Flooding by Earthquakes

A thesis on the influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding

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Abstract

The Groningen gas field was discovered in 1959 in Slochteren, a municipality in the eastern part of the province of Groningen. The gas field is located in the north-east of the province of Groningen and is the largest gas field in western Europe. It generates a significant amount of money for the Dutch State and is for that reason an important financial source. The gas is located three kilometres below ground level. The pressure in the gas reservoir decreases when the gas get extracted from the Groningen gas field, which can causes earthquakes. The earthquakes in the province of Groningen have damaged houses and buildings in and surround the gas field area. This is often a hot topic in the newspapers and in other news related platforms. The possible damage on waterworks through earthquakes is not that often pointed in the newspapers and in other news related platforms. However, the effects of a collapsing house will affect a small group of people, while a collapsing sea dike will affect an enormous group of people. For that reason, this research is about the influence of earthquakes on the flooding risk in the province of Groningen. That provides the following central research question:

What is the influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding?

This thesis is underpinned by data gathered from interviews and literature study. The gathered data from literature are from articles about waterworks, earthquake influences, measures for waterworks against earthquakes and applied policies against earthquakes. The gathered data from interviews are more focussed on the province of Groningen. The interviews were with employees of local and regional governments, employees of water boards and with an employee of an engineering company which works with earthquake issues in seismologic active areas abroad. The local and regional governments and water board gave data about the specific problem in the province of Groningen, while the interview with the employee of the engineering company was more general and gathered data for examples to compare to the situation in Groningen.

Dikes and other waterworks are the primary defence against flooding. The water boards are responsible for the waterworks and have to repair or strengthen the waterworks when they don't meet the norm. Those norms are made by the Dutch government. There are failure mechanisms which affect dikes. Those failure mechanisms weaken dikes or can cause a total dike collapse. The earthquakes in the province of Groningen can give extra pressure to those failure mechanisms, especially on the macro-stability of dikes. However, there are several measures to make dikes (more) earthquake resistant. Dikes are flexible, in contrast to for example houses. Flexible objects are more earthquake resistant. Another solution to make dikes more earthquake resistant is the placement of dam walls or geotextile.

Rijkswaterstaat (2012)

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Abbreviation list

Abbreviation	Definition
Bcm	Billion cubic meter
ENW	Expertise Netwerk Waterveiligheid, Expert Network Water safety
NAM	Nederlandse Aardolie Maatschappij, Dutch Oil Company
NCG	Nationaal Coördinator Groningen, National Coordinator Groningen
PGA	Peak Ground Acceleration
RVS	Rapid Visual Screening

1. Introduction

1.1 Background

The Netherlands has a long history in water defence. But water defence doesn't work all the time. Zeeland, a province of the Netherlands, was flooded during a big storm in 1953. Although this was not the biggest flooding disaster in the Netherlands, the impact was enormous on an individual level, for the Netherlands itself and for coastal engineers (Petersen & Bloemen, 2015). To never let such a disaster happen again, the Delta Commission was installed and introduced the Delta Plan. This plan should prevent such a disaster from occurring again in the Netherlands. This Delta Plan is still in use. The Groningen gas field is described in the Delta Plan of 2015 as a place where a significant economic loss can occur during a flooding and which should get a high level of protection against flooding (Petersen & Bloemen, 2015).

To defend the Netherlands against such flooding, there are norms for primary and secondary waterworks. Those norms are norms for the risk of a flooding in a certain amount of years. So a norm of 1/4,000 means that the risk of a flooding is one flooding in 4,000 years. The primary flood defences are part of the main water system and are given a norm by the national government. The provinces were responsible for the secondary flood defences and their norms (Jong & van den Brink, 2013), however the national government has the responsibility for all the waterworks now.

Dike failure can occur through numerous causes. Vorogushyn et al. (2009) claim that those causes are divided into four different groups of failure mechanisms. *Hydraulic failure, Geohydraulic failure, Global static failure* and *other mechanisms*. *Hydraulic failure* is caused by high water and waves and induces an increase in erosion. This can lead to a total dike collapse (Vorogushyn et al, 2009). *Geohydraulic failure* is caused by micro-instability. *Geohydraulic failure* is a flow of water in a dike, which induces internal erosion. This can lead to slope and core failure (Vorogushun et al., 2009). *Global static failure* is caused by water, ice, wind, waves and the dike's own weight (Vorogushun et al., 2009). This can lead to a dike collapse. The *other mechanisms* are caused in various ways, such as human-induced failure (e.g. sabotage or damage by maintenance) and failures of for example gated sluices and culverts or other dike crossing hydraulic structures (Vorogushun et al., 2009).

The earthquakes induced by gas extraction are a big topic in Groningen, especially during latest elections last March (2017) when there were parliamentary elections in the Netherlands. The first national debate between the different parties for the election was in Groningen and one of the main topics was gas extraction in the province of Groningen (AD, 2017).

The gas field of Groningen is located three kilometres below ground. The gas is captured under high pressure in a porous rock layer. Above the rock layer, there is a non-porous layer, so the gas is trapped inside the porous rock layer below the non-porous layer (KNMI, 2017). By removing the gas from the porous rock layer to gain gas, the pressure in the porous rock layer is reduced. This causes subsidence, which appears in two different situations. When the subsidence is gradual, there will be no earthquake. When the subsidence is jerky, it can cause an earthquake (KNMI, 2017).

The gas field of Groningen was discovered in 1959 (Breunese & Rispens, 1996) and is the largest natural gas field of western Europe. In 1959, the gas reserves were 3,582 billion cubic metres (bcm) (CBS, 2016) and nowadays approximately 940 bcm is left in the Groningen gas field, only 20% of the total gas reserves in 1959 (CBS, 2016). The gas field is located in the north-eastern part of the Province of Groningen (Figure 1).

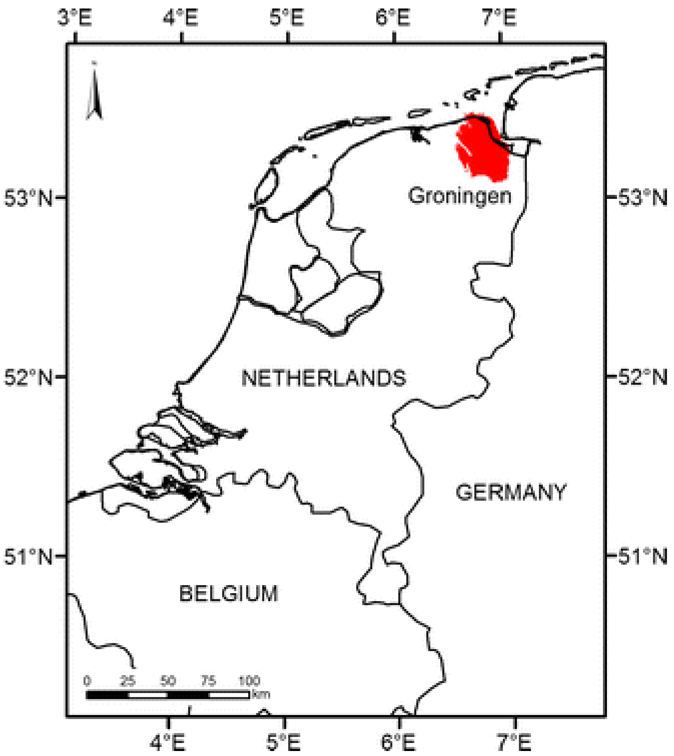

Figure 1. Location of the Groningen gas field (Kruiver, P.P. et al., 2017).

