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Response to the review comments

Summarizing report on additional studies into the direct effects of deep subsidence

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Summarizing report on additional studies into the direct effects of deep subsidence

Response to the review comments

Author(s)	C.P.W. Geurts, M.P.D. Pluymaekers, TNO J.G. Rots, P.A. Korswagen, TU Delft
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Contents

1 Introduction

In September 2020, The Instituut Mijnbouwschade Groningen (IMG) commissioned TNO and TU Delft to advise IMG with respect to the direct effects of deep subsidence on buildings. The key questions to be answered were formulated (in Dutch) as:

1: *Het IMG zou van TNO en TU Delft graag advies ontvangen over of welke bodemdaling en -stijging plaatsvindt boven en in de nabijheid van het Groningenveld en de gasopslag Norg en of deze bodemdaling direct tot het ontstaan of het verergeren van schade aan gebouwen kan leiden.*

2: Als TNO en TU Delft deze vraag bevestigend beantwoorden, dan wil het Instituut ook geadviseerd worden over welke methode een deskundige zou moeten hanteren om in een individueel geval te beoordelen of een gebrek/schade in een gebouw is of kan zijn veroorzaakt of verergerd door deze vorm van bodembeweging.

These questions have been translated into English[1] as:

1: The IMG would appreciate advice from TNO and TU Delft on what subsidence and uplift is occurring above and in the vicinity of the Groningen gas field and the Norg underground gas storage facility and whether this subsidence can directly lead to the occurrence or exacerbation of damage to buildings.

2: If TNO and TU Delft's answer confirms the occurrence of subsidence and uplift, the Institute would appreciate advice about which methods an expert should use to determine in individual cases whether a defect/damage to a building has been or could have been caused or exacerbated by this type of soil movement.

The questions focus on the 'effect area' as defined in the expert advice that was given to the Groningen Temporary Committee for Damage due to Gas Extraction (TCMG) in 2019 by a panel of experts [15]. This effect area was defined by two criteria: First, it is defined by a contour regarding earthquake vibration intensities; specifically, the contour was adopted within which the probability of a peak ground velocity of 2 mm/s or higher as a result of earthquakes from past events is at least 1%. This part of the effect area is known as the 'Huizinge circle', since the 2012 Huizinge Earthquake fully defines this circle. Secondly, the effect area was defined by the contours of the Groningen gas field including a 6 km buffer zone around it, and the Norg gas storage (UGS Norg) including a 6 km buffer zone around it. These contours and the Huizinge circle are shown in Figure 1. The contours imply that there are two areas, indicated as area 1 and area 2 in Figure 1, which lie outside the Huizinge circle but within the buffer zones. The study particularly focuses on those two areas.

[1] Source: Translation of ref [2] into English under auspices of the Ministry of EZK

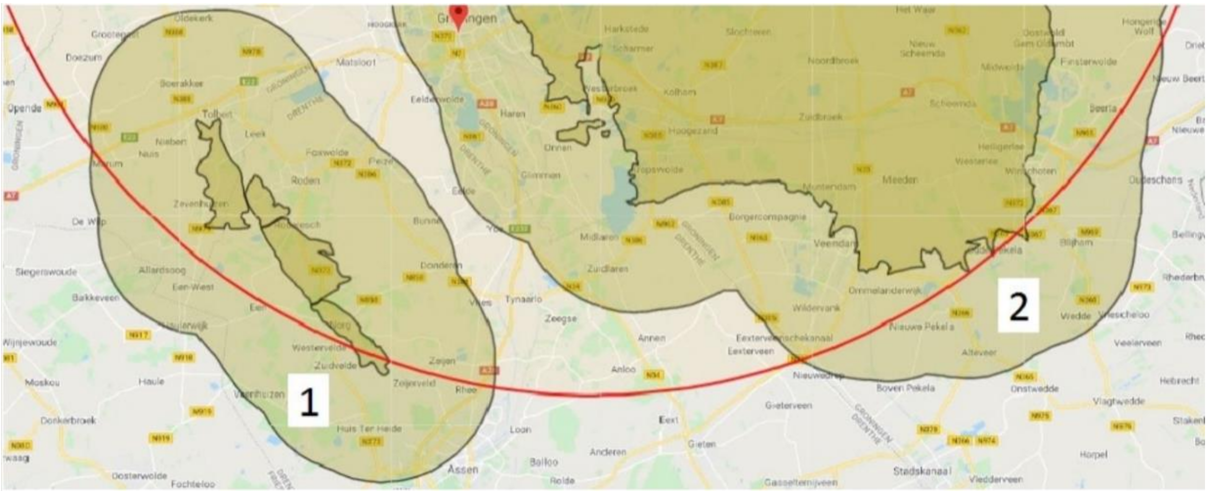

Figure 1: Effect areas around the Groningen Gas Field and Norg underground gas storage; the red line represents the so called 'Huizinge Circle, the areas 1 and 2 are defined by the 6 km buffer outside the Groningen Gas Field and UGS Norg, outside the Huizinge Circle.

The initial research was carried out in the period October 2020 to February 2021 and consisted of the following activities, each of which resulted in a report:
- A literature study into damage criteria related to subsidence [1];
- A geo-mechanical model study into the strains and curvatures at the soil surface as a consequence of deep subsidence [2];
- An analysis of INSAR observations to verify the geo-mechanical model results [3];
- A series of finite element modelling studies into the cracking damage of masonry structures subjected the strains and curvatures from deep subsidence [4].

The overall conclusions from those studies have been formulated in [5].

