Investigation of the Directional Effect on Low Cost Houses Due to the 2014 Orkney Earthquake

by

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Preface

The research contained in this thesis was completed by the candidate while based in the Discipline of Land Surveying, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard College, South Africa. The research was financially supported by National Research Foundation (NRF) and University of KwaZulu-Natal.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Dr Mayshree Singh

Date: 30 June 2020

Declaration: Plagiarism

I, Thando Nqasha declare that:

(i) The research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) This thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(v) This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

  a) Their words have been re-written but the general information attributed to them has been referenced;

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Abstract

The Orkney earthquake on the 5th August 2014 caused major damages to houses in Orkney and surrounding areas. A post field assessment was carried out to determine the amount of damage caused by the earthquake.

The Khuma township near Stilfontein was the most affected area where more than 600 houses were damaged. The damage caused by the 2014, Orkney earthquake was made worse by the poorly constructed low-cost houses in Orkney and the surrounding townships (Khuma, Kanana and Jouberton). These houses were vulnerable to earthquake damage.

This study sought to determine the effects of additional factors that contribute to earthquake damage such as: building excitation angle, exposure of building weak points to earthquake direction and building finishes.

In this study, results show that building excitation angle, exposure of weak points and finishes either plastered or un-plastered can contribute to the damage and vulnerability of a building during an earthquake tremor.

Buildings of excitation angles between 0° - 30° and 61°- 90° had more damages compared to houses that had an excitation angles of between 31°- 60° for all 3 townships (Khuma, Kanana and Jouberton). The excitation angle of 0°- 30° recorded the highest damage grade, followed by excitation angle of 61° - 90°. The least amount of damage was observed for the excitation angle of 31° - 60°. The reason for these effects was that for the excitation angle of 0° - 30° and 61° - 90°, two or more building walls were perpendicular to the earthquake direction hence the building becomes vulnerable to toppling.

Furthermore, houses that had weak points (windows and doors) exposed to the line of sight from the epicentre had reported more damages than houses that have no weak point exposed to the line of sight from the epicentre. Buildings that were completed with plaster were more resistant to earthquake damage than buildings that were un-plastered.

The findings in this study can used be to establish fundamental building vulnerability properties for low-cost developments which will help to improve the construction of low-cost houses and reduce their vulnerability to earthquake damage and protect human life.

Acknowledgments

This work would not have been possible without the financial support from the University of KwaZulu-Natal and National Research Foundation (NRF).

I am especially grateful to Dr Mayshree Singh, my lecturer and supervisor, in the Department of Land Surveying. She has been supportive throughout the project and worked actively to provide me with the academic support, advice and mentorship. As my supervisor and mentor, she has taught the values to become a good scientist. She had greatly influenced me to pursue this project.

I would like to thank my mother, Zikhona Nqasha, whose love and guidance are with me in whatever I pursue.

I am thankful to all of those with whom I had the pleasure working with throughout this project. Each member has provided me with extensive personal and professional support. I have been taught a great deal about scientific research and life in general.

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Chapter 1 : Introduction and Background to research

1.1 Introduction

On the 5th of August 2014, an earthquake occurred in the Orkney area in the North-West Province, South Africa. The earthquake was considered to be triggered by mining activities (Bateman, 2014; Hosken et al., 2014; Kolver, 2014). The tremor was felt widely, as far as Cape Town in South Africa, Maputo in Mozambique and Gaborone in Botswana (Raaf, 2014). It caused extensive damage to buildings in Orkney and surrounding areas of Khuma, Kanana and Jouberton.

After the earthquake, field assessments were carried out by Midzi et al. (2015) and Khoyratty (2016) to determine the damage it had caused. The Khuma Township, situated in close proximity to Stilfontein, was one of the most affected areas, with more than 600 houses damaged (Sapa, 2014; Midzi et al., 2015). Three clinics and two schools in the North West province were damaged by the Orkney earthquake (Sapa, 2014) and major damage was recorded in low-cost housing (Midzi et al., 2015; Khoyratty, 2016).

The damage caused by the earthquake on buildings is a function of; the nature of the earthquake, local geological conditions and building structure. Earthquakes with high magnitude and shallow depth are more likely to cause heavy damage than earthquakes with low magnitude and deeper depth (Zielinski, 2011). Soil that is loose, sandy, and soggy does not support building structures well and will liquefy if the earthquake has a high magnitude. Buildings that are closer to the epicentre experience more damage than building that are further from the epicentre, as was observed in Khuma during the 2014 Orkney earthquake (Khoyratty, 2016). Poorly-constructed unreinforced buildings built with substandard materials are more vulnerable to earthquake damage than well-constructed reinforced buildings built with high quality materials (Doğangün et al., 2008). Unavoidable features like windows and doors introduce weak points and make the building more vulnerable to earthquake damage (Zielinski, 2011).

The South African government invests millions of rands in low-cost housing for low-income citizens who cannot afford to build for themselves. Where continuous tremors occur they constitute a socio-economic issue for low-income citizens who cannot afford to repair their houses.

The factors that contributed to the level of damage in low-cost houses caused by the Orkney, 2014 earthquake, can be investigated to provide better housing to protect human life and quality of living.

1.2 Background to the research

Although Southern Africa usually experiences low levels of seismic activity compared to regions located near the boundaries of tectonic plates, however, there have been several reported medium sized earthquakes (Pule et al., 2015; Liebenberg et al., 2017). In South Africa, the main contributors to seismic activities are the deep-level platinum and gold mines. An increase in seismic activity has been observed in mines that were no longer operating in Gauteng, North West and Free State province (Davies and Kijko, 2003; Midzi et al., 2013; Kolver, 2014; Bateman, 2014; Midzi et al., 2015; Du Plessis et al., 2015).

In low seismic regions like South Africa, building codes are not always implemented, and many houses remain unreinforced. Low-cost houses, in particular, are often constructed from substandard material such as poor-quality cement and bricks and they often lack adequate door and window frames. In many cases, such houses are also poorly maintained. Since such buildings are constructed without considering seismic activities that may occur in the area, they are vulnerable to damage or collapse when seismic activities do occur.

The are several factors that contribute to the damage observed to buildings due to earthquakes, by understanding these factors it may be possible to construct houses that are less vulnerable to earthquake damage. Most of the factors that contribute to earthquake damage have been heavily studied e.g., epicentral distance and local geological conditions, however some of the factors like earthquake directional effect have been hardly studied.

Earthquake directional effect is mostly studied in structures that have greater length-base ratio like bridges and pipelines e.g. López and Torres (1997), Banerjee Basu and Shinozuka (2011) and Atak et al., (2014). There are few studies that have studied earthquake directional effect on building e.g. Fernandez-Davila et al. (2000) and Caselles et al. (2012), from these controlled experimental studies, earthquake directional effect have a significant effect on the damage observed in buildings. This field study will validate or reject the theories from these controlled studies.

1.3 Research Question

How does the excitation angle, building weak points exposure and plastering finishes affect the vulnerability of the low-cost houses to earthquake damage?

1.4 Aims and objectives

This research aimed to assess the factors that contributed to the level of damage in Orkney and the surrounding areas of Khuma, Kanana and Jouberton Township, due to the 2014 Orkney earthquake.

Factors assessed included building excitation angle, exposure of building weak points to the line of sight from epicentre and building finishes (whether un-plastered or plastered), to find how these contributed to the damage grade of the buildings observed.

More particularly, the following objectives were investigated:

(a) To assess the effect of building excitation angle on the amount of damage observed in the building.

(b) To evaluate how exposed building weak points like windows and doors affected the level of damage observed.

(c) To observe whether the building external wall finishes (either plastered or un-plastered) affected the level of damage.

(d) Finally, from an assessment of the factors contributing to earthquake damage, to make recommendations on how to reduce vulnerability of low cost housing in areas subject to mining-related seismic activity.

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1.5 Thesis structure

- Chapter 1(Introduction) provides background information of the 2014 Orkney earthquake . The study aims and objectives are highlighted and the factors identified that contributed to the level of damage caused by the 2014 Orkney earthquake to low cost housing in the surrounding townships of Orkney, e,g. Khuma, Kanana and Jouberton

- Chapter 2 (Literature review) describes the various types of low-cost housing and the quality of buildings in South Africa. The possible risks and vulnerabilities of low-cost housing to seismic activities are also discussed.

- Chapter 3 (Methodology): The research design is given in terms of methods and materials used to collect the following data: excitation angle, weak points exposure and building finishes.

- Chapter 4 (Results and Analysis): The data collected in the townships of Khuma, Kanana and Jouberton is presented. The damage grades are correlated with excitation angles, exposure of weak points and building finishes.
- Chapter 5 (Discussion): discusses how the excitation angle, exposure of weak point to earthquake direction and plastering finishes affect the level of damage in low-cost houses. The most favourable parameters are discussed.
- Chapter 6 (Conclusion and recommendations): Based on the findings of this study, guidelines are offered to government and other stakeholders, to improve the construction of low-cost housing in areas of significant seismic hazard, in order to minimise damage and protect human life.

Chapter 2 : Literature review

2.1 Seismic History in South Africa and Orkney

Southern Africa is considered to be a stable continental region, also known as an intraplate region (Brandt, 2011). Relative to regions near tectonic plate boundaries, intraplate regions usually experience low seismic activities. However there have been several reported medium size earthquakes of natural origin, in South Africa (Pule et al., 2015; Liebenberg et al., 2017), Most natural (tectonic origin) seismic events take place in the Western Cape and northern parts of KwaZulu-Natal (refer to seismic hazard map in Figure 2-1). About 90 percent of seismic activities in South Africa are mine related, which occur in Gauteng, North West and Free State provinces (Davies and Kijko, 2003; Midzi et al., 2013; Bateman, 2014; Kolver, 2014; Du Plessis et al., 2015; Midzi et al., 2015).

Once a mine has been closed, mine water is no longer extracted. This results in underground flooding and an increase in underground pressure. The increased water levels act as a geochemical catalyst between the mine rock strata, mine wastes, and oxygen. This process causes the water in underground voids in the mines to become acidic (Birch, 2014; Durrheim et al., 2006). The underground water, under great pressure, loosens fractures, fissures, and faults, which weakens the clamping forces. The steadiness of fractures, fissures, and faults is affected, allowing seismic events to be produced (Durrheim et al., 2006; Goldbach, 2010). Liebenberg et al. (2017) reported that even though there has been a decrease in the mining activities in the Witwatersrand area, the number of seismic events appeared to be increasing and was attributed to the acid mine drainage problem. Orkney has a total of eleven mining shafts but due to the financial crisis experienced by some mining companies, four mining shafts are no more operating (Motsumi, 2012). The seismic activities occurring in Orkney may well be partly caused by the same acid mine drainage phenomena in non-operating mining areas as has been observed in other parts of the Witwatersrand basin.

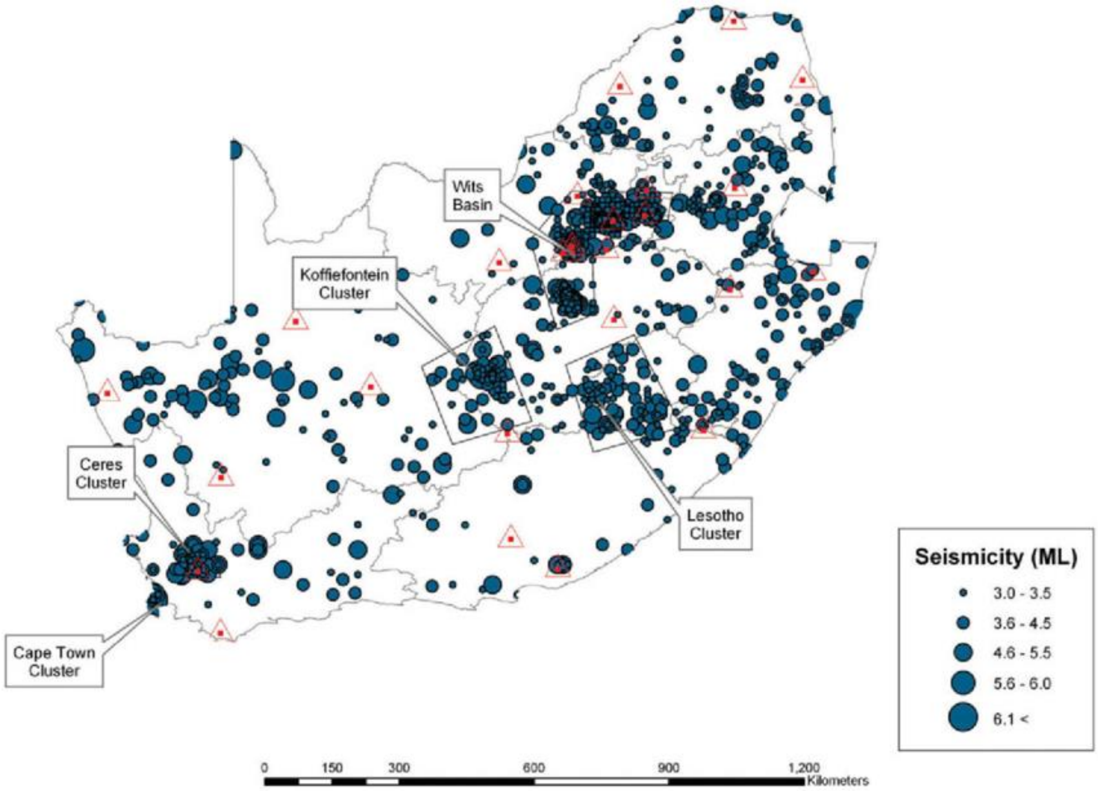


Figure 2-1: Seismicity map South African from 1682 to 2008, showing known clusters of natural and mining induced-seismicity (Singh et al., 2009)

The following are two notable and destructive earthquakes that have occurred in South Africa in recent decades. The 1969 Tulbagh earthquake with a magnitude of 6.2 M_W was considered the largest and the most destructive. It caused serious damage estimated at US$24 million with 12 deaths and many injured (Pule et al., 2015). On the 9th March 2005 in Stilfontein, North West province, an earthquake occurred approximately 2.4 km below the earth's surface with a magnitude 5.3 M_L. It caused damage to buildings (Midzi et al., 2015; Du Plessis et al., 2015; Liebenberg et al., 2017) with 24 people reported injured and 2 deaths while 42 miners were trapped underground due to rock falls (Midzi et al., 2013).

The epicentre of the Stilfontein earthquake was situated approximately 200km from Johannesburg (Saunders et al, 2008), Major damages were seen in Stilfontein with a maximum intensity of VIII. The buildings with the most structural damages were the Driefontein Primary School and Bal Eaton building. It was reported that windows were broken, and cracks were seen in the walls. The buildings were declared unsafe.

2.2 August 05, 2014 Orkney Earthquake

On 05 August 2014 at 12:22 pm (SAST) an Earthquake with a magnitude of 5.5 M_L and an estimated focal depth of 5.0 km, struck Orkney. The earthquake was the largest mine related earthquake in South Africa (Waywell, 2014; Manzunzu et al., 2017).

Tremors from this event were felt as far as Cape Town in South Africa and in neighbouring Mozambique and Botswana. More than 600 homes were damaged, including three clinics and two schools (Waywell, 2014; Midzi et al., 2015; Khoyratty, 2016). It left many people injured and claimed one life when a wall collapsed on a man.

Studies by Midzi et al. (2015) and United States Geological Survey (USGS) showed the earthquake intensity ranged from I to VII on Richter intensity (Figure 2-2). The maximum intensity of VII was experienced in the Khuma Township near the epicentre (Midzi et al., 2015; Khoyratty, 2016).

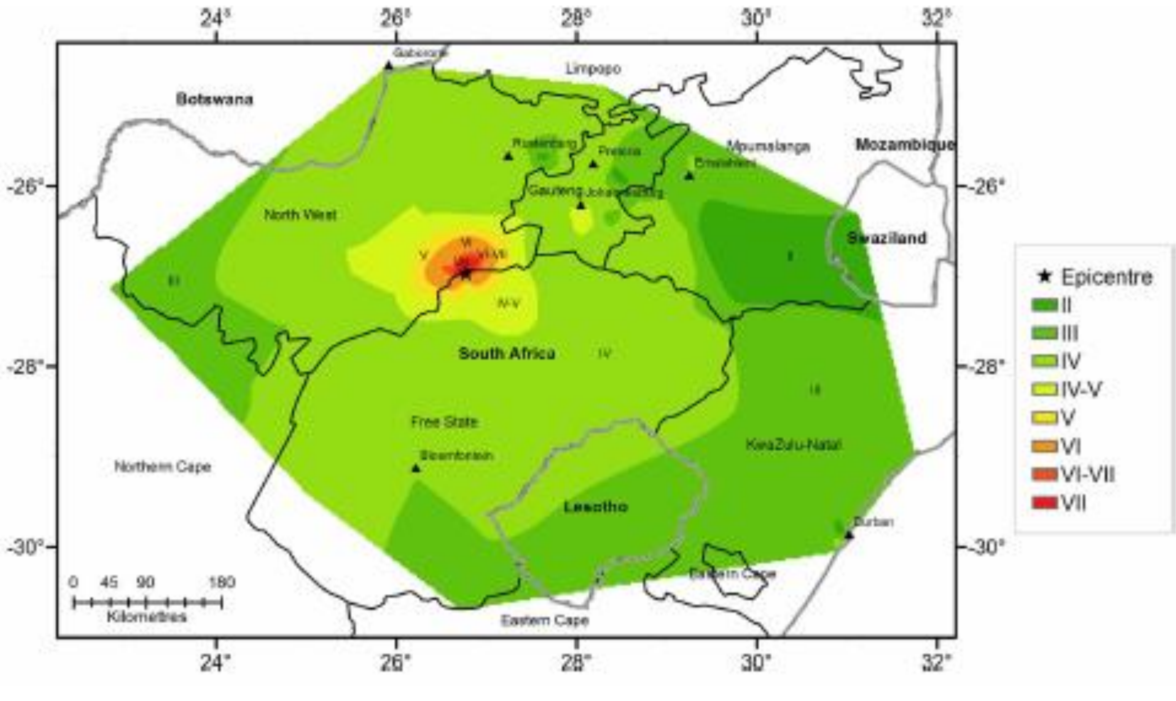


Figure 2-2: Intensity map of the 2014 Orkney earthquake (Midzi et al., 2015)

The wide extent of current and past mining activity in South Africa poses a risk of seismic activities (Manzunzu et al., 2017). These relatively small seismic events have a considerable effect on low-cost houses because these houses are built with low-cost masonry material and very basic engineering (Cameron, 1996; Fokazi, 2013). Studies have found that when masonry building have been constructed using good quality materials they can withstand medium size tremors (Doğangün et al., 2008). However Mostafaei (2013) and Doğangün et al. (2008) found that even relatively small seismic events can cause heavy damage to poorly constructed and unreinforced masonry buildings.

During the 2014 Orkney earthquake, low-cost houses experienced the most damage (Fokazi, 2013). Field assessments were carried out by Khoyratty (2016) to investigate the amount of damage caused by the earthquake on low-cost houses in Khuma, Kanana and Jouberton townships.

In Khuma a total of 32 houses were damaged with damage grade ranging from 20% (hairline cracks) to 100% (total collapse of a house). The average damage grade was 60% (heavy damage) and 3 homes were totally destroyed.

In the Kanana township a total of 17 houses were reportedly damaged, with a damage grade ranging from 40% (moderate damage) to 60% (heavy damage), the average damage grade being 50% (moderate to heavy damage).

Jouberton was the least affected township, with a total of 7 homes damaged. The damage grade ranged from 20% (slight damage) to 60% (heavy damage) with an average damage grade of 30% (slight to moderate damage). Khoyratty (2016) observed a repeated pattern of damage to building weak points such as: corner cracks in houses, falling of plaster, hairline cracks, damage above windows and door openings (Figure 2-3)

Figure 2-3: Damages observed in low-cost homes during the 05 August 2014 Orkney earthquake (Khoyratty, 2016).

A macro-seismic survey of the M_L5.5, 2014 Orkney earthquake conducted by Midzi et al. (2015) also reported damage to low-cost houses in the following regions: Orkney, Stilfontein and Khuma (Figure 2-4), which are located at epicentral distances of 15.8, 11.8 and 11.0 km, respectively. As observed by Khoyratty (2016), low-cost houses in Khuma experienced the most damage.

Figure 2-4: Damages observed in RDP homes during the 05 August 2014 Orkney earthquake (Midzi et al., 2015).

2.3 Low-cost housing in South Africa and the Orkney region

Orkney is a moderately sized town situated in the Klerksdorp district of the North West province, South Africa. It is surrounded by the following townships: Khuma, Kanana and Jouberton (Figure 2-5). It lies on the banks of the Vaal River and is approximately 180 km south-west from Johannesburg.

Orkney is primarily known for platinum and gold mines, which attracted many people from around South Africa. This resulted in a sudden increase of mine workers and their families inhabiting low-cost housing (Kunene, 2018). Today the housing stock in Orkney is evidence of rapid growth and high population.

Three types of low-cost housing were observed in the area: Pre-1994 low-cost housing, Post-1994 low-cost housing, and informal squatter camps. People living in Pre-1994 and Post 1994 low-cost houses reported the following problems: mortar cracks, foundation failure, degradation of weak points, wall cracks at the rafter joints, wall cracks throughout the building, and structural failure above doors and windows. These shortcomings are typically caused by poor workmanship and poor maintenance.

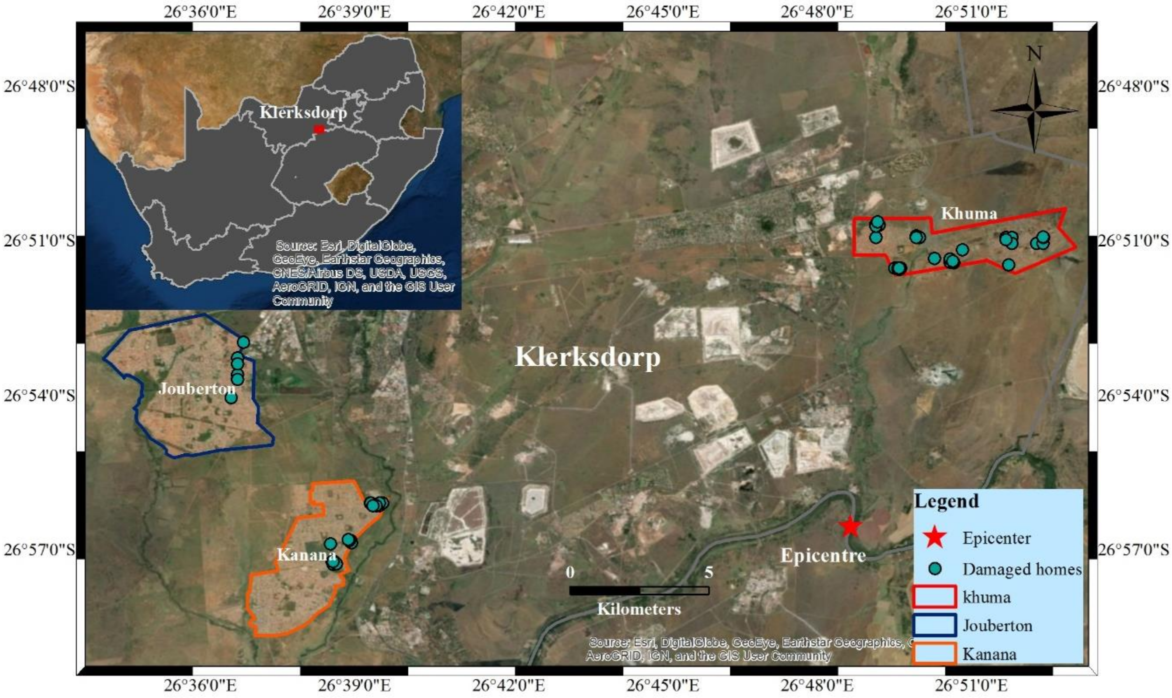


Figure 2-5: Study area showing Klerksdorp and the surrounding townships: Khuma, Kanana and Jouberton, and the Orkney 2014 earthquake.

2.3.1 Pre-1994 low-cost houses

The Pre-1994 low-cost houses were built for government workers. They were built with good quality building materials and adequate engineering (Figure 2-6). These were the second most damaged houses according to Khoyratty (2016) and Kunene (2018) which they attributed to a lack of maintenance leaving them in a dilapidated state and vulnerable to seismic events.

Figure 2-6: Structural makeup of Pre-1994 low-cost houses (Khoyratty, 2016)

2.3.2 Post-1994 low-cost houses

The post-1994 low-cost housing programme was introduced to compensate victims of the apartheid land segregation policy, by providing them with decent housing. These houses were built with low-cost masonry materials and very basic engineering (Figure 2-7), due to the high demand.

Figure 2-7: Structural makeup of Post-1994 low-houses (Khoyratty, 2016).

2.3.2.1 Inadequacies in Post 1994 low-cost housing construction

Over the years, several government-initiated investigations have found that low-cost (RDP) housing schemes had been abused and construction moneys diverted. Consequently the quality of housing decreased and smaller houses were built (Kunene, 2018).

In Mount Ayliff and Mount Frere in Eastern Cape 2015, one of the rectification projects confirmed poor workmanship by building contractors. Tomlinson (2015) reported that communities and housing organisations agreed that these houses were often poorly built. Community members agreed that they could build better houses for themselves if they were given direct access to a housing subsidy.

In an effort to improve these housing issues, government introduced the people’s housing project, in which building contractors would train house owners to build their own homes. This process will allow workers to obtain skills which will help them gain employment in the future. However Tomlinson (2015) found that this programme was mismanaged by contractors, who did not train the workers adequately.

The Department of Rural Development and Land Reform investigated the extent of damage needing to be fixed as part of a rectification programme. It was found that the public were not sufficiently skilled in house construction, which explained the shortcomings found. Several houses had to be demolished and rebuilt from scratch, while others were fixed.

The instability of post-1994 low-cost housing was evident in the findings of two earthquakes studies in KwaZulu-Natal. The 6th February 2016, Durban earthquake with a magnitude of 3.8 M_L and the 16^{th} of June 2015 Sundumbili earthquake magnitude 4.3 $M_{L,}$ both sent tremors to areas as far as Mpangeni, Stanger, Ballito, eShowe and Gingindlovu. Most of the damages were seen in low-cost housing in KwaMbonambi and Hammarsdale (Myeza, 2017).

On 15^{th} March 2018 more than 15 houses were damaged due to a tremor that took place in KwaXimba. This tremor was assumed to be caused by exfoliation of a granite dome (Ngubane, 2018; Vilakazi, 2018). Low-cost houses close to the source of the tremor could not withstand the slight seismic load produced (Ngubane, 2018; Vilakazi, 2018). Mrs Duma's house experienced the most damage, which included falling of plaster and hairline cracks on walls (Figure 2-8).

Figure 2-8: Damages sustained by Mrs Duma's house during the tremor

2.3.3 Informal settlement in form of shacks

The movement of people to Orkney and the surrounding areas put pressure on existing housing stock (Naidu and Isaacson, 2009; Moolla et al., 2011; Kunene, 2018). The unforeseen rapid growth in population together with slow progress in low-cost house construction, resulted in many people staying in informal shack settlements. (Bond and Tait, 1997; Chikitolo, 2009; Greyling, 2009; Moolla et al., 2011). Shacks are a form of housing that are usually built by informal settlers, constructed using corrugated iron sheets or wood (Figure 2-9). Since these houses are made with light weight material, they do not pose a serious threat to human life during an earthquake. No damage or casualties were recorded in shacks during the 2014 Orkney earthquake. Even though these types of housing are not vulnerable to seismic activities, they are not considered a favourable type of housing because of the various health and safety risks they create.

Figure 2-9: Structural makeup of the shack (Chikitolo, 2009).

2.4 Potential weak points of low-cost houses

The damage to unreinforced low-cost houses is made worse by a number of critical weak points. Buildings transfer lateral loads such as wind and seismic activities to the foundation through the building walls. The rigidity of the building walls will control the amount of movement during the transfer of load (Gillie, 2016).