The Netherlands earns a significant amount of money by selling the extracted gas of the Groningen gas field. The total amount of money the Netherlands has earned so far is about €290 billion (NOS, 2017). That is a lot of money for the Netherlands, especially in the year 2013 when it was 9% of the public revenue of the Netherlands (CBS, 2016). For that reason, the Groningen gas field is an important financial source for the Netherlands.

The Nederlandse Aardolie Maatschapij, NAM in short, extracts the gas on behalf of the Dutch state. The amount of gas extracted is never constant. There were peaks in the years 1976, 1985, 1993 and 2013. After the peaks there were periods of reduced gas extraction from the Groningen gas field (NAM, 2017). Nevertheless, the number of earthquakes shows an increase. There were two earthquakes in the year 1992, thirty-two in 2003 and one-hundred-and-nineteen in 2013 (NAM, 2017).

According to Zuada Coalho et al. (2015), the dikes in the province of Groningen can be in danger because of the earthquakes. Their article concludes that 45% of the primary dikes and 25% of the secondary dikes are not safe against the maximum expected accelerated increase of earthquakes. However, this is the worst case scenario and therefore a bit conservative, according to Zuada Coalho et al. (2015). 45% of the primary and 9% of the secondary dikes will be affected in an average ground scenario (Zuada Coalho et al., 2015).

The earthquakes caused by extraction of gas from the Groningen gas field damage houses in the specific area of the Groningen gas field and in areas nearby. In the period from August 2012 till July 2014, 19,712 damage claims were sent to NAM (Van der Voort & Vanclay, 2015). So the houses in this specific area get damaged by the earthquakes. Apart from the houses getting affected by earthquakes, will the waterworks get affected by earthquakes too?

1.2 Problem statement

The waterworks defend the Netherlands, so the province of Groningen as well, against flooding. The waterworks have norms to guarantee a certain security level for the protection against flooding. Nevertheless, according to Zuada Coalho et al. (2015), earthquakes in the province of

Groningen do have influence on the primary and secondary dikes. Only, will they have such an influence on the waterworks that the earthquakes will cause the waterworks to exceed their norms and therefore not safe enough against flooding? If so, are there measures which may protect the waterworks against earthquakes or are there policies to defend regions against earthquakes? Those questions will be answered in this thesis.

The influence of earthquakes induced by gas extraction on the protection of flooding in the province of Groningen will be investigated on the basis of the following main research question and secondary research questions:
Central research question:

What is the influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding?

Secondary research questions:

- **What are the regulations for the dikes on flood risk in the province of Groningen?**
- **What can be the consequences of earthquakes on waterworks?**
- **Are there any known solutions to protect the dikes against earthquakes or to make them earthquake proof?**

1.3 Structure

This report starts with an overview and explanation of the methodology used during the research. The literature used for this report will be discussed in the theoretical framework. This particular chapter describes and explains the relevant theories and concepts from literature to provide an overview of the current situation of the dikes and earthquakes in Groningen, the possible influence of earthquakes and possible consequences of a dike failure. The methodology chapter describes the research method and how data are collected. The results of the research are presented in the chapter concerned. The secondary research questions are answered by means of literature and data of the interviews. The final chapter describes the conclusions of this research and gives an answer to the main research question. It discusses the answer on the main research questions, gives recommendations for further research and reflects on the process of this thesis.

2. Theoretical framework

2.1 Regulations waterworks

The total number of flood events has increased during the last century (White, 2010). There are two different strategies to deal with flood hazards. ''The goal of a resistance strategy is to reduce the probability of a flood hazard, whereas resilience aims at minimizing the consequences of flooding'' (Restemeyer et al., 2015, p. 46). Resilience strategies are more focussed on the risk management of a possible flooding, instead of focussing on the hazard control (Vis et al., 2003). Restemeyer et al. (2015) suggest that resilience is divided into three aspects: Robustness, Adaptability and Transformability. Robustness is the first defence, like dikes and sluices (Restemeyer et al., 2015). However, when Robustness defence isn't enough to stop a flooding, Adaptability is crucial (Restemeyer et al., 2015).

Adaptability is necessary to decrease the possible damage of a flooding on the hinterland (Restemeyer et al., 2015). Important for Adaptability are the adjustments of the physical environment as well as the social sphere (Restemeyer et al., 2015). Houses built on poles or the acceptation and adaptation to controlled flooding are examples of adjustments of the physical environment and the social sphere (Restemeyer et al., 2015).

Only when the physical environment and the social sphere are changed in such a way that there is a shift from fighting against the water to living with the water, there is a transformation (Restemeyer et al., 2015). Transformability is in fact the transformation of this whole phenomenon.

So, Robustness is part of resilience and is the first defence against water and requires large public funds to construct (Restemeyer et al., 2015). Dikes are an example of robustness.

To protect the Netherlands properly, the dikes need to meet the norms made by the national government for primary and secondary flood defences. ''Water managers consider flooding risks as measurable norms based on technical-engineering knowledge about cause-effect relations, that is, the probability of the occurrence of peak discharges and the strength and height of the dikes.'' (Jong & van den Brink 2013, p.161).

However, dikes can have failures. Ambruster-Veneti (1999) divide those failures into four different groups of failure mechanisms, namely *Hydraulic failure, Geohydraulic failure, Global static failure* and *other mechanisms* (Figure 2). Those failure mechanisms groups are divided into those four groups, because they have different causes.

Hydraulic failure is the collapse of dikes by overtopping and wave scour (Vorogushyn et al., 2009). Wave swashing and the water level exceeding the crest height can lead to overtopping (Vorogushyn et al., 2009). ''The surface erosion of the landward slope can then be initiated if the shear stress induced by the overtopping flow exceeds the critical shear stress of the dike material'' (Vorogushyn et al., 2009, p.1384). Total dike collapse may follow by the progressive erosion (Vorogushyn et al., 2009).

Geohydraulic failure is erosion within a dike which can lead to failure of the inner slope by micro-instability. The flow of water through or under a dike, piping, will transport material in or under the dike and will lead to a sagging of the dike core, slope failure and collapse (Vorogushyn et al., 2009). Even animal holes in the dikes can cause erosion within the dikes and could cause core failure (Vorogushyn et al., 2009).

With *Global static failure,* dike collapse can be caused by pressure forces of water, ice, wind, waves and the dike's own weight (Vorogushyn et al., 2009). Failure by gravity and pressure is denoted as macro-instability (Vrijling, 2001).

The last of the failure mechanisms groups is the *Other mechanisms.* Human-induced failure, like sabotage and damaging during maintenance, are part of the *Other mechanisms* (Vorogushyn et al., 2009). Such mechanisms occur very seldom (Vorogushyn et al., 2009).

