World Health Organization
Number of hospitals per 100 000 people	0.14	0.14	0.12	World Health Organization
Number of doctors per 100 000 people	1.8	1.6	1.3	World Health Organization
Number of firemen per 100 000 people	0.55	0.4	0.5	City of Cape Town
Distance from building to hospital	4km	5km	7km	Visual inspection
Distance from building to fire station	7km	9km	8km	Visual inspection
Individuals dependent on residents	50%	43%	40%	Statistics South Africa
Access to landline	45%	34%	32%	Statistics South Africa
Access to cellphone	95%	91%	85%	Statistics South Africa
Access to radio	65%	70%	81%	Statistics South Africa
Access to TV	75%	87%	91%	Statistics South Africa

8.2 Step 2: Calculation of Sub-Factor Scores

The calculation of the score for each sub-factor is specified in section 7.6. Table 8.2 illustrates the score of each sub-factor as it was calculated for the example.

Table 8.2: Indicator score for each sub-factor

Principal Factor	Description	Building A	Building B	Building C
Seismic Hazard	x_{S1}	0.93	0.94	0.94
	x_{S2}	0.88	1	1
	x_{S3}	0.2	0.4	0.4
	x_{S4}	0.4	0.2	0.2
Building Exposure & Vulnerability	x_{B1}	0.6	0.8	0.4
	x_{B2}	0.5	0.75	1
	x_{B3}	0	0.375	0.06
	x_{B4}	0	0	0
	x_{B5}	0	0	0
	x_{B6}	0	0	0
	x_{B7}	1	0	0
Individuals' Exposure & Vulnerability	x_{I1}	0.75	0.50	0.63
	x_{I2}	0.10	0.06	0.08
	x_{I3}	0.52	0.61	0.81
Emergency Response and Recovery Capability	x_{E1}	0	0	0
	x_{E2}	0	0	0.14
	x_{E3}	0	0.11	0.28
	x_{E4}	0	0.27	0.09
	x_{E5}	0.57	0.71	1.00
	x_{E6}	0.78	1.00	0.89
	x_{E7}	0.75	0.50	0.63
	x_{E8}	0.5	0.57	0.60
	x_{E9}	0.55	0.66	0.68
	x_{E10}	0.05	0.09	0.15
	x_{E11}	0.35	0.30	0.19
	x_{E12}	0.25	0.13	0.09

8.3 Calculation of Overall Risk Scores

Lastly the risk score for each category was determined. This was based on the mathematical combinations as given in section 5.3.7 using the weights as it were identified in Chapter 6. Table 8.3 illustrates the risk scores for each category and each building.

Table 8.3: Overall risk scores for each category and building

				Risk score for each building		
Principal Factor	**Description**	**Sub-Factor Weights**	**Principal Factor Weights**	**Building A**	**Building B**	**Building C**
Seismic Hazard	x_{S1}	0.400	0.280	0.659	0.692	0.692
	x_{S2}	0.190				
	x_{S3}	0.220				
	x_{S4}	0.190				
Building Exposure & Vulnerability	x_{B1}	0.157	0.250	0.293	0.328	0.275
	x_{B2}	0.204				
	x_{B3}	0.131				
	x_{B4}	0.112				
	x_{B5}	0.198				
	x_{B6}	0.102				
	x_{B7}	0.097				
Individuals' Exposure & Vulnerability	x_{I1}	0.388	0.285	0.466	0.380	0.492
	x_{I2}	0.340				
	x_{I3}	0.272				
Emergency Response and Recovery Capability	x_{E1}	0.108	0.185	0.270	0.331	0.376
	x_{E2}	0.131				
	x_{E3}	0.127				
	x_{E4}	0.114				
	x_{E5}	0.088				
	x_{E6}	0.088				
	x_{E7}	0.078				
	x_{E8}	0.064				
	x_{E9}	0.054				
	x_{E10}	0.054				
	x_{E11}	0.047				
	x_{E12}	0.047				
Total Score				**0.44**	**0.45**	**0.47**

8.4 Results

Figure 8.1 illustrates the risk score of each category the building was assessed for. From the figure it is clear that Building B and C together show the highest risk for a seismic hazard. Building B showed the highest risk in terms of the building exposure and vulnerability. Building C showed showed the highest risk in terms of the individuals' exposure and vulnerability and the emergency response and recovery capability.