Building features such as large openings in load-bearing walls e.g. windows and doors, lack of vertical confining elements, poor quality mortar, unconfined interior walls and poor foundations, all create weak points (Doğangün et al., 2008). These weak points are more likely to results in damage during the transfer of seismic load from the ground. Doğangün et al. (2008) stated that unavoidable features in buildings like windows and doors present critical weak points where most damage starts.

In a post-earthquake field assessment manual by Baggio et al. (2007), one of the key features that determined whether a building has been affected by an earthquake, were found to be cracks propagating from windows and door frames. In the post-earthquake field assessment conducted by Khoyratty (2016), a consistently repeated type of damage was seen where cracks propagated from the windows and door openings (Figure 2-10). A study by Martínez et al. (2006) in characterization of the seismic response of the Mallorca Cathedral, cracks propagating from windows and doors were observed when the building was exposed to earthquake acceleration.

Figure 2-10: Building damages observed in Orkney after the 2014 earthquake. Cracks propagated from windows and door frames (Khoyratty, 2016).

2.5 Contributing factors to earthquake damage in buildings

Some of the principal factors contributing to earthquake damage in buildings are listed below:

a) The earthquake magnitude
b) Depth of earthquake
c) Distance from the epicentre
d) Architecture and construction materials
e) Local geological conditions
f) Earthquake propagation and directional effect

These factors are described below with their isolated effects. However, at any given site a number of these factors can come into play and it is sometimes difficult to isolate factors in a small dataset.

(a) The earthquake magnitude

The bigger the magnitude of an earthquake, the more energy it releases, thus causing more destruction. The number assigned to represent the amount of seismic energy released by an earthquake is the Richter magnitude scale, it is logarithmic scale, so each the increase in magnitude by 1 represents an increase in energy by a factor of 10. The 1969 Tulbagh earthquake with a magnitude 6.3 M_L caused more damage than the 2014 Orkney earthquake which had a magnitude of 5.5 M_L (Midzi et al., 2013; Liebenberg et al., 2017).

(b) Depth of earthquake

The deeper the earthquakes the less destruction it is likely to cause as some of the energy dissipates before reaching the surface. Two earthquakes can be compared that occurred a year apart in Christchurch, New Zealand. On the 22nd February 2011 an earthquake with magnitude 6.2 Mw with depth of 5 km caused buildings to collapse, triggered landslides and flooding, and killed many people. While the September 2010 earthquake of magnitude 7.1 M_W with depth of 10 km sent tremors into the city causing little damage with no fatalities, as the earthquake depth was deeper (Zielinski, 2011).

(c) Distance from the epicentre

The closer a building or settlement is to the earthquake's epicentre; the more damage will occur. This due to the fact that near the epicentre the Peak Ground Acceleration (PGA) is higher, compared further from the epicenter. The PGA of an earthquake is a function of ground movement intensity, the earthquake magnitude, and the distance from the earthquake's epicentre (Irwansyah et. al, 2013). During the 2014 Orkney earthquake, more damaged buildings were observed in the Khuma Township than in Jouberton Township, because Khuma was closer to the earthquake's epicentre than Jouberton (Khoyratty, 2016).

(d) Architecture and construction materials,

Poorly constructed and unreinforced buildings are more likely to experience damage by an earthquake. Extensive damage to buildings was observed in Orkney and the surrounding area because of poorly constructed buildings (Seale, 2014; Khoyratty, 2016). In the 2010 Haiti earthquake, extensive damage was seen as buildings were poorly constructed and did not meet the building standards needed to withstand such a natural disaster (Zielinski, 2011).

(e) Local geologic conditions

The nature of the ground at the surface can have a major impact on the level of damage. Soil that is loose, sandy, and soggy, cannot properly support building structures and can liquefy during a strong tremor. During the 1995 Kobe earthquake in Japan most of the damage observed in buildings was due to foundation failure caused by soil liquefaction (Wakamatsu and Numata, 2004).

During the 26 September 1997 Umbria-Marche earthquake, significant amplifications of ground movement were observed even at large distances from the epicentre. This was ascribed to the geological conditions in the area (Pergalani et al., 1999; Marsan et al., 2000). Rosset et al. (2002) demonstrated that another parameter with significant influence on local amplification of ground motion is the steepness of the topography.

According to the South African geology map; Kanana and Jouberton have similar geology (Figure 2-11).

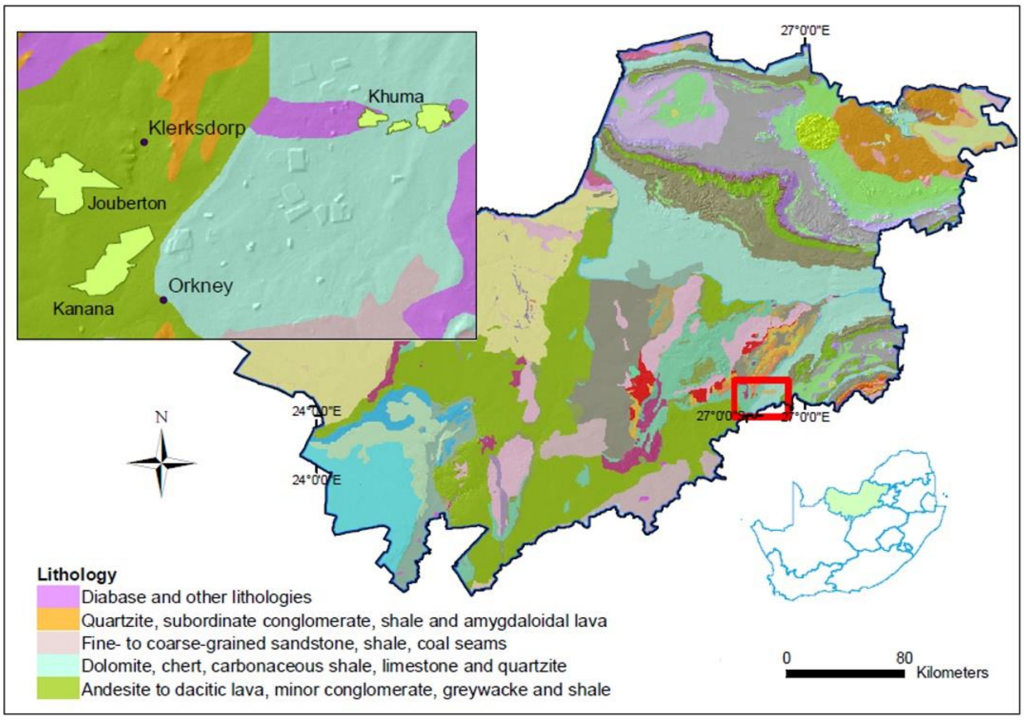


Figure 2-11: Geology underlying the study area (Khoyratty, 2016).

For most of Khuma the underlying geology is dolomite, chert, carbonaceous shale, limestone, and quartzite (Figure 2-11). Dolomite, chert, carbonaceous shale, and limestone are sedimentary rocks. Dolomite and chert are hard sedimentary rocks and they tend not to liquify during an earthquake. Limestones and carbonaceous shale are easily soluble in water and may liquefy during an earthquake. Quartzite is a hard, non-foliated metamorphic rock which was originally pure quartz sandstone, it does not liquefy during an earthquake.

In some parts of Khuma the underlying geology is diabase (Figure 2-11), which is a hard-dark coloured igneous rock. It is composed of plagioclase feldspar and pyroxene. Since diabase is hard it does not liquify during an earthquake.

In Kananan and Jouberton the underlying geology is andesite to dacitic lava, minor conglomerate, greywacke and shale (Figure 2-11). Andesite is an extrusive igneous rock, which does not liquefy during an earthquake. Conglomerate, greywacke, and shale are sedimentary rocks. Conglomerate and greywacke are hard and do not liquefy. Shale is soluble in water and may liquefy during an earthquake.

Even though some of the rock compositions under Khuma, Kanana, and Jouberton can liquify, however, there were no reported site liquifications during the 2014 Orkney earthquake in these regions.

(f) Earthquake propagation and directional effect

While the geology of an area, construction materials and the nature of an earthquake are contributing factors to earthquake damage as discussed above, other factors can also play a role. Exposure of the building weak points to the earthquake propagation direction and the excitation angle are also important factors that affect the level of damage seen in a building after an earthquake. These factors can be considered as the earthquake propagation and directional effect and are explored in more detail in the next section.

2.6 Earthquake propagation and directional effect

This section discusses the earthquake propagation and directional effect. *Earthquake propagation* explains the direction of propagation of an earthquake from the epicentre (Figure 2-12). *Earthquake directional effect* (in this study) looks at the earthquake propagation direction with respect to the longitudinal axis of the building. This is represented by the excitation angle (Figure 2-12)

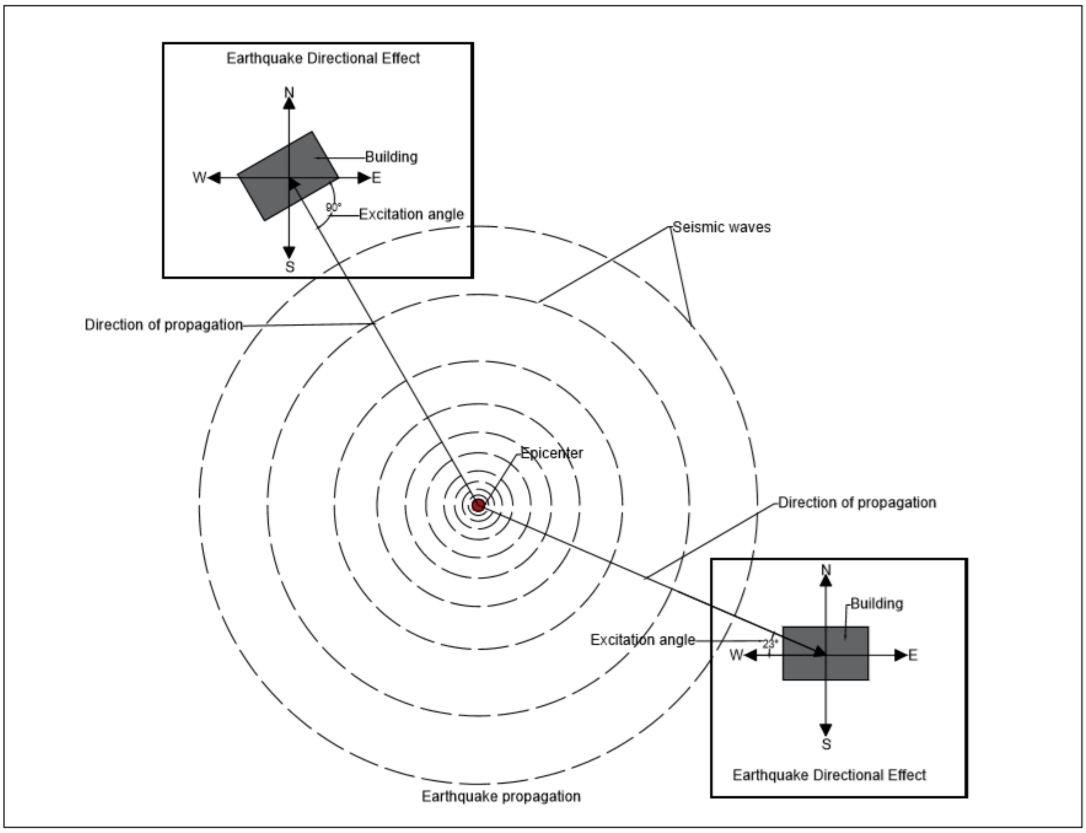


Figure 2-12: Earthquake propagation from the epicentre to the building and earthquake directional effect on building.

2.6.1 Earthquake propagation.

An earthquake propagates in the form of seismic waves from the point source. There are two main types of seismic waves:

(a) Body waves, which propagate through the volume of the earth and

(b) Surface waves, which travel along the surface of the Earth.

Surface waves are the more destructive and are responsible for the majority of damage caused by the earthquake (Zhao et al., 1992). Large earthquakes propagate intensely in the direction of the fault rupture, hence there is a greater amount of energy in the direction of the fault, this can lead to variations in ground acceleration with direction from the epicentre (Boore and Joyner, 1978; Elnashai and Di Sarno, 2015).

According to Wu and Wu (2008) earthquakes of small and medium magnitude propagate radially outwards with the same intensity in all directions from a point source, in the form of seismic wave, as a function of medium and distance from the source (Figure 2-12 and Figure 2-13).

The 2014 Orkney earthquake was considered to be a medium size earthquake and as it was suspected to be mine related, its epicentre could be represented by a single point source. The earthquake propagation direction can be obtained by taking the direction from the epicentre to the point of interest (line of sight from the epicentre).

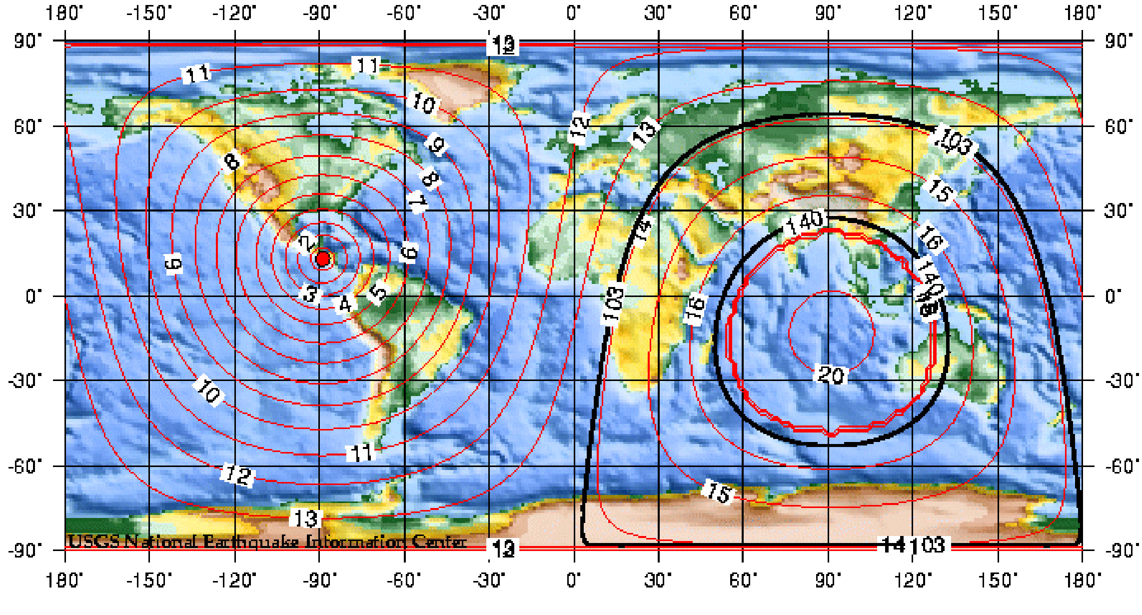


Figure 2-13: Propagation of body waves from Central America to around the globe (USGS).

2.6.2 Earthquake directional effect and excitation angle

The earthquake directional effect is the study of how the earthquake excitation angle affects the response of the structure due to the earthquake acceleration (González, 1992; Atak et al., 2014). Excitation angle is the acute angle between the longitudinal axis of the structure and the direction of propagation of the earthquake. It is commonly used in seismic structural design. It is used to analyse the structural response to earthquake acceleration coming from various directions and to determine the most favourable orientation for construction (Sesigur et al., 2004; Banerjee Basu and Shinozuka, 2011).

During a study of the directional effect of strong ground motion on the seismic behaviour of bridges by Atak et al., (2014) it was established that there was a relationship between earthquake propagation direction and the response of the bridge. Atak et al. (2014) established that the excitation angle that produced maximum response was 90° (i.e. when the earthquake propagation direction was perpendicular to the longitudinal axis of the bridge) and the excitation angle that produced minimum damage was 0° (i.e. when the earthquake propagation direction was parallel to the longitudinal axis of the bridge).

Banerjee Basu and Shinozuka (2011) determined the effect of ground motion directionality on fragility characteristics of a highway bridge, finding that ground motion direction played a significant role in the estimation of maximum seismic response. In this study it was observed that the maximum seismic response of the bridge was when motions propagated between excitation angles 30° to 60°. López and Torres (1997) determined the minimum structural response in both major and minor axis to be at excitation angle 34° to 57°, with the maximum response in the major axis at 0° and maximum response in the minor axis at 90°.

Earthquake directional effect studies have been mainly conducted on structures with great length-base ratio for example bridges, pipelines and dam walls, However, a few studies have used the earthquake directional effect to determine the response of buildings under different excitation angles. Studies of earthquake directional effect on buildings have looked at the exposure of weak points to the earthquake direction and the orientations of building walls relative to the earthquake propagation direction.

Fernandez-Davila et al. (2000) conducted a study on the bi-directional effects and the seismic angle variations in building design. When the earthquake was projected along the major axis and minor axis, the maximum response was observed at excitation angles 0° and 90° respectively.

A study by Caselles et al. (2012) characterized the seismic response of Mallorca cathedral when the building was excited along the major axis and the minor axis. It was discovered that when the seismic wave was directed along the major axis, the building experienced more damage than when it was directed along the minor axis. This was because, along the major axis the building potential weak points, including large doors and windows, were exposed to the earthquake direction.

Magliulo et al. (2014) studied the influence of earthquake direction on the seismic response of irregular plan reinforced concrete frame buildings, establishing that the excitation angle significantly influenced the response of the buildings structures, the critical excitation angle (the excitation angle that produces the maximum response), provided an increase of up to 37% in terms of roof displacements. From this study the maximum response was obtained when the earthquake propagation direction was perpendicular to the external walls of the buildings.

2.6.3 Building response to excitation angle

The building response with respect to the earthquake force can best be explained in terms of force, pressure and equations of motion.

The orientation of the walls of the building relative to the earthquake direction can be modelled as a two-dimensional plane with components in the X and Y direction (Figure 2-14).

The long axis/major axis of the building can be assigned to the X axis. Hence the resultant acceleration vector (earthquake acceleration $\mathbf{a_g}$) will make an angle with respect to the long axis of the building. This is the excitation angle.

When the earthquake direction is parallel to the major axis of the building (zero excitation angle) the ground acceleration will only have one component with respect to the building, $\mathbf{a_g}=\mathbf{a_x}$ (Figure 2-14, Equation 2.1, 2.2 and 2.3). This will result in a maximum displacement in the X component of the building.

The walls that are perpendicular to the earthquake direction (in this case, the short walls of the building) will experience more force based on the Pressure equation 2.4. This equation states that when the area that is perpendicular to the direction of acceleration increases, the force will also increase since the area ‘A’ is directly proportional to force ‘F’. The maximum area is obtained when the earthquake propagation direction is perpendicular to the walls. For short walls of the building, the maximum area perpendicular to the earthquake direction is obtained at excitation angle 0° (Figure 2-14).

When the earthquake direction is parallel to the minor axis of the building (excitation angle 90º) the ground acceleration will only have one component with respect to the building, $\mathbf{a=a_y}$ this will result in maximum displacement in Y component of the building (Figure 2-14, Equation 2.1, 2.2 and 2.3). The walls that are perpendicular to the earthquake direction (in this case, the long walls of the building) will experience more force, because of the force based on pressure equation (Equation 2.4). For long walls of the building, the maximum area perpendicular to the earthquake direction is obtained at excitation angle 90° (Figure 2-14).

Components of the resultant ground acceleration:

$$a_g = a_x + a_y \tag{2.1}$$

X component of resultant ground acceleration:

$$a_x = a_g \cos\theta \tag{2.2}$$

Y component of resultant ground acceleration:

$$a_y = a_g \sin\theta \tag{2.3}$$

Force based on pressure:

$$p = F/A \tag{2.4}$$

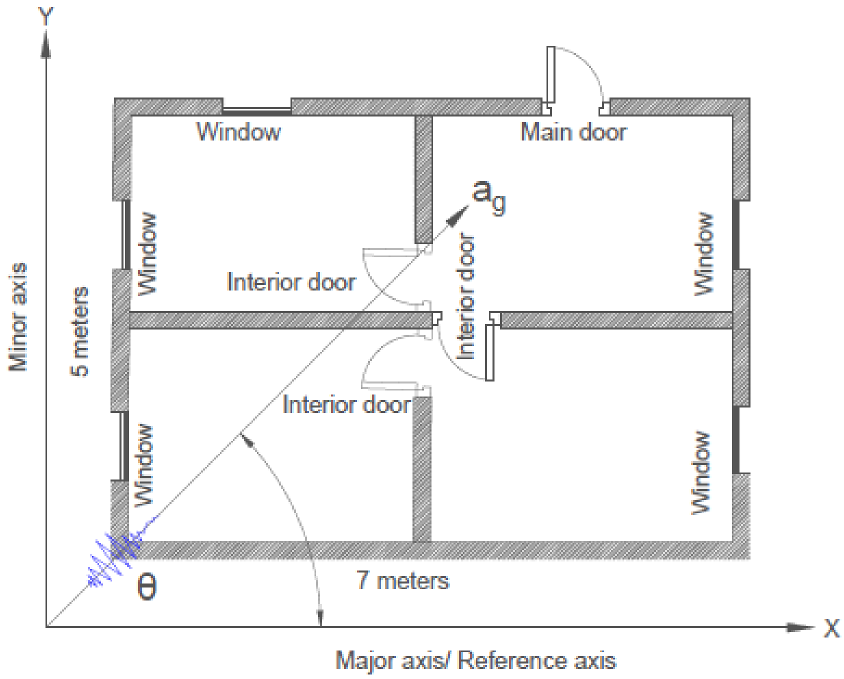


Figure 2-14: The interaction of ground acceleration with the major axis of the building.

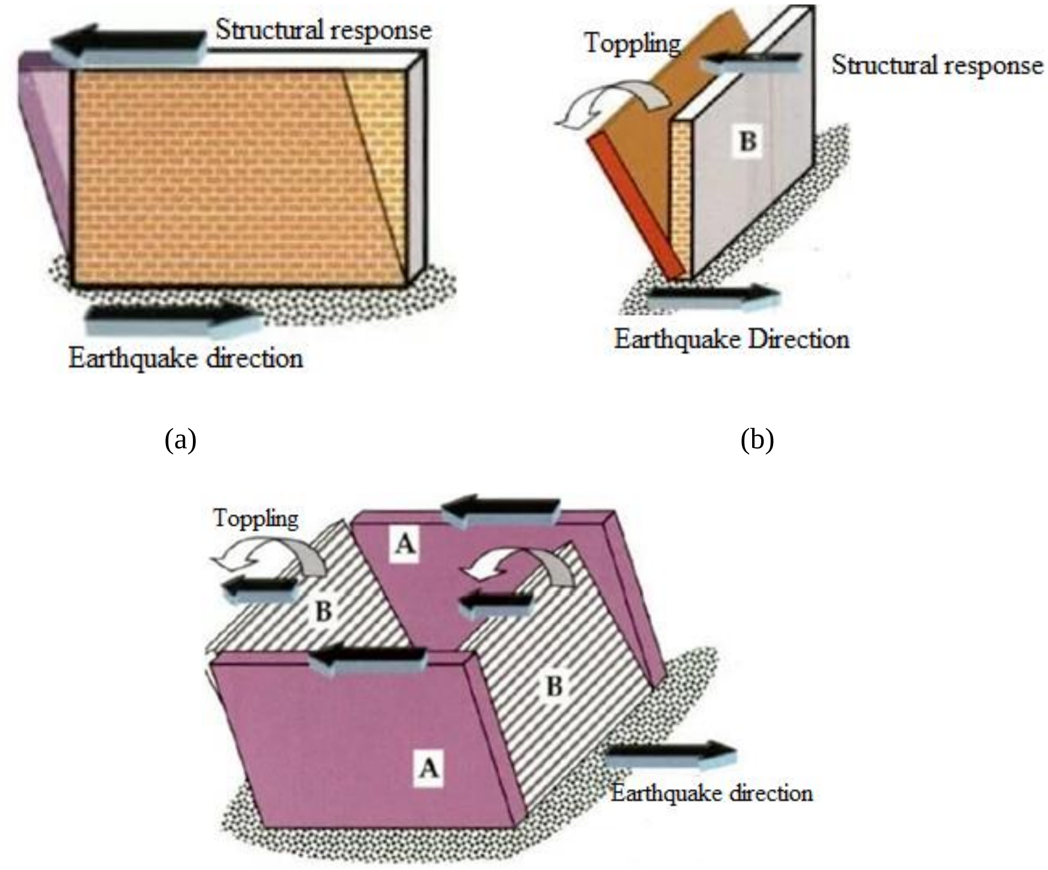
At excitation angle=0° and 90° the building experiences the most ground acceleration in X and Y, respectively.

According to a simple equation of motion

$$a = 2d/t^2. \tag{2.5}$$

Large ground acceleration will result in large displacement (Equation 2.5). Large displacements result in higher damage. Walls that are perpendicular to the earthquake direction experience higher acceleration resulting in higher displacement and they will be more likely to fail (Figure 2-15 b and c). Walls that are parallel to the earthquake direction have minimum area perpendicular to the earthquake direction, will experience minimum acceleration and displacements and they may not experience damage (Figure 2-15 a and c).

When the excitation angle is midway between the extremes of 0^o and 90^o the ground acceleration will have two smaller components (Equations 2.2 and 2.3). This will result in minor displacement in X and Y of the building implying that at an intermediate excitation angle, the building will be less vulnerable to earthquake damage (Figure 2-14).



(a) (b)

(c)

Figure 2-15: (a) Structural response for a wall parallel to the earthquake direction. (b) Structural response for a wall perpendicular to earthquake propagation direction may result in toppling (c). Walls labelled “A” are more resistant to earthquake acceleration because the area that is perpendicular to earthquake direction is minimum. Walls labelled“ B ” are more vulnerable to earthquake acceleration because the area that is perpendicular to earthquake direction is maximum. (Murty et al., 2012).

In unreinforced masonry buildings each wall has a maximum allowable displacement before damage occurs. A large displacement in one wall will result in a higher damage grade than smaller displacements in multiple walls (Maeda et al., 2004; Murty et al., 2012). This means that buildings that have some walls perpendicular to the earthquake direction will experience more damage. If none of the building walls are perpendicular to the earthquake direction, all the walls will experience smaller displacement and the building will experience lower damage.

Chapter 3 : Methodology

This chapter describes the research design, the type of data used and how the study was carried out, software used, methods for data collection and methods of data analysis. The data analysis section discusses the methods used for analysing and displaying data.

3.1 Research design

This research was a quantitative study using secondary data obtained from post field assessments and literature after the occurrence of the 2014 Orkney earthquake. The reasons for using secondary data were firstly, due to financial constraints of the project. Furthermore, since the earthquake occurred in the year 2014, most of the houses that had been damaged by the earthquake were presumably repaired, hence the damage grade data that would have been collected would be greatly distorted. However, a second field visit is recommended in future research, to increase the number of data points and to improve accuracy of the data collected.

Variables discussed in the previous chapters that would complicate an analysis of damage grade, like earthquake magnitude and depth, did not come into play since the damage to the houses was caused by the same single earthquake. Similarly, the geology beneath two of the townships Kanana and Jouberton, were similar (although Khuma. had different geology). In addition, the houses were located within close proximity of each, so differences in local geological conditions had a minimum effect on the damage grade.

The epicentral distance had a great effect on damage grade (see Figure 7-1 (a) in Appendix A) however it had a negligible difference within each township (see Figure 7-1 (b), (c), and (d) in Appendix A), therefore within each township a common epicentral distance could be adopted and variation in travel path effects was considered to be minimal.

Houses in these townships had a similar architectural design, approximately the same mass and were constructed using similar materials, therefore could be assumed that these factors had a similar effect on the grade of damage.

Statistical analyses were conducted on the datasets collected. The accuracy of the study was greatly dependent on the post-earthquake field assessments data .