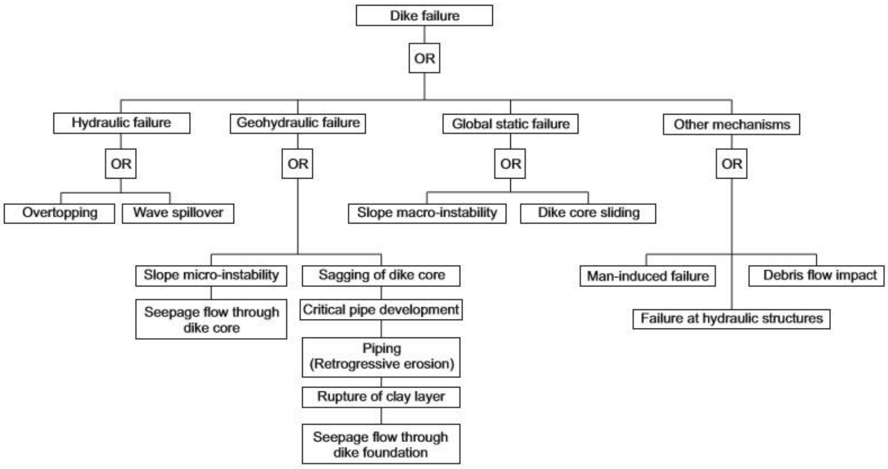

Figure 2. Failure mechanisms (Armbruster-Veneti, 1999).

2.2 Effects of earthquakes on waterworks

Gas extraction is responsible for almost all the earthquakes in the northern part of the Netherlands. The first earthquake, caused by gas extraction, was in Assen in 1986. There have been about a thousand earthquakes since the earthquake in 1986 (KNMI, 2017). Most of them were below the magnitude of 2.0 on the Richter scale. However, the strongest earthquake had a magnitude of 3.6 on the Richter scale in Huizinge, a small village in the north-eastern part of the province of Groningen, in 2012 (Hagoort, 2017).

The earthquakes in the province of Groningen are caused by gas extraction. Such earthquakes occur in and around the gas reservoir. The gas is captured under high pressure, three kilometres below ground level, in a porous rock layer (KNMI, 2017). When the gas gets removed, the pressure decreases and the porous ground layer shrinks. This can happen gradually or jerkily. The jerky land subsidence causes earthquakes (KNMI, 2017).

The number of observed earthquakes, with a magnitude larger than 1.5, corresponds with the gas production of the Groningen gas field (Hagoort, 2017). There were 284 earthquakes (Figure 3), with a magnitude larger than 1.5 on the Richter scale, until January 1st, 2017. Hagoort (2017) says that there will be around 700 earthquakes with a magnitude larger than 1.5 on the Richter scale in total. There are about 400 earthquakes to be expected, with, according to Hagoort's (2017), a maximum magnitude of 4.4 on the Richter scale. There will be only one that strong (between magnitude 4-4.5 on the Richter scale) according to Hagoort (2017). Furthermore, there will be three earthquakes between magnitude 3.5-4 on the Richter scale, ten earthquakes between magnitude 3-3.5 on the Richter scale, 31 earthquakes between magnitude 2.5-3 on the Richter scale, 97 earthquakes between magnitude 2-2.5 on the Richter scale and 304 earthquakes between magnitude 1.5-2 on the Richter scale (Table 1).

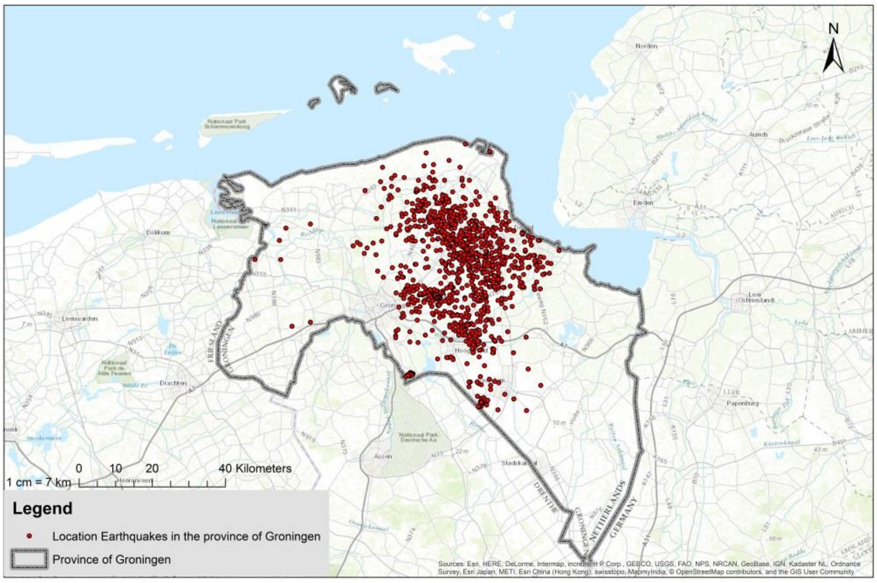

Figure 3. Locations of the earthquakes in the province of Groningen (own source).

Magnitude on the Richter scale	Number of expected earthquakes
4-4.5	1
3.5-4	3
3-3.5	10
2.5-3	31
2-2.5	97
1.5-2	304
Total	**446**

Table 1: number of earthquakes per Magnitude on the Richter scale (own source).

Zuada Coalho et al. (2015) conclude that 45% of the primary dikes and 25% of the secondary dikes (regional) are not safe enough to meet the norms in case of the maximum expected earthquake. Nevertheless, in the average ground scenario it would be 45% for the primary dikes and 9% for the secondary dikes respectively (Zuada Coalho et al., 2015).

Dikes can be affected by earthquakes like those in Groningen (Zuada Coalho et al., 2015). Zuada Coalho et al. (2015) state that the macro-stability of dikes can be influenced by earthquakes in Groningen. Those can weaken the dike and can give three effects, namely *dike sliding movement, compaction* and *squeezing*. When there is dike sliding movement, a piece of the dike will slide off the dike, so the dike will be lower or thinner. When there is compaction, the sand will be more compact and the dike will be lower in the end and when there is squeezing the dike will get lower because of the pressure of the weight of the dike on the undersoil and the surrounding parts will get slightly higher (Zuada Coelho et al., 2015). The main reason why earthquakes can damage the dike is Peak Ground Acceleration (PGA). PGA is the acceleration of the earthquake in the earth in m/s^2 (Zuada Coelho et al., 2015).

''The stability of buildings in seismic prone areas depends upon the structural behaviour of the building when subjected to ground motion'' (Rajarathnam & Santakumar, 2015, p.784). Buildings with an irregular nature to geometry or stiffness are more vulnerable for earthquakes than buildings that have regular configuration (Rajarathnam & Santakumar, 2015).

Rajarathnam & Santakumar (2015) describe different irregularities. The stiffness irregularity is: ''The lateral stiffness is less than 70% of that in the storey above or less than 80% of the average lateral stiffness of the three storeys above. This can occur due to soft storey or due to opening provided for shop front'' (Rajarathnam & Santakumar, 2015, p.787). The mass irregularity has a link with the weight of a storey. When one storey has more than 200% of the adjacent storey, there is mass irregularity (Rajarathnam & Santakumar, 2015). Those irregularities increase the vulnerability to earthquakes.

2.3 Measures

Stiffness has an influence on the vulnerability to earthquakes (Rajarathnam & Santakumar, 2015). To detect damage by earthquakes, Rajarathnam & Santakumar (2015) suggest Rapid Visual Screening (RVS). The purpose of RVS is to inspect buildings visually after an earthquake. The buildings are divided into different classes of hazard level and are classified in damage potential (Rajarathnam & Santakumar, 2015).