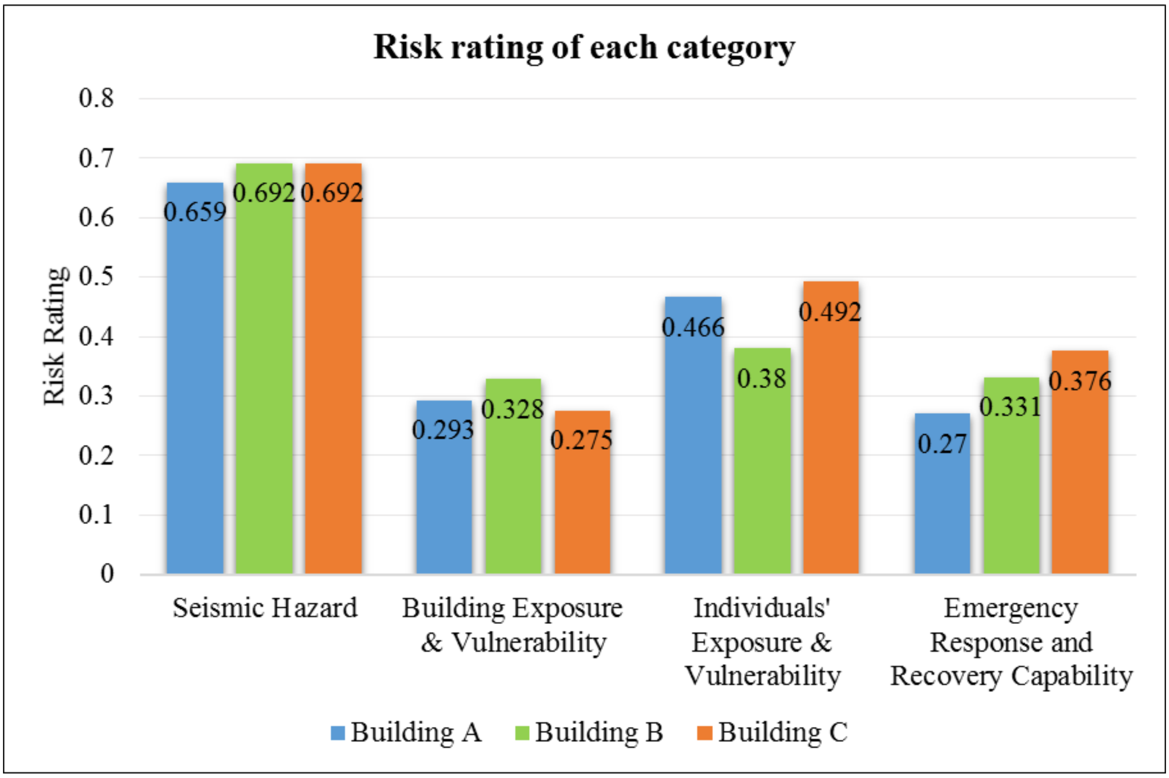

Figure 8.1: Risk score of each category

Figure 8.2 illustrates the overall risk rating for all three buildings. This shows that building C would have had the highest risk using the ERAM model to calculate the different risks. This illustration is however not the best way of illustrating the differences between the buildings since it contains little information (single scalar value). With this result (and that of the above) one can now prioritize which buildings need to be seismically reinforced first.

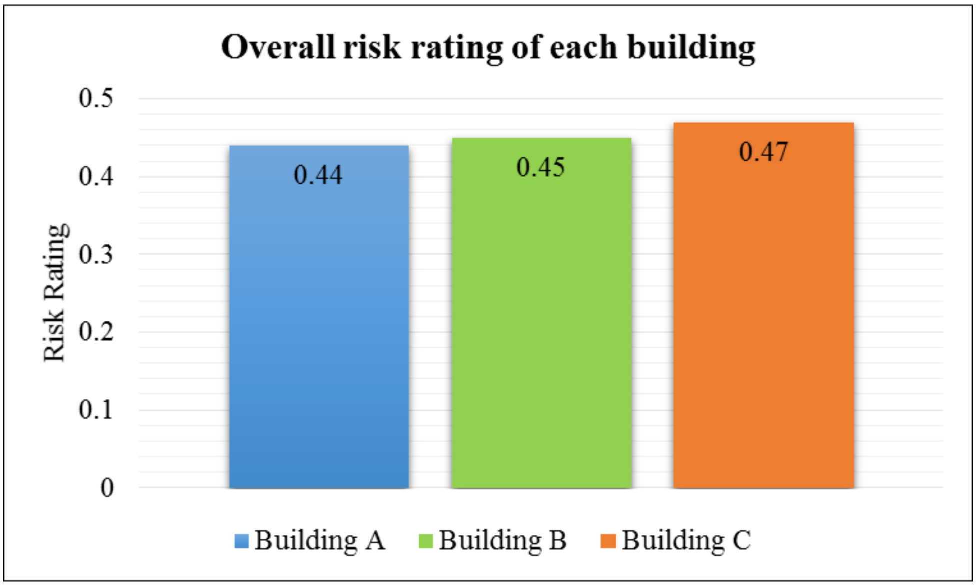

Figure 8.2: Overall risk score calculated for each building

8.5 Sensitivity of Sub-Factor Weights

Two of the indicators were previously identified that should be further investigated, namely Fire and Building Storeys. Following a simple variation in the indicator scores (Tables 8.4 & 8.5), the final scores were calculated. The final score, when varying the Fire score from 0.5 to 1, varies between 0.446 and 0.473 whereas when varying the score for Building Storeys from 0.5 to 1, the final score varies between 0.441 and 0.446 . This is a difference of 0.027 for Fire and 0.005 for Building Storeys. A change of 50% in the Fire score can have a 5.7% effect on the final score, whilst a 50% change in the Building storey score, can have a 1.1% effect on the final score.

The effect of Building Storey score is relatively insignificant, whilst the score on the Fire has a bigger influence. Nevertheless, when a comparison is made between buildings, then the effect of the choice for the Fire indicator may still allow to identify the more critical building. This shows that the development of a proper indicator scoring mechanism can have a meaningful difference on the outcome of the model and it is recommended that an in depth sensitivity analysis be conducted in future research to establish the exact risk scores.

Table 8.4: Variation in the final score of Building A if the indicator score for Fire is varied

Indicator score: Fire	**Final score**
0.5	0.446
0.6	0.451
0.7	0.457
0.8	0.462
0.9	0.467
1	0.473

Table 8.5: Variation in the final score of Building A if the indicator score for Building storeys is varied

Indicator score: Building Storeys	**Final score**
0.5	0.441
0.6	0.446
0.7	0.451
0.8	0.456
0.9	0.461
1	0.446

The sensitivity of the five most influential sub-factors were also tested (as discussed in section 7.4). Table 8.6 illustrates the final scores, showing variation from as little as 0.393 to 0.528 .

Table 8.6: Variation in the final score of Building A for 5 most important sub-factors

Indicator score	**PGA: 500 year** return period	**Population density**	**Percentage of population aged 0-4 and 65+**	**Per capita GDP**	**Liquefaction** susceptibility
0.5	0.393	0.459	0.413	0.48	0.439
0.6	0.404	0.465	0.424	0.489	0.447
0.7	0.415	0.472	0.435	0.499	0.455
0.8	0.426	0.478	0.446	0.509	0.462
0.9	0.437	0.484	0.457	0.518	0.47
1	0.449	0.49	0.468	0.528	0.478

8.6 Conclusion

This chapter illustrated the functioning of the ERAM by applying it to a fictitious example. The chapter discussed how data was gathered and how it could be used to draw a meaningful conclusion.