3.2 Software

The following software packages were used for the data collection:

a) Google Earth and
b) ArcGIS

Google Earth was used to determine: the propagation direction of the earthquake from the epicentre, comprising the line of sight from the epicentre (LOSE), the direction of longitudinal axis (Dir (LA)) of the building, exposure of building weak points to the earthquake direction and details about the plastering finishes on the external walls.

Google Earth is software that renders a 3D representation of the earth, based on primary satellite imagery. It allows the users to view satellite images and aerial photography, to view structures and landscapes from various angles, and to obtain spatial data. .

ArcGIS is a geographic information system (GIS) software that works with maps and geographical information. This system is used for creating maps, compiling geographic data, and analysing mapped information.

ArcGIS was used to create the damage grade maps showing the extent of damage in each township and the positions of the affected buildings relative to the epicentre

3.3 Methodology for Data Collection and Analysis

Many aspects can be considered from the dataset hence the exploration and analysis of the data is best shown graphically in Figure 3-1.

The post field assessment conducted by Khoyratty (2016), specifically the coordinates of the damaged houses, were exported as a readable Google Earth file (*.*kmz*).

A remote-sensed field survey using Google Earth was conducted to collect the earthquake propagation and directional effect variables namely: the direction of the longitudinal axis of the building, exposure of weak points to earthquake direction and the external building finishes (either plastered or un-plastered).

The excitation angle could not be directly measured using any Google Earth tool, but was obtained for each house from the earthquake propagation direction and the direction of the longitudinal axis of the building.

Thereafter a graphical and spatial analysis of damage grade with respect to earthquake propagation and directional effect variables was done.

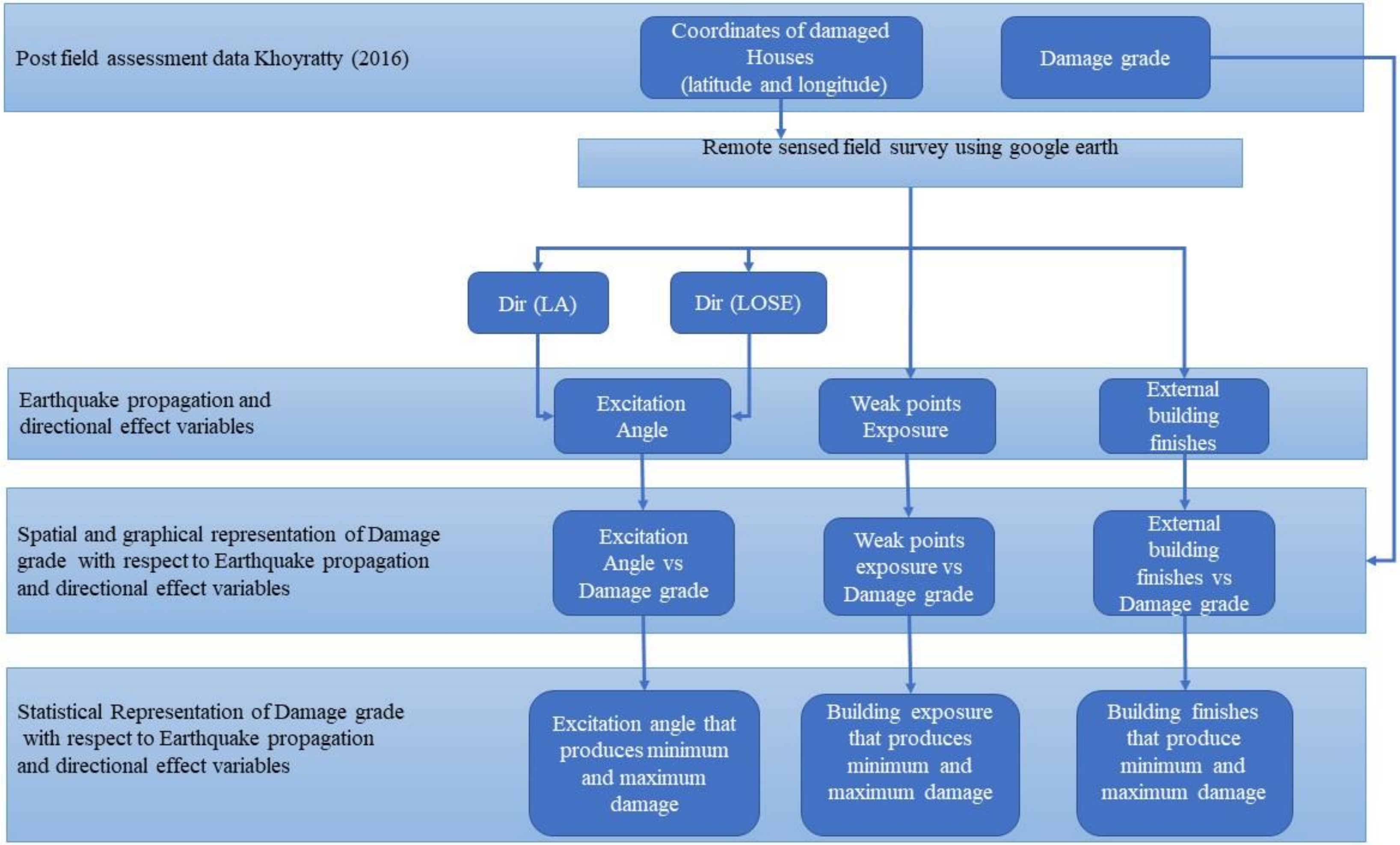


Figure 3-1: Flowchart of the steps involved data collection and analysis.

3.3.1 Building Floor Plan and Direction of Longitudinal axis (Dir (LA)

The floor plan for a low-cost house was obtained from the department of human settlements (2012). The outline was rectangular with an area of 35 m^2 (7 m length by 5 m width. The house comprised 2 bedrooms, a lounge and kitchen. The building had 5 external windows and a main door, with 3 internal doors (Figure 3-2). The front of the building had one main door and a window, while each side of the building had two windows. The back of the building had no windows or doors. All windows had an area of 1m^2 and all doors have an area of 1.6 m^2.

The direction of longitudinal axis (Dir (LA)) was taken as the direction of the longest side of the building relative to Grid North . Therefore, Dir (LA) of the building was the direction of the 7-meter side. This direction was measured in Google Earth.

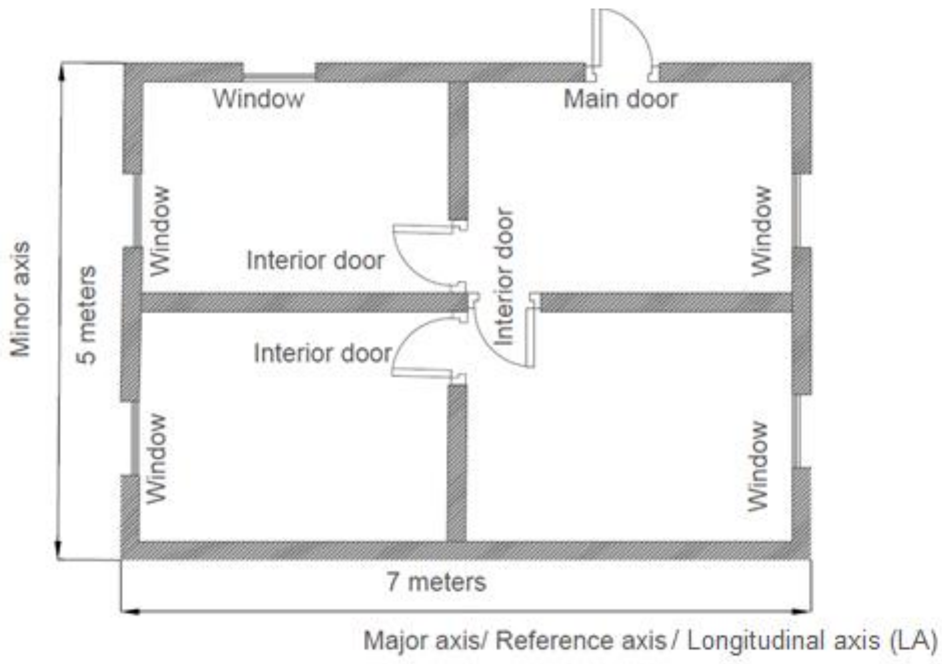


Figure 3-2: Low-cost house floor plan

3.3.2 Direction of propagation of the earthquake and Dir (LOSE)

Earthquakes of small magnitude are frequently generated by sources that can be represented by a single point, since the rupture only extends a few kilometres (Elnashai and Di Sarno, 2015). The 2014 Orkney earthquake was relatively small therefore it could be represented by a single point. The direction of propagation of an earthquake was sensed as direction from North of the line of sight from the epicentre (Dir (LOSE)) to the point of interest (Figure 3-3). This direction was obtained in Google Earth.

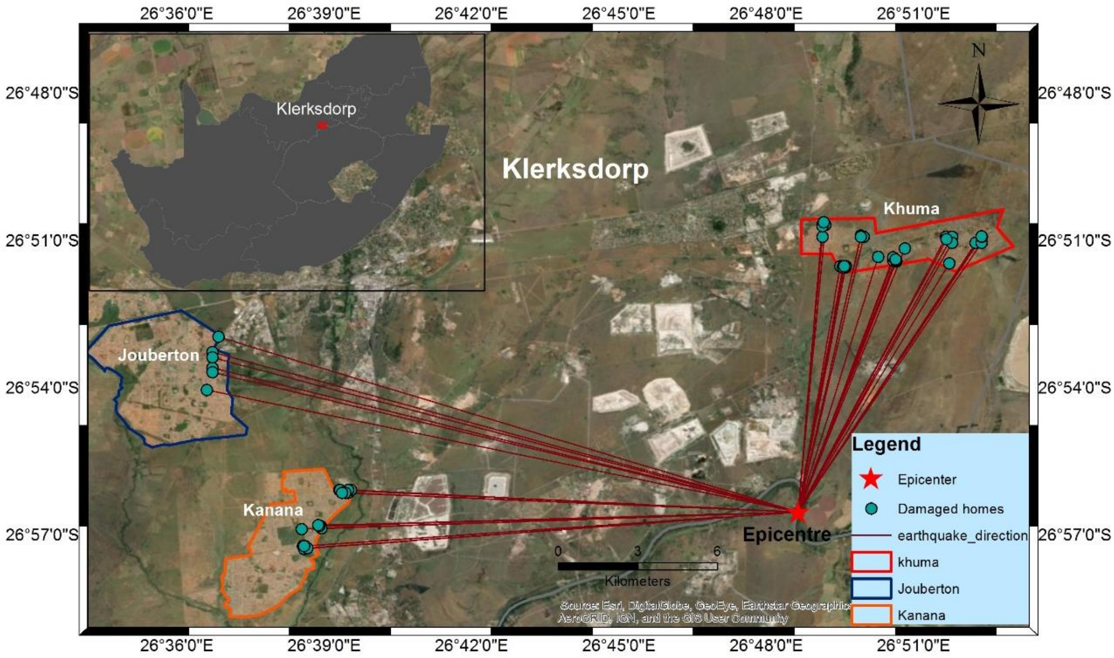


Figure 3-3: The propagation direction of an earthquake from the epicentre to the damaged buildings in Khuma, Kanana and Jouberton Townships

3.3.3 Methodology for determining excitation angle

Excitation angle is used to represent the orientation of the building walls relative to the earthquake direction. The method used to assign excitation angle in this study was that used by Magliulo et al. (2014) in assessing the response of the structure to the earthquake acceleration. In order to obtain excitation angle, the direction of the longitudinal axis of the building (Dir (LA)) (Figure 3-4) and the direction of line of sight for the epicentre the earthquake from the epicentre (Dir (LOSE)) must be determined. These were obtained in

Google Earth. Magliulo et al. (2014) used an excitation angle interval of 30° and measured the displacement as the response. In this study, excitation angle intervals of 30° were used and the excitation angle was compared with damage grade.

Excitation angle (θ) was obtained by subtracting direction of line of sight from the epicentre to the building Dir (LOSE) (Figure 3-5) from direction of the longitudinal axis of the building Dir (LA) or vice versa (Equation 3.1 and Figure 3-6). These directions were both measured in Google Earth.

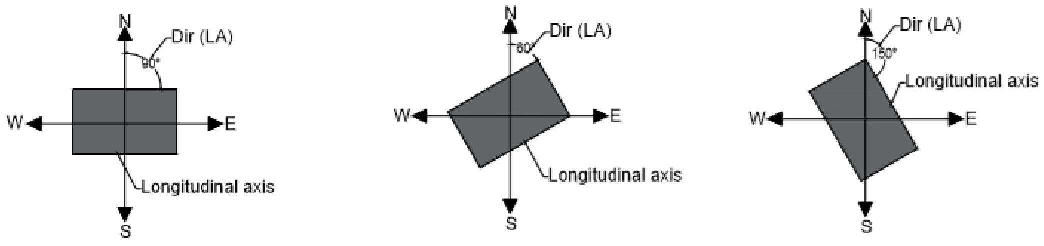
Buildings that had an excitation angle that was:

$0° \leq \theta \leq 30°$, had 2 external short walls perpendicular to the LOSE (Figure 3-6 c).

$30° < \theta \leq 60°$, had none of their walls perpendicular to the LOSE (Figure 3-6 a).

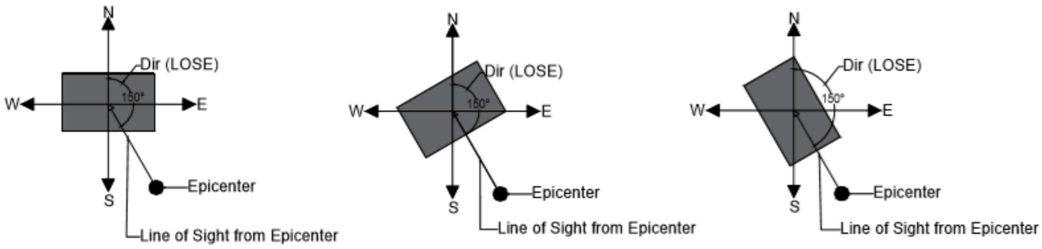
$60° < \theta \leq 90°$, had 2 external long walls perpendicular to the LOSE (Figure 3-6 b).

The minimum excitation angle was 0° (where the earthquake direction is parallel to the long axis of the building) (Figure 3-6 c) and the maximum excitation angle was 90° (where the earthquake direction was perpendicular to the long axis of the building)(Figure 3-6 b).



(a) (b) (c)

Figure 3-4: Directions of the longitudinal axis of the building Dir (LA) measured relative to True North.



(a) (b) (c)

Figure 3-5: Direction of line of sight from the epicentre to the building Dir (LOSE) with varying building orientations measured relative to True North.

Excitation angle θ is the smallest angle between the direction from the epicentre to the centroid of the house (Dir (LOSE)) and the direction of longitudinal axis for a building (Dir (LA)).

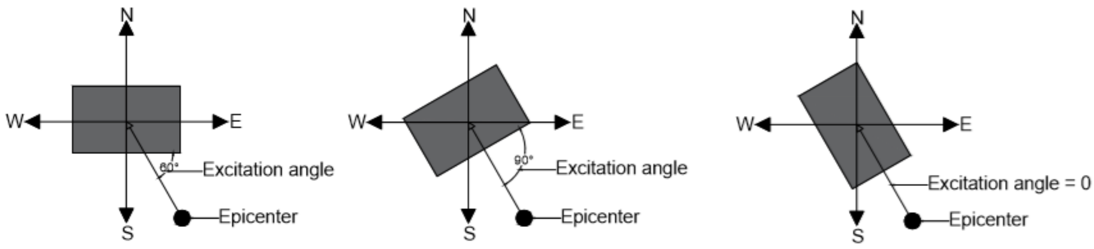
Equation 3.1:

$Dir\ (LA) = Direction\ of\ the\ longitudinal\ axis\ of\ the\ building\ .$

$Dir\ (LOSE) = Direction\ of\ line\ of\ sight\ from\ the\ epicenter.$

$Dir\ (LOSE) \geq Dir\ (LA) \qquad \theta = Dir\ (LOSE) - Dir\ (LA)$

$Dir\ (LOSE) < Dir\ (LA) \qquad \theta = Dir\ (LA) - Dir\ (LOSE)$



(a) (b) (c)

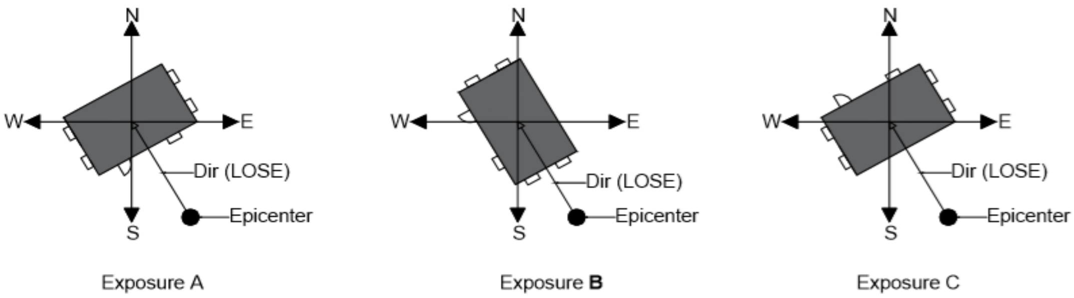
Figure 3-6: Variations of the excitation angle. Left: none of the walls are perpendicular to LOSE. Middle: Two long walls are perpendicular to LOSE. Right: 2 short walls are perpendicular to Dir (LOSE)

Accuracy of excitation angle

For excitation angle 0°-30°, the long walls of the building were considered to be parallel to the earthquake propagation direction. This assumption was most accurate for excitation angle 0°, and became less true for greater excitation angle up to excitation angle 30°. In a building with excitation angle 31°-60°, none of the building walls were parallel to the earthquake direction, In buildings with excitation angle 61°-90°, the short walls of the building were deemed parallel to the earthquake propagation direction. This approximation was exact for excitation angle 90°, and became least accurate at excitation angle 61°.

3.3.4 Methodology for assigning exposure of building weak points

Buildings that had one window and one door exposed to the Dir (LOSE) were assigned "Exposure A." Exposure A was then for buildings where the entrance faced the epicentre (Figure 3-7 a). Buildings with 2 windows exposed to the Dir (LOSE) were assigned "Exposure B", Exposure B was then where the entrance faced perpendicular to the earthquake direction (Figure 3-7 b). Buildings with none of their weak points facing the epicentre were assigned "Exposure C", Exposure C was then for buildings with enterence facing away from the epicentre (Figure 3-7 c).



(a) (b) (c)

Figure 3-7: Exposure of building weak point. (a)Exposure A, 2 building weak points (1 window and 1 door) are exposed to Dir (LOSE). (b) Exposure B, 2 building weak points (2 windows) are exposed to Dir (LOSE). (c)Exposure C, none of the building weak points are exposed to Dir (LOSE).

3.3.5 Methodology for identifying building finish details

The building finish variable referred to whether plaster was present on the external wall of a low-cost house (Figure 3-8 a and b). Google Earth was used to view the external walls where possible.

(a) (b)

Figure 3-8: External building finishes, (a)Plastered house. (b) Un-plastered house (Khoyratty, 2016).

3.3.6 Damage grade Classification to masonry buildings

The damage grade data for this study was obtained from the post field assessment conducted by Khoyratty (2016), who classified the damage grade in masonry buildings using the EMS classification. This method classifies damage grade into 6 categories, ranging from 0 to 5.

- Damage grade 0 indicates no damage
- Damage grade 1 indicates negligible to slight damage (hair line cracks in very few walls and fall of small pieces of plaster)
- Damage grade 2 indicates moderate damage (cracks in many walls and fall of large pieces of plaster)
- Damage grade 3 indicates substantial to heavy damage (large and excessive cracks in most walls, roof tiles detach and failure of individual non-structural elements)
- Damage grade 4 indicates very heavy damage (serious failure of walls and partials structural failure of roof and foundation)
- Damage grade 5 indicates destruction (total or near collapse)

Since this study correlated damage grade to other variables and small differences in damage were involved, damage grade was converted to percentage. This scaling change avoided presenting results in terms of decimal fractions. The categories of damage grades converted to percentage are expressed below.

- Damage grade 0 is 0%
- Damage grade 1 is 20%
- Damage grade 2 is 40%
- Damage grade 3 is 60%
- Damage grade 4 is 80%
- Damage grade 5 is 100%

3.3.7 Methodology for data Analysis

The collected data was collated for all affected houses in terms of their damage grade and experimental variables. The data could then be analysed to establish the relationship between excitation angle and damage grade for display in tables, graphs and maps. Damage grade maps were prepared using ArcMap showing damage grade, position of the houses, excitation angle, building weak points exposure and building finishes.

The excitation angle results were presented as a relationship between excitation angle (θ), the number of damaged houses and as the relationship between excitation angle (θ) and average damage grades.

The weak point exposure results were presented as a relationship between building exposure, number of damaged houses and as the relationship between building exposure and average damage grade.

The plastering finishes results were presented as a relationship between plastering finish and number of damaged houses and as the relationship between plastering finish and average damage grade.

As stated in section 3.1, each township was studied separately to eliminate the local geological conditions effect and distance and travel path effects. As a final outcome, the variable values that produced the least damage were isolated for recommending in low-cost housing construction in mining-affected areas.

Chapter 4 : Results and analysis

This chapter reports the data collected on the variables described in the previous chapter. These data are analysed to establish the relationships between the variables, displayed in form of tables, graphs and maps.

The experimental variables for this study were excitation angle, building weak-points exposure and external building finishes. These were tested against damage grade. For each variable, the number of damaged houses and the weighted average damage were determined . The weighted average damage grade was calculated by taking the sum of multiplying the number of houses with a certain damage grade with that damage grade and divided by the total number of damaged houses, See (4.1) below.

$$W = \frac{n20(20)+n40(40)+n60(60)+n80(80)+n100(100)}{n20+n40+n60+n80+n100} \text{..........................(4.1)}$$

Where: **W** is the weighted average damage grade.

n is the number of houses at with a certain damage grade e.g., <u>n20</u> is the number of houses with <u>damage grade 20</u>.

The weighted average damage grade was then used to determine seismic vulnerability.

The excitation angle (θ) results were represented as a relationship between excitation angle (θ) and number of damaged houses, and average damage grade. The weak-points exposure results were represented as a relationship between "Exposure", number of damaged houses and the average damage grade. The external building finishes results were represented as a relationship between building finishes, the number of damaged houses, and average damage grade. As stated in chapter 3, each township was studied separately to eliminate the effect of local geological conditions and distance and travel path effects.

A study conducted by Khoyratty (2016) surveyed a total of 57 houses in the townships of Khuma, Kanana and Jouberton, during the earthquake post field assessment.The average epicentral distance from these townships were 10 km, 18 km, and 23 km for Khuma, Kanana and Jouberton, respectively. The highest levels of damage were recorded in Khuma. The number of dwellings documented as damaged were 32 in Khuma, 17 in Kanana and 8 in Jouberton.

4.1 The Directional Effect Variables

The results for the variables tested are shown in Table 7-1,Table 7-2 and Table 7-3 in Appendix B for the township of Khuma, Kanana and Jouberton respectively . These results were collected as described in the Methodology section and summarized in Figure 3-1.

As explained in the methodology chapter (chapter 3) the variables tested were: excitation angle, building weak points exposure and external building. These variables were tested against damage grade. As explained, the excitation angle described the orientation of the building walls relative to the earthquake propagation direction.

Buildings with an excitation angle of 0° to 30° or 61° to 90° had two external walls roughly perpendicular to the Dir (LOSE) while buildings with excitation angle of 31° to 60° were considered to have none of their walls perpendicular to the Dir (LOSE).

The building finishes variable referred to the presence or absence of plaster on the external walls of the house.

4.2 Effect of excitation angle on damage grade

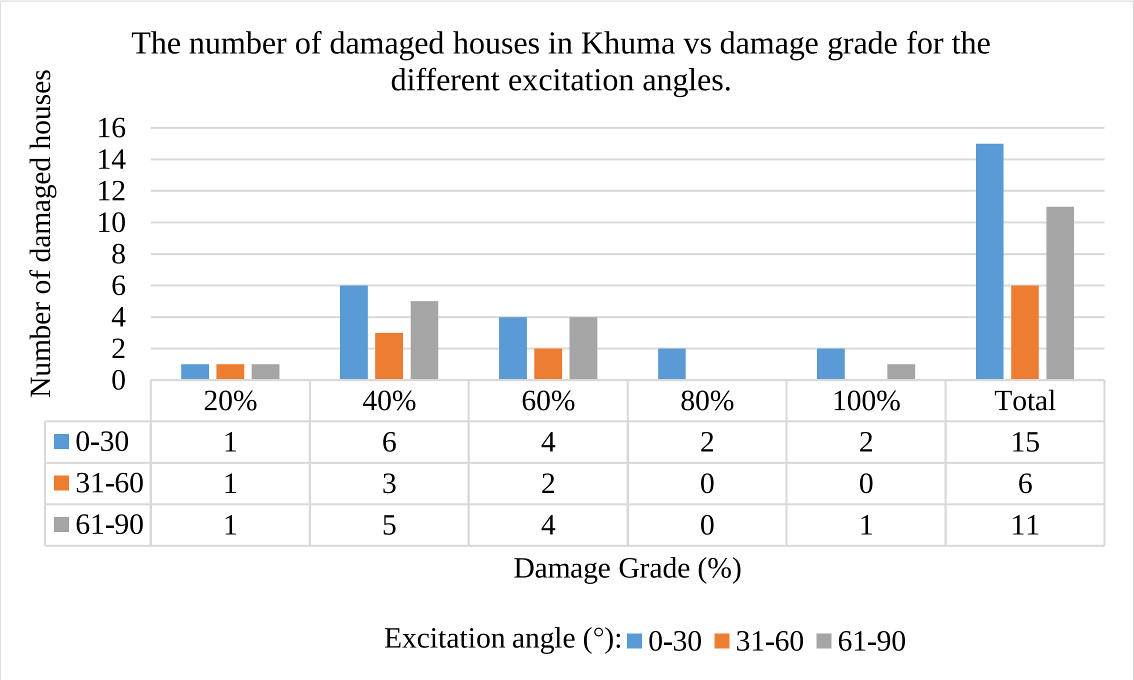
4.2.1 Khuma: Graphical and spatial representation of excitation angle and damage grade

Khuma township experienced the most damage from the 2014 Orkney earthquake, since it was the closest settlement to the epicentre, with an average epicentral distance of 10 km (Appendix C, Figure 7-2). The highest number of damaged houses in this study were observed in Khuma, with a total of 32. The graphs and maps produced indicate the number of damaged houses and the damage grade (intensity). The damage grade data was interpolated using the kriging technique in ArcGIS.

The map of damage in Khuma(Appendix C, Figure 7-2) shows that the highest number of damaged houses was for excitation angle 0° - 30° while the second highest number of damaged houses was observed for excitation angle 61°- 90°. The excitation angle 31° - 60° had the least number of damaged houses. Excitation angles 0° - 30° had the most houses with damage grade 80 and 100% (Appendix C, Figure 7-2). From this map three zones of high levels of damage grade can be observed. In all three zones these houses with high damage had excitation angles of 0° - 30° and 61°- 90°. Two damage zones on the west showed damage grades of 100%.

Figure 4-1 provides the same information as the map however the variable relations can be seen quantitatively. For example, the total number of damaged houses with excitation angle 0°- 30° was 15, while excitation angle 31° - 60° had 6 damaged houses and excitation angle 61° - 90° had 11 damaged houses.

In terms of damage grade 100%, 2 damaged houses had excitation angle 0°- 30° and 1 damaged house had excitation angle 61°- 90°. Damage grade 80% had only 2 damaged houses, with excitation angle 0°- 30°. For damage grade 60%, excitation angle 0°- 30° and 61°- 90° had the same number (4) of damaged houses while excitation angle 31°- 60° had 2 damaged houses. For damage grade 40%, there were 6, 3 and 5 damaged houses for excitation angles 0°- 30°, 31°- 60°, and 61°- 90° respectively. For damage grade 20% all excitation angles had 1 damaged house.