The damage of the buildings will be checked by aerial photograph analysis and actual ground truth verification. Aerial photograph analysis is used to ''identify a few of the important irregularities causing seismic vulnerability of building'' (Rajarathnam & Santakumar, 2015, p. 792). All the other irregularities, which cannot be detected by aerial photograph analysis, will be checked by actual ground truth verification (Rajarathnam & Santakumar, 2015).

The article of Restemeyer et al. (2015) discusses that just robustness alone is not the solution for flood resilience. The article claims that adaptability and transformability are necessary as well for water resilience. So just strengthening dikes or making dikes earthquake proof cannot be the only or best solution for this problem. Because the research area has a significantly high economic value, according to Petersen and Bloemen (2015), the government of the Netherlands should be more interested to keep this area safe from flooding than an area with a lower significant economic value.

The upwards trend in the frequency of earthquakes till 2013 is reversed by the new maximum for the production rates of gas from the Groningen gas field allowed by the Dutch government. It went from 53.87 billion cubic meters per year in 2013 to 42.41, 28.10 and 27.95 billion cubic meters per year in 2014, 2015 and 2016. This has resulted in a relatively lower pressure on the gas reservoir and therefore a reduction in earthquake frequency (Hagoort, 2017).

The government of the Netherlands has decided to decrease the maximum production rate to 24 billion cubic meters per year, which can rise to 30 billion cubic meters per year during a cold winter (Rijksoverheid, 2016). According to Hagoort (2017) this will cause a decrease in the frequency of earthquakes per year and spread the frequency more evenly over the years.

2.5 Conceptual Model

A conceptual model involves a statement of the basic interactions between the components of a system (Clifford et al., 2012, p.276). This conceptual model (Figure 4) is a visual representation of this thesis. It's built up by theories and concepts of the theoretical framework to support this thesis. The hexagons (in the model) are concepts of the main research question, while the rectangles are supportive theories and concepts to answer the main research question. The influence of the earthquakes on dikes and the change of a flooding will be researched in this thesis. The research will be supported by the macro-stability of the dikes, the goals for robustness and the influence of policy on earthquakes.

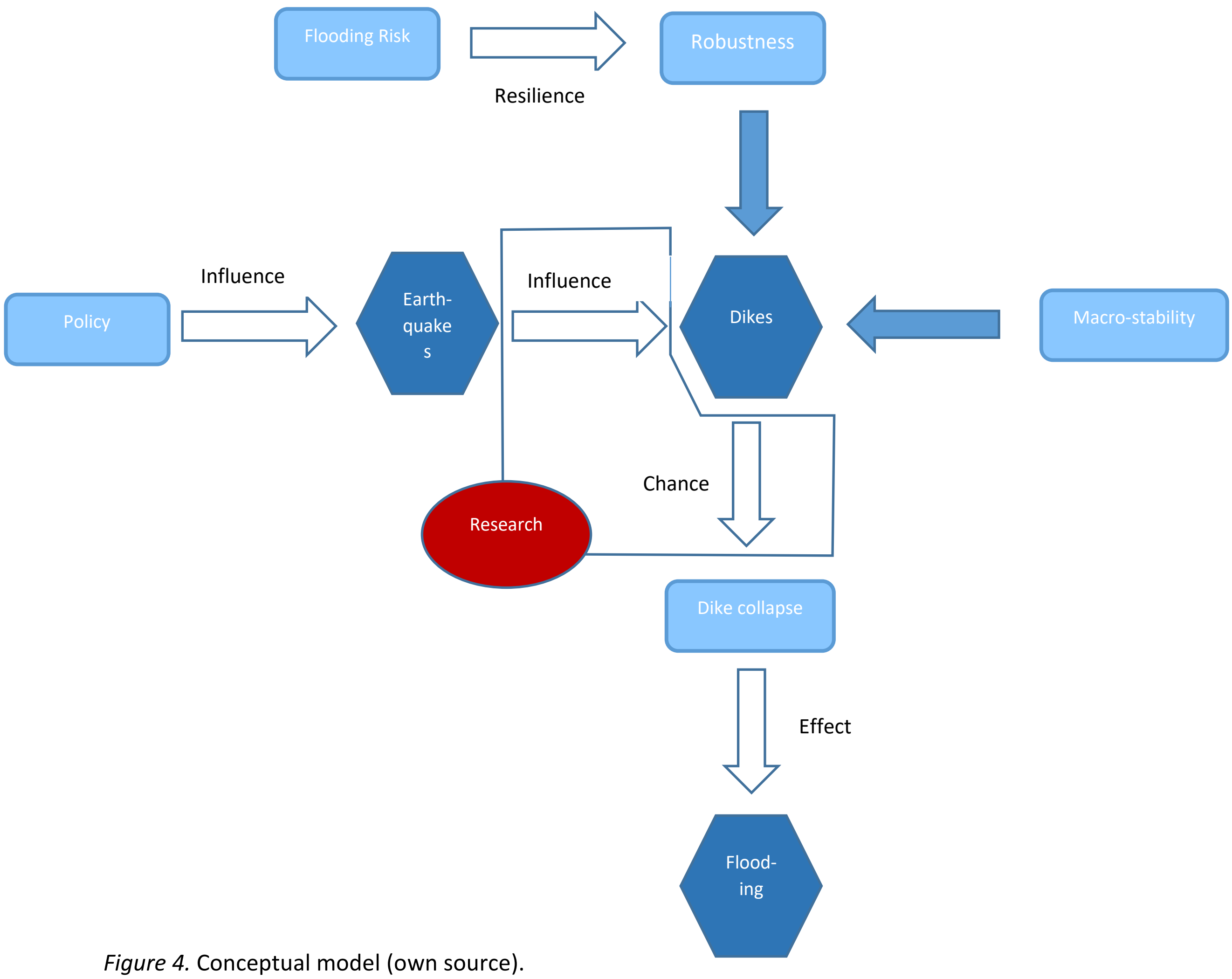

Figure 4. Conceptual model (own source).

3. Methodology

The aim of this thesis is to give an overview of the influences of the earthquakes in Groningen on the flooding hazard in the province of Groningen. The following research methods were applied to gain the data: literature analysis and semi-structured interviews. These have been used to answer the secondary research questions. Those questions having been answered, it will lead to an answer to the main research question:
What is the influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding?

3.1 Case Selection

The Groningen gas field is unique in the Netherlands and western Europe, it is namely the biggest gas field in western Europe. Besides that, there are tensions between the local residents who live in and around the Groningen gas field, because houses in the area are damaged by earthquakes, and the government, because the Groningen gas field provides a relatively high amount of money for the state of the Netherlands. There are conflicting interests between the government of the Netherlands and the local residents on money and safety of the residents, but the government is responsible for the safety of their residents. The houses and the waterworks need to be safe to ensure the safety in the province of Groningen. The government has to search for a solution that guarantees the safety of the residents, and is profitable for the state. *NAM* is responsible for the extraction of the gas from the Groningen gas field and for the damages caused by earthquakes. The water boards *Noorderzijlvest* and *Hunze en Aa's* are responsible for the affected waterworks in the area by the earthquakes.

There was a lot of media attention, and there still is, for the actually and potentially damaged houses, only there isn't much media attention for the actually and potentially damaged waterworks. This has made this thesis an topical problem. Broken waterworks can have a catastrophic impact, like the Watersnoodsramp in Zeeland (Petersen & Bloemen, 2015). It would be dangerous for the residents in the specific area and it would be a significant economic loss (Petersen & Bloemen, 2015).