Chapter 9

Research Validation

9.1 Introduction

When conducting research, it is important to keep in mind that all research should in some form be validated. This ensures that the research is accurate and relevant with regard to academic research. Validation techniques should be precise to avoid any biased- or factually flawed data. To validate the research, it should be compared to the findings of your research to that of other researchers. This chapter discusses the methods that were used to validate the ERAM model.

Validating research is not always possible. When creating new procedures, techniques, methodologies or models it may be difficult to find a similar example to validate the research against. Fortunately, in this case it was possible to partially validate the ERAM model. There exists three other studies which investigates disaster contributing parameters. The studies were conducted by Davidson and Shah (1997), Cockburn and Tesfamariam (2012) and the ATC (2009). These three role players also identified quantitative weightings for parameters that were used in their research. These weightings were found to be the only accurate, feasible way to validate the ERAM model against. Here follows a description of the validation process that was followed for the ERAM model.

9.1.1 Principal Factor Validation

The ERAM model had two types of weighted factors, namely principal factors and subfactors. In order to obtain these weightings, two sources were used to gather the weightings from: a study of the literature and a survey amongst professionals from the disaster management community. Section 7 discussed these sources and techniques in detail.

Fortunately, all of the weights for the principal factors were obtained from literature. Davidson and Shah (1997) established the quantitative importance of a number of disaster contributing parameters. This was then confirmed by Cockburn and Tesfamariam (2012) which further developed this research. The researcher therefore decided that there was no need to validate the principal factor weights again, since it has been reviewed twice before by peer assessment.

9.1.2 Sub-Factors Validation

The evaluation of the sub-factor weights was the only method of validating the research. These factors were chosen to be site specific, and therefore represented new combinations of factors which were hard to validate. Findings from Davidson and Shah (1997), Cockburn and Tesfamariam (2012) and the ATC (2009) made the validation possible. Table 9.1 shows which sub-factors could have been validated with information obtained from the three sources. It was possible to identify 10 validation weights (of the 26), with no information available for the other 16 weights.

Table 9.2 displays the validation of the weights according to Davidson and Shah (1997) and Cockburn and Tesfamariam (2012). The factor weights, as it were determined by industry professionals, are displayed first. The validation weights were included next, which were obtained from the sources mentioned previously. Lastly the difference between the factor weight and validation weight is displayed, to indicate the actual percentage difference.

Table 9.3 displays the validation weights, according to the ATC (2009). Here the column definitions are applied the same as before. Only two validation weights were obtained for the Building Exposure and Vulnerability group, namely that of the Vertical- and Plan Irregularities.

The percentages from Table 9.2 and 9.3 are illustrated in Figure 9.1. Here the green bars indicate the percentage difference between the factors from this study and the values from literature. The results vary from 8% to 84.7%.

Concerning the validation itself, it was found that most of the factor weights differed quite extensively. There could be a variety of reasons for these differences. The factors will be discussed individually, starting with the Vertical Irregularity first. The validation factors for this factor were obtained from FEMA 154 documentation. The manual outlines a rapid visual screening process for potential seismic hazards in buildings. The reasoning behind this is that the FEMA 154 manual has been developed to fulfil a different purpose to that for which the ERAM model was developed. The FEMA 154 manual was developed as a rapid visual screening procedure to identify buildings which needs further (detailed) investigation. The FEMA weights were not obtained from an industry survey but were rather chosen by the developers to indicate whether a building needed further investigation. The weights of these factor therefore differ, hence the observation in Figure 9.1.

Table 9.1: Validation possibility of each sub-factor.

Principal Factors	**Sub-Factors**	**Validation Possible**
Seismic Hazard	PGA: 500 year return period	Yes
	Soil conditions	Yes
	Liquefaction susceptibility	Yes
	Fire	Yes
Building Exposure & Vulnerability	Building age	No
	Building storeys	No
	Vertical irregularity	Yes
	Plan irregularity	Yes
	Post-code retrofitting	No
	Falling hazards	No
	Buildings' proximity	No
Individuals' Exposure & Vulnerability	Population density (I1)	No
	% of population aged 0-4 or 65+	No
	Per capita GDP	Yes
Emergency Response and Recovery Capability	Emergency planning indicator	No
	Num. of hospitals per 100 000 people	Yes
	Num. of doctors per 100 000 people	Yes
	Num. of firemen per 100 000 people	Yes
	Distance to nearest hospital	No
	Distance to nearest fire station	No
	Population density (E7)	No
	Individuals dependency	No
	Access to landline	No
	Access to cellphone	No
	Access to radio	No
	Access to TV	No

The weights that were obtained by the survey can be argued to give a less accurate reflection. The fact that only 4 local respondents took part may influence this. A better way to evaluate the weight of the factors would have been to distribute the survey to participants the four largest cities in South Africa. The number of participants in each city should be chosen so that the results of the returning surveys may show a large degree of confidence.

In conclusion, it was found that the weights of the ERAM model differed quite extensively when compared to other similar research. The differences range from 8.0% to 84.7%. Possible reasons are also supplied for the varying results.

Table 9.2: Validation of sub-factor weights, according to Davidson and Shah (1997) and Cockburn and Tesfamariam (2012).