	20%	40%	60%	80%	100%	Total
0-30	1	6	4	2	2	15
31-60	1	3	2	0	0	6
61-90	1	5	4	0	1	11

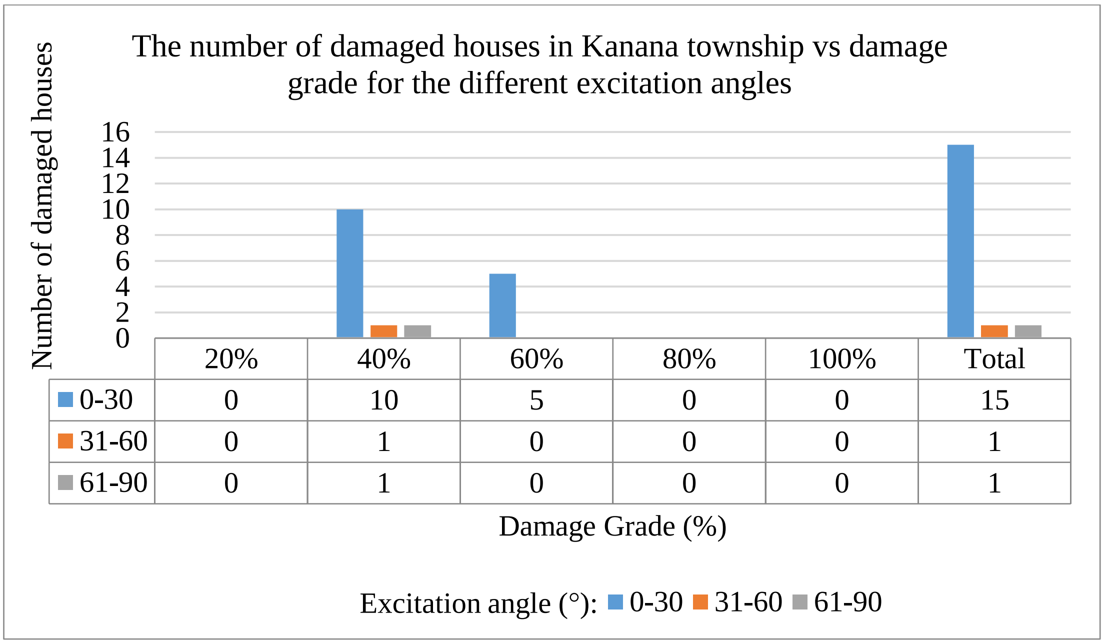
Figure 4-1: Number of damaged houses classified according to excitation angle and damage grade in Khuma

4.2.2 Kanana: Graphical and spatial representation of excitation angle and damage grade

Kanana was the second most damaged township during the 2014 Orkney earthquake, with an average epicentral distance of 18 km and a total of 17 damaged houses (Figure 7-3 in Appendix C). The graphs and maps produced indicate the number of damaged houses and the damage grade. The damage grade data was interpolated with the kriging technique in ArcGIS.

In Kanana, the map (Figure 7-3 in Appendix C) shows that most damaged houses had damage grade 20%. The highest number of damaged houses was observed for excitation angle 0° - 30°. The excitation angle 31° - 60° and 61°-90° had the least number of damaged houses. Excitation angles 0° - 30° had the most houses with damage grade 40% and 60% (Figure 7-3 in Appendix C). From this map two zones of high levels of damage grade can be seen, and in both zones the damaged houses had excitation angles of 0° - 30°. The damage zones showed damage grade of up to 60%.

Figure 4-2 provides the same information as the map in Figure 7-3, but with the variable relations being given quantitatively. For example, the total number of damaged houses with excitation angle 0°-30° was 15 and both excitation angles 31°-60° and 61°-90° had 1 damaged house. For damage grade 60%, there were only 5 damaged houses, all with excitation angle 0°-30°. For damage grade 40% there were 10 damaged houses for excitation angle 0°-30° and both excitation angle 31°-60° and 61°-90° had 1 damaged house.



	20%	40%	60%	80%	100%	Total
0-30	0	10	5	0	0	15
31-60	0	1	0	0	0	1
61-90	0	1	0	0	0	1

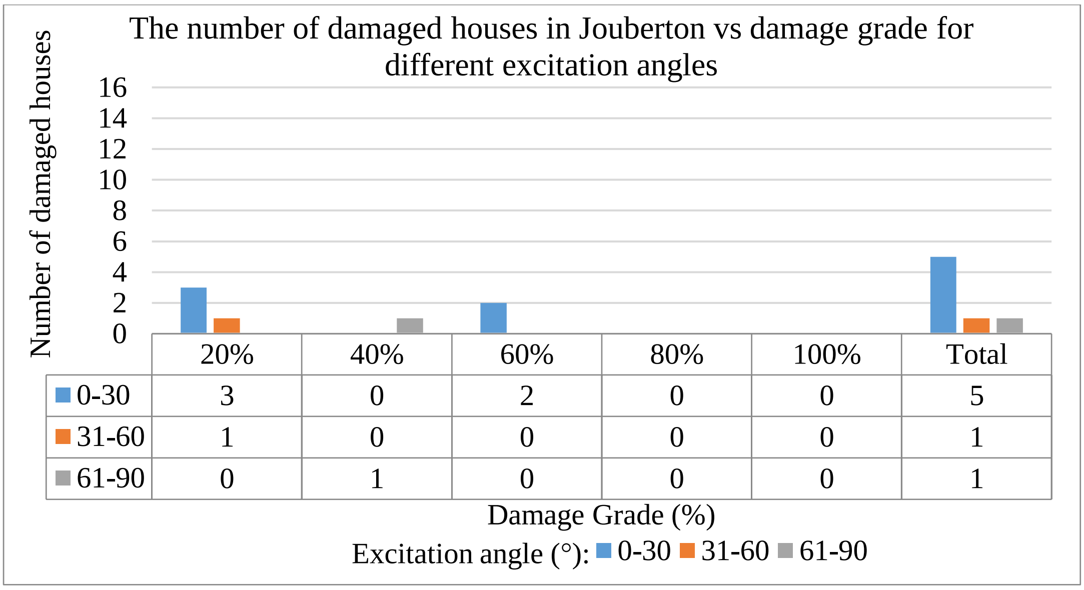
Figure 4-2: Number of damaged houses classified according to excitation angle and damage grade in Kanana.

4.2.3 Jouberton: Graphical and spatial representation of excitation angle and damage grade

Among the three settlements investigated, Jouberton experienced the least amount of damage from the 2014 Orkney earthquake, being furthest from the epicentre, with an average epicentral distance of 23 km (Figure 7-4 in Appendix C). The lowest number of damaged houses in this study are observed in Jouberton, with a total of 7 damaged houses. The graphs and maps produced indicate the number of damaged houses and the damage grade.

The map (Figure 7-4 in Appendix C) shows that the highest number of damaged houses in Jouberton were for excitation angle 0° - 30°. Both excitation angle 31° - 60° and 61°-90° had 1 damaged house, with damage grade 20% and 40% respectively. Excitation angles 0° - 30° had the most damaged houses for damage grade 60%. From this map, a zone of high levels of damage grade can be observed, the houses in this zone having excitation angles of 0° - 30°. This damage zone at grade of 60% is shown.

Figure 4-3 provides the same information as the map in (Figure 7-4 in Appendix C), but given quantitatively. For excitation angle 0°-30° there were 5 damaged houses. Excitation angle 61°-90° and 31°-60° there was 1 damaged house for each (Figure 4-3). For damage grade 60% there were only 2 damaged houses both with excitation angle 0°-30°. For damage grade 40% there was only 1 damaged house and it had excitation angle 61°-90°. For damage grade 20% there were 3 damaged houses with excitation angle 0°-30° and 1 damaged house for excitation angle 31°-60°.



	20%	40%	60%	80%	100%	Total
0-30	3	0	2	0	0	5
31-60	1	0	0	0	0	1
61-90	0	1	0	0	0	1

Figure 4-3: Number of damaged houses classified according to excitation angle and damage grade in Jouberton.

4.2.4 Khuma: Statistical representation of excitation angle and damage grade

Table 4-1 and Figure 4-4 provide the relationships between the excitation angle and weighted average damage grade, minimum and maximum damage grade in Khuma.

- The damage grade for excitation angle 0°-30° ranged from 20% to 100% with the highest weighted average damage grade being 60%.
- Excitation angle 31°-60° produced damage grades ranging from 20% to 60% and the lowest weighted average damage grade of 40%.
- The damage grade for excitation angle 61°-90° ranged from 20 % to 100% and second highest weighted average damage grade of 50%.
- From excitation angle 0°-30° to 31°-60°, the weighted average damage grade decreased by 20% while it increased by 10% between excitation angle 31°-60° and 61°-90°.

Table 4-1: Shows the minimum, maximum, mode and average damage grade observed in Khuma for all the excitation angles

Excitation Angle (°)	Damage Grade (%)				
	Minimum	Maximum	Mode	Mean	STD
0-30	20	100	40	60	25
31-60	20	60	40	40	15
61-90	20	100	40	50	20

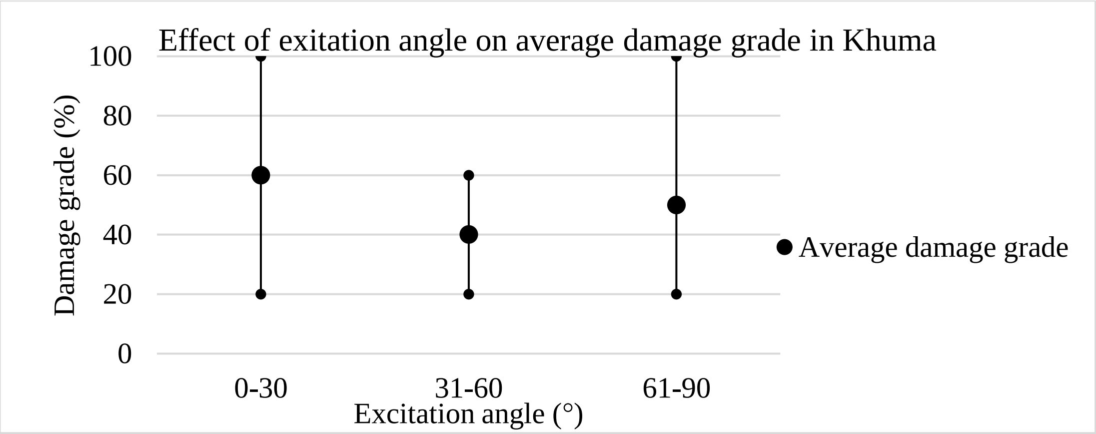


Figure 4-4: The minimum, maximum and average damage grade percentage for the respective excitation angle in Khuma.

4.2.5 Kanana: Statistical representation of excitation angle and damage grade

The data was too sparse and not enough to do any statistics for excitation angle in Kanana.

4.2.6 Jouberton: Statistical representation of excitation angle and damage grade

The data was too sparse and not enough to do any statistics for excitation angle in Jouberton

4.2.7 Summary: Excitation angle versus damage grade

In all three townships excitation angle 0°-30° had the greatest number of damaged houses (Figure 4-5). In Khuma excitation angle of 31°-60° produced the least number of damaged houses; In Kanana, excitation angles of 31°-60° and 61°-90° experienced the fewest damaged houses and in Jouberton, excitation angle of 31°-60° had the fewest damaged houses. To summarise, in all three townships excitation angle of 31°-60° had the fewest damaged houses (Figure 4-5).

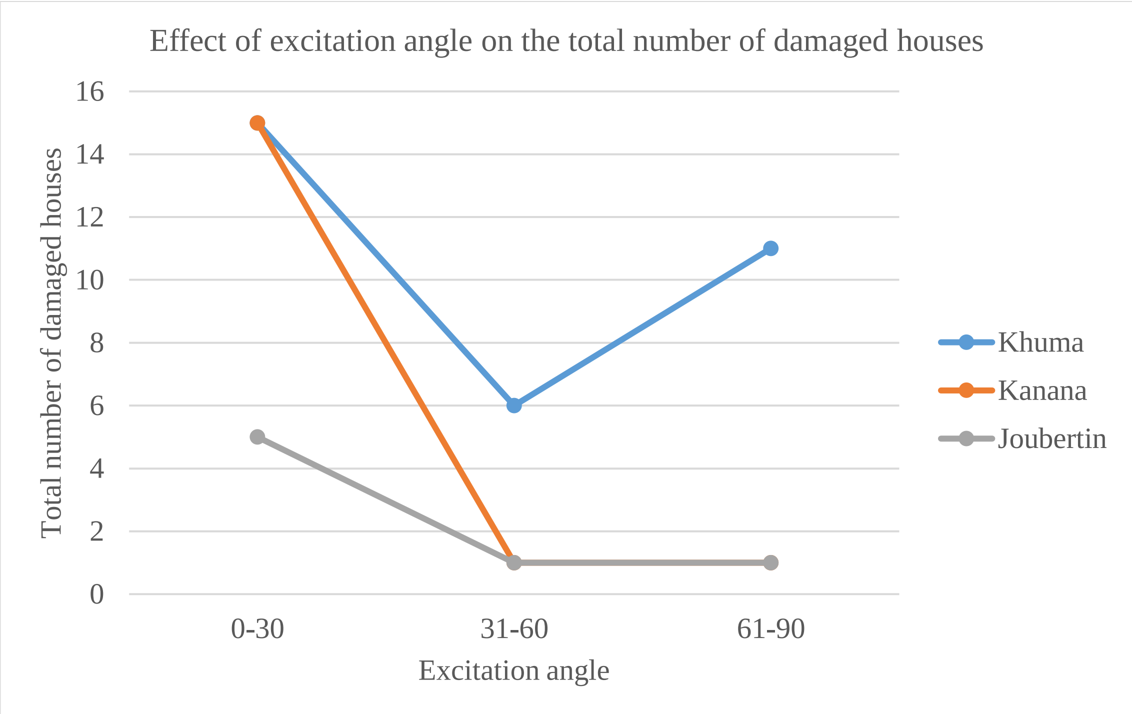


Figure 4-5: Total number of damaged houses classified according to excitation angle in all affected townships.

In Khuma township excitation angle 0°-30° had the highest weighted average damage grade (Figure 4-6). The lowest weighted average damage grade, In Khuma corresponded to excitation angle of 31°-60° In Kanana and Jouberton the data was too sparse and not enough to do any statistics for excitation angle.

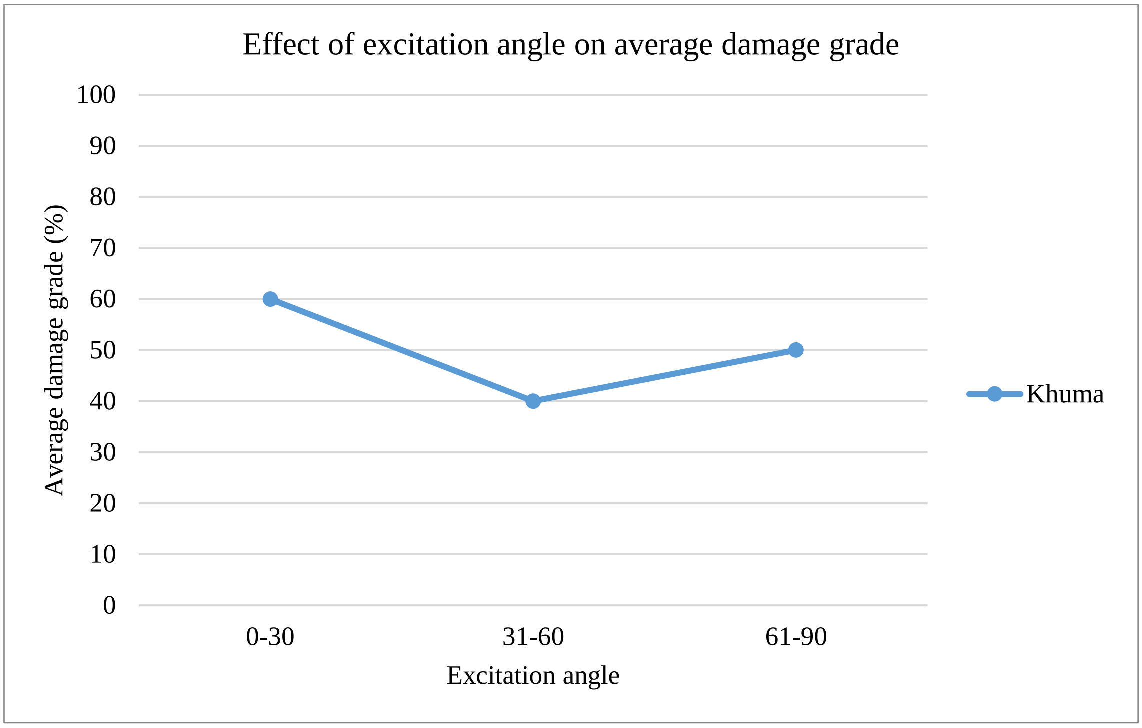


Figure 4-6: Effect of excitation angle on the average damage grade in Khuma.

From the results obtained in this section, the most vulnerable excitation angle on low-cost houses was 0°-30°. since this angle recorded the highest number of damaged houses in all townships and the highest weighted average damage grade in Khuma. The most favourable angle on low-cost houses was excitation angle 31°-60°; this angle recorded the lowest number of damaged houses in all townships and the lowest weighted average damage grade in Khuma.

The average difference in damage grade between the most and the least favourable excitation angle exposure was 15%.

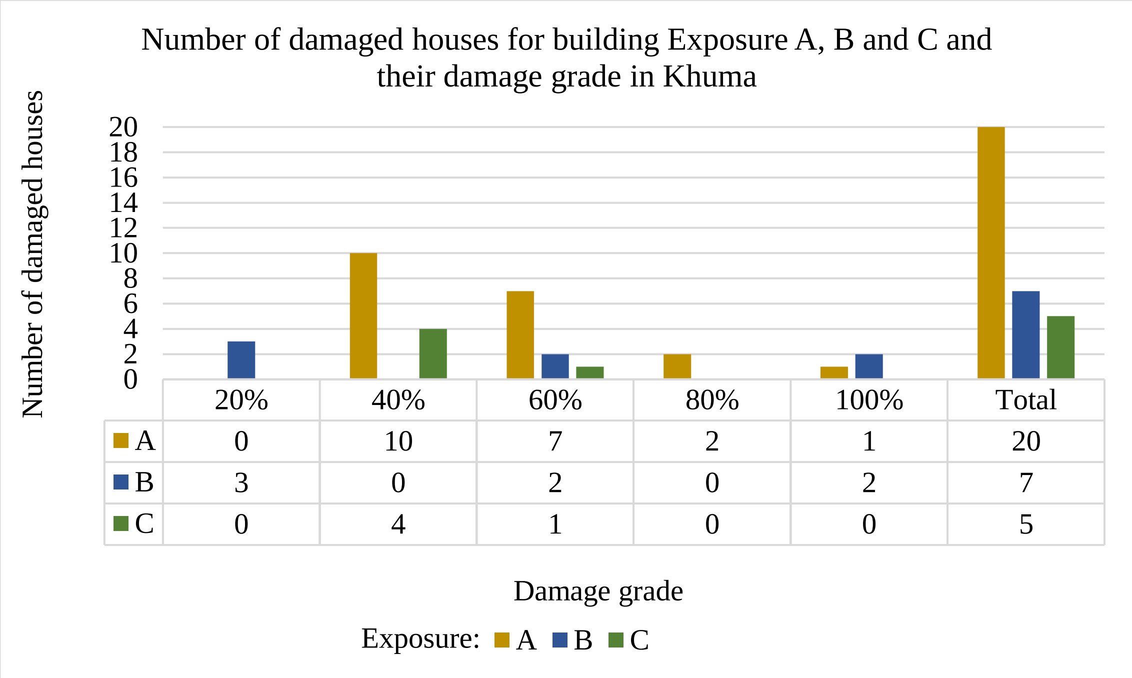
4.3 Effect of building weak-points exposure on damage grade

As described in chapter 3, the label "Exposure A" was applied to buildings with a single door and a single window facing the epicentre. "Exposure B" was applied to buildings with 2 windows facing the epicentre and "Exposure C" to buildings with no weak-points in the form of doors or windows, facing the epicentre.

4.3.1 Khuma: Graphical and spatial representation of building weak points exposure and damage grade

In Khuma, the map (Appendix D, Figure 7-5) shows that the highest number of damaged houses was for exposure A, the second highest number for exposure B and the least number of damaged housed for Exposure C. Exposure A and B had the most houses damaged at grade 80 and 100% (Appendix D, Figure 7-5). From this map three zones of high levels of damage grade can be observed. In all three zones one will find that these houses had exposure A and B. The two damage zones on the West had damage grades of 100% and the damage grade zone on the East had 80% damage grade.

Figure 4-7 provides the same information as the map but with variable relations given quantitatively. For example, the total number of damaged houses with the exposure A was 20, while exposure B had 7 damaged houses and exposure C had 5 damaged houses. For damage grade 100%, there was 1 damaged house with exposure A and 2 damaged houses with exposure B. Damage grade 80% had only 2 damaged houses, both with exposure A. For damage grade 60%, exposure A had 7 damaged houses, exposure B had 2 damaged houses and exposure C, one damaged house. For damage grade 40%, there were 10, 0 and 4 damaged houses for exposures A, B, and C, respectively. For damage grade 20%, there were only 3 damaged houses, all with exposure B.



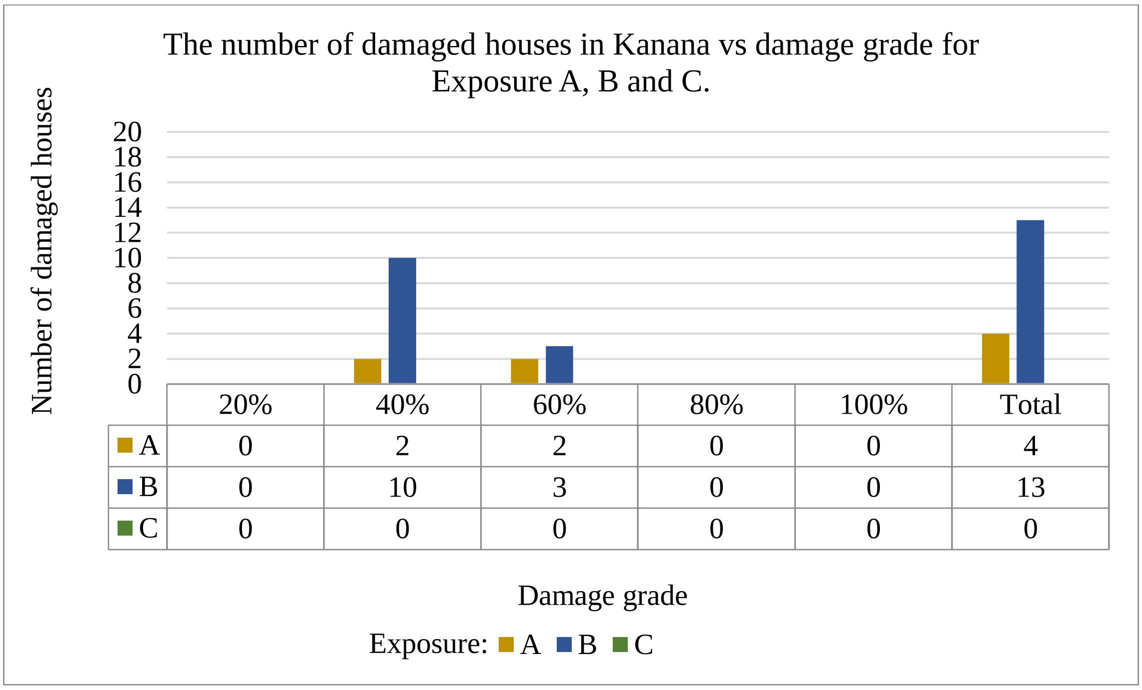
	20%	40%	60%	80%	100%	Total
A	0	10	7	2	1	20
B	3	0	2	0	2	7
C	0	4	1	0	0	5

Figure 4-7: Number of damaged houses classified according to Exposure and damage grade in Khuma.

4.3.2 Kanana: Graphical and spatial representation of building weak points exposure and damage grade

In Kanana, the map (Figure 7-6 in Appendix D) shows that most damaged houses suffered damage grade 40%. The highest number of damaged houses was observed for exposure B. There were no damaged houses with exposure C. Exposure B had the most damaged houses for damage grade 60% (Figure 7-6 in Appendix D). From this map two zones with high levels of damage grade can be observed, in both zones one will find that these houses had exposure B. The two damage zones showed damage grade of up to 60%.

Figure 4-8 provides the same information as the map in Figure 7-6, however the variable relations can be seen quantitatively. The total number of damaged houses with exposure A was 4, exposure B had a total of 13 damaged houses and exposure C had no damaged house. For damage grade 60%, there were 2 damaged houses with exposure A and 3 houses with exposure B. For damage grade 40% there were 2 damaged houses with exposure A and 10 damaged houses with exposure B.



	20%	40%	60%	80%	100%	Total
A	0	2	2	0	0	4
B	0	10	3	0	0	13
C	0	0	0	0	0	0

Figure 4-8: Number of damaged houses classified according to exposure and damage grade in Kanana.

4.3.3 Jouberton: Graphical and spatial representation of building weak points exposure and damage grade

Jouberton experienced the least damage from the 2014 Orkney earthquake, being the furthest from the epicentre, with an average epicentral distance of 23 km (Figure 7-7 in Appendix D) and the fewest (7) damaged houses. The graphs and maps produced indicate the number of damaged houses and the damage grade.

The map for Jouberton (Figure 7-7 in Appendix D) shows that the highest number of damaged houses had exposure B. Exposure A and C had the same number of damaged houses. Exposure A and B both had 1 house at damage grade 60%. From this map, a zone of high levels of 60% damage grade can be observed, in this zone, houses had exposures A or B.

Figure 4-9 provides the same information as the map in (Figure 7-7 in Appendix C), but quantitatively. The total number of damaged houses for exposure A was 2, 3 damaged houses had exposure B and 2 had exposure C. For damage grade 60%, exposure A and B had one damaged house. For damage grade 40% there was only 1 damaged house with exposure A. For damage grade 20%, exposure B and C each had 2 damaged houses.

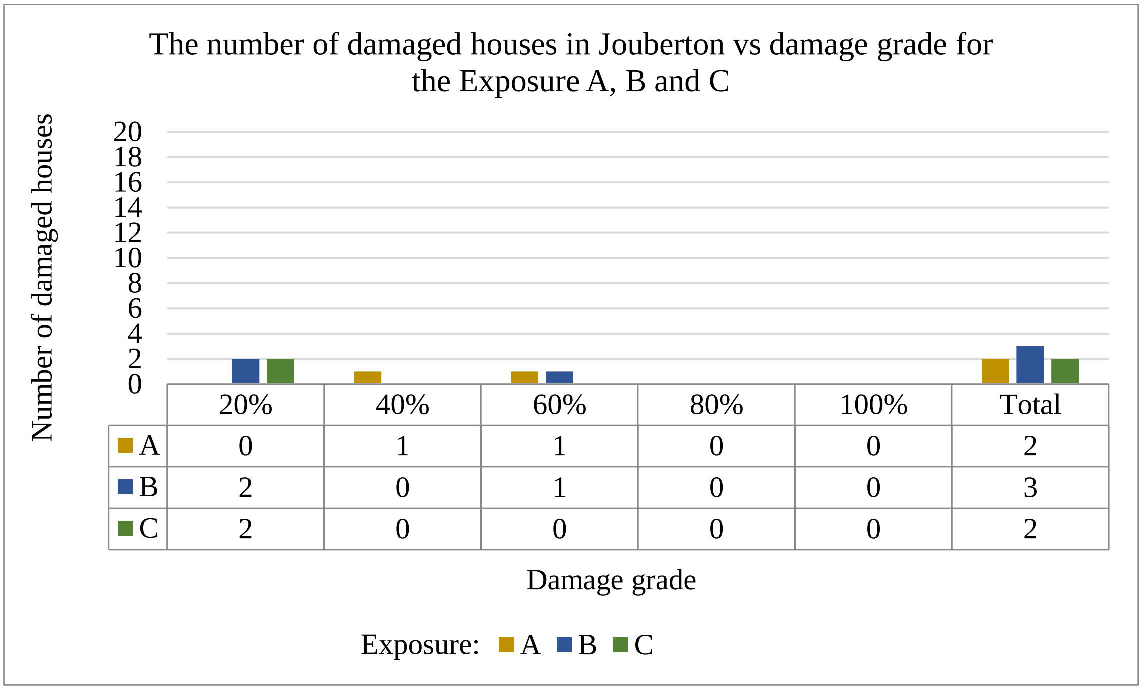


Figure 4-9: Number of damaged houses classified according to Exposure and damage grade in Jouberton.