3.2 Literature analysis

The theory is based on several peer-reviewed scientific articles and reports. However, there were not many peer-reviewed scientific articles on the case of the Groningen gas field. This case is quite actual. The scientific articles used in this thesis give an insight into the current situation, the effects of earthquakes and how earthquakes in Groningen arise and what could be possible counter measures. So, there aren't many peer-reviewed scientific articles about this particular case.

Nevertheless, there were several helpful articles for the theory of the thesis. The articles of Restemeyer et al. (2015) and Vorogushyn et al. (2009) helped by analysing the articles to give a theory for the waterworks and the failure mechanisms of waterworks. The article of Zuada Coalho et al. (2015) gives a theory of the possible effects of earthquakes on dikes. Those possible effects could have influences on the failure mechanisms of waterworks. The articles of Rajarathnam & Santakumar (2015) and Hagoort (2017) helped by analysing the theory for possible measures to minimalize such influences on the failure mechanisms.

The semi-structured interviews and reports were an extra data collecting method (Clifford et al., 2012) to gather enough information for the thesis.

3.4 Semi-structured interviews

Employees of the water boards *Noorderzijlvest* and *Hunze en Aa's*, of the municipality of *Eemsmond* and of the engineering firm *Royal Haskoning DHV* have been interviewed in a semi-structured way. A semi-structured interview is an interview with a list of predetermined questions. However, the interviewer can ask more about topics he or she thinks is important and interesting (Clifford et al, 2012). That is why a semi-structured interview was chosen for this thesis. The interviewee could tell something which hadn't been thought of before the interview. In semi-structured interviews it is possible to ask more about those subjects, told by the interviewee, which could be important for the research. Clifford et al. (2012) describe it as: ''This form of interviewing has some degree of predetermined order but still ensures flexibility in the way issues are addressed by the informant.'' (Clifford et al., 2012, p.105).

The interview with an employee of the municipality of *Delfzijl* was an open interview. The interview with the employee of the municipality of *Delfzijl* was focused on a project of the sea dike of Delfzijl on local, regional and national level. Many different parties are involved to make such a project feasible. There is chosen for an open interview, because the list with predetermined questions wouldn't fit to this certain topic.

An open interview gave the opportunity to ask questions about the project of the sea dike of Delfzijl. The interviewer in an open interview introduces discussion topics to the interviewee and keeps the conversation going. This makes it more accessible to ask through on certain topics (Reulink & Lindeman, 2005).

The interviewees that participated for this thesis and were interviewed in a semi-structured way are:

- Ate Wijnstra, Projectmanager Delfzijl-Eemshaven for the water board *Noorderzijlvest*. He is concerned with the most unstable dike in the province of Groningen.
- Walja Karten, program manager water barriers for the water board *Noorderzijlvest*. He is involved with the primary and secondary waterworks.
- Albert Wiggers, principal geotechnical engineer for the engineering company *Royal Haskoning DHV*. He has a lot of experience with waterworks and seismic damages in foreign countries.
- Henk van der Leij, as employee of the water board *Hunze en Aa's* responsible for the waterworks and safety.
- Boudewijn van Baal, employee of the municipality of *Eemsmond* and specialised in earthquakes in the province of Groningen.
- Namda Pellenborg, internal coordinator of the earthquake issues of the municipality of Eemsmond.
- Jornald Veldman, employee of the municipality of *Delfzijl* and concerned by the Marconi project.

The interviews with Albert Wiggers of *Royal Haskoning DHV* and with Ate Wijnstra of water board *Noorderzijlvest* were interviews by phone. The interview was recorded directly on the phone by the application *ACR*. The interviewee was immediately told that the interview would be recorded to transcribe, code and analyse the data and was asks if there were any complains about the fact that it would be recorded. So the interview was recorded to transcribe, code and analyse the data.

The other interviews, with Walja Karten of the water board *Noorderzijlvest*, Henk van der Leij of the water board *Hunze en Aa's*, Jornald Veldman of the municipality of *Delfzijl* and Boudewijn van Baal and Namda Pellenborg of the municipality of *Eemsmond*, were face to face interviews in the offices of the interviewees. The interviewees were informed that the interviews would get recorded for transcribing, coding and analysing the data. The interviews were recorded on a mobile phone.

All interviews were based on the same predetermined questions and sub-questions, expect Jornald Veldman of the municipality of *Delfzijl*. First, the interviewees were asked to introduce themselves and tell something about their company, water board or municipality. After the introduction, the main questions and sub-questions about flooding hazards, effects of earthquakes, measures and policies were asked and, where necessary, the interviewees were asked to elaborate on specific answers. The interviewee was asked if he or she had some extra information or wanted to give some extra explanation about a certain topic or question at the end of the interview.

The interview with Jornald Veldman of the municipality of *Delfzijl* was focused on their project on the sea dike of Delfzijl. All the questions were about the project.

3.5 Quality of data

All of the interviewees were directly or indirectly involved with (a part of) the research question *What is the influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding?* The water boards *Noorderzijlvest* and *Hunze en Aa's* both have their own area within the province of Groningen. The differences and similarities of those water boards will become clear through the interviews. The differences and similarities are useful to show the different reasons and considerations for a certain decision or policy. Walja Karten (*Noorderzijlvest)* and Henk van der Leij (*Hunze and Aa's*) both have a good overview of the organisations of waterworks within their water board. Ate Wijnstra (*Noorderzijlvest*) is directly involved with the sea dike Eemshaven-Delfzijl and can give inside information about the characteristics of the dike and the measures that are taken against earthquakes.

Albert Wiggers (*Royal Haskoning DHV*), Boudewijn van Bouw and Namda Pellenborg (both *municipality of Eemsmond*) are experienced with earthquakes and the possible effects of earthquakes. However, Boudewijn van Bouw is more specialised in the Groningen earthquakes and Albert Wiggers has a lot of experience with earthquakes abroad. The differences and similarities are useful for the search for possible measures and what the province of Groningen can learn from foreign cases. Albert Wiggers and Boudewijn van Bouw were interviewed more in depth about the earthquakes, because they are really specialised in this certain topic.

Boudewijn van Baal and Namda Pellenborg (both *municipality of Eemsmond*) and Jornald Veldman (*Municipality of Delfzijl*) are both employees of municipalities which have to deal with earthquakes. It is interesting to see what are the similarities and differences between the two municipalities and the reasons why they do what they do to tackle earthquake problems. The municipalities are more focussed on their region and are asked more about this certain topic during the interview. The cooperation between water boards and municipalities becomes clear through the interviews and how the different parties see this cooperation.

3.6 Data analysis

The data of the interview are analysed on the basis of an analysis scheme (*table 2*). The analysis scheme is categorized into three different main subjects, waterworks, earthquakes and measures, and several sub-subjects, like the characteristics of the waterworks, damages through time by earthquakes and the quality of a measure. This scheme was filled in by coded citations of the transcript.

The source for analysing the data are the transcriptions. All interviews were recorded directly. By recording the interview, the interviewer is fully focused on the conversation, which is a bit harder when taking notes (Clifford et al., 2012). The recorded interview is transcribed afterwards.