Principal Factors	**Sub-Factors**	**Factor Weight**	**Validation Weight**	**Difference (%)**
Seismic Hazard	PGA: 500 year return period	0.400	0.298	25.5
	Soil conditions	0.190	0.105	44.7
	Liquefaction susceptibility	0.220	0.1	54.5
	Fire	0.190	0.05	73.7
Individuals' Exposure & Vulnerability	Per capita GDP	0.272	0.2	26.5
Emergency Response and Recovery Capability	Num. of hospitals per 100 000 people	0.131	0.042	67.9
	Num. of doctors per 100 000 people	0.127	0.042	66.9
	Num. of firemen per 100 000 people	0.114	0.042	63.2

Table 9.3: Validation of sub-factor weights, according to ATC (2009).

Principal Factors	**Sub-Factors**	**Factor Weight**	**Validation Weight**	**Difference (%)**
Building Exposure & Vulnerability	Vertical irregularity	0.131	0.242	84.7
	Plan irregularity	0.112	0.121	8.0

9.1.3 Indicator Validation

No suitable validation could be found for the indicators. The risk rating of each indicators was based on reliable sources, as it was described in section 7.6. The lack of validating the indicators are however not a major concern for the study. As mentioned earlier, the purpose of the ERAM model is to apply it to a range of similar buildings and indicate where the seismic risk would be the highest. This would be explained the easiest with the use of an example.

Say there exists buildings A, B and C. Buildings A and B are three storey buildings where building C is a four storey building. In terms of risk ratings, the earthquake risk of building A and B would be exactly the same. The earthquake risk of building C must however be larger than buildings A and B, due to taller buildings having a larger earthquake risk than shorter buildings. This example highlights that the absolute value of the risk rating is not as important as ranking these building according to their risk. The model will fulfil its duty as long as buildings A and B are rated equally, and lower than building C (the purpose is to arrange buildings according risk).

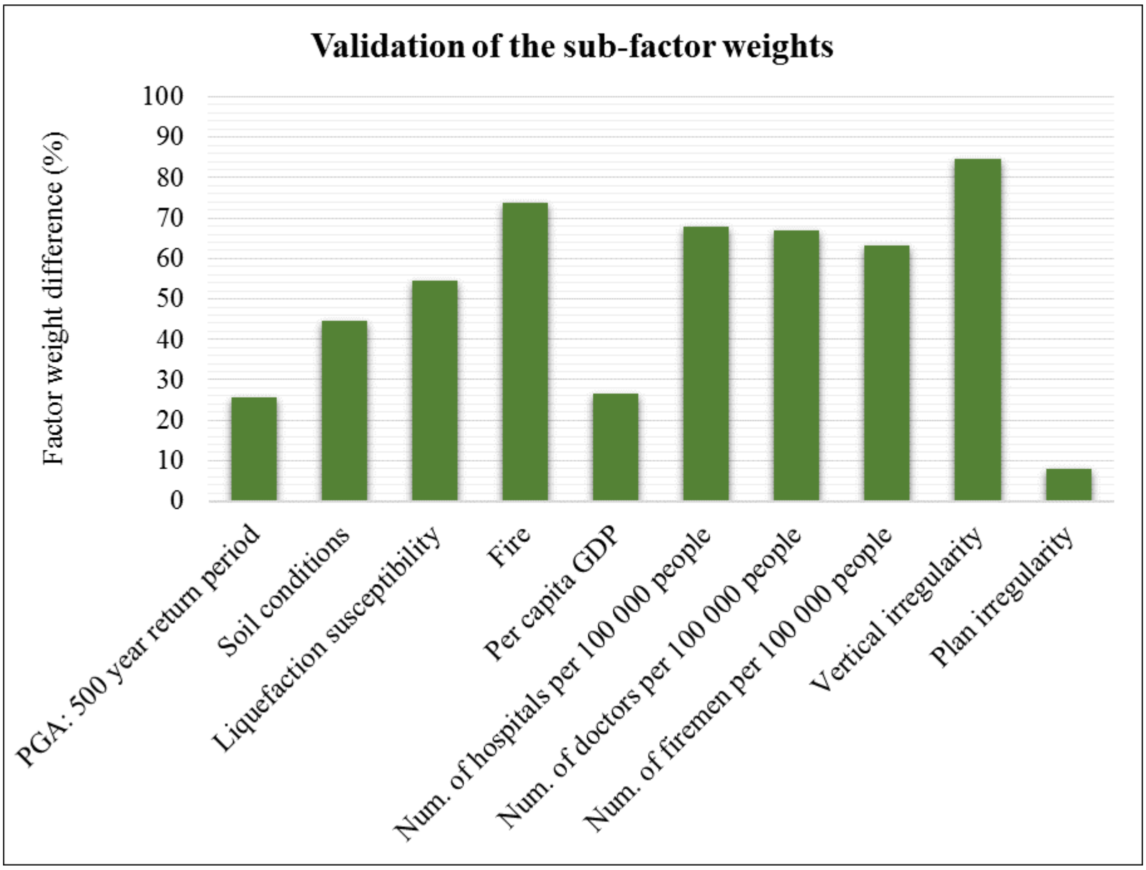

Figure 9.1: Validation of sub-factor weights

However, it is also true that the indicator values of different sub-factors are not a reflection of the relative risk between them. The model is therefore a simplification and only a first step to determine the more critical building. More research would be needed to calibrate the indicator values between the different factors.

9.2 Critical Evaluation of Model

The critical evaluation of the model is needed in order to discuss and identify any shortcomings which have arisen or been overlooked during the development of the model. The shortcomings were identified after developing the ERAM model and should be addressed in future research.