4.3.4 Khuma: Statistical representation of building weak point exposure and damage grade

Table 4-2 and Figure 4-10 in show the relationships between building weak-point exposure and the weighted average damage grade, minimum and maximum damage grade in Khuma.

- The damage grade for exposure A ranged from 40% to 100% and tied with exposure B for the highest weighted average damage grade of 50%.
- The damage grade for exposure B ranged from 20% to 100% and tied with exposure A for the highest weighted average damage grade of 50%.
- Exposure C damage grade ranged from 40% to 60% and had the lowest weighted average damage grade of 40%.
- From these results, exposure C was the least vulnerable to earthquake damage and exposure A and B were the most vulnerable.

Table 4-2: Shows the minimum, maximum, mode and average damage grade observed in Khuma for Exposure A, B and C

Exposure	Damage Grade (%)				
	Minimum	Maximum	Mode	Mean	STD
A	40	100	40	50	20
B	20	100	20	50	40
C	40	60	40	40	10

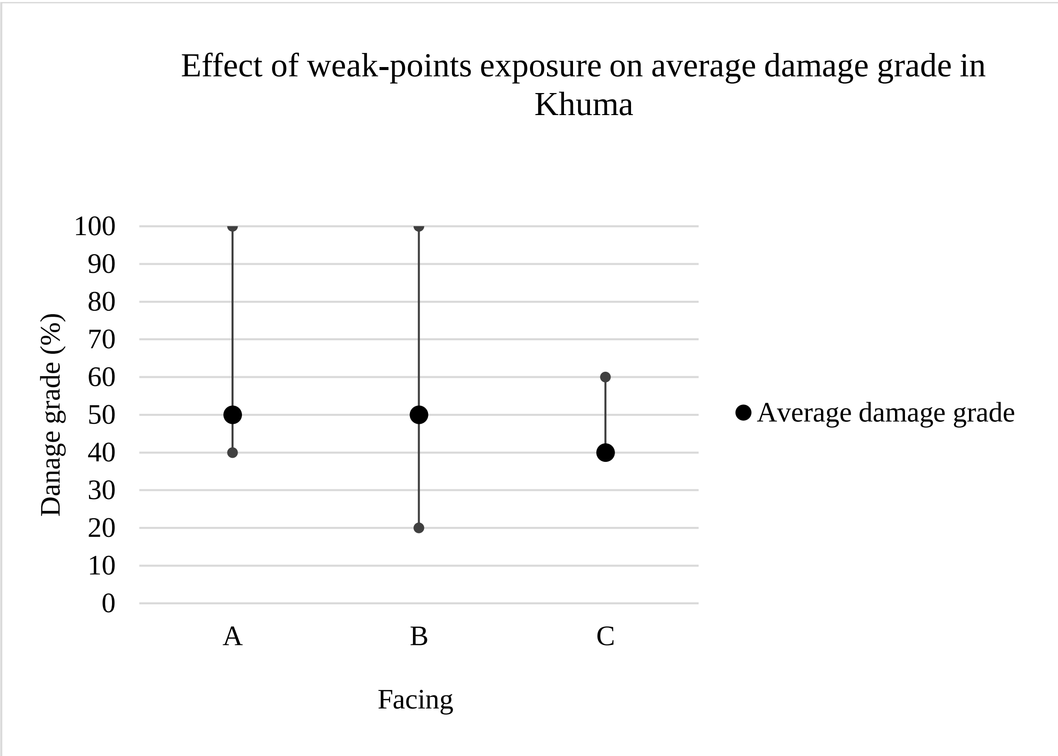


Figure 4-10: Average damage recorded for Exposure A, B and C in Khuma

4.3.5 Kanana: Statistical representation of building weak points exposure and damage grade

Table 4-3 and Figure 4-11 provide the relationships between the building weak-points exposure and the weighted average damage grade, minimum and maximum damage grade in Kanana.

- Exposure A and B both had damage ranging from 40% to 60% with the highest weighted average damage grade of 50%.
- There was no damage observed for exposure C.

- In Kanana since there were no damaged houses with exposure C while exposures A and B had the same weighted average damage grade. Thus exposure C has the lowest weighted average damage grade.

Table 4-3: Shows the minimum, maximum, mode and average damage grade observed in Kanana for Exposure A, B and C

Exposure	Damage Grade (%)				
	Minimum	Maximum	Mode	Mean	STD
A	40	60	40 and 60	50	10
B	40	60	40	50	10
C	0	0	0	0	0

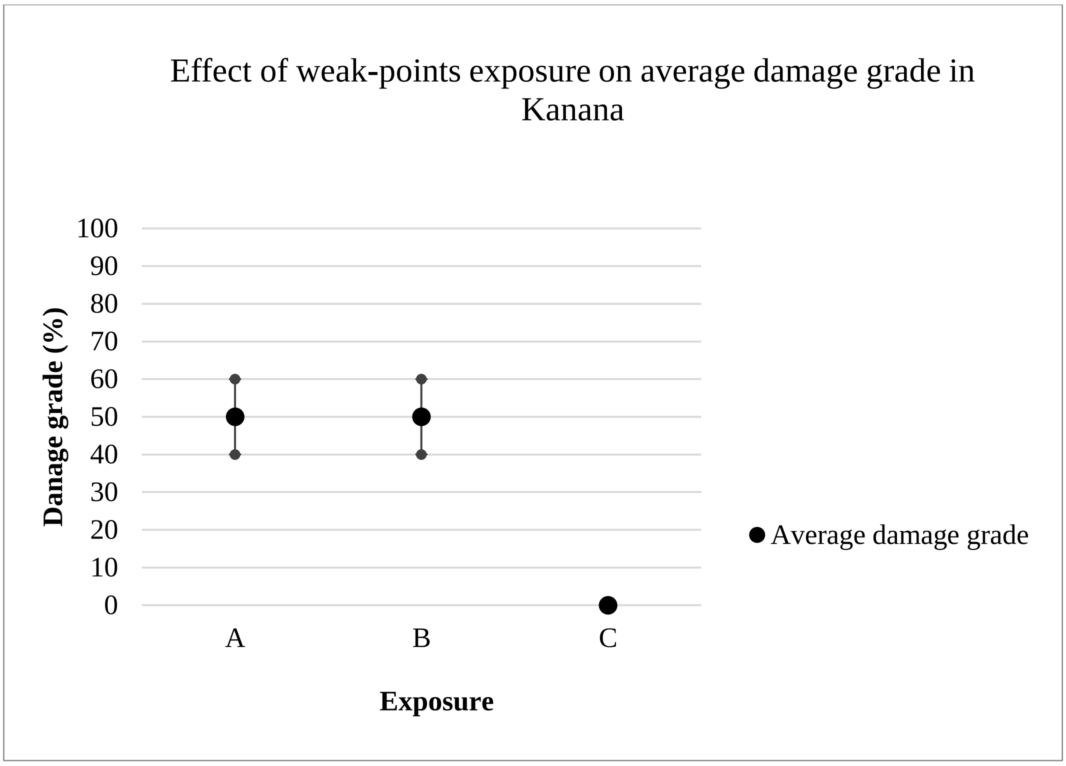


Figure 4-11: Average damage recorded between Exposure A, B and C in Kanana

4.3.6 Jouberton: Statistical representation of building weak points exposure and damage grade

Table 4-4 and Figure 4-12 provide the relationships between the building weak-points exposure and the weighted average damage grade, minimum and maximum damage grade in Jouberton.

- Exposure A had a damage grade range of 40% to 60% and the highest weighted average damage grade of 50%.
- Exposure B had a damage grade range of 20% to 60% and the second highest weighted average damage grade of 30%.
- All the damaged houses with exposure C had 20% damage grade.
- From these results, exposure C had the lowest weighted average damage grade and was the least vulnerable to earthquake damage while exposure A had the highest weighted average damage grade and so was the most vulnerable to earthquake damage.
- In Jouberton, there were few data points, and this decreased the reliability of the results obtained in this settlement.

Table 4-4: Shows the minimum, maximum, mode and average damage grade observed in Jouberton for Exposure A, B and C

Exposure	Damage Grade (%)				
	Minimum	Maximum	Mode	Mean	STD
A	40	60	40 and 60	50	10
B	20	60	20	30	20
C	20	20	20	20	0

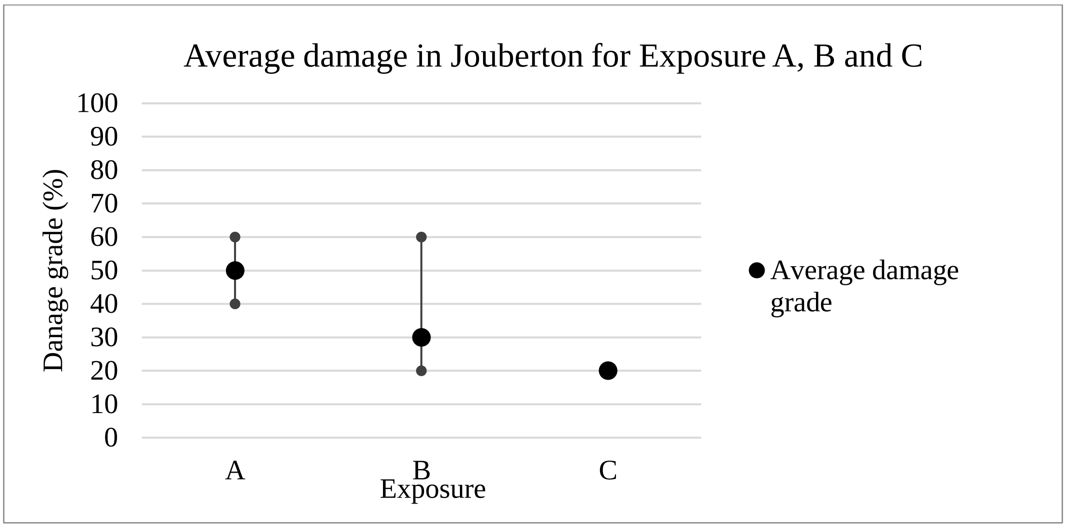


Figure 4-12: Average damage recorded between Exposure A, B and C in Jouberton

4.3.7 Summary: Building weak points versus damage grade

In all three townships exposure C had the least number of damaged houses (Figure 4-13). In Khuma, Kanana and Jouberton, exposures A, B and B respectively, had the most damaged houses (Figure 4-13). So for two of the three settlements, exposure B had the highest number of damaged houses while exposure A had the highest number of damaged houses in only one township (Khuma).

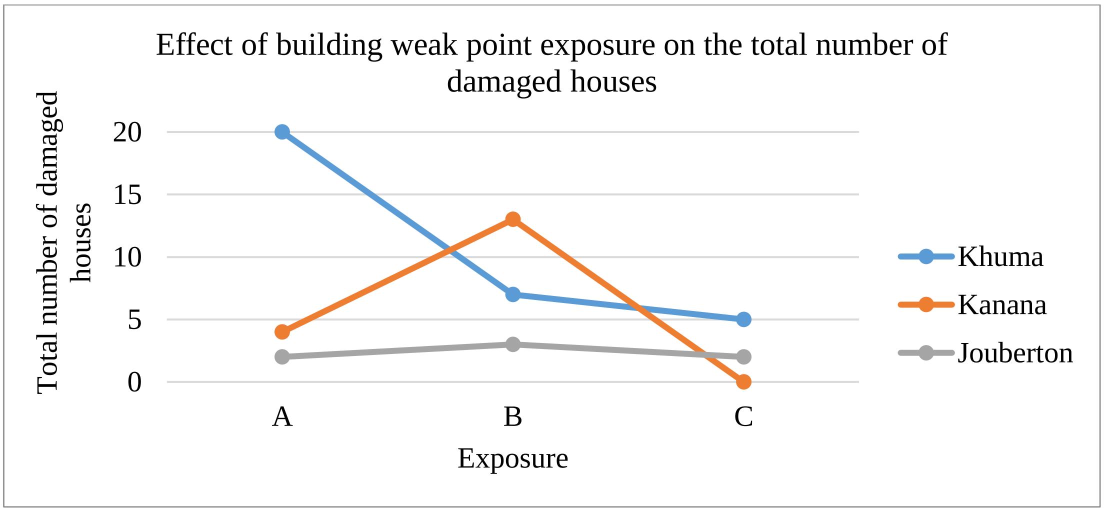


Figure 4-13: Total number of damaged houses classified according to building weak points Exposure in all affected townships.

In all three townships exposure C had the lowest weighted average damage grade (Figure 4-14). In Khuma and Kanana exposure A and B had the highest and similar weighted average damage grade. In Jouberton, exposure A had the highest weighted average damage grade and exposure B the second highest (Figure 4-14). The results in Jouberton were not very reliable, since this settlement had few data points.

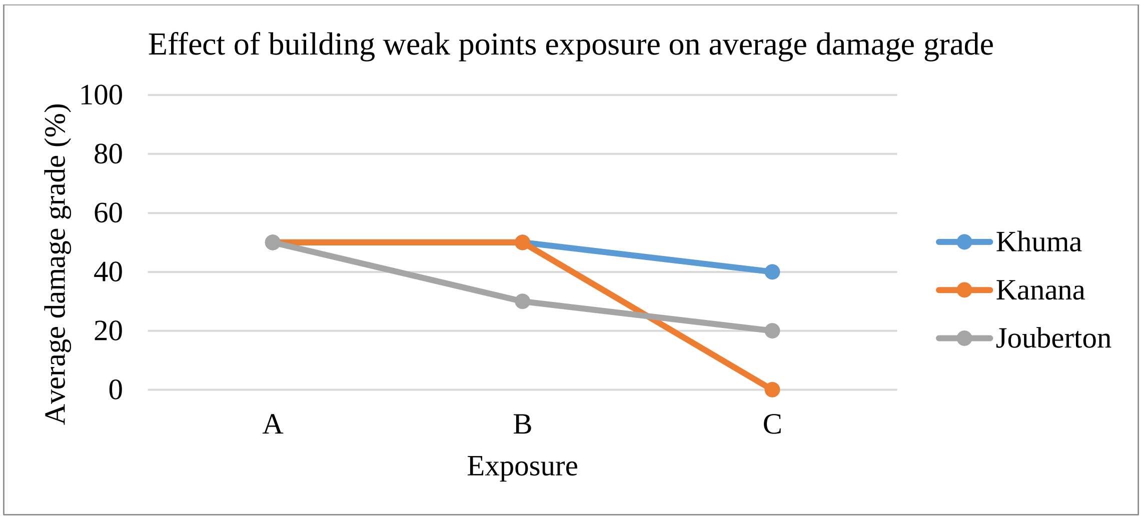


Figure 4-14: Effect of building weak points Exposure on the average damage grade in Khuma, Kanana and Jouberton

The most favourable building weak points exposure was exposure C, with the lowest number of damaged houses and lowest weighted average damage grade in all three townships. The most vulnerable building weak points exposure was between exposure A and exposure B. Exposure A had the highest number of damaged houses for Khuma township and highest weighted average damage grade in all three townships. Exposure B had the highest number of damaged houses in two townships (Kanana and Jouberton) and the highest weighted average damage grade for two townships (Khuma and Kanana).

The average difference in damage grade between the most and the least favourable building weak points exposure was 15%.

4.4 Effect of external building finishes on damage grade

The building finishes variable referred to whether the external walls of the house were plastered or un-plastered.

4.4.1 Khuma: Graphical and spatial representation of external building finish and damage grade

In Khuma, (the most damaged settlement) the damage map (Appendix E, Figure 7-8) shows that the highest number of damaged houses had a plastered finish. However, most damaged un-plastered houses had higher levels of damage grade. From this map three zones of high levels of damage grade are shown. In all three zones these houses were un-plastered. The two damage zones on the west showed damage grades of 100%.

Figure 4-15 provides the same information as the map in Figure 7-8 however the variable relations can be seen quantitatively. The total number of damaged plastered houses was 15 and the total damaged un-plastered houses was 17. For damage grades 80% and 100, all the damaged houses were un-plastered. For damage grade 60%, there were 3 damaged plastered houses and 7 damaged un-plastered houses. For damage grade 40%, there were 12 damaged plastered houses and 1 damaged un-plastered house. For damage grade 20%, there were 2 damaged plastered houses and 1 damaged un-plastered house.

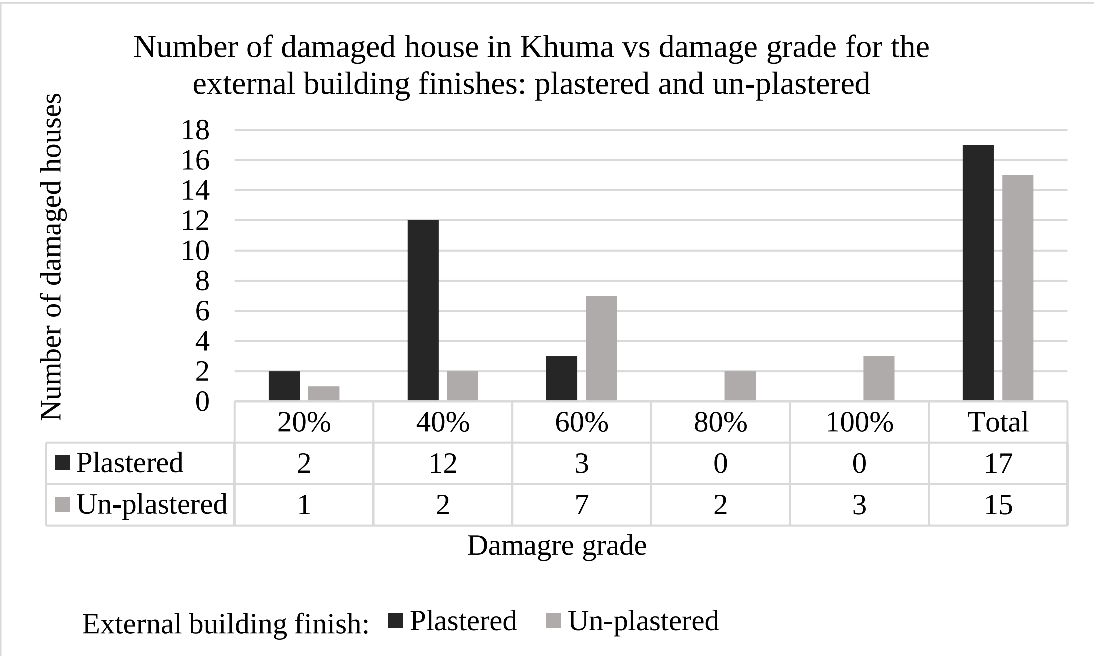
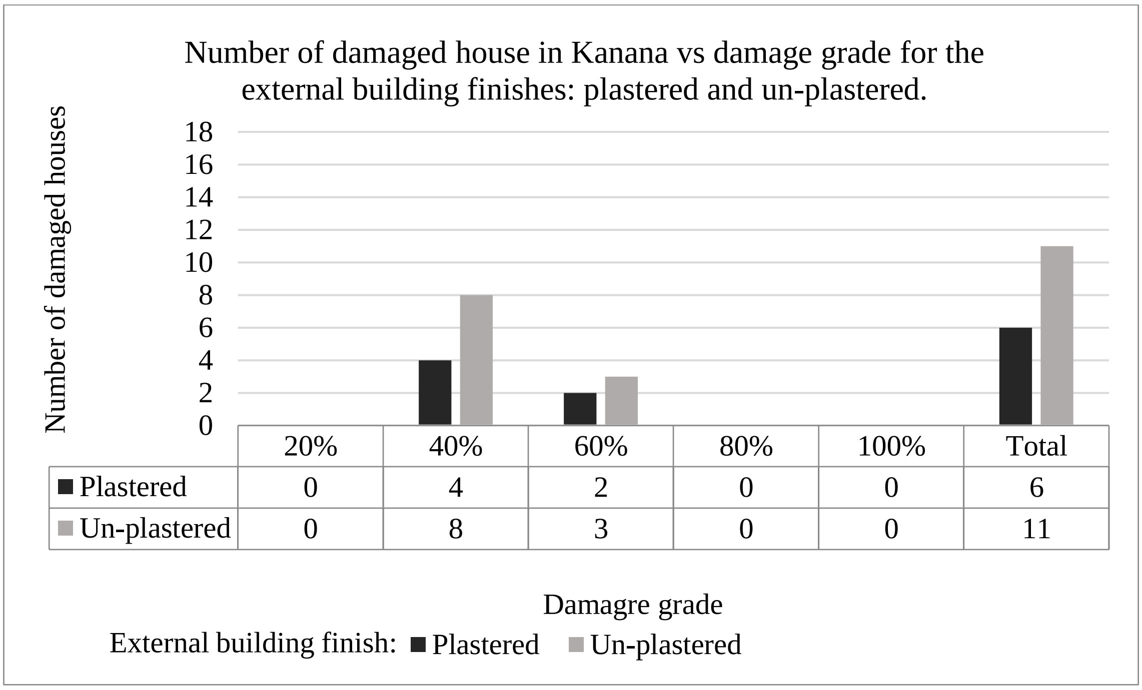


Figure 4-15: Number of damaged houses classified according to external building finish (plastered or un-plastered) and damage grade in Khuma.

4.4.2 Kanana: Graphical and spatial representation of external building finish and damage grade

In Kanana (the second most damaged settlement with 17 damaged houses), the damage map (Figure 7-9 in Appendix E) shows that most damaged houses had damage grade 40%. The highest number of damaged houses were un-plastered and there were fewer damaged plastered houses. Most damaged un-plastered houses had damage grade 40% and 60%. This map has two zones of high levels, in both zones the houses were un-plastered. The two damage zones show damage grade of up to 60%.

Figure 4-16 provides the same information as the map in Figure 7-9, but quantitatively. The total number of damaged plastered houses was 6 and for un-plastered houses, 11. For damage grade 60%, there were 2 damaged plastered houses and 3 damaged un-plastered houses. all these houses having excitation angle 0°-30°. For damage grade 40%, there were 4 plastered houses and 8 un-plastered houses.



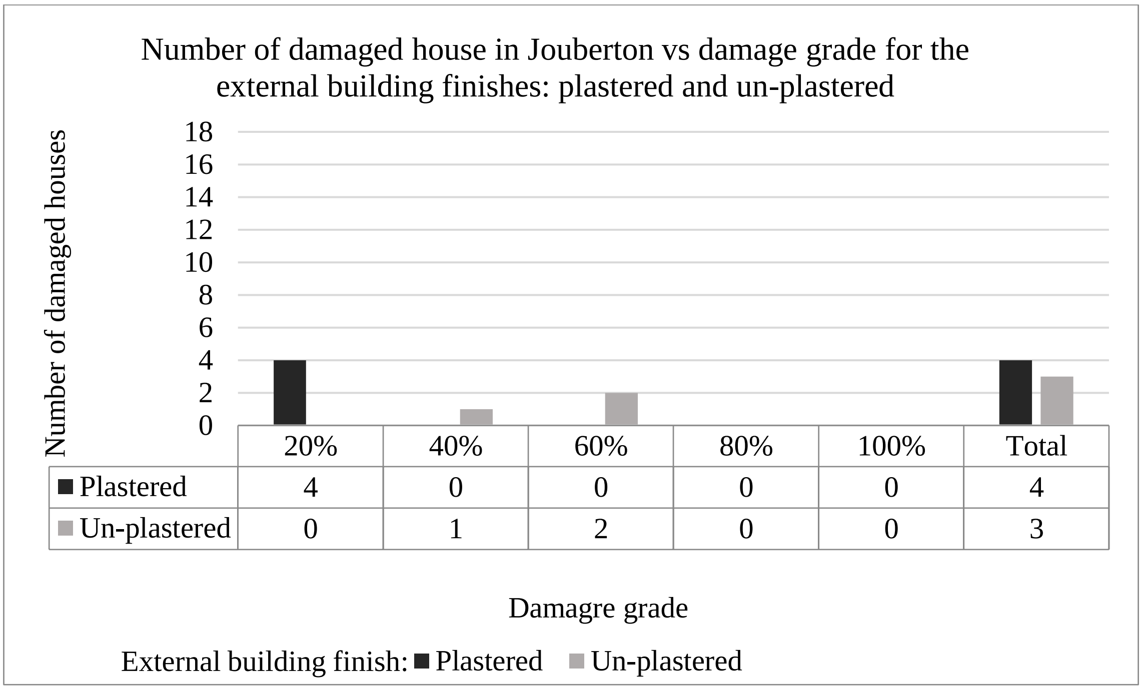
	20%	40%	60%	80%	100%	Total
Plastered	0	4	2	0	0	6
Un-plastered	0	8	3	0	0	11

Figure 4-16: Number of damaged houses in Kanana vs damage grade for the building finishes: plastered and un-plastered.

4.4.3 Jouberton: Graphical and spatial representation of external building finish and damage grade

In Jouberton (furthest from the epicentre with only 7 damaged houses), the map (Figure 7-10 in Appendix E) shows that the highest number of damaged houses were plastered. However, there was a higher number of un-plastered houses with damage grade 60%. In the zone of high levels of damage up to 60%, the houses are un-plastered.

Figure 4-17 provides the same information as the map in Figure 7-10, but quantitatively. Four of the damaged houses were plastered and 3 were un-plastered. For damage grade 60% there were only 2 damaged un-plastered houses. For damage grade 40% there was only 1 damaged un-plastered house. For damage grade 20% there were 4 damaged plastered houses.



	20%	40%	60%	80%	100%	Total
Plastered	4	0	0	0	0	4
Un-plastered	0	1	2	0	0	3

Figure 4-17: Number of damaged houses in Jouberton vs damage grade for the building finishes: plastered and un-plastered.

4.4.4 Khuma: Statistical representation of external building finish and damage grade

Table 4-5 and Figure 4-18 provides the relationship between the external building finish and the weighted average damage grade, minimum and maximum damage grades in Khuma.

- The damage grade for plastered houses ranged from 20% to 60% with the lowest weighted average damage grade of 40%.
- Un-plastered houses had damage grade that ranges from 20% to 100% and the highest weighted average damage grade of 70%.
- Hence un-plastered houses were more vulnerable to earthquake damage.

