2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

LIABILITY AND DAMAGE CLAIM ISSUES IN INDUCED EARTHQUAKES: CASE OF GRONINGEN

Ihsan Engin BAL[1], Eleni SMYROU[2] & Elles BULDER[3]

Abstract: *Groningen gas field is the largest on-land gas resource in the world and is being exploited since 1963. There are damaging earthquakes, the largest of which was 3.6 magnitude. The recursive induced earthquakes are often blamed for triggering the structural damages in thousands of houses in the area. A damage claim procedure takes place after each significantly felt earthquake. The liability of the exploiting company is related to the damages and the engineering firms and experts are asked to correlate the claimed damages with a past earthquake. Structures in the region present high vulnerabilities to the lateral forces, soil properties are quite unfavourable for seismic resistance, and structural damages are present even without earthquakes. This situation creates a dispute area where one can claim that most structures in the region were already damaged because of the fact that the soil is soft, the ground water table oscillates, and structures are vulnerable to external conditions anyhow and deteriorate in time, which can be the main cause of such structural damages. This ambiguity of damage vs earthquake correlation is one of the main sources of the public unrest in the area up until today.*

This study presents the perspective of people in the region in terms of liveability and the social acceptance of earthquakes in their lives. An attempt has been made to translate these social effects and expectations into structural performance metrics for ordinary houses in the region. A new seismic design and assessment approach, called Comfort Level Earthquake (CLE) has been proposed.

Introduction to the Groningen Case

Groningen Gas Field was discovered in 1959 and the gas production started in 1963. It is a giant energy source; the largest on-land gas field in the world. The estimated reserve is about 2800BcM while approximately 2200BcM has already been extracted as of end-2018. The field is operated by Nederlandse Aardolie Maatschappij (NAM), that is a half-half joint venture of Royal Dutch Shell and Exxon Mobil on behalf of "*Maatschap Groningen*", which is a partnership of NAM (60%) and Energie Beheer Nederland (EBN). EBN is owned by the Dutch state while managing personnel of NAM is provided by Shell.

The Groningen gas is trapped in Rotliegend Sandstone with an initial pressure of 350bar. This pressure, after years of production, decreased to the level of 60bar. The reservoir is at 3km depth, thus the weight on top of it compacts the whole gas field as the reservoir pressures decreases. This compaction varies within the gas field but so far has reached up to 40 to 50cm in the heart of the field. There are approximately 2500 faults in the gas field that are time to time activated due to the huge pressure on top and differences of pressure (Bommer et al., 2018), causing shallow small-magnitude earthquakes.

The tectonic structure of the gas field was silent until 1991. Questions arose following the first registered earthquake in another relatively small gas field in Assen, south of Groningen. The NAM headquarters are also in the same city. The first earthquake in the Groningen field was registered by KNMI (Royal Dutch Meteorological Institute) in 1991. Despite the resistance and denial by the licensee company (NAM) until 1993, a study by KNMI and SoDM (the regulatory body – State Supervision of Mines) exhibited a relationship between the by-then-smaller earthquakes and the gas production operation (KNMI, 1992). In the awake of the potential of hazard, KNMI further investigated the case and came up with an expected maximum earthquake magnitude of M_L3.3.

---

[1] Prof., Hanze University of Applied Sciences, Groningen, Netherlands, i.e.bal@pl.hanze.nl
[2] Assoc. Prof., Hanze University of Applied Sciences, Groningen, Netherlands, e.smyrou@pl.hanze.nl
[3] Prof., Hanze University of Applied Sciences, Groningen, Netherlands, e.a.m.bulder@pl.hanze.nl

Basic Gutenberg-Richter recurrence formula was employed in their analyses, which is pretty much valid for stationary fault activities of natural tectonic earthquakes. Induced earthquakes, however, as further studies have shown in the following years, largely depend on the production rate. In other words, even if the production keeps a constant pace, an ever-increasing subsidence and compaction would translate into increase in magnitude and frequency of earthquakes. Realizing this fact, KNMI has further increased the expected maximum magnitude to M_L3.9 in 2006 (van Eck et al., 2006), 6 years before the Huizinge event of 2012 with magnitude M_L3.6 already.

Most of the arrangements and research focused on soil subsidence. Due to the impact of subsidence on surface water management, that is an important issue in an agricultural region, an agreement was made between NAM and the Province Groningen in 1983 for monitoring and managing the water level. Until 2012, focus was the soil subsidence (Gussinklo et al., 2001), not the earthquakes.

Although the first signs were clear, at least looking at the past, neither NAM nor SoDM had conducted further research to understand the possible extend of the problem, uncertainties associated or the levels of risk as function of the production rates. That was the case until 2012.

The history of earthquake engineering is filled with "*black swans*" (Taleb, 2010), that are the events which fit in the definition of "*highly improbable*". Although smaller than the expected maximum magnitude defined by KNMI 6 years ago, in a region that has never experienced such an event the black swan of Groningen was the 2012 Huizinge event. The earthquake took place in August, with a magnitude of M_L3.6. KNMI, by then, had 6 accelerometer stations close-by, the closest of which recorded 0.08g PGA in horizontal direction. More than 2000 damage claims were filed, 80% of which are estimated to be related to the event (NAM, 2016).There were two striking outcomes from this event: i) larger magnitude earthquakes are possible, ii) earthquakes in the gas field have potential to cause structural damage and eventually losses of life.