9.2.1 Comments on Validation

The ERAM model was validated using weights from the factors of similar research. Only ten factors could be identified (out of twenty six) to validate the model with. It is suggested that when conducting similar research, a better method of validation be developed. This is easily stated, though hard to execute. The problem with developing a model for the first time is that one will always have difficulty obtaining any validation criteria or examples. In this case it was simply not possible for the author to find other validation weights since they did not exist. Disaster case studies in other countries (where earthquakes occur) can also be used to validate the model by identifying the actual factors that contributed the most to the consequences. Nevertheless, it is proposed that a follow up study be conducted that aims to provide feedback on the weighting of factors. In addition, the parameters are to be better defined and this can be identified through a sensitivity analysis. A sensitivity analysis could also have other meaningful purposes such as understanding the relationships between input and output variables or to identify possible errors in the model.

9.2.2 Strengths of the Model

The model is intended to comparatively evaluate the seismic risk of a range of different buildings. It addresses the problem statement as it was discussed in Chapter 1 and provides a procedure to prioritize buildings according to different the different characteristics a building has.

9.2.3 Shortcomings of the Model

The following shortcomings have been identified for the model:

- A quantitative model does not always allow for the correct description of building characteristics, though in this case it was the best option.
- When assigning the indicator scores, one should also try avoid any subjective scoring of an indicator, as this can wrongly influence the scores obtained from the ERAM model. This can be avoided by using illustrative examples to set a standard according to which indicators can be scored against.
- The indicator scores that have been assigned for each factor were based on values from other research, and may be adapted by the user if it was found to be unsatisfactory.

The last shortcoming that has been identified for the ERAM model regards the final risk rating. It was previously mentioned that the indicator scores would be mathematically combined with the factor weights to obtain a final, single risk rating for each building. It is rather advised that the user of the ERAM model calculate the risk scores for each category (Seismic Hazard, Building Exposure and Vulnerability etc.) and compare these categories with each other. Normalizing the weights of the sub-factors is dependent on the number of factors, therefore more factors would result in lower average weight values. This can be observed for all the sub-factors in Figure 7.5. The opposite is also true where less factors would result higher sub-factor weights. An example of this can be seen in Figure 7.4.

9.2.4 Suggestions for Improvement

The following suggestions were made for the improvement of the ERAM model:

- Further research is still needed do determine the exact relationship between principal and sub-factors
- The indicator scoring could be improved with an in-depth study for each factor
- A follow-up study is recommended for the implementation of the model

9.3 Conclusion

This chapter discussed the validation process that was used to validate the ERAM model. Weights of the model were compared to weights obtained from literature. The validation found that 9 out of the 26 weights were inaccurate and needed more research.

Chapter 10

Research Conclusions and Recommendations

It was identified that there are a great number of 2, 3 and 4 storey URM buildings in Cape Town that could be vulnerable to a moderately sized earthquake. There exists great uncertainty whether these buildings were designed for seismic actions and whether they meet the current design provisions. The buildings are the property of the City of Cape Town, and house approximately 11 000 individuals. All of these individuals have a monthly income of between R800 and R3500, placing them in one of the lowest income groups. This creates the context for a problem which may have disastrous consequences.

The primary objective of the study aimed to solve this by creating a seismic risk prioritization procedure that could identify the buildings with the highest seismic risk. The procedure was based on the work of others with some minor adjustments, creating a new procedure. The model was successfully implemented in an example in Chapter 8. The procedure consisted of developing a model that determines the earthquake risk of a range of buildings, taking into account various factors which could have an influence. The result of the model quantitatively indicates the risk rating for a building. The secondary objectives comprised of all of the steps needed to create the Earthquake Risk Assessment Model. The completed ERAM model represents a means to calculate the earthquake risk of each building, fulfilling the primary objective of the research.

10.1 Conclusions

The completion of the ERAM model fulfilled the primary objective the study set out to answer. Secondary objectives of the study involved identifying the local factors which contribute to seismic risk, determining their importance against each other and the selection of suitable rating scale for each factor. The study found that:

- Industry experts rated short term effects which occurred during earthquakes higher than medium- to long term effects. It is theorized that the most injuries or damage are caused during the earthquake itself and these factors will therefore have a higher rating.
- Factors relating to medium- and long term damage were rated lower. This follows the theory above that the most injuries or damage is sustained during an earthquake rather than after an earthquake.
- Overall, concerning the principal factors for the ERAM model, it was found that the vulnerability of the individuals were rated the most important and very similar the effects of the seismic hazard (28%), building exposure and vulnerability (25%) and the emergency response and recovery capability (18.5%) being rated lowest.
- In the study, the seven local factors which most influence the seismic risk were found to be (in ascending order):
  - The ground acceleration: PGA with a 500 year return period (11.2%)
  - The occupation density of the building (11.1%)
  - Percentage of individuals from vulnerable age groups (9.7%)
  - The income of each individual (Per capita GDP) (7.8%)
  - The liquefaction susceptibility of a building (6.2%)
- The least important factors were found to be:
  - The number of individuals dependent on the residents (1.2%)
  - The residents' access to a landline telephone (1.0%)
  - The residents' access to a cellphone (1.0%)
  - The residents' access to a radio (0.9%)
  - The residents' access to a television (0.9%)
- Suitable indicators were determined for each factor

The ERAM model is a tool and if used correctly it may be of great value. The model can assist in determining where the seismic risk is the greatest in a city/state/country; indicating where funds and retrofitting efforts should be applied first. It can also be used in disaster management planning, providing information for earthquake scenarios.