Table 4-5: Shows the minimum, maximum, mode and average damage grade observed in Khuma for plastered and u-plastered houses

External building finish	Damage Grade				
	Minimum	Maximum	Mode	Mean	STD
Plastered	20	60	40	40	10
Un-plastered	20	100	60	70	20

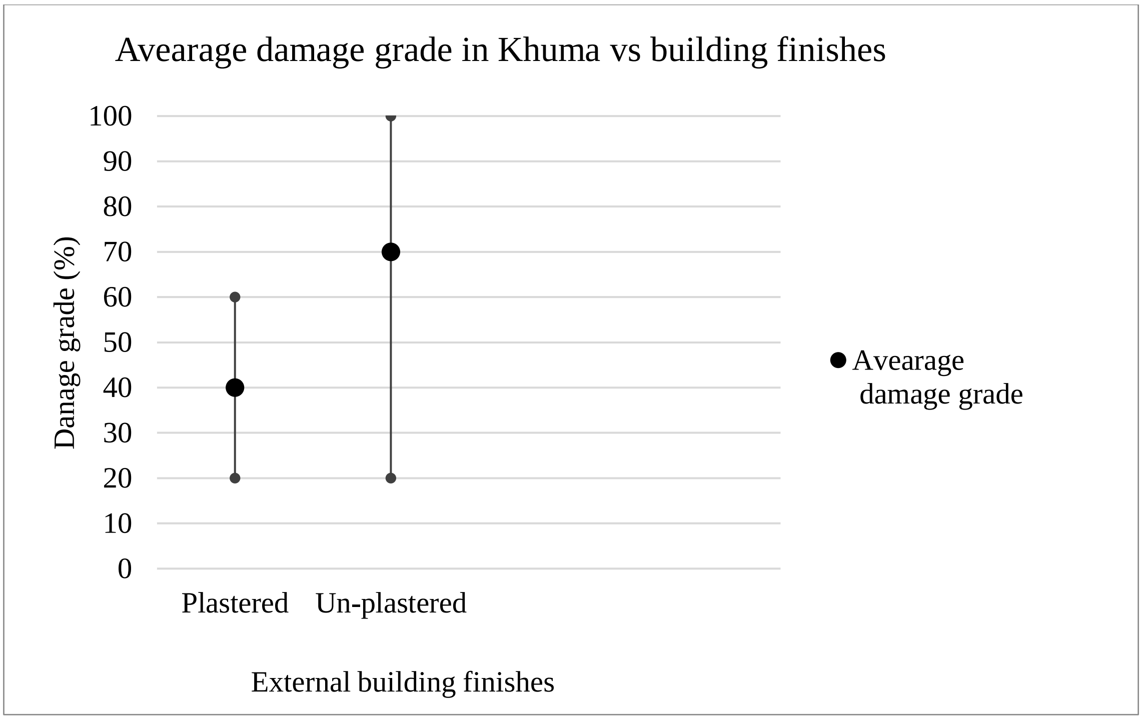


Figure 4-18: Average damage recorded between plastered and un-plastered houses in Khuma.

4.4.5 Kanana: Statistical representation of external building finish and damage grade

Table 4-6 and Figure 4-19 provides the relationship between the external building finish and the weighted average damage grade, minimum and maximum damage grade in Kanana.

Both plastered and un-plastered houses had a damage grade ranging from 40% to 60% and a weighted average damage grade of 50%.

Table 4-6: Shows the minimum, maximum, mode and average damage grade observed in Kanana for plastered and u-plastered houses

External building finish	Damage Grade				
	Minimum	Maximum	Mode	Mean	STD
Plastered	40	60	40	50	10
Un-plastered	40	60	40	50	10

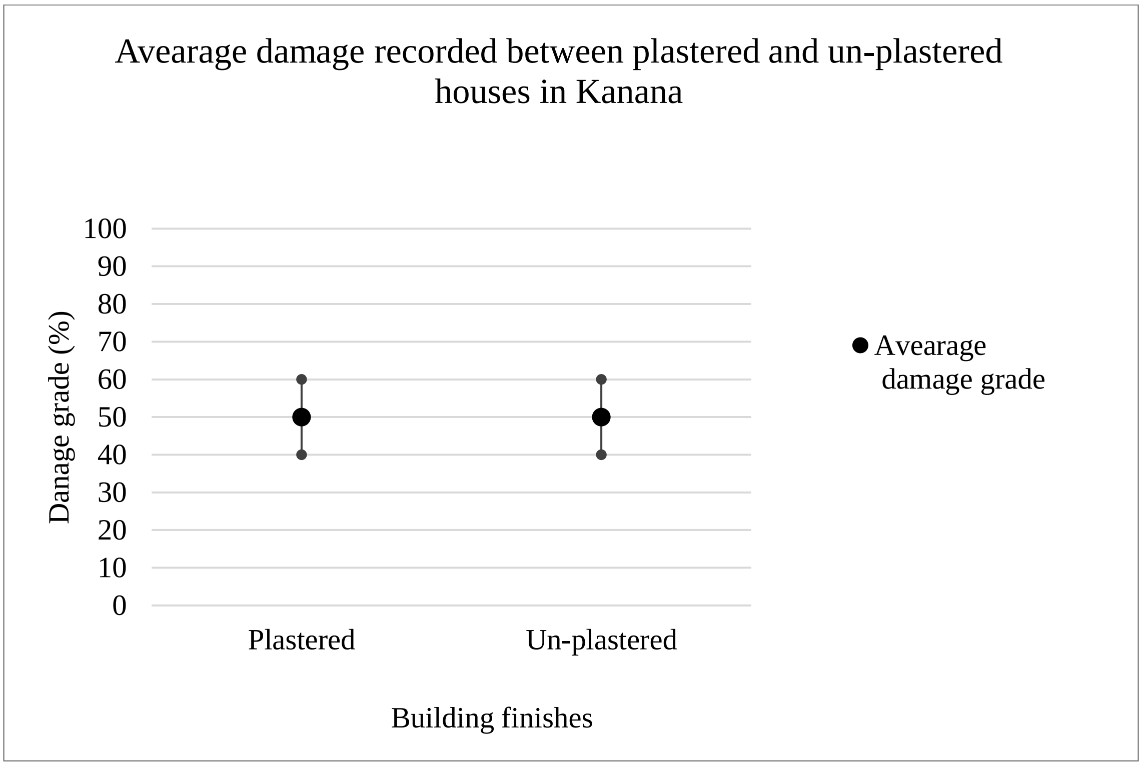


Figure 4-19: Average damage recorded between plastered and un-plastered houses in Kanana.

4.4.6 Jouberton: Statistical representation of external building finish and damage grade

Table 4-7 and Figure 4-20 provides the relationship between the external building finish and the weighted average damage grade, minimum and maximum damage grade in Jouberton.

- All the damaged plastered houses had a damage grade of 20%; and correspondingly the minimum, maximum and average of 20%.
- Un-plastered houses had a damage grade ranging from 40% to 60% and the weighted average damage grade of 50%.
- Hence, un-plastered houses were more vulnerable to earthquake damage. However, in Jouberton, there were few data points, which decreased the reliability of the results obtained in this settlement.

Table 4-7: Shows the minimum, maximum, mode and average damage grade observed in Jouberton for plastered and u-plastered houses

External building finishes	Damage Grade				
	Minimum	Maximum	Mode	Mean	STD
Plastered	20	20	20	20	0
Un-plastered	40	60	60	50	10

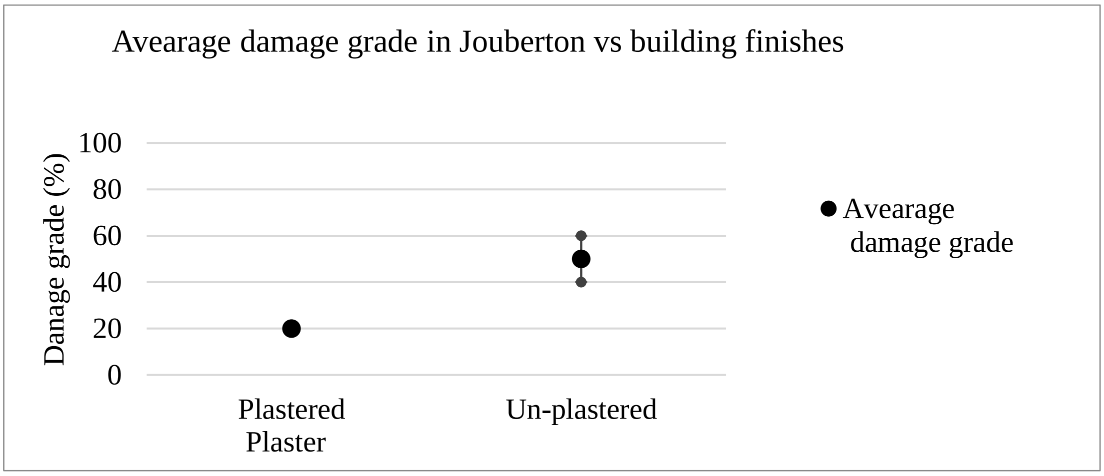


Figure 4-20: Average damage recorded between plastered and un-plastered houses in Jouberton.

4.4.7 Summary: External building finish versus damage grade

From Figure 4-21, in Khuma, more damaged houses were plastered than un-plastered. In Kanana more damaged houses were un-plastered houses and the fewest damaged houses were plastered. In Jouberton more damaged houses were plastered houses less un-plastered. In two of the three settlements then (Khuma and Jouberton) more damaged houses were plastered.

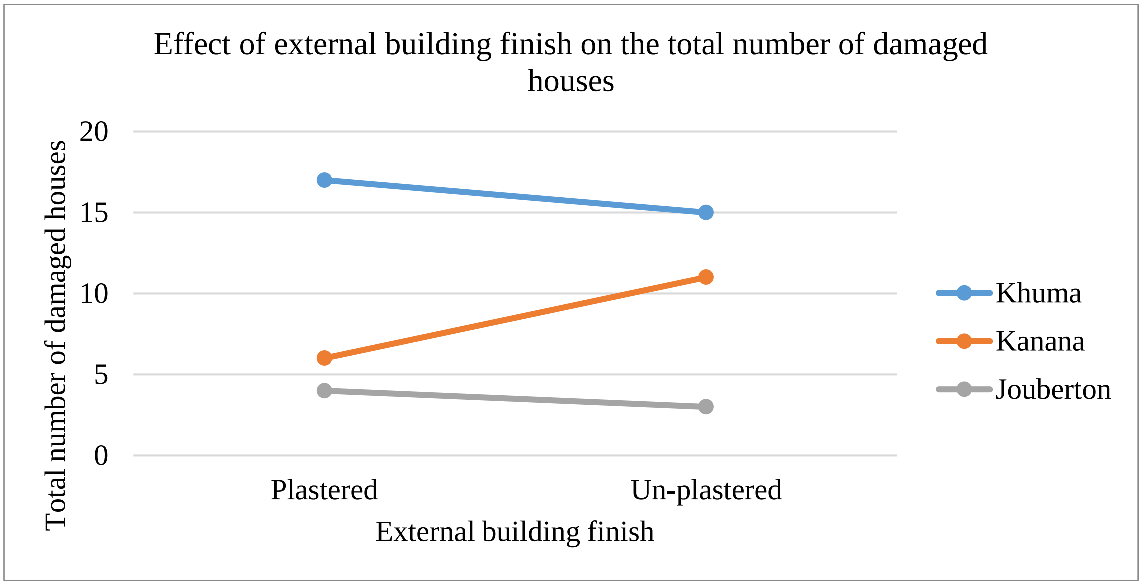


Figure 4-21:: Total number of damaged houses classified according to externa building finish in all affected townships.

From Figure 4-22, in Khuma, the average damage grade for plastered houses was lower than average damage grade for un-plastered houses. In Kanana, both plastered and un-plastered houses had the same average damage grade. In Jouberton, the weighted average damage grade was higher in un-plastered houses. Un-plastered houses then had the higher damage grade in two townships, with the exception of Kanana where damaged plastered and un-plastered houses suffered the same levels of damage. Again, the results in Jouberton were not very reliable, since this settlement had few data points.

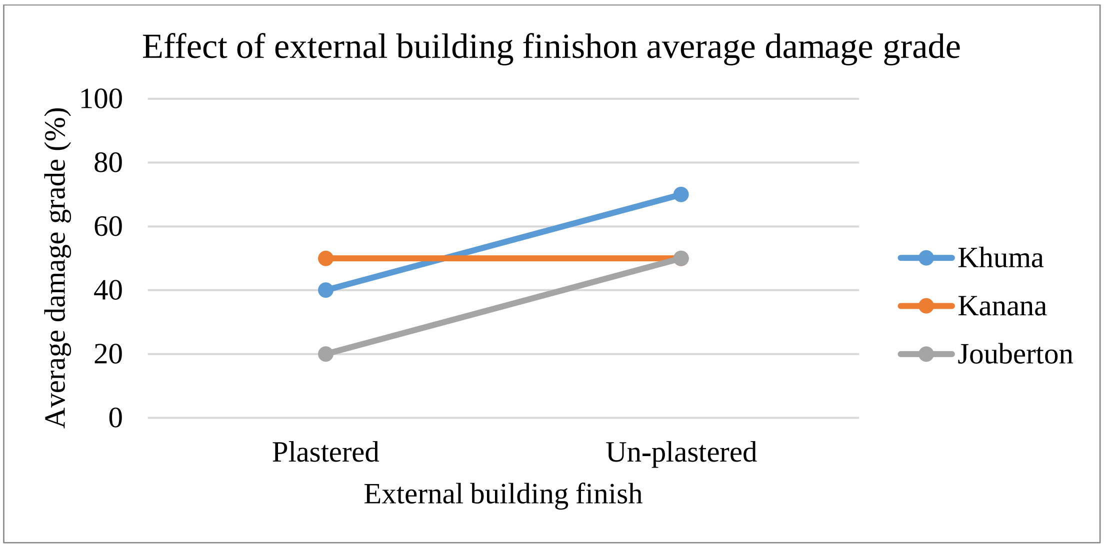


Figure 4-22: Effect of external building finish on the average damage grade in Khuma, Kanana and Jouberton

Overall, un-plastered houses were more vulnerable, having the higher weighted damage grade for two townships and the higher number of damaged houses for Kanana. The average difference in damage grade between the more and the less favourable external building finish was 20%.

4.5 Critical variables

Critical variable are variables representing the most favourable and the least favourable variable. The information on critical variables is shown in Table 4-8 below.

Table 4-8: Most favourable and least favourable variable for low-cost houses development

Variable	Most favourable	Least favourable
Excitation Angle (°)	31°-60°	0°-30°
Exposure	C	A and B
External building finish	Plastered	Un-plastered

4.6 Highest contributing variables

The presence or absence of plaster in the houses was then the highest contributing factor for damage grade in this study. This information is also represented in Figure 4-23

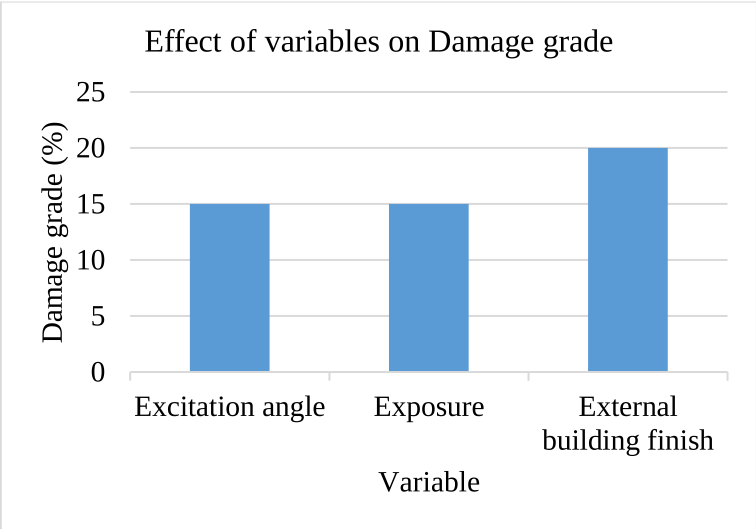


Figure 4-23: The effect of excitation angle, exposure and external building finish on damage grade.

4.7 Estimation of damage using damage index

A damage index number ranging from 1 to 3 was assigned to each contributing variable based on its effect on damage grade. Variable values that resulted in an increase in damage grade were given high index value and variables that had minimum effect on damage grade were given low index (See Table 4-9).

Table 4-9: Damage matrix rationale

Variables	Damage index		
	1	2	3
Excitation angle	31°-60° Least amount of damage	61°-90 Moderate damage°	0°-30° Most amount of damage
Exposure	C. Least of amount of damage		A and B. Most amount of damage
External wall finish	Plastered. Least amount of damage		Un-plastered. Most amount of damage

The index for all variables was combined for each house to correlate damage to index. The lowest total damage index was 3 and the highest was 9

- Houses with the highest total damage index (8 to 9) were expected to have high damage.
- Houses with medium total damage index (6-7) were expected to have medium damage.
- Houses with low total damage index (3-5) were expected to have low damage.

This information is also shown in Table 4-10

Table 4-10: Estimation of expected damage based on total damage index

Total damage index	Expected damage
3-5	low
6-7	medium
8-9	high

A damage index matrix was used to predict the damage level for each house. The total of the matrix was computed to determine expected damage (Table 7-4, Table 7-5 and Table 7-6 in Appendix F).

From these tables it can be observed that in Khuma, and in Jouberton, most houses were expected to have either high damage or low damage. In other words, a combination of the most and least vulnerable variables. In Kanana, it is observed that more houses were expected to have high damage. This implies that in Kanana most houses had a combination of variable values making them vulnerable.

The damage index totals were compared to damage grade recorded by Khoyratty (2016) to determine the accuracy of the damage prediction. This was done using regression analysis. From Figure 7-11 and Figure 7-13 in Appendix G, in Khuma and Jouberton there is a positive correlation between damage index and damage grade and the correlation is negative in Kanana (Figure 7-12 in Appendix G). The correlation between these variables was expected to be positive. R-squared of 0.46 for Khuma (moderate correlation), 0.05 for Kanana (no correlation) and 0.83 for Jouberton (high correlation). These values suggest that the modelling was moderately successful for Khuma and Jouberton and unsuccessful for Kanana. Maybe in Kanana other factors affected the damage grade more than the factors that were considered in this study. This modelling can be improved by including more factors that contribute to the earthquake damage.

Chapter 5 : Discussion

The number of damaged houses for each variable can indicate its effect on the vulnerability to earthquake damage, however this finding might be biased if there were many houses with a particular character, such as a plastered exterior, in the area. While the weighted average damage grade can give the effect of a variable on the average damage grade, various unmeasured factors also affect the damage grade. In this study some of these unmeasured factors were minimized by the uniformity of construction in the settlements studied.

5.1 Effect of excitation angle on the vulnerability of the house

The results from this study showed that an excitation angle of 31° to 60° was the most favourable angle for building construction. This excitation angle had the least number of damaged houses and the lowest average damage grade in all 3 townships. The reason for the minimum damage at this angle is because none of the building walls are perpendicular to earthquake direction. The pressure equation shows that when the area perpendicular to the force increases, the force will also increase. When none of the walls are perpendicular to earthquake direction, the area perpendicular to earthquake direction is also a minimum, minimizing the force experienced by the walls. Minimum force results in minimum acceleration in the X and Y components and less acceleration, resulting in minimum displacement and hence lower damage.

The excitation angles of 0°-30° and 61°-90° were found to be the least favourable angles for building construction. Excitation angle of 0°-30° recorded the highest number of damaged houses and the highest weighted average damage grade in all three townships. One should also note a significant bias in the dataset. Most of the houses were built with this orientation. In order to remove this bias, one would need to look at a different study area. Excitation angle 61°-90° had the second highest number of damaged houses and the second highest weighted average damage grade, for all three townships. The reason for the high damage at these angles is because some of the building walls are approximately perpendicular to earthquake direction. These walls have the maximum area perpendicular to the earthquake direction, which increases the force experienced by the walls during an earthquake and results in high damage to the house.

These were the first results obtained using field data on earthquake directional effect and they agreed with various laboratory studies that have been conducted.

These findings also agree with Magliulo et al. (2014), who found that the maximum displacement of a reinforced structure under earthquake shaking was when the earthquake direction was perpendicular to the longitudinal axis. In unreinforced structures, these displacements might well result in significant structural damage as was observed in Orkney during the 2014 earthquake.

Also, Atak et al. (2014) established that the excitation angle that produced the maximum response in a bridge, was 90° (when the earthquake propagation direction was perpendicular to the longitudinal axis of the bridge) and the excitation angle that produced minimum damage was 0°. However the Atak et al. (2014) study was conducted on structures with a much greater length/base ratio than the houses in the current study.

5.2 Effect of building weak point exposure on the vulnerability of the house

Khoyratty (2016) observed a pattern of damage in houses, which was that cracks propagated from the windows and doors. This study found that most damage was observed when these weak points were facing the epicentre. In all the townships Exposure A and B had the highest amount of damage; that is, when the weak points (windows or doors) were exposed to the epicentre. Caselles et al. (2012) observed more damage when the building potential weak points, including large doors and windows were exposed to the earthquake direction. Doğangün et al. (2008) stated that the unavoidable features in buildings like windows and doors present critical weak points and most damage starts to occur at these points.

From the earthquake post field assessment manual, one of the features to look for in order to know if a building had been affected by the earthquake, are the cracks propagating from windows and door frames. In all three townships, houses with Exposure C had the lowest number of damaged houses and lowest average damage grade. This was because with Exposure C there were no weak points facing the epicentre.

5.3 Effect of external building finish on the vulnerability of the house

In all 3 townships un-plastered houses had the highest average damage grade. Khuma and Jouberton had the most damaged plastered houses and Kanana had the most damaged un-plastered houses. In total the number of damaged plastered houses was greater than the number of damaged un-plastered houses, however, this did not mean that the plastered houses were more vulnerable to earthquake shaking, since these houses had the lowest average damage grade for most townships. The reason for the higher number of plastered houses may be that there were more plastered houses in the settlement.

Even though damaged un-plastered houses were fewer, they had the highest damage grade. All of the houses that experienced damage grade of 100% and 80% were un-plastered. Un-plastered houses do not have the advantage of a stronger wall finish, thus making them more vulnerable to earthquake shaking.

Chapter 6 : Conclusion and recommendations

The main aim of this study was to assess the factors that contributed to the level of damage in Orkney and the surrounding areas (Khuma, Kanana and Jouberton Townships) due to the 2014, Orkney earthquake. The following variables were observed; excitation angle, exposure of building weak points to the line of sight from the epicentre and building finishes (either un-plastered or plastered), to assess how these contributed to the damage grade of the buildings.

In this section we look at the intended objectives, the completed tasks and summary of results achieved. From these summaries a list of recommendations is provided either for future research or for reducing the vulnerability of houses.

- OBJECTIVE 1 *To isolate and investigate the contributing factors that cause earthquake damage.*

  Some of the factors that contributed to earthquake damage were isolated by studying each region separately. By doing this, the effects of epicentral distance, local geological conditions on damage grade variation were minimised.

  There was good evidence to indicate that the epicentral distance had an effect, from comparing the three settlements, However within each settlement there was no conclusive evidence of the effect of variation in epicentral distance.

  The underlying geology within Kanana and Jouberton was similar. In Khuma there were two types of underlying geology, however these units were both hard rock. After and during the 2014 Orkney earthquake there was no reported soil liquification. Therefore, within each township the effect of varying local geological conditions on damage grade was minimal.

  The houses were affected by the same earthquake of particular magnitude and depth and considered as a point source; therefore, these factors did not contribute to the varying damage grades. The houses studied all had the same architecture and mass, hence these factors also did not contribute to the varying damage grades.

- OBJECTIVE 2: *To assess the effect of building excitation angle on the amount of damage observed in the building.*

  The excitation angle that produced the most damage was 0^o-30^o, where the short side of the building was roughly perpendicular to the direction of the earthquake. Another factor that contributed to damage was that the short side of the building had two weak points (windows). This excitation angle produced the highest average damage grade in all three townships. The excitation angle that produced the least damage was 31^o-60^o, where none of the building walls were perpendicular to earthquake direction. This angle had the lowest number of damaged houses and lowest average damage grade.

- OBJECTIVE 3: *To evaluate how the exposed building weak points exposure like windows and doors affect the level of damage observed.*

  The exposure that had the most damage was exposure A and B. Exposure A was when the building had two weak points (one window and one door) exposed to the epicentre; exposure B was when two weak points (two windows) were exposed to the epicentre; These exposures had the highest number of damaged houses and highest average damaged grade in all three townships. Exposure C, when no building weak points were exposed to the epicentre, produced the lowest number of damaged houses and lowest average damage grade in all three townships.

- OBJECTIVE 4: *To observe whether the building external wall finishes (either plastered or un-plastered) affect the level of damage observed.*

  Buildings that were not finished with plaster had higher damage levels compared to plastered buildings in all townships. Un-plastered houses do not have the advantage of stronger wall finishes that the plastered houses have, thus making them more vulnerable to earthquake shaking. This factor contributed the most in damage grade, since there was 20% difference in average damage grade between plastered and un-plastered houses.

- OBJECTIVE 5: Finally, an assessment/recommendation of building vulnerability with respect to the above factors can be determined.

  If the walls of the building are perpendicular to earthquake direction (excitation angle 0°-30° and 61°-90°) the walls will experience more force, this will in turn increase the pressure on the wall. When there are weak points added to the walls (windows and doors), cracks may start to form from them. If these walls have no plastering finish, they will be more likely to experience damage, that may spread to the rest of the building.

If the walls are not perpendicular to the earthquake direction, the area perpendicular to the earthquake direction is reduced; this reduces the forces experienced by the walls, and this decreases the pressure on the walls. When there are no windows and doors exposed to the epicentre, the wall has no weak-point exposed to the epicentre, and there will not be any weak points where the damage will start to occur; and if the building is completed with plaster, this will increase the strength of the building and it will be less vulnerable to earthquake damage.

From this study it is clearly that the excitation angle, building weak-points exposure and plastering finishes have a great impact on the vulnerability of low-cost houses to earthquake damage (see objective 2 to objective 4). The findings of this study supports the findings of previous studies by Atak et al. (2014), Magliulo et al. (2014) and Caselles et al. (2012) on earthquake directional effect on buildings.

Recommendations for Improving low-cost houses in the context of seismic activities

This study examined variables that contributed to the level of damage observed in low-cost houses during an earthquake tremor. Knowledge of the effects of these parameters would help in improving the construction of low-cost housing in South Africa to withstand seismic activities and earthquake tremors. This will save millions of Rands being invested by governments and other stake holders in re-construction and maintenance of low-cost housing and the protection of human life.

From this study, the following factors were observed to minimize the damage caused by the earthquake in building:

- *Determine possible seismic sources and locate houses away from these areas*: This study has shown that houses that were closer to the seismic source suffered more damage. However, re-locating houses may not be a simple solution in South Africa since most seismic sources may be in mining areas. Most of the residents in the study area were miners and their families, who naturally prefer to be close to the work place.

- *Houses should be plastered*: This study has shown that most houses that were un-plastered experienced higher damage levels. Plastered houses have an advantage of stronger wall finishes
- *Orientate the building in a preferred direction*: This study has shown that buildings that had either of their walls (short axis or long axis) perpendicular to the earthquake direction were more vulnerable to earthquake damage. Buildings that had walls that were not perpendicular to the earthquake direction were less vulnerable to earthquake damage.
- *Ensure that no building weak points (windows and doors) are exposed to the potential source*: In this study it was found that buildings with windows or doors facing the epicentre experienced more damage because these features present critical weak points, where most damage starts to occur.
- *Improve building quality control or inspection*: Most of the buildings studied were vulnerable to earthquake damage due to poor construction and sub-standard materials used in these buildings. Using good construction materials and adequate engineering, will reduce the vulnerability of these houses to seismic activities.
- *Routine Maintenance of old low-cost houses*: Some of the old low-cost houses were vulnerable to earthquake damage because they were in a bad state due to lack of maintenance. Maintenance such as plastering of cracks and general repairs prevent deterioration of the building.

These recommendations can be included in the building codes for low cost houses in areas that have a high risk of seismic activities. This will ensure that architectures include these factors in the design, this will decrease the vulnerability of low-cost houses to seismic activities and improve the overall quality of these houses.

Recommendations for future studies

Even though it was clear that these factors did affect the level of damage observed in the settlements studied, it would not be possible to estimate expected damage grade based only on these factors. At any point in time, many factors affect the level of damage during an earthquake. More data points are needed to provide more certainty on the variable relations explored of this study.

This study has shown using a few factors, one can determine the building vulnerability and risk of earthquake damage.

For future research, a prediction of damage by the earthquake in the investigation area will be done by simultaneously considering all the known factors that contribute to earthquake damage.

A quantitative technique like the well-known Principal Component Analysis (PCA) can be used for this purpose. Cluster analysis can be used to estimate the variables that contribute the most to damage observed in the buildings and to estimate the correlation between these variables.