In most active tectonic regions of the world, earthquakes close to magnitude 3.6 happen every week, if not every day. Such earthquakes are not even recorded in the archives. That is one misleading fact which, for earthquake researchers and engineers who are not familiar with all angles of the Groningen issue, leads to serious underestimation of the facts. There are three arguments which dictate to take the seismic activity in Groningen more serious:

1. the soil is weak, with close-to-surface ground water table
2. local construction practice renders structures extremely vulnerable to earthquakes
3. induced earthquakes are liability cases, lowering thus the tolerance of people to earthquake-related damages

Despite the shocking event of 2012, the gas production hit the history-highest in 2013 with 54BcM that year. Report by Dutch Safety Board (Dutch Safety Board, 2014) and the decision of Council of State (Raad van State, 2015) forced the Dutch government to gradually decrease the production. The annual production thus decreased to 42.5BcM in 2014, 24Bcm in 2016, and was at the level of 19.4BcM in 2018-2019 period.

The denial narrative of NAM until 1993, and the underestimation of the issue even after the 2012 Huizinge event, eroded the trust amongst locals, which traditionally already feel neglected by the central government residing in The Hague in the western part of the Netherlands. Their feelings were not unjust, considering that in the period 1995-2009 the investments from the Dutch Infrastructure Fund – FES, which received 40% of the Groningen gas income, went to the Randstad area (Amsterdam-The Hauge-Rotterdam) and only 1% was spent for the three northern provinces, including but not limited to Groningen.

Although an extensive effort has been made by NAM, resulting in world-class research on finally determining the risk with all its fronts, it was too late for social acceptance. Especially the lack of local technical institutions that can focus on seismic risk and structural damages, that can produce counter arguments to those of NAM, and can be appreciated as independent at the same time, helped in generating an "*alternative public science*" (Sintubin, 2018). The lack of technical expertise in earthquake engineering, and the strategy of national experts in adapting existing non-seismic knowledge to earthquake engineering discipline while closing eyes and ears to what was readily available, fuelled this alternative public science, creating an augmented reality, a parallel Dutch treatment of earthquakes, often ending with the poisonous conclusion of "*Groningen earthquakes are different!*" (Bal, 2018).

A series of recent developments changed the course of the Groningen issue over the last 4 years. In 2015, the Dutch government expanded the application of the Meijdam norm to Groningen. This is a norm defining a risk of death for an individual from external causes such as flooding. That practically meant that the risk of dying from earthquake in Groningen should be limited to 1 in 100,000 annually. A lower level of 1 in 10,000 per year is also allowed provided that the risk will be reduced to the norm within 5 years. In 2016, the Dutch mining law was changed shifting the "*burden of proof*" from the claiming body to the licensee, only for Groningen gas field. This resulted a boom in damage claims and a drastic increase in engineering expenses of damage claim evaluations. In 2018, a court case confirmed that the beneficiary of the field should pay the losses in the house real estate value, and at the time which the house owner will decide (not necessarily at the time of selling). In the last couple of months, NAM has also lost symbolic cases concerning farmhouses in which large compensations were claimed.

Rapid decrease in the production of gas until 2018 and the fact that the magnitude of earthquakes until then was relatively small as compared to that of Huizinge, led to the impression that the earthquake problem was finally under control. An earthquake of M_L3.4 close to Zeerijp on the 8th of January 2018 was enough to bring back the feeling of insecurity. The maximum PGA recorded during the Zeerijp Earthquake was 0.11g, higher than that of the Huizinge event in 2012, and slightly above the limit of 0.10g of the traffic light scheme of SoDM, activating different protocols. The Ministry of Economic Affairs immediately ordered further reduction in gas production to 12BcM. In the following months, the Minister announced that the gas production in Groningen would stop by 2030, however this could also be as early as 2025.

Distrust, lack of technical expertise of earthquake engineering in the area and even in the country, ever-changing hazard maps, banning of the European structural code for seismic design (Eurocode 8) and replacing it with a nationally-made code that has also been ever-changing, retrofitting decisions that contradict each other even in neighbouring houses, and finally, the struggle for compensation affecting people living in damaged houses, lead to a loss of the social license to operate (SLO) for the companies exploiting the Groningen Gas Field. A conscientious article focussing on developments leading up to this loss of the SLO, which inspired part of the introduction here as well, is written by van den Beukel and van Geuns (2019).

Situation in Groningen in Damage Claims

Due to the liability structure of induced seismicity, people are entitled to claim damages after an earthquake. This claim procedure has been cumbersome since the beginning in 2012 being subject to several changes on the way.