The transcription of a semi-structured interview is a self-generated document (Clifford et al, 2012). Self-generated documents are own sources, like the transcripts from an interview (Clifford et al., 2012). Self-generated documents can be directed into the direction of your research question. So the questions can be asked in a certain direction. The transcript is coded by selective coding. ''This is a more systematic approach to coding that is done when a central or 'core' category is identified and followed.'' (Clifford et al., 2012, p.446). The central theme is the central research question: *What is the influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding?* And the relating other themes are related to the secondary research questions. There are distinctive labels within the different central categories (*table 2)*.

The analysis scheme is filled in after the coding. The coded themes and labels are put in the analysis scheme within their category. This gives an overview per interview per theme and analysis the different themes.

Theme	**Label**	**Sublabel**	**Answer**
General	Who		
	Where		
	Others		
Waterworks	Present condition	Strengths	
		Weaknesses	
	Flood risks	Present flood risk	
		Waterworks on level	
Earthquakes	Damage waterworks	Past	
		Present	
		Future	
	Consequences	Waterworks	
		Flood risks	
	Flood risks	Waterworks	
		Where	
Measures	Existing measures	What	
		Where	
		How	
	Effectiveness	Quality	
		Feasible	
	Policy	Current Policy	
		Future Policy	

Table 2. Analysis scheme (own source).

3.7 Ethics

Ethical considerations have played a part during the research process. As described in the sections above, the interviewees were informed that they would get recorded for coding, transcribing and analysis. Afterwards they were asked if it was allowed to use quotes of the interviewees in this thesis with their names or that they wanted to stay anonymous.

According to Clifford et al. (2012) there are two important ethical issues, namely confidentiality and anonymity. The participants need to be sure that the data will be secure. The participants are told that the data will only be used for this thesis and for no further purposes. ''Participants will remain anonymous, unless they desire otherwise'' (Clifford et al., 2012, p. 111). The participants were asked if they wanted to stay anonymous or if it was alright to cite them with their names in the thesis. After the interview, the interviewees were asked if they wanted to have a summary of the thesis. Clifford et al. (2012) claim that it is ''sound research practice'' to offer a hard copy to the participants. There weren't any sexist, racist or other offensive expressions by the interviewee and there weren't cultural differences.

4. Results

4.1 Regulations waterworks

Flood resilience is departed in three different aspects, Robustness, adaptability and transformability. Dikes are the primary defence against water and part of the first aspect, robustness, of flood resilience (Restemeyer et al., 2015).

The national government of the Netherlands is responsible for the norms for the primary water defences and the norms for the secondary water defences (Jong & van den Brink, 2015). The water boards are required to repair or to strengthen the waterworks when a specific waterwork doesn't meet the norm. The norm is established per section. Regional waterworks do have lower norms than primary waterworks. Primary waterworks are for example sea dikes, who will have a way bigger influence when a flood occur than for instance a flooding of a canal (Henk van der Leij, Appendix D). When the consequences of a flooding are high (deaths, injured and economic loss) for a particular area, the norms will be high (Walja Karten, Appendix B). The water boards have the responsibility to let their waterworks meet the norm before the year 2050 (Walja Karten, Appendix B).

The most critical waterworks, the waterworks which are the most below the norm, have the priority to get repaired or to be strengthened. So, the waterworks with the highest flooding chances have the priority. The sea dike Eemshaven-Delfzijl is a waterwork with a high priority, which is located between Eemshaven and Delfzijl (Figure 5). The sea dike in Delfzijl is right-angled with the sea, what makes it extra dangerous (Jornald Veldman, Appendix E). The sea dike can move when water finds a way to the subsoil of the dike and the sea dike was disapproved on the global static failure (Ate Wijnstra, Apendix A). Global static failure is one of the four failure mechanisms divided by Ambruster-Veneti (1999) and denoted as macro-instability. Macro-instability is the risk of the inner core sliding off (Zuada Coalho et al., 2015)(Ate Wijnstra, Apendix A). The dike was disapproved by a testround. Once in the six years an instrumentarium will be developed for water boards to test their water works (Walja Karten, Appendix B). When a dike don't get through the testround, it needs to be repaired or strengthened.

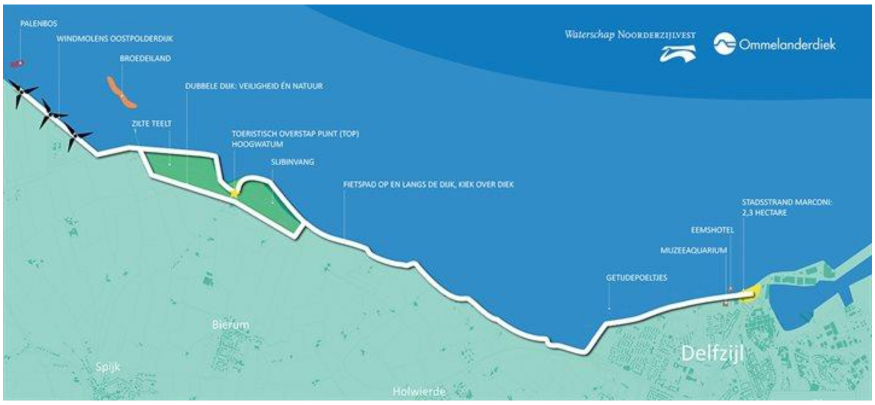

Figure 5. Sea dike Eemshaven-Delfzijl (Noorderzijlvest, 2017)

The waterworks which don't meet the norm will go in an improvement path. Different experts will check the dike during this improvement path and will look for what should get improved and how to get the failure mechanisms at the level which the specific norm prescribes (Albert Wiggers, Appendix F). During this improvement path, a process will start. The parties responsible for the waterworks have to inform the surrounding residents and a lot of parties who are connected with certain waterworks will get involved (Albert Wiggers, Appendix F). This improvement path will take a couple of years (Albert Wiggers, Appendix F). NCG (Nationaal coordinator Groningen) is a cooperation of municipalities in the province of Groningen about the reinforcements by earthquakes with Hans Alders (the national coordinator) in charge (Boudewijn van Baal, Appendix C). NCG decides which earthquake reinforcement tasks have the highest priority and have precedence for maintenance.

4.2 Effects of earthquakes on waterworks

While there is a lot of damage on houses in the province of Groningen by earthquakes (Van der Voort & Vanclay, 2015), there isn't found any damages on waterworks in the province of Groningen through earthquakes (Appendix A,B,C,D,E). Earthquakes will not lead to a different kind of damage on waterworks, all waterworks will always need to be tested. Earthquakes will not change that, waterworks still need to be strong enough to fulfil the norms. Earthquakes are just an extra failure mechanism (Walja Karten, Appendix B). It's quite hard to ascertain if present damage is really damage from an earthquake. Like there could be damage through land subsidence. Earthquakes are just one of the reasons that cause land subsidence. But it's not the only one, so that makes it quite difficult (Walja Karten, Appendix B).

Another influence of earthquakes is softening within and under the dike. The subsoil can be weakened when there is water in the subsoil of a dike (Ate Wijnstra, Appendix A). This will increase the chance of dike sliding (Zuada Coalho et al., 2015). This is a serious issue for the sea dike Eemshaven-Delfzijl (Water board *Noorderzijlvest)* (Ate Wijnstra, Appendix A), however, this isn't an expected problem for the waterworks of the water board *Hunze en Aa's* (Henk van der Leij, Appendix D). The sea dike Eemshaven-Delfzijl is a relative old and qualitative weaker dike than the sea dike of water board *Hunze en Aa's*. So the location and the quality of the waterworks have influence on the vulnerability to earthquakes. The combination of an earthquake with high tide could be another risk for the sea dikes (Albert Wiggers, Appendix F).