This can be achieved through the following steps:

- Review other factors that could potentially affect the level of damage observed in the region. Some of these factors include: epicentral distance, geology or site characteristics and ground motion attenuation.
- For the factors reviewed above, determine whether there are any correlations between these factors
- Determine which factors contribute most to the earthquake damage
- Review and apply models for Vulnerability and Risk Analysis
- Produce an Earthquake Risk Map for the Region

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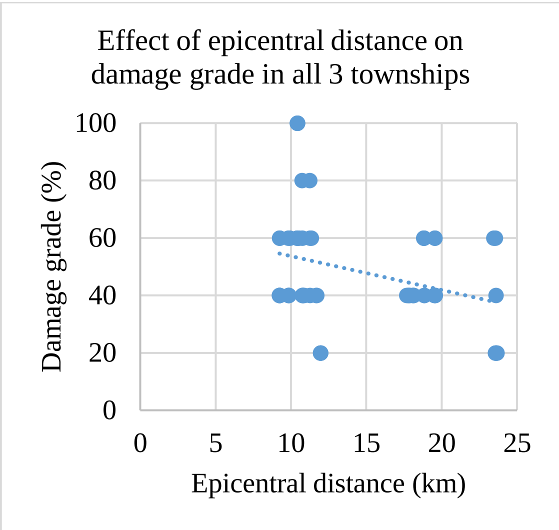
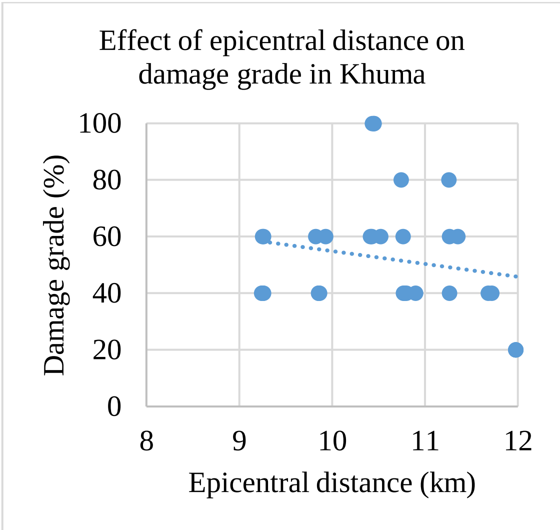
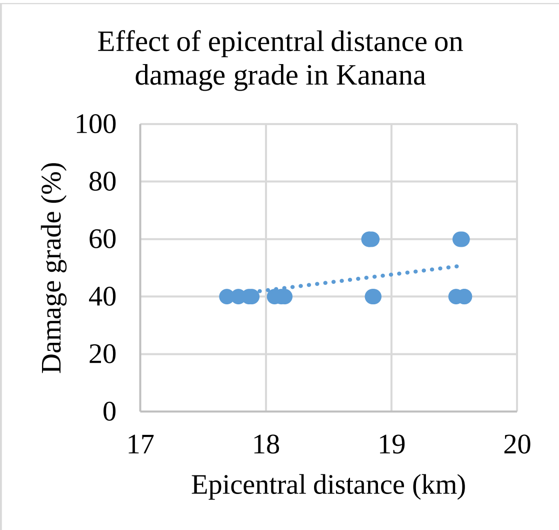
Chapter 7 : Appendixes

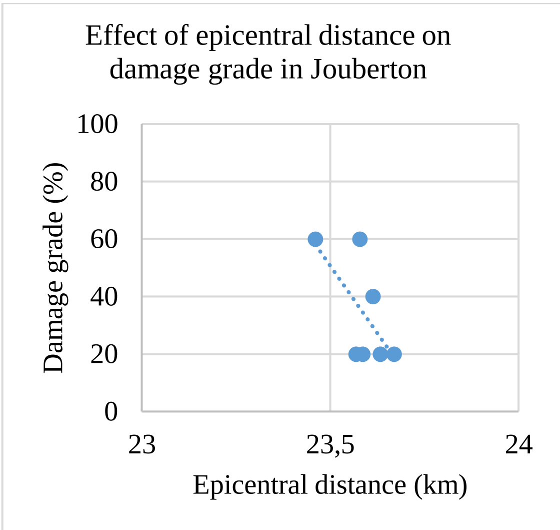
Appendix A: Effect of epicentral distance on damage grade





(a) (b)





(c) (d)

Figure 7-1: Effect of epicentral distance in; (a) all 3 townships, (b) Khuma, (c)Kanana, and (d) Jouberton.

Appendix B : Directional effect variables for all three townships

Table 7-1: Directional effect variables; Excitation angle, Exposure and External building finish obtained for Khuma township

ID	IDP Latitude (Khoyratty, 2016)	IDP_ Longitude (Khoyratty, 2016)	Epicentral distance(km) (Khoyratty, 2016)	Damage Grade (%) (Khoyratty, 2016)	Direction from Epicentre Dir (LOSE) (°)	Direction of Longitudinal axis Dir (LA) (°)	Excitation angle (°)	Exposure	External building finish
KM01	-26,849000	26,861000	11,356	60	10	30	20	A	Plastered
KM02	-26,849000	26,863000	11,265	60	10	70	60	C	Plastered
KM03	-26,851000	26,863000	11,265	40	10	40	30	A	Plastered
KM04	-26,851000	26,871000	11,684	40	30	90	60	C	Plastered
KM05	-26,851000	26,873000	11,722	40	30	80	50	A	Un-plastered
KM06	-26,849000	26,873170	11,979	20	30	110	80	B	Un-plastered
KM07	-26,849000	26,873000	11,979	20	30	110	80	B	Plastered
KM08	-26,848800	26,873000	11,979	20	355	75	80	B	Plastered

ID	IDP Latitude (Khoyratty, 2016)	IDP_ Longitude (Khoyratty, 2016)	Epicentral distance(km) (Khoyratty, 2016)	Damage Grade (%) (Khoyratty, 2016)	Direction from Epicentre Dir (LOSE) (°)	Direction of Longitudinal axis Dir (LA) (°)	Excitation angle (°)	Exposure	External building finish
KM09	-26,853000	26,847000	10,429	60	355	15	20	A	Un-plastered
KM10	-26,857000	26,843000	9,824	60	355	55	60	B	Un-plastered
KM11	-26,858000	26,862000	10,524	60	355	75	80	A	Un-plastered
KM12	-26,849000	26,819000	10,767	60	5	35	30	A	Un-plastered
KM13	-26,844670	26,819000	10,745	80	5	15	10	A	Un-plastered
KM14	-26,845000	26,819000	10,778	40	5	45	40	A	Plastered
KM15	-26,845000	26,820000	10,768	40	5	55	50	C	Plastered
KM16	-26,845389	26,819000	10,800	40	25	45	20	A	Plastered
KM17	-26,844000	26,819389	10,900	40	25	35	10	C	Plastered
KM18	-26,848553	26,832000	10,434	100	12	12	0	B	Un-plastered
KM19	-26,849000	26,833000	10,451	100	350	0	10	B	Un-plastered
KM20	-26,849000	26,832000	10,415	60	0	0	0	B	Un-plastered
KM21	-26,859308	26,826783	9,262	60	0	10	10	A	Un-plastered

ID	IDP Latitude (Khoyratty, 2016)	IDP_ Longitude (Khoyratty, 2016)	Epicentral distance(km) (Khoyratty, 2016)	Damage Grade (%) (Khoyratty, 2016)	Direction from Epicentre Dir (LOSE) (°)	Direction of Longitudinal axis Dir (LA) (°)	Excitation angle (°)	Exposure	External building finish
KM22	-26,859000	26,825000	9,241	40	0	90	90	A	Plastered
KM23	-26,859000	26,826000	9,251	40	20	110	90	A	Plastered
KM24	-26,859389	26,826000	9,251	60	30	40	10	A	Un-plastered
KM25	-26,859000	26,827000	9,262	40	30	80	50	C	Plastered
KM26	-26,857306	26,844167	9,866	40	30	100	70	A	Plastered
KM27	-26,857000	26,844000	9,856	40	10	80	70	A	Plastered
KM28	-26,856000	26,843000	9,931	60	10	20	10	A	Plastered
KM29	-26,859000	26,826389	9,251	40	10	100	90	A	Un-plastered
KM30	-26,856667	26,843825	9,856	40	0	70	70	A	Plastered
KM31	-26,849822	26,861111	11,259	80	0	10	10	A	Un-plastered
KM33	-26,855833	26,837889	10,452	100	10	20	10	A	Un-plastered

Table 7-2: Directional effect variables; Excitation angle, Exposure and External building finish obtained for Kanana township

ID	IDP Latitude (Khoyratty, 2016)	IDP_ Longitude (Khoyratty, 2016)	Epicentral distance(km)	Damage Grade (%) (Khoyratty, 2016)	Direction from Epicentre (°)	Direction of Major axis (°)	Excitation angle (°)	Exposure	External building finish
KN01	-26,954000	26,643382	19,581	40	260	260	0	B	Plastered
KN02	-26,954000	26,642618	19,581	40	260	260	0	B	Un-plastered
KN03	-26,955000	26,643000	19,516	40	260	350	90	B	Plastered
KN04	-26,954803	26,644125	19,564	60	260	280	20	A	Un-plastered
KN05	-26,947292	26,648769	18,826	60	270	300	30	B	Un-plastered
KN06	-26,948000	26,649000	18,845	60	270	300	30	A	Plastered
KN07	-26,947262	26,648336	18,823	60	270	290	20	B	Plastered
KN08	-26,947000	26,647875	18,861	40	260	260	0	A	Un-plastered
KN09	-26,948356	26,642206	18,851	40	265	305	40	A	Plastered
KN10	-26,954000	26,643000	19,549	60	265	265	0	B	Un-plastered
KN11	-26,936000	26,658000	17,783	40	275	275	0	B	Un-plastered
KN12	-26,935000	26,659000	17,689	40	270	280	10	B	Plastered
KN13	-26,935000	26,658000	17,865	40	265	265	0	B	Un-plastered

ID	IDP Latitude (Khoyratty, 2016)	IDP_ Longitude (Khoyratty, 2016)	Epicentral distance(km)	Damage Grade (%) (Khoyratty, 2016)	Direction from Epicentre (°)	Direction of Major axis (°)	Excitation angle (°)	Exposure	External building finish
KN14	-26,936000	26,657000	17,890	40	260	275	15	B	Un-plastered
KN15	-26,935000	26,655000	18,124	40	260	260	0	B	Un-plastered
KN16	-26,935000	26,655289	18,151	40	275	295	20	B	Un-plastered
KN17	-26,936000	26,656000	18,069	40	275	275	0	B	Un-plastered

Table 7-3: Directional effect variables; Excitation angle, Exposure and External building finish obtained for Khuma township

ID	IDP Latitude (Khoyratty, 2016)	IDP_ Longitude (Khoyratty, 2016)	Epicentral distance(km)	Damage Grade (%) (Khoyratty, 2016)	Direction from Epicentre (°)	Direction of Major axis (°)	Excitation angle (°)	Exposure	External building finish
JB01	-26,888100	26,612000	23,670	20	280	280	0	B	Plastered
JB02	-26,893499	26,612000	23,579	60	280	290	10	B	Un-plastered
JB03	-26,890000	26,612000	23,634	20	290	0	70	B	Plastered
JB04	-26,895000	26,612000	23,461	60	285	300	15	A	Un-plastered
JB06	-26,883000	26,614000	23,587	20	285	305	20	C	Plastered
JB07	-26,883000	26,614000	23,569	20	290	320	30	C	Plastered
JB08	-26,901000	26,610000	23,614	40	290	330	40	A	Un-plastered

Appendix C: Spatial representation of excitation angle and damage grade

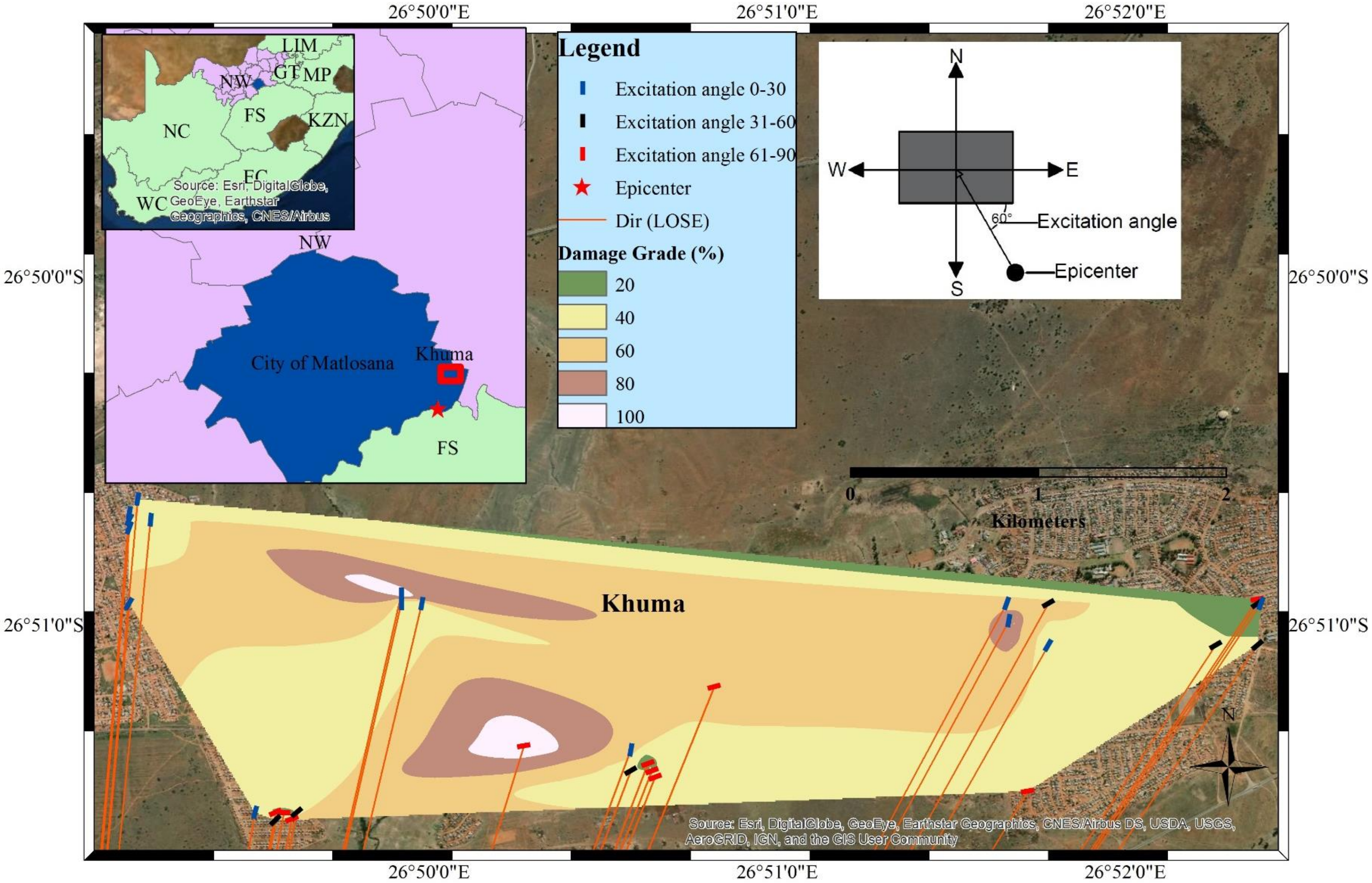


Figure 7-2: Spatial representation of excitation angle and damage grade in Khuma.

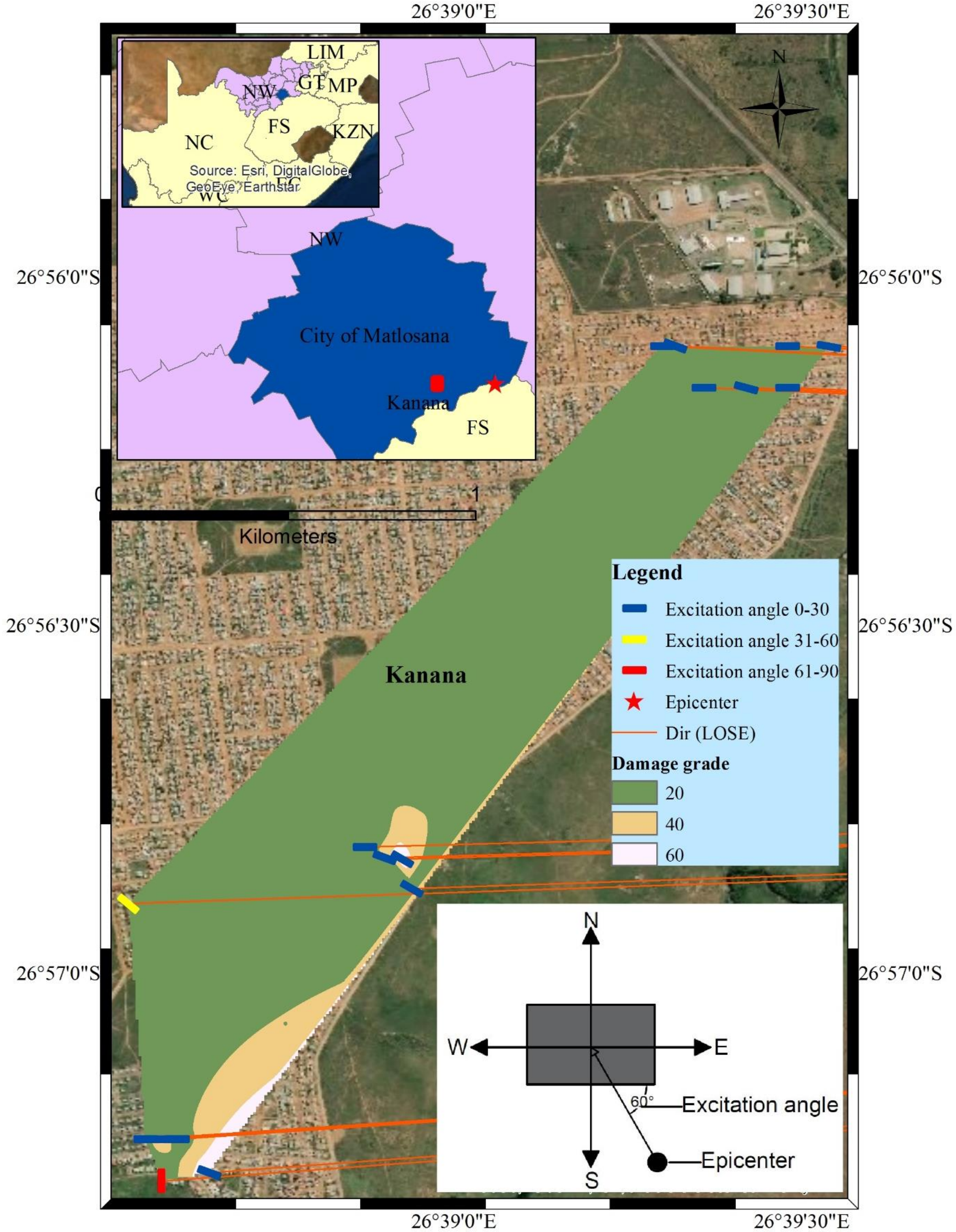


Figure 7-3: Spatial representation of excitation angle and damage grade in Kanana.

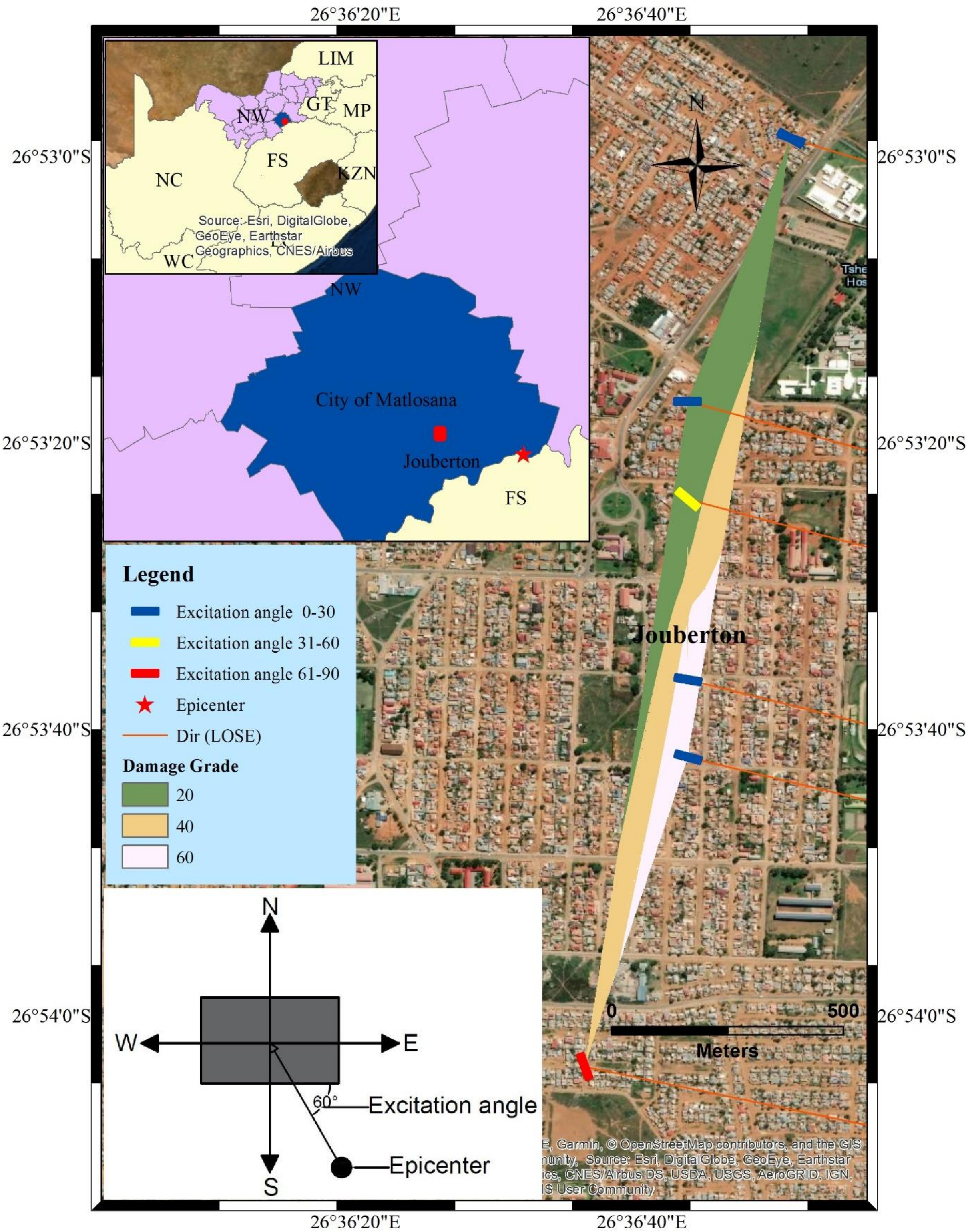


Figure 7-4: Spatial representation of excitation angle and damage grade in Jouberton.

Appendix D: Spatial representation of building weak points exposure and damage grade.

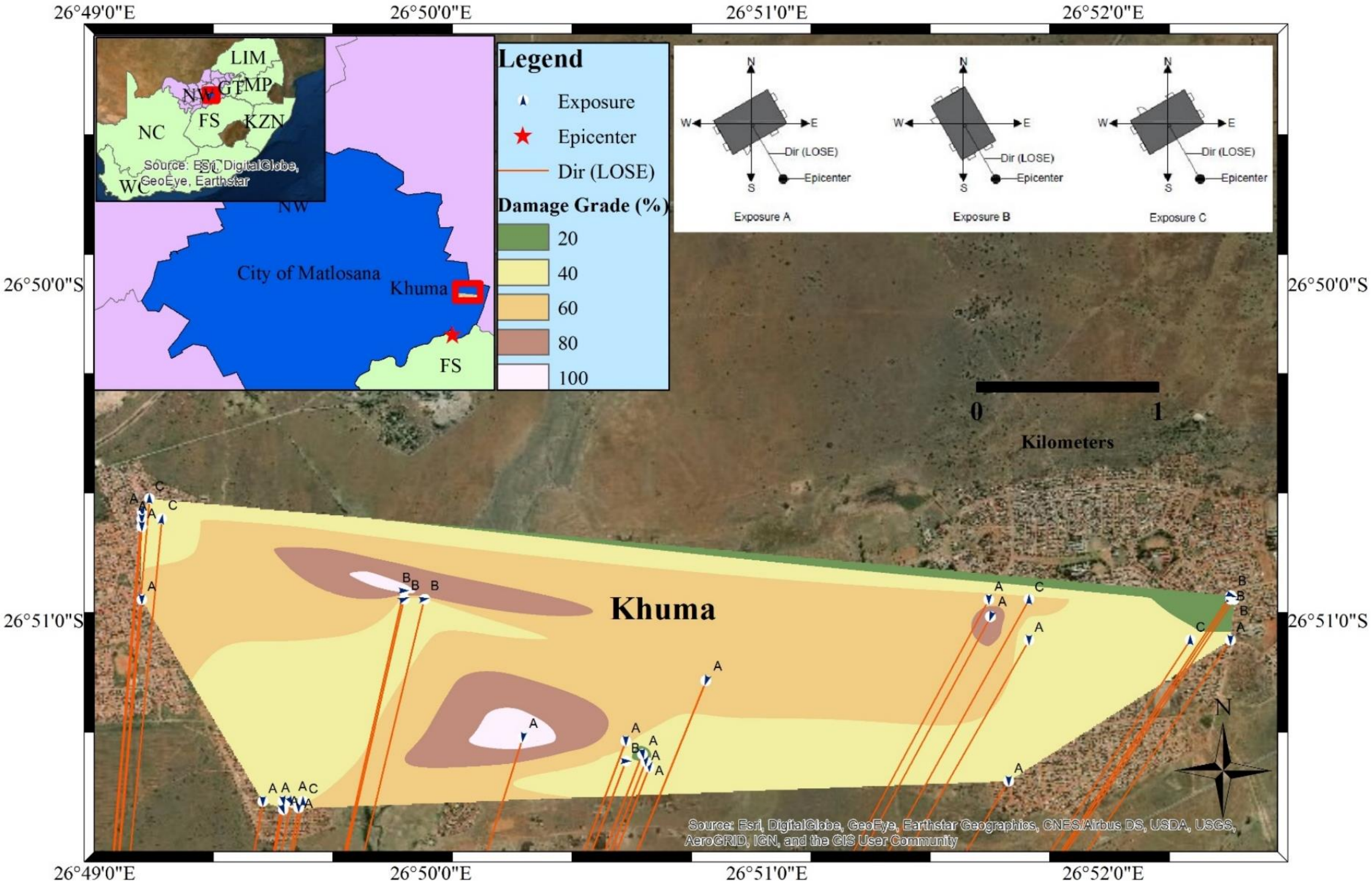


Figure 7-5: Spatial representation of building weak points exposure and damage grade in Khuma.