10.2 Recommendations for Future Investigations

Further research is still needed in order to develop a fully functional seismic risk assessment procedure. This study lays the foundation for a assessment procedure and is intended to be a starting point. The recommendations for future research include:

- A comprehensive survey should be performed to determine the importance of factors which influences seismic risk. The survey should be aimed at disaster management practitioners who have extensive knowledge in the field of disaster risk management.
- Further research to determine rating scales which are more refined and which correlate to the true condition of a factor is required. In the research, indicator scores were based on similar allocations in the literature. This has to be more refined and curtailed to be site specific scores, indicating the true state or condition of each factor. A follow up survey with a more representative number of respondents is needed.
- Future research into an appropriate validation technique for the ERAM model. There exists no method that can suitably validate the results of the ERAM model. The only way the model can currently be validated is by evaluating the importance of each factor and the score of each associated indicator.
- A sensitivity analysis to test the robustness of the model results. A sensitivity analysis could have other meaningful purposes such as understanding the relationships between input and output variables or to identify possible errors in the model.
- The implementation of the model on existing buildings. This is one of the intended purposes of the model. It requires a study of its own due to the considerable amount of work that is associated with collecting the data from the field.
- Extending the ERAM model to include other types of buildings as well. This forms a part of the ultimate goal: to develop a comprehensive model that evaluates the seismic risk of a whole city.

10.3 Concluding Statement

The study set out to develop a risk assessment procedure in order to prioritize the seismic risk of 2, 3 and 4 storey URM buildings (Chapter 1). The ERAM model was conceptualized to fulfil this role. A comprehensive literature study served as a much needed framework to develop the ERAM model (Chapter 2, 3 and 4). The actual development of the model is discussed in the remainder of this document (Chapter 5 and 6).

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Appendices

Appendix A

Earthquake Intensity Scale

A.1 Correlation between intensities of earthquakes

Richter Magnitude	Modified Mercalli scale	Acceleration (m/s^2)	Description
Up to 2.5	I	< 1	I. People do not feel any earth movement. Registered only by seismographs.
2.5 - 3.5	II	1 - 2	II. Felt by a few persons at rest, especially on upper floors of tall buildings. Delicately suspended objects may swing.
3.5 - 3.9	III	2 - 5	III. Felt indoors. Many people outside might not realize an earthquake occurring. Vibration like passing of light trucks.
4.0 - 4.9	IV - V	5 - 20	IV. Felt indoors by many, outdoors by few during the day. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rock noticeably. V. Felt by nearly everyone. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

Richter Magnitude	Modified Mercalli scale	Acceleration (m/s^2)	Description
5.0 - 5.9	VI - VII	20 - 100	VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. VII. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
6.0 - 6.9	VII - VIII	100 - 200	VIII. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls.
7.0 - 7.9	IX - X	200 - 1000	IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. X. Serious damage to dams and embankments. The ground cracks in large areas. Railroad tracks bent. Most masonry and frame structures destroyed; some bridges destroyed.
8.0 - 8.9	XI - XII	> 1000	XI. Rails bent greatly and thrown out of position; underground pipelines completely out of service. Large cracks appear in the ground. Few, if any (masonry) structures remain standing. Most buildings collapsed. XII. Large-scale changes in the structure of the ground, waves seen on ground surface, objects thrown into the air. Damage nearly total; Almost everything is destroyed.

Appendix B

Ethical Screening Application

B.1 Departmental Ethics Committee Application

Department of Civil Engineering

Stellenbosch University

Departmental Ethics Screening Committee questionnaire.

This questionnaire shall be completed by each researcher (and or student) who wishes to involve persons/animals in their research.

1. General information :
   a. Name and surname: Charlie de la Harpe
   b. Application date: 30 June 2014
   c. Project title: An Earthquake Risk Assessment Model for Existing Unreinforced . Masonry Buildings in Cape Town, South Africa
   d. If for degree purposes, which degree: MEng Civil
   e. Study leader (if applicable) : Prof. J. Wium

2. Type of people to be surveyed:

☐ Adults	☐ General population
☐ Children	☐ Other?
☐ Stellenbosch university students	______________________________
☐ **Professionals in industry**	

3. Roughly how many involved?

Five professionals

4. Form of survey:

☐ Qualitative interview with individual	a) face-to-face
	b) telephone interview
☐ Qualitative interview with group (focus group)	
☐ **Quantitative survey tool**	**a) hard copy form**
	b) electronic online survey

5. How will you ensure the participants are well informed about the purpose of the research and how the research results will be disseminated?

   By attaching a cover letter to all of the questionnaires. The cover letter will include the details of the institution, researcher and supervisor, a summary of the research, the objectives of the questionnaire and what the results will be used for.

6. How will you record their consent to participate?

   Included in the questionnaire is a section where participants give their details and consent for participation. The participants can also stay anonymous and still complete the questionnaire. This feature is included in order to protect the identity of the participant from any harmful consequences that may arise from completing the questionnaire.

7. Communication issues

☐ Are there likely to be any communication issues due to language or education?

NO

☐ If YES, how will you ensure that the person is fully informed of their rights?

____

8. Nature of information requested:

☐ Any personal information recorded (name, address, id number)?

Yes

☐ If Yes what information?

Each validators name, position and academic qualification

☐ Any information of a personal nature (personal experiences?)

No

☐ If Yes what information?___________________________________

☐ Any information of a particularly sensitive nature (relating to traumatic experiences, potentially triggering memories of traumatic events; relating to unsafe or illegal activities?)

No

☐ If Yes what information?___________________________________

☐ Any information relating to other identifiable people?

No

☐ If Yes what information and from what people?___________________________________

9. How will you ensure rights to privacy and confidentiality?

   All of the personal information will be kept at a secure location which is accessible to the researcher. Included in the questionnaire is a section in which the participants can choose to stay anonymous.

10. How will you keep data safe and available for future auditing?

    The information will be kept in a file in the office of the supervisor, Prof. Jan Wium.

11. Will the respondents benefit in any way – directly – from participating? ie do they stand to gain financially/ are you providing an incentive etc?

    No

12. How will you ensure fair selection of research participants?

    By identifying qualified and experienced participants in the disaster management fields.

13. Provide details of a risk benefit analysis/disadvantages.

    Not applicable

14. How will research in a community be coordinated in order not to place unwarranted burden upon such community?

    Not applicable

Appendix C

Normalization of Principal Factors

Davidson and Shah (1997) obtained the following importance values from a questionnaire supplied to experts with a experienced earthquake disaster risk background.