The gas extraction of the Groningen gas field will give around the 700 earthquakes with a magnitude higher as 1.5 on the scale of Richter in total, with around the 400 earthquakes with a magnitude higher as 1.5 on the scale of Richter to come (Hagoort, 2017). The maximum earthquake would get a magnitude of 4.4 on the scale of Richter (Hagoort, 2017). This could be a problem, because 45% of the primary dikes and 25% of the secondary dikes will fail to meet the norm by the maximum expected earthquake (Zuada Coalho et al., 2015). Earthquakes could have effects on macro-stability (Zuada Coalho et al., 2015). However, the PGA of such a heavy earthquake is quite unsure, because the ground is very heterogeneous and vibrations affect each other (Walja Karten, Appendix B). This makes the influences of earthquakes very complex and hard to predict.

The highest risk for deaths and injured victims is a dike breakthrough (Boudewijn van Baal, Appendix C), so when a dike totally collapse. The four groups of failure mechanisms of Ambruster-Veneti (1999) have influence on the stability of the dike and the risk on flooding. The earthquakes in Groningen have an effect on the macro-stability (or macro-instability) of a dike (Zuada Coalho et al., 2015), like it has on the sea dike Eemshaven-Delfzijl. Macro-stability or instability weakens dikes. Dike sliding movement, compaction and squeezing of the dike can be consequences (Zuada Coalho et al., 2015). Vorogushyn et al. (2015) describe macro-instability as the failure by gravity and pressure and can cause a dike collapse. However, the sea dike Eemshaven-Delfzijl isn't disapproved for a specific earthquake reason. The problems would occur without the earthquakes (Ate Wijnstra, Appendix A). So the earthquakes give just an extra risk for the macro-stability of the dike.

Structures of buildings aren't comparable with structures of dikes. Dikes are made of clay or sand (Henk van der Leij, Appendix D) and for that reason way more flexible and are not that stiff (Albert Wiggers, Appendix F) as a building is. The clay and sand, so as the flexibility, makes the dikes more a regular nature to geometry. This makes dikes less vulnerable to earthquakes than buildings.

However, the construction of dikes should be of equal stiffness, otherwise dikes have to deal with stiffness irregularities (Rajarathnam & Santakumar, 2015). Stiffness irregularties will make the dike more vulnerable for earthquakes (Rajarathnam & Santakumar, 2015). The relative weight of a storey has influence to the vulnerability for earthquakes on buildings, the mass irregularity. When a storey is 200% of an adjacent storey in a building, the building has a mass irregularity. It's necessary to prevent a mass irregularity in the construction of dikes. This will make it more vulnerable to earthquakes.

The sluices and water pumping stations will probably not have damages through earthquakes in the province of Groningen. The sluices and water pumping stations are really heavy and robust, what makes them very strong (Henk van der Leij, Appendix D).

4.3 Measures

The knowhow about the soil is important to decide which measure is best (Ate Wijnstra, Appendix A). Every type of soil has their own characteristics and reacts in a different way to earthquakes (Ate Wijnstra, Appendix A). It is dangerous to build a waterwork on a subsoil of unpacked material or on a subsoil which get weaker through earthquakes (Albert Wiggers, Appendix F). This could cause a sudden subsidence of the soil. An earthquake could pressures the unpacked material into a compact subsidence. The water between the unpacked material splits from the unpacked material and the unpacked material and the water become drift sand. This can causes sudden subsidence (Albert Wiggers, Appendix F). Information about the influence and consequences is required to know how to repair waterworks or defend waterworks against earthquakes (Boudewijn van Baal, Appendix C). Research to the influences and consequences will be useful to make this more clear.

There are some known measures for possible earthquake influences and damages. One of the measures is covering dikes with dam walls (Ate Wijnstra, Appendix A). Dam walls make dikes stronger and make dikes more waterproof. This provides dike sliding, because dam walls make it harder for the water to reach the inner core. Water within the inner core makes the inner core unstable, which can causes dike sliding (Ate Wijnstra, Appendix A). However, Henk van der Leij (Appendix D) claims that a dam will have a negative effect on earthquakes. A dam wall has its own vibration number and when the dam wall gets founded in a compact sand layer, the dam wall will vibrate with the earthquake and will have an extra influence on the dike with dam walls (Henk van der Leij, Appendix D). The placement of dam walls can be quite a operation and is a relative expensive operation (Walja Karten, Appendix B).

Wave-breakers are built in various forms. One of those forms are just really big rocks who blocks the waves impact to protect the dike. Those big rocks are quite earthquake resistant (Albert Wiggers, Appendix F). All wave-breakers in the Netherlands are quite flexible and are not very vulnerable to earthquake (Albert Wiggers, Appendix F). However, there are wave-breakers shaped in triangle blocks of concrete who fit in each other. Those wave-breakers can't deal well with ground deformation, which occur during an earthquake. For that reason, such wave-breakers are way more vulnerable for earthquakes than the wave-breakers in the Netherlands.

Three measures will be applied by water board *Noorderzijlvest* to make the sea dike Eemshaven-Delfzijl earthquake proof. One part of the sea dike Eemshaven-Delfzijl is completely built of sand. Those parts will get a layer of geotextile between the sand layer and the stone cladding of the dike. There could get cracks in the stone cladding by earthquakes and causes leaks (Walja Karten, Appendix B). Those leaks in the stone cladding could causes micro-instability (Vorogushyn et al., 2015). The other two measures by *Noorderzijlvest* on the sea dike Eemshaven-Delfzijl are the placements of emergency clay-depots near the dike to repair damages quickly and the placement of a monitoring system in the sea dike to collect data, which consist how the dike is affected through the latest earthquake (Walja Karten, Appendix B). The data collected by the monitoring system will

give useful information about the transformation and subsidence of the sea dike (Walja Karten, Appendix B). Those three measures are according to Walja Karten (Appendix B) perfectly feasible, they a lot cheaper than for instance dam walls.
RVS is an approach to check after the earthquake if there is any visible damage on buildings on the basis of aerial photograph analysis (Rajarathnam & Santakumar, 2015). It could also be used to check waterworks after an earthquake. When the damage isn't visible in the aerial photograph analysis, the invisible damages will be checked by actual ground truth verification (Rajaranthnam % Santakumar, 2015). The actual ground truth verification is already part of a protocol of the water boards after an earthquake upward of a magnitude of 3.0 on the scale of Richter (Henk van der Leij, Appendix D). The RVS is, like the emergency clay-depots, not a measure which will make the dike more earthquake resistant, but a measure that has influences after an earthquake occasion.