Handling of Damage Claims so far

From 1991 up until now, Groningen has been hit by more than 1,300 induced earthquakes. One of the issues that keep the tension alive is the damage claims after earthquakes. The tension gets higher as new earthquakes occur, new damage claims are filed and the backlog on responding to these claims gets deeper, creating a vicious cycle. There are approximately 100,000 claims filed since the Huizinge event in 2012. Although it is a clear conflict of interest, and as part of the mismanagement of the Groningen case, the claims were handled directly by NAM at the beginning. NAM had handled 80,982 claims until June 2017, paying 1.172b€ compensation (NU, 2018; Mulder and Perey, 2018), 64% of which was paid by the state. There are still 650 cases awaiting decision from NAM.

In 2015, a new organization was assigned for handling the strengthening program as well as the damage claim: Centrum Veilig Wonen (CVW, Center for Safe Living). Although it raised questions due to its association with NAM, CVW had been handling the damage claims until March 2017. The National Coordinator Groningen (another new institution by then, created for handling the earthquake issue in Groningen on behalf of central and local administration), ordered CVW to keep collecting damage claim files but stop evaluating them. In January 2018, shortly after the Zeerijp Earthquake, the Minister decided that the damage claims would be evaluated by a temporary committee on behalf of the central government: Tijdelijke Commissie Mijnbouwschade Groningen (TCMG, Technical Committee of Mining Damages Groningen). TCMG, in doing so yet another institution was created from scratch to handle the damage cases, received 13,500 damage claim files from CVW. There are still 16,000 claims lying on the shelves of TCMG waiting for a decision. While this number does not include damage reported after the recent event on the 22nd of May.

A recent earthquake of M_L3.4 was recorded near Westerwijtwerd on the 22nd of May 2019, early in the morning. The earthquake generated a maximum PGA of 0.03g, lower than what would be expected for its magnitude. The difference this time was that the earthquake was relatively closer to the centre of Groningen city, resulting thus that half of the 2,000 damage claims were reported from the city.

Technical Background

The "*gas extraction-earthquake-damage-claim-compensation*" cycle in Groningen given in Figure 1 has issues from a technical point of view. This is a legal liability case, but the proof is expected from technical people. The required proof however does not fit to the earthquake engineering perspective. The very reason for this is the ambiguous relationship between small recursive earthquakes and visible structural cracks. A clear relationship is further hindered by the particular soil and structural properties in the Groningen region.

Figure 1. The earthquake cycle in Groningen.

One can claim that most structures in the earthquake region were already damaged because the soil is weak, the ground water table oscillates, and structures are vulnerable to external conditions anyhow and deteriorate in time. This would indeed not be a wrong proposition. The other side of the coin, however, is that the quite small and recursive earthquakes can cause serious damages on structures, not because of the direct loading on the load bearing system but due to the interaction between the soft soil and the structure. Most structures in the region are masonry, a brittle material that cannot compensate even slight foundation movements. In this case, recursive earthquakes can easily move the soil, imposing support settlement to the structural bearing system that can take place even after the earthquake. This would cause damages that look like triggered by soil movement, but the question whether these cracks are really caused by the soil settlement or by the earthquakes remains. Confirming or excluding one or the other causes can be quite complicated and cumbersome, if not pointless, in terms of engineering work, time and money.

One good example to show the difficulty of this task is the work by Dais et al., 2018. The study focuses on Fraeylemaborg, a noble house in the earthquake region from the 13th century. The monument experienced serious damages in recent earthquakes and was repaired twice in 2015. Detailed structural computer simulations did not explain why these damages had occurred as the estimated accelerations were too low to create structural damage. After scrutinized work and with the help of an extensive real-time monitoring system on the building, a damage scenario was built. Comparison of this scenario with real damages is shown in Figure 2. According to that, the mostly-damaged North-West wing of the structure must have lost support in order to trigger the cracks observed on that part of the structure. This loss of support can only occur if the masonry retaining structure, together with the foundations, moved forcing the load bearing walls to follow in a mostly lateral direction. There are signs around the structure supporting this scenario. In this case, the observed cracks may seem soil-related to a technical person who does not know the earthquake history of Fraeylemaborg. However, the soil movement is most probably related to the earthquakes. This is collateral damage that is extremely difficult to prove, and yet the presented scenario remains just a scenario even after the detailed work.

Surprisingly, additional cracks on the walls were observed in the summer of 2018, although there had no significant earthquake occurred at that time. Further investigation revealed that an earthquake of the magnitude M_L1.9 had occurred 15km distant to Fraeylemaborg. The accelerometer network in the structure recorded the motion but only very weak amplitudes, 0.001g at the base and 0.006g on the tower were recorded as maximum values. The earthquake motion, by any means, was far from creating a structural damage. When the tiltmeter installed at the basement (on a foundation wall) was further investigated, a very slow process was discovered (Figure 3). Considering the speed of the movement and the fact that the summer of 2018 was extremely dry, this movement could well be related to the ground water, that might have been moving caused by the very small distant earthquake. The point here is that, such a slow movement that takes progress of 5 days after the earthquake, in parallel to the very small and rather insignificant accelerations recorded on the structure and at the base, could lead to an engineering decision that the damages observed a couple of days after the event are not related to the earthquake.