Table C.1: Normalized principal factors

	Importance of Factors		
Description	**Importance**	**External Context removed**	**Normalized**
Seismic Hazard	0.25	0.25	0.28
Building Exposure and Vulnerability	0.223	0.223	0.25
Individuals' Exposure and Vulnerability	0.255	0.255	0.29
External Context	0.107		
Emergency Response and Recovery Capability	0.165	0.165	0.18
Total	**1**	**0.893**	**1.00**

Appendix D

Earthquake Risk Assessment Questionnaire

D.1 Questionnaire

Earthquake Risk Assessment Questionnaire

UNIVERSITEIT • STELLENBOSCH • UNIVERSITY

Department of Civil Engineering

Construction Engineering and Management Division

Developed by: C.W.H. de la Harpe

Date: April 30, 2014

Dear Professional,

I am performing research for a Master of Engineering degree at the Department of Civil Engineering at Stellenbosch University. As part of my master's degree, I am developing an earthquake risk assessment procedure that aims to:

- allow a comparison of multi-storey unreinforced masonry buildings (built before 1989) in terms of their earthquake risk, and
- describe the relative contributions of various factors that contribute to the overall earthquake risk of these buildings.

I would like to invite you to participate in this study and would appreciate your valuable feedback in the questionnaire. The following questionnaire is intended to capture the opinions of professionals concerning the relative importance of the factors that contribute to the earthquake risk of a single building. Your participation will help to identify the influence of each factor on the earthquake risk of an individual.

Please take a few minutes to complete this questionnaire. Please supply your details or otherwise choose to remain anonymous. If you include your return address in Question 3, a copy of the results will be forwarded to you when it becomes available.

The research is conducted under the supervision by Professor Jan Wium, who can be reached at janw@sun.ac.za or +27 21 808 4348 for more information.

Thank you very much for your time and interest.

Sincerely,

Charlie de la Harpe
MEng Civil Engineering Student
Department of Civil Engineering
Construction Engineering and Management Division
Stellenbosch University
Cellphone nr: 076 684 2332
Email address: 15367908@sun.ac.za

1. Definitions

In completing this survey, please apply the following definitions:

Earthquake risk refers to the undesirable consequences which follows an earthquake. Specifically relating to multi-storey unreinforced masonry buildings, this risk would not only be a function of the physical impact on the residents, but also the response by emergency services and how severe the residents will feel the effect in terms of the social, economic, political and cultural contexts.

Seismic hazard refers to the severity of ground shaking, foundation soil conditions and secondary hazards which are triggered by ground shaking (collateral hazards). These hazards may include phenomena such as soil liquefaction or fires that are produced as a result of an earthquake.

The **building exposure and vulnerability** conveys information regarding a building and its structural characteristics. The procedure takes into account the building age, design, vertical and plan irregularities (irregular shapes in according to view), falling hazards (chimneys, cladding etc.) and other buildings in close proximity.

An **individuals' exposure and vulnerability** focuses on the human factors that describe the residents living in the buildings. The choice of factors focuses on characteristics of vulnerable groups, the income of the residents and the population density.

Emergency response and recovery capability represents the ability of emergency services to respond rapidly to emergency situations, accommodate the casualties following an earthquake and evaluates the recovery capability of the residents to recover after such an event.

2. Remarks

Please assign weight factors, w_i, such that

(a) w_i describes the relative importance of factor *i* to the overall earthquake risk.

(b) Each weight w_i has a value from 1 to 10 (i.e. $1 \leq w_i \leq 10$ for all w_i).

(a) The factor(s) that are most important have a weight $w_i = 10$, and all other factors are weighted in relation to the most important one(s). The sum of the weights is unimportant.

3. Questions

Anonymity (Yes/No): ______________________________

If "No" is selected above, please state the following details:

Participants name and surname: ______________________________

Participants position ______________________________

Participants academic qualifications: ______________________________

Date: ______________________________

Question 1

Several factors have been identified which contribute to the earthquake risk of an unreinforced masonry building. These factors are listed in **Table 1**. Please assign weights to these factors to indicate their influence, according to your opinion. Refer to **Remarks** (section 2) for guidelines on completing the table. **Table 2** on page 5 contains an example of a completed questionnaire. Please refer to it before completing the questionnaire.

Question 2

List any factors that, in your opinion, are important in determining the earthquake risk of a building, but were not considered in Table 1.

____

____

____

____

Question 3

If you are interested in receiving a copy of the results of this survey, please provide the email address to which it should be sent.

____

____

____

Table 1: Factors that contribute to the earthquake risk of multi-storey unreinforced masonry buildings.

Category	**Factor**	**Weight Value**, w_i
Seismic Hazard	Peak Ground Acceleration: 500 year return period	
	Soil conditions of foundation	
	Liquefaction susceptibility of soil	
	Fire (due to earthquake)	
Building Exposure and Vulnerability	Building age	
	Building storeys	
	Vertical irregularity	
	Plan irregularity	
	Post-code retrofitting	
	Falling hazards	
	Buildings' proximity	
Individuals' Exposure and Vulnerability	Population density	
	Percentage of population aged 0-4 or 65+	
	Per capita GDP	
Emergency Response and Recovery Capability	Emergency planning measures	
	Number of hospitals per 100 000 people	
	Number of doctors per 100 000 people	
	Number of firemen per 100 000 people	
	Distance to nearest hospital	
	Distance to nearest fire station	
	Population density	
	Individuals dependent on residents	
	Access to landline	
	Access to cellphone	
	Access to radio	
	Access to TV	

Table 2: Example of a completed questionnaire.