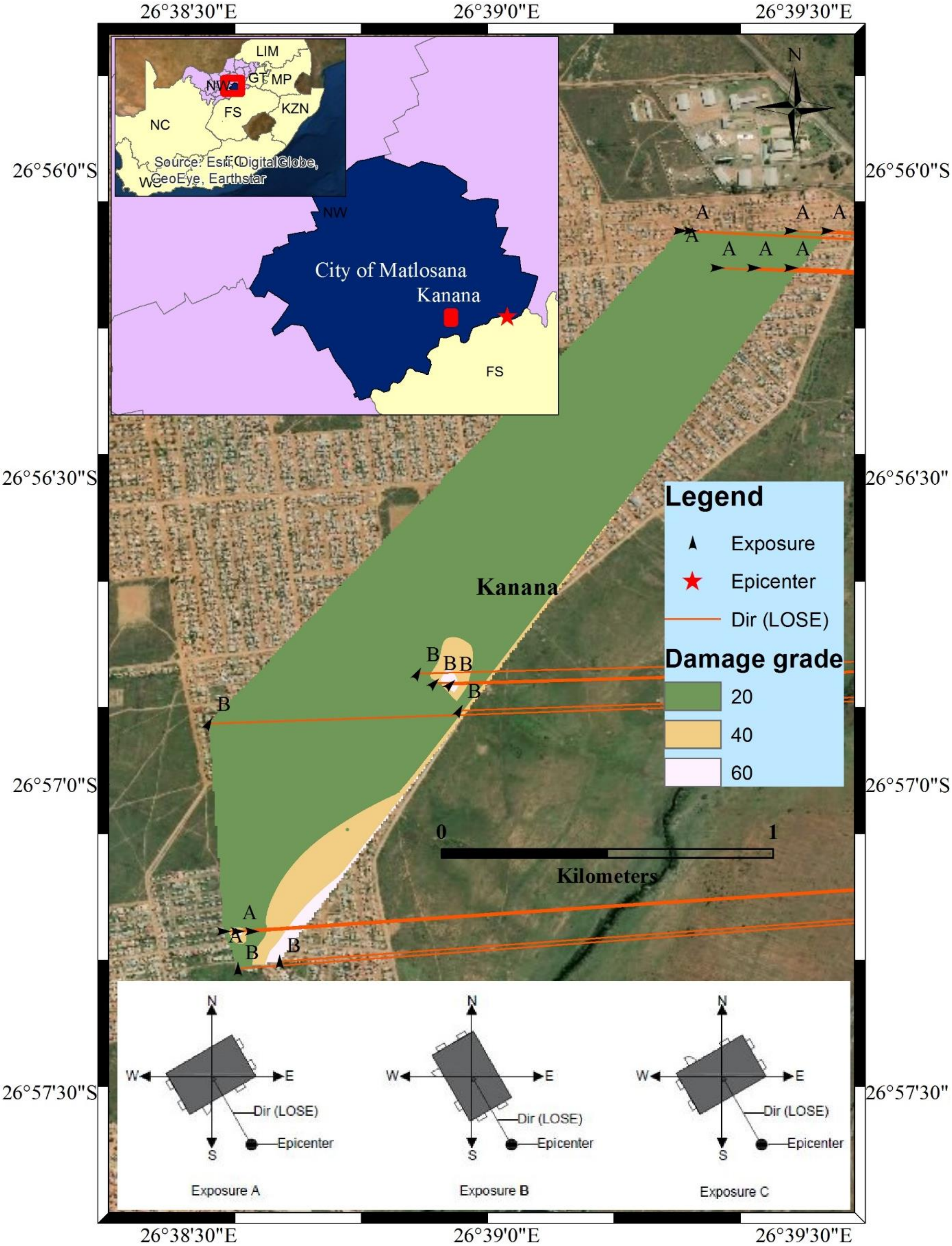


Figure 7-6: Spatial representation of building weak points exposure and damage grade in Kanana

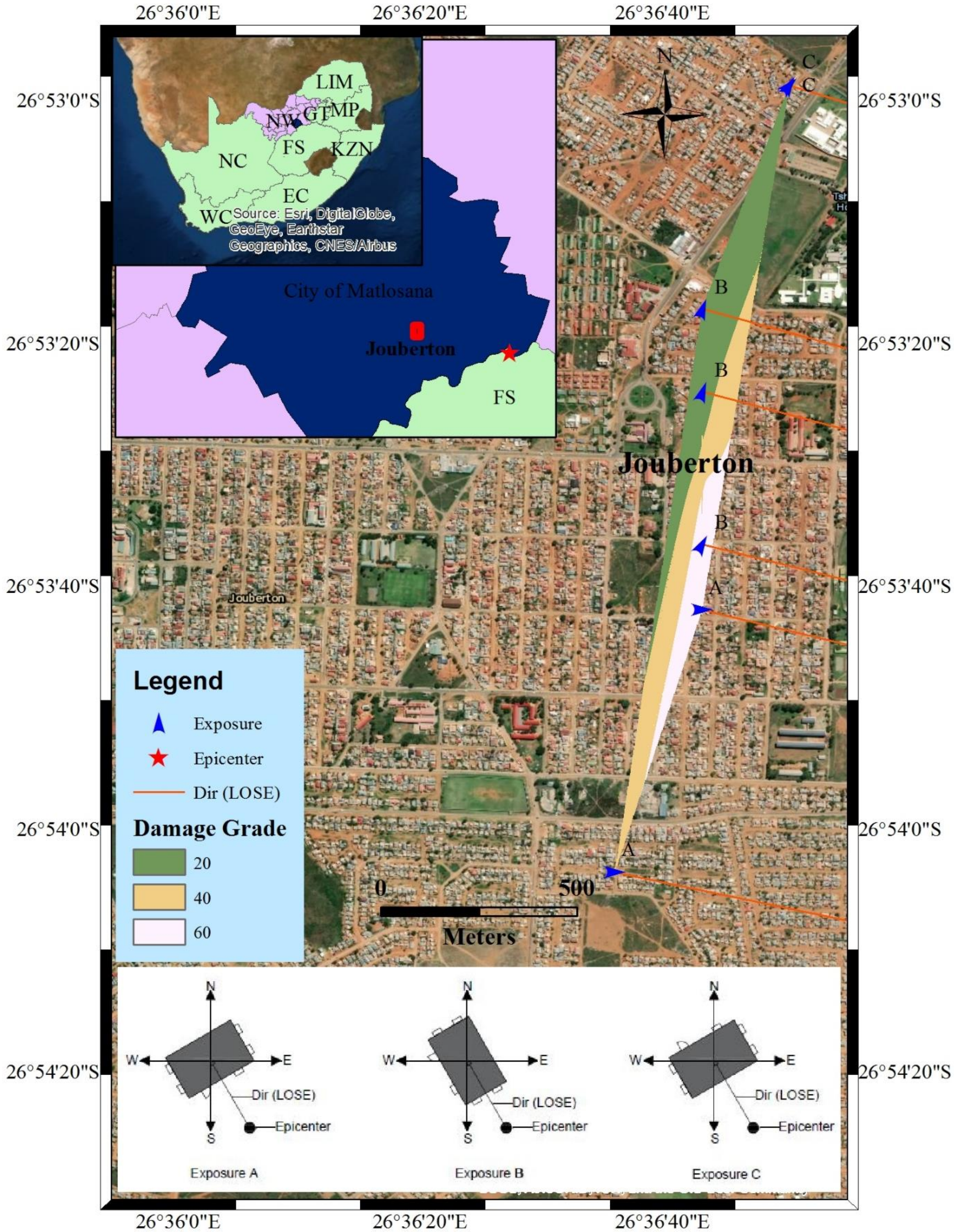


Figure 7-7: Spatial representation of building weak points exposure and damage grade in Kanana

Appendix E: Spatial representation of external building finish and damage grade

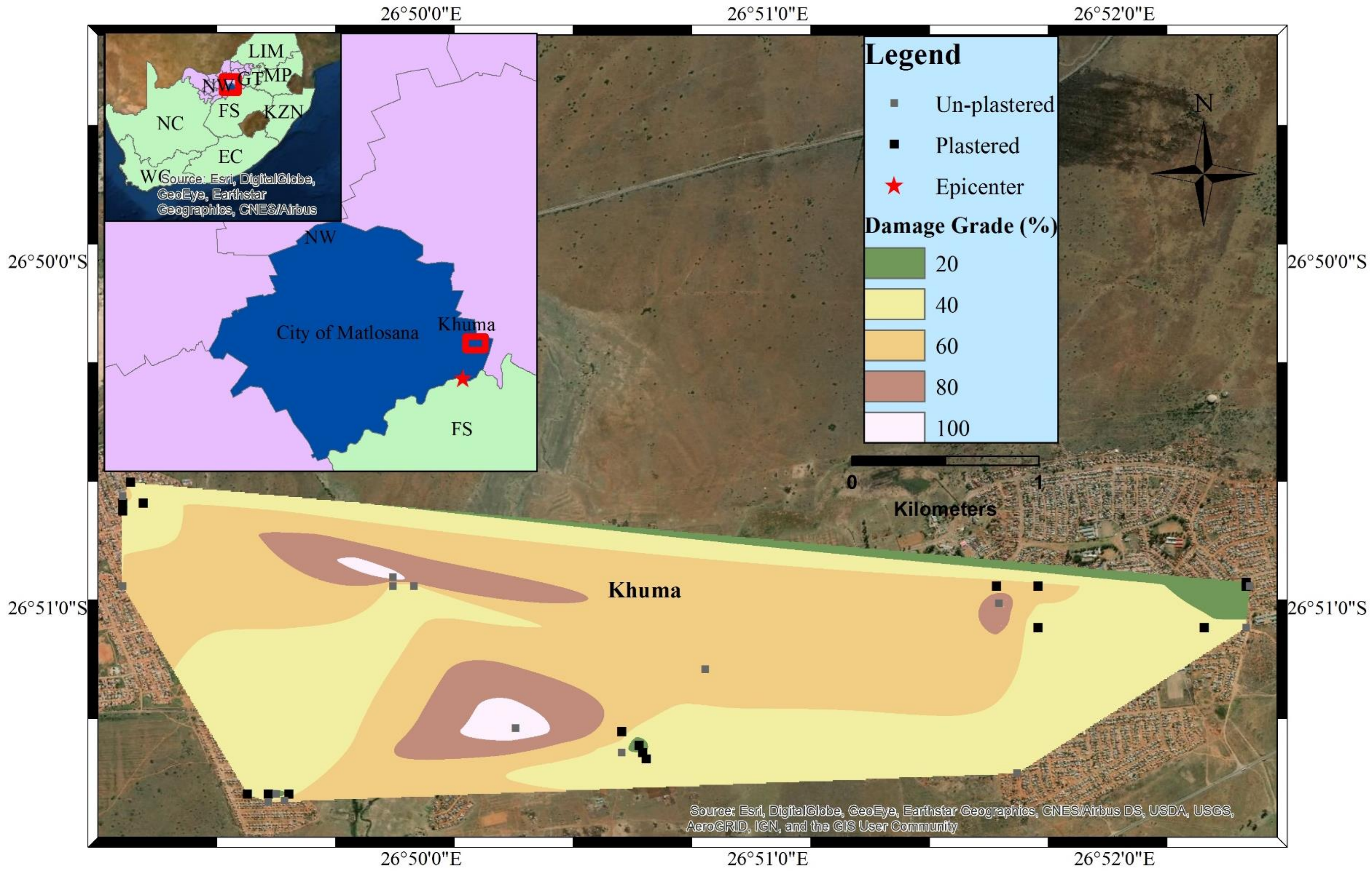


Figure 7-8: Spatial representation of external building finish and damage grade in Khuma

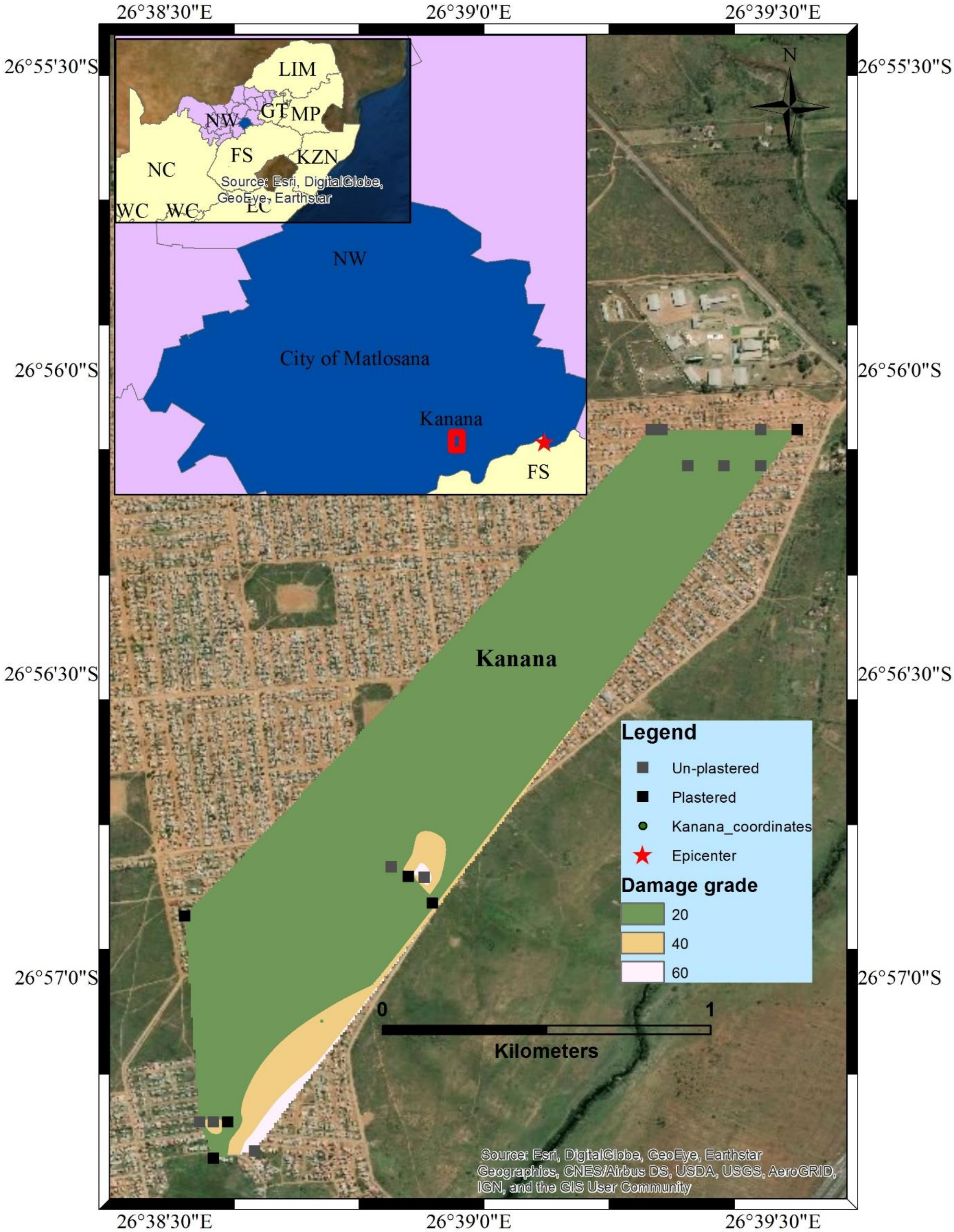


Figure 7-9: Spatial representation of external building finish and damage grade in Kanana

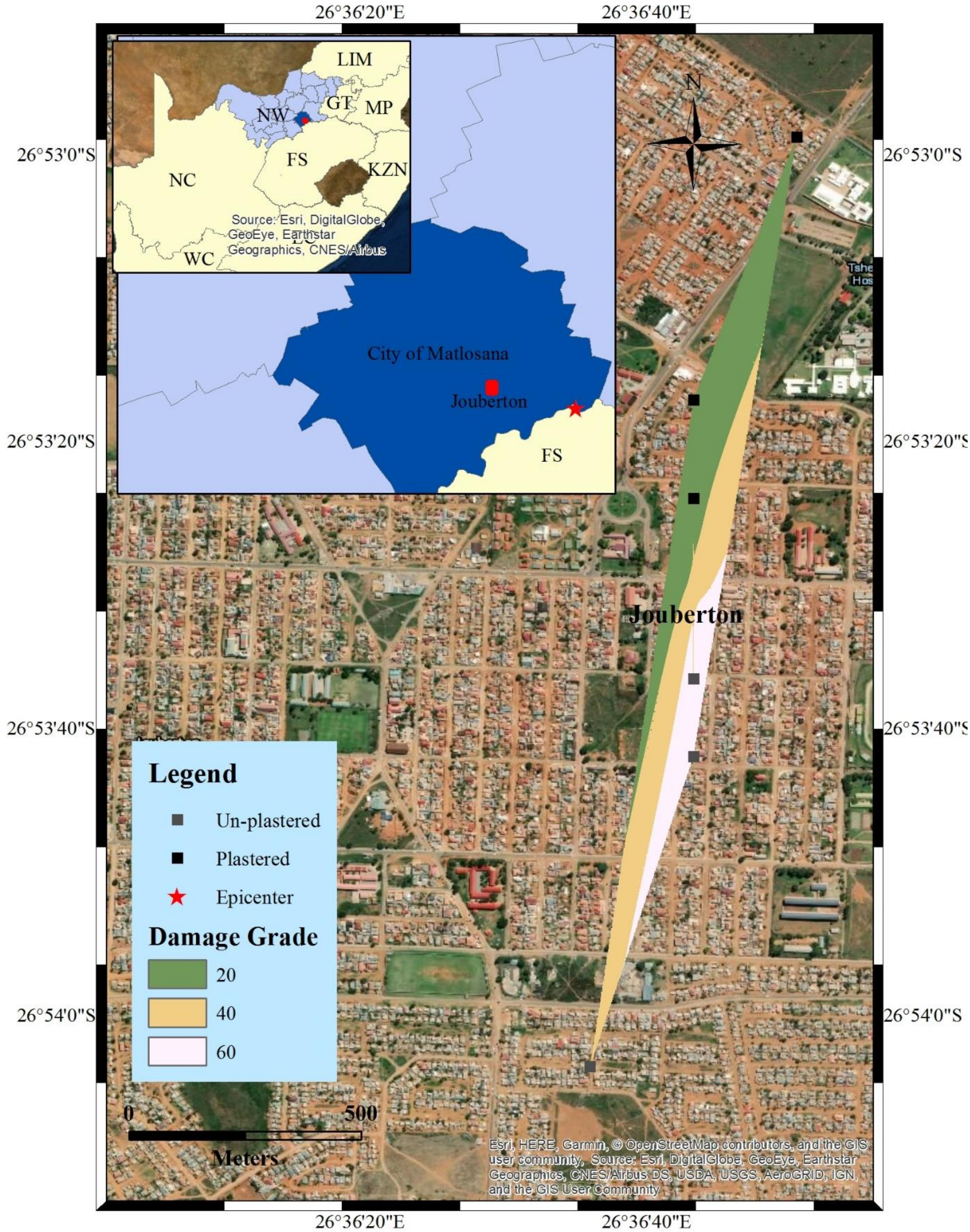


Figure 7-10: Spatial representation of external building finish and damage grade in Jouberton.

Appendix F: Damage index matric with expected damage and damage grade

Table 7-4: Damage index matrix showing expected and actual damage in Khuma

ID	Excitation	Exposure	Plastered/ Un-plastered	Total	Expected damage	Damage grade
KM01	3	3	1	7	medium	60
KM02	2	1	1	4	low	60
KM03	3	3	1	7	medium	40
KM04	2	1	1	4	low	40
KM05	2	3	3	8	high	40
KM06	1	3	3	7	medium	20
KM07	1	3	1	5	low	20
KM08	1	3	1	5	low	20
KM09	3	3	3	9	high	60
KM10	2	3	3	8	high	60
KM11	1	3	3	7	medium	60
KM12	3	3	3	9	high	60
KM13	3	3	3	9	high	80
KM14	2	3	1	6	medium	40
KM15	2	1	1	4	low	40
KM16	3	3	1	7	medium	40
KM17	3	1	1	5	low	40
KM18	3	3	3	9	high	100
KM19	3	3	3	9	high	100
KM20	3	3	3	9	high	60
KM21	3	3	3	9	high	60
KM22	1	3	1	5	low	40
KM23	1	3	1	5	low	40
KM24	3	3	3	9	high	60
KM25	2	1	1	4	low	40
KM26	1	3	1	5	low	40
KM27	1	3	1	5	low	40
KM28	3	3	1	7	medium	60
KM29	1	3	3	7	medium	40
KM30	1	3	1	5	low	40
KM31	3	3	3	9	high	80
KM33	3	3	3	9	high	100

Table 7-5: Damage index matrix showing expected and actual damage in Kanana

ID	Excitation	Exposure	Plastered/ Un-plastered	Total	Expected damage	Damage grade
KN01	3	3	1	7	medium	40
KN02	3	3	3	9	high	40
KN03	1	3	1	5	low	40
KN04	3	3	3	9	high	60
KN05	3	1	3	7	medium	60
KN06	3	3	1	7	medium	60
KN07	3	1	1	5	low	60
KN08	3	3	3	9	high	40
KN09	2	3	1	6	medium	40
KN10	3	3	3	9	high	60
KN11	3	3	3	9	high	40
KN12	3	3	1	7	medium	40
KN13	3	3	3	9	high	40
KN14	3	3	3	9	high	40
KN15	3	3	3	9	high	40
KN16	3	3	3	9	high	40
KN17	3	3	3	9	high	40

Table 7-6: Damage index matrix showing expected and actual damage in Jouberton

ID	Excitation	Exposure	Plastered/ Un-plastered	Total	Expected damage	Damage grade
JB01	3	3	1	7	medium	20
JB02	3	3	3	9	high	60
JB03	1	3	1	5	low	20
JB04	3	3	3	9	high	60
JB06	3	1	1	5	low	20
JB07	3	1	1	5	low	20
JB08	2	3	3	8	high	40

Appendix G: Correlation between damage index and damage grade

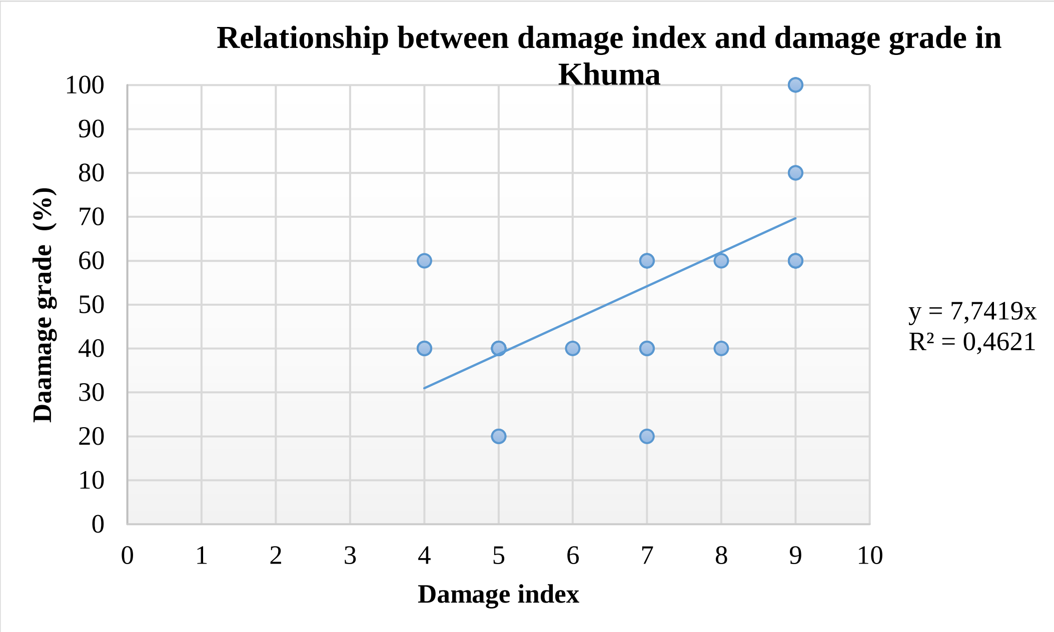


Figure 7-11: Correlation of damage index and damage grade in Khuma

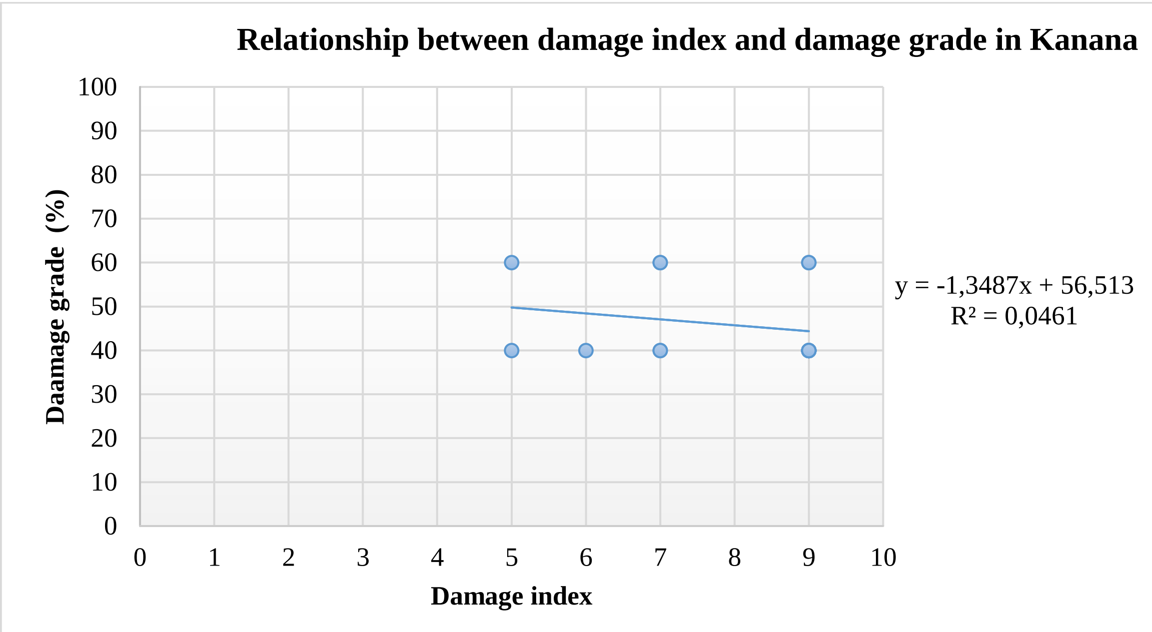


Figure 7-12: Correlation of damage index and damage grade in Kanana

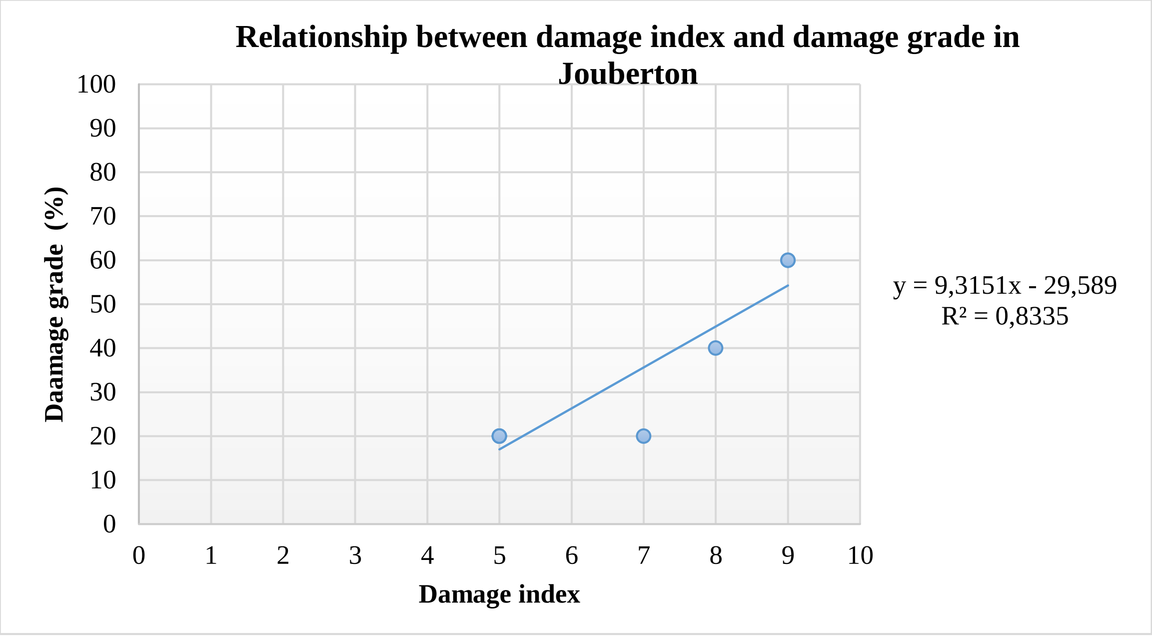


Figure 7-13: Correlation of damage index and damage grade in Jouberton

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