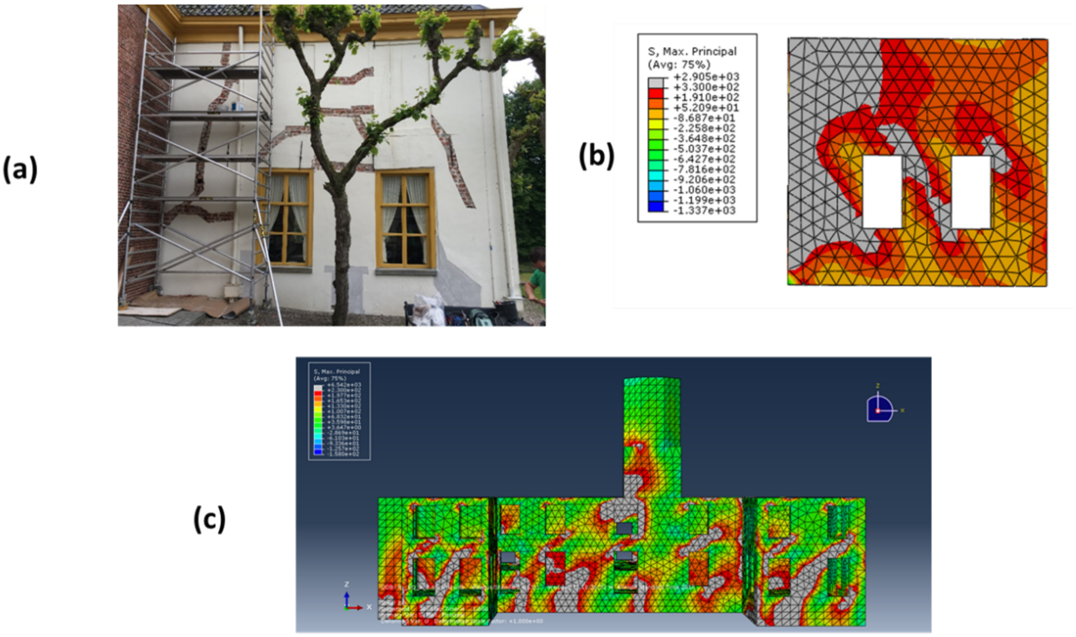

Figure 2. Fraeylemaborg in Slochteren, (a) The real crack pattern observed in North-West wing of the structure, (b) the response of the same wall for the seismic scenario simulated in the computer with maximum principal stresses in kPa (c) the response of the entire structure for the same seismic scenario (the grey contours show the regions at which cracks would be expected).

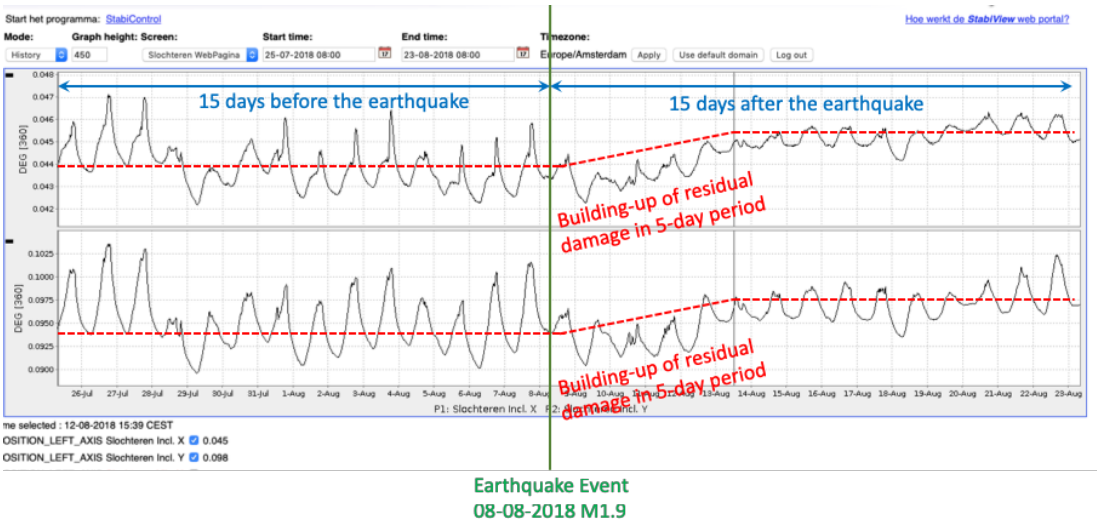
Start het programma: StabiControl
Mode: History
Graph height: 450
Screen: Slochteren WebPagina
Start time: 25-07-2018 08:00
End time: 23-08-2018 08:00
Timezone: Europe/Amsterdam
me selected : 12-08-2018 15:39 CEST
OSITION_LEFT_AXIS Slochteren Incl. X ☑ 0.045
OSITION_LEFT_AXIS Slochteren Incl. Y ☑ 0.098

Figure 3. Tiltmeter data, 15 days before and after an earthquake in Appingedam, magnitude ML1.9, on 8th of August 2018 (courtesy of StabiAlert).