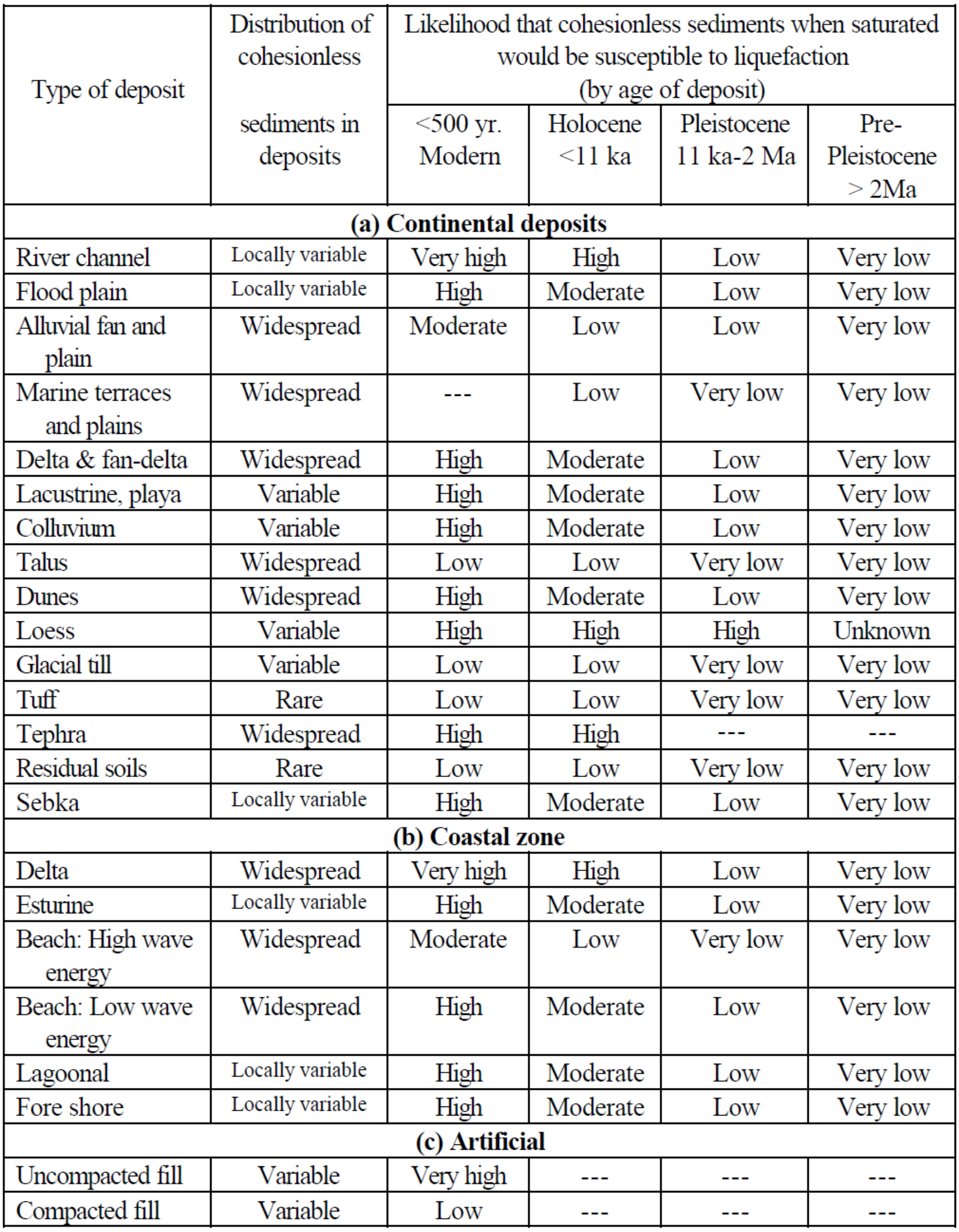
Category	**Factor**	**Weight Value**, w_i
Seismic Hazard	Peak Ground Acceleration: 500 year return period	10
	Soil conditions of foundation	4
	Liquefaction susceptibility of soil	3
	Fire (due to earthquake)	4
Building Exposure and Vulnerability	Building age	7.5
	Building stories	7.5
	Vertical irregularity	10
	Plan irregularity	5
	Post-code retrofitting	7.5
	Falling hazards	5
	Buildings' proximity	7.5
Individuals' Exposure and Vulnerability	Population density	10
	Percentage of population aged 0-4 or 65+	7
	Per capita GDP	7
Emergency Response and Recovery Capability	Emergency planning	10
	Number of hospitals per 100 000 people	7
	Number of doctors per 100 000 people	7
	Number of firemen per 100 000 people	7
	Distance to nearest hospital	5
	Distance to nearest fire station	5
	Population density	5
	Individuals dependent on residents	5
	Access to landline	2
	Access to cellphone	2
	Access to radio	2
	Access to TV	2

Appendix E

Indicators: Supplementary Information

E.1 Liquefaction Susceptibility of Soil

Figure E.1: Liquefaction susceptibility of sedimentary deposits (Youd and Perkins, 1978)



Type of deposit	Distribution of cohesionless sediments in deposits	Likelihood that cohesionless sediments when saturated would be susceptible to liquefaction (by age of deposit)			
		<500 yr. Modern	Holocene <11 ka	Pleistocene 11 ka-2 Ma	Pre-Pleistocene > 2Ma
(a) Continental deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread	---	Low	Very low	Very low
Delta & fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine, playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	---	---
Residual soils	Rare	Low	Low	Very low	Very low
Sebka	Locally variable	High	Moderate	Low	Very low
(b) Coastal zone					
Delta	Widespread	Very high	High	Low	Very low
Esturine	Locally variable	High	Moderate	Low	Very low
Beach: High wave energy	Widespread	Moderate	Low	Very low	Very low
Beach: Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
(c) Artificial					
Uncompacted fill	Variable	Very high	---	---	---
Compacted fill	Variable	Low	---	---	---