Municipalities are responsible for the residents of their municipality, the spatial planning and the liveability of the residents and water boards are responsible for the quality of the waterworks (Jornald Veldman, Appendix E). However, a cooperation can provide a win-win situation for both parties (Namda Pellenborg, Appendix C). The Marconi project is an example of a cooperation with a win-win result. The Marconi project is a cooperation between the municipalities of Eemsmond and Delfzijl, the water boards Hunze en Aa's and Noorderzijlvest, the national government, the province Groningen, the Groningen Landscape and Groningen Seaports (Delfzijl, 2016). It is a cooperation between local, regional and national governance (Jornald Veldman, Appendix E). All parties have their own interests and responsibilities. However, some of those interests and responsibilities can have corresponding interests. The water board *Noorderzijlvest* have to strengthen the sea dike and the municipality wants to make the sea dike more liveable and accessible for the residents (Jornald Veldman, Appendix E). By combining those two interests and with the cooperation between *Noorderzijlvest* and the municipality of Delfzijl, there is created a measure which let the dike meet the norm, made it resistant to earthquakes and liveable for the residens (Jornald Veldman, Appendix E). The dike will get a small beach and a boulevard, a wish of the municipality of Delfzijl (Figure 6) and the dike would get stronger to meet the norm, a wish of the water board *Noorderzijlvest*. Those cooperation was an economic valuable measure to fulfil both interests and responsibilities (Jornald Veldman, Appendix E). The cooperation between *Noorderzijlvest* and the municipality of Delfzijl is a coupling chance (Namda Pellenborg, Appendix C).

Figure 6. The sea dike Eemshaven-Delfzijl in Delfzijl with a beach and a boulevard (Rijkswaterstaat, 2016).

Dams located in a seismologic area have to deal with earthquakes. There are two different strategies to protect those dams against earthquakes (Albert Wiggers, Appendix F). The first strategy is to make the dams strong enough, so the dams can deal with all earthquakes. Another strategy is to make the dams more flexible, so the dams are able to move a bit (Albert Wiggers, Appendix F).

The national government has made a change in the gas production policy to decrease the earthquakes effects. The national government decided to decrease the maximum production rate of gas from the Groningen gas field rate to 24 billion cubic meters per, which can rise to 30 billion cubic meters per year during a cold winter (Rijksoverheid, 2016). This has resulted in a reduction in earthquake frequency (Hagoort, 2017).

There are contradictory interests between the water boards and NAM. NAM wants to keep the costs as low as possible (Walja Karten, Appendix B). However, the water boards prefer to be a bit more conservative than NAM is and want to invest more in certainty of waterworks, so they will be safe enough (Walja Karten, Appendix B).

The models of water boards, which calculate the effects of earthquakes, have taken into account a maximum of 5.0 on the Richter scale (Walja Karten, Appendix B), decided by the KNMI (KNMI, 2016)(Walja Karten, Appendix B). However, in the state of Oklahoma (US) was a kind of similar situation as in the province of Groningen with one unexpected and heavy earthquake (Henk van der Leij, Appendix D).

5. Conclusions

5.1 Main findings

There aren't waterworks damaged through earthquakes so far in the province of Groningen. The models for waterworks in the province of Groningen are calculated for a maximum magnitude of 5.0 on the Richter scale (Walja Karten, Appendix B). When there will get an unexpected earthquake, like the one in Oklahoma (US), with a higher magnitude as 5.0 on the Richter scale, all models need to be recalculated (Walja Karten, Appendix B). An earthquake with a magnitude of 5.0 on the Richter scale will increase the risk of damage on the dikes, because the subsoil moves and there will be land subsidence. However, the subsidence is of such a small level, there will be no risk for flooding (Ate Wijnstra, Apendix A).

Zuada Coalho et al. (2015) conclude something completely different. They claim that ''45% of the primary dikes are not safe against the maximum expected earthquake. The value is slightly less for regional dikes, at 25%'' (Zuada Coalho et al., 2015, p.790). Those values are calculated for the worst ground scenario, which makes them conservative (Zuada Coalho et al., 2015). ''Considering the average ground scenario, 45% of the primary and 9% of the regional dikes are susceptible to earthquake damage'' (Zuada Coalho et al., 2015, p.790). The dominant failure mechanism would be macro-stability in 95% of the dikes in Groningen.

So, there is contradiction between the data off the interviewees and the data of Zuada Coalho et al. (2015) about the influence of earthquakes on waterworks. However, they both agree that earthquakes could have influence on the macro-stability of dikes.

Water boards in Groningen have special policies, which include the influences of earthquakes (Ate Wijnstra, Appendix A). Earthquakes are an extra failure mechanism for the dikes in Groningen (Walja Karten, Appendix B). Dikes in the province of Groningen need to be earthquake resistant, which can be tested by ENW (Expertise Netwerk Waterveiligheid). ENW is a group of independent experts who will check if the repaired or strengthen dikes are of will be earthquake resistant (Walja Karten, Appendix B).

A significant economic loss can occur during a flooding on the Groningen gas field (Petersen & Bloemen, 2015). The economic value of the gas in the Groningen gas field is enormous, but the safety of the people is the first priority of the NCG (Boudewijn van Baal, Appendix C).

Waterworks in the province of Groningen are focused on the defence against water. Most focus is on preventing a flooding, so fighting against water (Restemeyer et al., 2015). However, dikes have to deal with norms, which are based on a flooding once in a given amount of years (e.g. 1/4000 years) (Appendix A, B, D & F). According to the norms, there is a risk that there will be a flooding.

Flooding is the highest risk for the safety of the residents of the Groningen gas field (Boudewijn van Baal, Appendix C). The influence of flooding can be enormous, so it is quite a risk to only trust waterworks to stop every threat of a flooding. When there will be an earthquake with an unexpected high magnitude in combination with high tide, dikes might collapse and causes a flooding. The hinterland should adapt to a situation in such a way, a flooding will not causes substantial damage (Restemeyer et al., 2015). The flooding will be controlled. Transformability is not a realistic goal for the waterworks and the hinterland, because such flooding happen in a very low frequency (Albert Wiggers, Appendix F) and adaptability will be enough to deal with such low frequent flooding's.

5.2 Reflection

The influence of earthquakes induced by gas extraction in the province of Groningen on the protection of the region against flooding is hard to measure precisely. There are a lot of unknown variables, such as the subsoil and the maximum expected earthquake. There is a contradiction between the interviewees and the theory of Zuada Coalho et al. (2015). The research and knowledge about the earthquakes and the effects of earthquakes on dikes are developed well in the last two years, so the theory of Zuada Coalho et al. (2015) could be based on older knowledge. However, the gap between 45% of the primary dikes are not safe against the earthquakes (Zuada Coalho et al., 2015) to all primary dikes are safe against earthquakes is a remarkable gap.

There isn't looked very specific to all waterworks in the province of Groningen. Waterworks have to deal with different variables and are for that reason very heterogeneous. There isn't one type of waterwork for the province of Groningen. This fact makes it hard to give a specific answer to the main research question.

The interviewees were all experts in their field of study and were well informed about their expert topics. The interviewees gave an insight in how the processes went between different parties. This gave useful data which isn't easy to collect in literature.

5.3 Outlook

Cooperation between different (governmental) parties can lead to a qualitative and economic beneficial results for both parties. A research about cooperation for earthquake issues could provide a better insight about cooperation for parties who aren't used to work together with other parties.

A lot of the variables are not clear to understand the influence of an earthquake on waterworks. Technical research on the soil and the effects of earthquakes on different constructions of waterworks could give more information about the influence on specific waterworks. This is necessary, because all waterworks have their own soil, circumstances and other variables. The influence can be measured when it is clear how all variables should be measured.

A further research about the adaptability of the province of Groningen is necessary to know what the real consequences of flooding will be, on a personal level and on an economic level. A research about how this could be applied or improved in the province of Groningen will be useful.

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