In short, even with education and some level of experience in earthquake engineering, most engineers would not be able to clearly connect or disconnect visible structural cracks in Groningen houses with the earthquakes that have not exceeded M_L 3.6 so far. Cracks would be much more pronounced if the earthquakes occurred in larger magnitudes, because then the identification of cracks caused by earthquakes would be a much easier job. In the existing situation of small magnitude earthquakes, one can always have "*opinion and speculations*", but not "*proof*". There is, however, a great gap between a personal and rather subjective opinion and technically sound conclusions to create base for a financial claim or to decline such a claim. This is reason why a different approach is proposed here for responding to damage claims.

CLE – Comfort Level Earthquake

The earthquake engineering was subject to a paradigm shift after 1994 Northridge Earthquake which caused no life losses but an extensive financial loss (Kathleen and Dahlhamer, 1997). Until then the seismic design codes imposed a single option where the life safety was the prime limit while financial losses were omitted. "Vision 2000" document (OES, 1995), that is the *Magna Carta* of the modern earthquake engineering design philosophy, proposed a performance-based design where various seismic performance levels could be selected by the owner. A probabilistic approach was needed for the purposes of this proposal. Seismic hazard assessment with varying probabilities of exceedances are used to fill in the demand side of the problem. In the following years, different earthquake levels were defined for varying performance requests. 4 of those levels remained as the main pillars of the performance-based earthquake engineering. Due to the interdisciplinary nature of the paper, it is necessary to explain these 4 levels in summary for the non-technical reader. These earthquakes are defined by probability of exceedance in a number of year or with a return period.

The first level is the SLE – Serviceability Level Earthquake. That is pretty much the same in European seismic norm Eurocode 8 and it corresponds to a level of earthquake at which structural damage is not expected and a slight damage to non-structural components may be possible. This is the level where 10% probability of exceedance is expected in 10 years, translating into 95 years return period.

The second level is the DBE – Design Basis Earthquake. This is the level that defines the seismic design of ordinary structures with 10% probability of exceedance in 50 years, translating into 475 years return period. Structures are expected to undergo moderate but repairable damage during such earthquakes.

The third level is UBE – Upper Bound Earthquake. This is a second line of defence that is sometimes needed in special structures. This earthquake level corresponds to 5% probability of exceedance in 50 years, translating into 975 years return period.

The final level is MCE – Maximum Credible Earthquake. MCE-level earthquakes are very rare but very large events with serious extended damage and possible collapses in old building stock. This is the red-line type of seismic design level at which even important structures, such as hospitals or fire brigade structures are expected to undergo moderate damage. No structure is supposed to collapse at this level of earthquake, but most of the ordinary buildings will be unusable.

The CLE, Comfort Level Earthquake proposed in this paper, is based on several assumptions, which, of course, need to be investigated in terms of social acceptance. First of fall, the 30-year period of a regular house mortgage in the Netherlands is used as a base. The reason for this is that people are able to make life plans for a 30-year period, as they do when buying a new house. Furthermore, the number of exceedances is assumed 2 here. The practical meaning of 2 is that, in a 30-year "*foreseeable*" period, there may be several earthquakes, but the two largest ones will be considered as significant. In other words, the seismic hazard model with 30/2=15 years return period will provide the expected earthquake level.

The centre of Loppersum, that is pretty much the heart of the earthquake region in Groningen gas field, is used here to demonstrate an example. The KNMI/NEN seismic hazard map is used to find the acceleration spectra for 95, 475, 975 and 2475 year return periods. These numbers were extracted from a continuous line of annual probability of exceedance by KNMI when the seismic hazard map is prepared, but the authors do not have access to those annual probability curves. Instead, and only for the sake of demonstration, the 4 points of the annual probability curve (4 return periods) are used to reconstruct the curve and then extrapolate it to 15 years return period. This operation resulted the plots in Figure 4. The extrapolation gives spectral acceleration demands for the case of 15 years return period, or in other words, 6.5% annual probability of exceedance.

In order to run this demonstration, 3 different building typologies are used. These building typologies are extensively used in Groningen hazard and risk models (Crowley et al., 2019) and are given below in Table 1. The fundamental periods are assumed 0.25sec, 0.08sec and 0.4sec for URM3L, URM7L and URM2L typologies, respectively (Crowley et al., 2019). These fundamental periods are then used for finding structure-specific seismic demand on the building. The annual hazard curves in Figure 4 are generated by using the spectral demands at these fundamental periods.

Code	**Description**	**# of Buildings**	**Sa(T1) @ CLE**
URM3L	URM wall-slab-wall (i.e. terraced-style) with cavity walls and concrete floors, low-rise	46,143	0.055g
URM7L	URM wall – wall with cavity walls and concrete floors low-rise	14,633	0.030g
URM2L	URM wall – slab – wall with solid walls and timber floors low rise	7,862	0.035g

Table 1. Building typologies used in demonstration (by Crowley et al., 2019)

After defining the CLE spectral acceleration levels, as shown in Table 1, all past earthquakes with magnitude equal to or larger than M_L2.0 were examined. There are 29 earthquakes since 2012 fitting that description. The strong ground motion station of KNMI with the code BLOP (B-station in Loppersum) is used for this purpose and the acceleration records from all these 29 events are used (BLOP did not exist during 2012 Huizinge event, thus the results of a close-by station in Stedum are used). 5% damped acceleration spectra are produced and the Sa(T1), the spectral acceleration demand at the T1 fundamental period for each of the three building types are calculated. When compared to the CLE spectral acceleration levels, plots in Figure 5 are obtained. In the last 8 years period with the highest but dropping production rates, the CLE level of 15 years return period (2 events in 30-year time) are exceeded once in URM3L and in URM2L, and twice in URM7L.

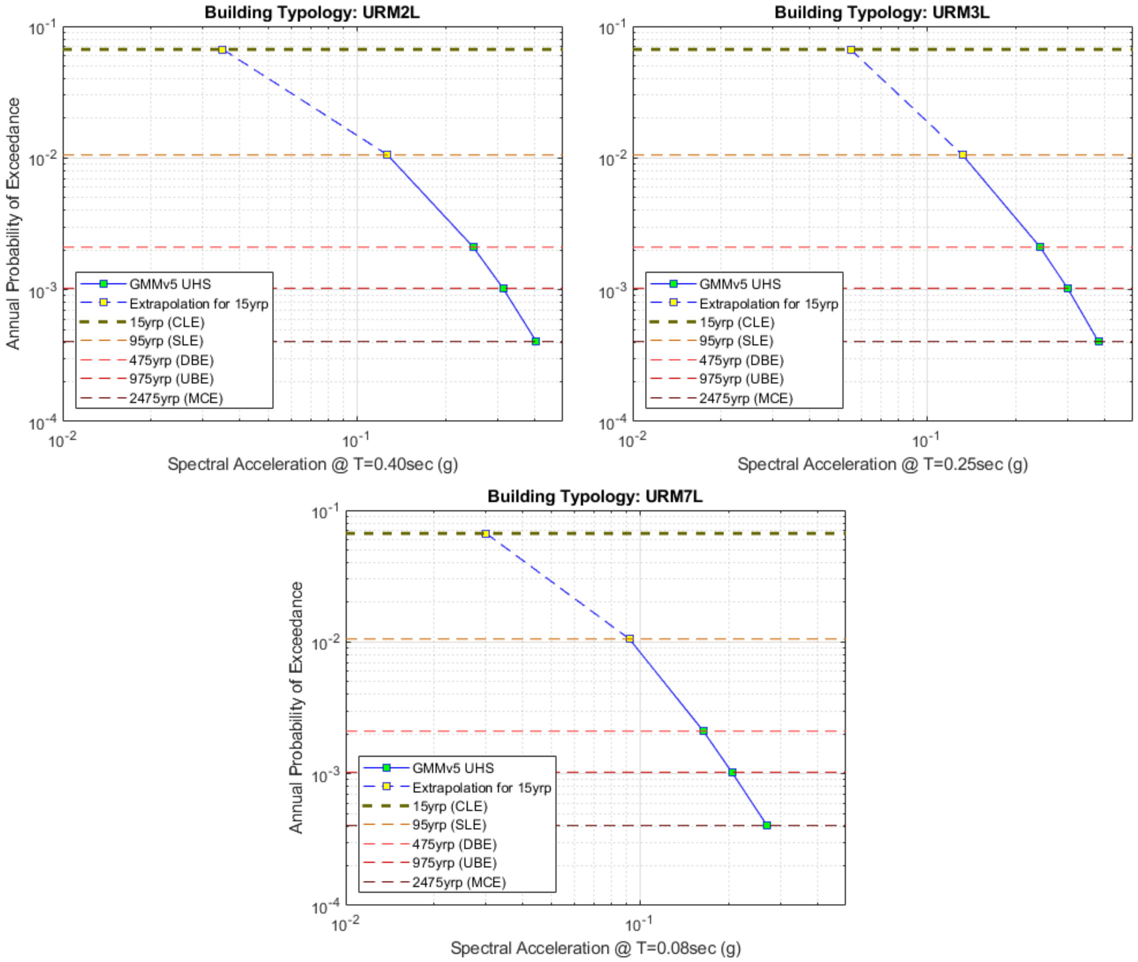

Figure 4. Annual hazard curves and assumed extrapolations for building typologies URM2L (top-left), URM3L (top-right), and URM7L (bottom).

Proposed Compensation Scheme and the use of CLE

Due to the inherent difficulties of correlating damages with small recursive seismic events, as explained above, a compensation scheme is proposed here in combination with the CLE earthquake risk level. According to this, a risk-based (not hazard-based) annual compensation per-house should be defined by the government. This compensation may have an index value of 100 in Loppersum, at the heart of the gas field, and go down to zero outside of the buffer zone of the risk map. The idea is that, when people receive this unconditional (i.e. not related to damage) support, they will be given two options. Option 1: An annual, unconditional, risk-based financial compensation, and right to file a claim after every earthquake, as happens today; Option 2: A higher annual compensation than that of Option 1, and right to claim damages only if the earthquake exceeds the pre-defined CLE level at the exact location of the building. Option 2 may also have sub-options such as 1, 2- or 3-times exceedance of a certain earthquake level in 30 years, instead of 2 times that is used in the example here, which will all have different influences on the annual compensation amount.

Prerequisites for Applying the Proposed Scheme

The proposed scheme requires a well-maintained, world-class strong ground motion monitoring network in operation. The household network of NAM has 400+ accelerometer sensors at the moment, installed according to the Dutch SBR guidelines (SBR, 2017), but the collected data is not usable for earthquake engineering purposes for multiple reasons (Bal, 2018).

A zero-state recording is needed for every single house in the stock. This does not necessarily mean a costly engineering work, but it may also well be simple photographs of all the walls and connections of a house. Even a simple app can be used for this purpose from which photographs are collected by the house owners and uploaded to a central server with geo-codes.

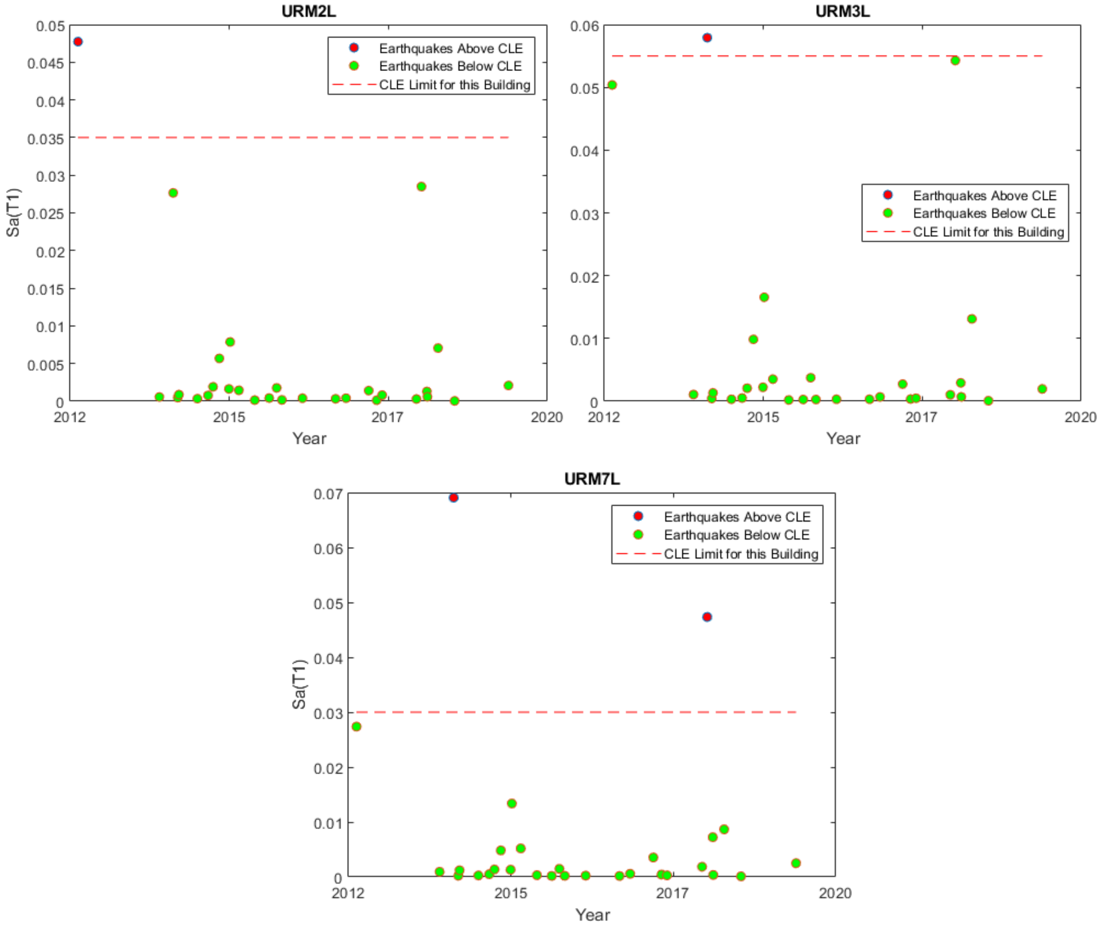

Figure 5. Elastic spectral acceleration demands for all earthquakes above magnitude M_L2.0 and comparison with the CLE spectral acceleration limits for building typologies URM2L (top-left), URM3L (top-right) and URM7L (bottom) - please note that the red dots show the earthquakes that would exceed the CLE level earthquake limit in the last y years, since 2012 Huizinge event.

As another prerequisite , a comprehensive risk study is needed. As part of that, a typology has to be assigned to every single building in the stock.

Furthermore, benchmark buildings with the most representative typologies should be selected from the core and from the periphery of the gas field, and they should be properly monitored for seismic action, similar to the monitoring conducted at Fraeylemaborg (Bal, 2019).

Last but not the least, a white page needs to be opened with the remaining damage claims by NAM and by TCMG before moving to a new era.

Conclusions

Groningen gas field is a giant hydrocarbon energy source that is being exploited since 1961. Earthquakes are recorded since 1991, with the largest in 2012 with a magnitude of M_L3.6. 100,000 damage claims have been filed out since then. Approximately 81,000 have been handled by NAM, while 650 cases are still unresolved. After consecutive changes in the handling institutions, another 18,000 files concerning actual damage are still waiting on the shelves. A general mismanagement of the earthquake issue, as explained in detail in this paper, resulted in a loss of the social license to operate (SLO). One of the major inducements in that was the handling of damage claims, a problem that has not been solved up until now.

This paper proposes a paradigm shift in handling the claims. The damage handling scheme proposed here contains an unconditional risk-based compensation scheme. On top of that, a different earthquake level is proposed; CLE – Comfort Level Earthquake, at the exceedance of which the building owners will be entitled to further claim damages. The proposed approach may ease the handling of the damages in the Groningen gas field until (and possibly after) the gas production is ended and as such reduce social tension in the region.

References

Bal IE (2018). Myths and Fallacies in the Groningen Earthquake Problem. Hanze University of Applied Sciences. Available at: https://www.hanze.nl/assets/corporate/Documents/Public/HANZE-18_0452%20Ihsan%20Bal%20Earthquake%20Resistant%20Structures_LR.pdf (Accessed 22/05/2019).

Bal IE (2019). Our Acceleration Measurements at Fraeylemaborg. DOI: 10.13140/RG.2.2.33356.05768/1 https://www.researchgate.net/publication/333372843_Our_Acceleration_Measurements_at_Fraeylemaborg (Accessed 22/05/2019).

Beukel van del J and van Geuns L (2019). Groningen gas: the loss of a social license to operate, The Hauge Centre for Strategic Studies.

Bommer J, Edwards B, Kruiver PP, Rodriguez-Marek A, Stafford P J, Dost B, Ntinalexis M, Ruigrok E, and Spetzler J (2018) V5 Ground-Motion Model for the Groningen Field, Report Prepared for NAM.

Dais D, Smyrou E, Bal IE and Pama J. (2018). Monitoring, assessment and diagnosis of Fraeylemaborg in Groningen, Netherlands, SAHC 2018, Peru.

Dutch Safety Board (2014), Earthquake risks in Groningen. Available at: https://www.onderzoeksraad.nl/en/page/3190/earthquake-risks-in-groningen. (Accesses 27/05/2019)

Eck van T, Goutbeek FH, Haak HW and Dost B (2006). Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in the Netherlands, Engineering Geology, 2006, 87.

Kathleen JT, Dahlhamer JM (1997). Business Disruption, Preparedness And Recovery: Lessons From The Northridge Earthquake, University of Deleware Disaster Research Center. Available at : http://udspace.udel.edu/handle/19716/657 (Accessed 22/05/2019).

KNMI (1993). Eindrapport multidisciplinair onderzoek naar de relatie tussen gaswinning en aardbevingen in Noord-Nederland. Available at: http://bibliotheek.knmi.nl/knmipubDIV/Eindrapport_BOA_relatie_aardbevingen_en_gaswinning_NNL1993.pdf (Accessed 22/05/2019)

Mulder, M. and P. Perey (2018). Gas production and earthquakes in Groningen; reflection on economic and social consequences, Centre for Energy Economics Research, CEER Policy Papers 3 - University of Groningen, The Netherlands.

NAM (2016) Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field. Available at: https://nam-feitenencijfers.data-app.nl/download/rapport/e2d7d52c-fa09-4b44-92f0-8dadcf3ada98?open=true (Accessed 29/05/2019)

NU.nl (2018). Available at: https://www.nu.nl/gaswinning- groningen/5089997/nederlandse-staat-betaalt-grootste-deel-van-aardbevingsschade-groningen.html (Accessed 22/05/2019)

OES (1995). California Office of Emergency Services Vision 2000: Performance Based Seismic Engineering of Buildings. Prepared by Structural Engineers Association of California, Sacramento, CA 1995.

Raad van State (2015) Gaswinning in Groningen voorlopig beperkt tot 27 miljard kubieke meter. Avaiable at: https://www.raadvanstate.nl/@8695/gaswinning-groningen/ (Accessed 22/05/2019)

SBR (2017). Trillingsrichtlijn A: Schade aan bouwwerken. SBRCURnet, Delft, November 2017.

Sintubin M. (2018) The Groningen Case: When Science Becomes Part of the Problem, Not the Solution, Seismological Research Letters (2018) 89 (6): 2001-2007 (https://doi.org/10.1785/0220180203)

Taleb NN (2010). The Black Swan: The Impact of the Highly Improbable, Random House, USA.