In 2022, the Ministry of Economic Affairs and Climate (EZK) asked Movares to organize an independent peer review on these reports. This review was published in [6].

The outcomes of the review concerned mainly references [2, 3, 4] and the overall conclusion in [5]. The review panel mainly provided comments and suggestions to further quantify the uncertainties and the effects these might have on the overall conclusions. The comments regarding the uncertainties both apply to the hazard side (the resulting horizontal soil strains and curvatures from deep subsidence [2]) and the resistance side (the cracking damage response of buildings subjected to those soil strains and curvatures [4]). Regarding the literature study [1], the reviewers concluded that it was deemed exhaustive to come to representative damage thresholds. A more extensive description of the review comments is given in [6].

The outcomes of the review have been discussed between IMG, TNO and TU Delft. Following these review comments, TNO and TU Delft carried out additional studies and calculations, the results of which are reported in resp. [7] and [8-11]. These calculations are extensions and further elaborations of the studies reported in resp. [2] and [4].

This report provides the synthesis of the results of the additional activities and an update of the overall conclusions of the study.

Please note that this report does not consider the *in*direct effects of deep subsidence. The indirect effects caused by groundwater level interventions because of the deep subsidence were studied by Deltares [12] and are outside the scope of the present study. Also, the study does not include the combined effects of multiple mining activities, such as the combined subsidence from adjacent small gas fields in the study area, or the cumulated effect of earthquakes and deep subsidence. The study was limited to the original question by IMG as articulated in the beginning of this introduction.

2 Results of additional studies

2.1 Overview

Following the reviewers comments, additional studies, both on the hazard side and on the resistance side (as defined in chapter 1) have been carried out. The hazard side refers to the modelling of the deep subsidence and its impact on the deformation of the ground level. The resistance side deals with the response of buildings to these deformations.

Regarding the hazard side additional studies to quantify the horizontal soil strains and curvatures from deep subsidence have been provided by TNO in a single report [7].

Regarding the resistance side and the probability that the soil strains and curvatures will lead to damage, the responses by TU Delft have been split into several documents. The additional analyses of the cracking damage response of buildings subjected to soil strains and curvatures are reported in [8-10]. Based on the results of [7-10], a probabilistic assessment of the probability of damage is given [11]. Detailed point-by-point replies to smaller questions, including comments not addressed in the four appendices, have been gathered in two tables [13,14].

The sections below summarize the outcomes.

2.2 Subsidence Modelling

Initial modelling studies were carried out by TNO for both the Norg Underground Gas Storage (UGS Norg) as well as the Groningen gas field. For UGS Norg , three situations have been assessed: One represents the situation in 1995, when the maximum reservoir depletion was reached after a number of years of gas production (before being used as storage facility). The other two situations correspond to the minimum reservoir pressure due to production of stored gas as well as the maximum reservoir pressure due to injection of gas allowed by the current permit. For the Groningen situation, a pressure depletion scenario that is representative for the situation occurring after the year 2020 has been assessed. The modelling assumptions, input parameters and results in terms of curvatures and strains have been presented in [2].

Following the comments of the reviewers, additional modelling studies have been carried out for both the UGS Norg as well as the Groningen gas field. For UGS Norg, the 1995 situation gives the results with the highest strains and curvatures and this situation is regarded as conservative for the full period of exploitation as a gas storage. The effects of these adjusted modelling assumptions are presented in [8] and compared with the initial outcomes. Results are presented in table forms for both hogging and sagging. The maximum values of both the horizontal strains and curvatures are given. The main conclusions are:

- Including heterogeneity of the reservoir rock conditions in the calculation leads to a slight increase of predicted strains.
- Assessing the results in a 2D field instead of a 1D intersect also leads to a small increase of the predicted maximum values of both horizontal strains and curvatures.
- Adding additional scenarios for the vertical distributions of the subsurface (elastic) parameters provides a range of results. Based on these scenario's an estimate is made of the variation of the horizontal strain and curvature. Taking elastic heterogeneity in the vertical domain into account results in an increase of predicted horizontal strains.
- The values of the curvatures are small that its effects in the assessments of damage are negligible compared to the effects of the horizontal strains.

Based on these observed results, for every location above the UGS Norg and the Groningen gas field, values for the median and standard deviation of the horizontal strains have been derived and an associated distribution function has been chosen. These have been provided as input for further analysis of the damage probabilities, as presented in the following sections. Compared to horizontal strain results, curvature values are negligible and therefore disregarded as input for the fragility study.

2.3 Building response modelling

Regarding building response modelling due to deep subsidence the reviewers suggested to further underpin the applied worse-case scenarios from [4] by contemplating three additional variations:
- stiffer masonry,
- more vulnerable foundations, and
- no connections to transversal walls.

Additional variation studies have been carried out and reported [9], which include: the disconnection of facades from transversal walls which may have provided some beneficial constraints, the reduction of the width of unreinforced masonry foundations to account for extremely flexible foundations, and the doubling of masonry stiffness to observe the cases of facades possibly being more sensitive to soil deformations. The results from the nonlinear FEM models show that indeed all three effects, independently and in combination, lead to increased vulnerability; however, a margin remains between the maximum observed strains in the models and the strains that would lead to damage, i.e. the occurrence of just-visible cracks in a building. In this study, full application of the soil deformations to the base of the masonry models (enforcing a full 100% strain transfer from soil to façade) does not cause visible damage. In order to quantify the margin, an amplification factor is defined which increases the soil deformations to the value that would cause visible damage in the models. In comparison to the original studies [4], a reduction of this amplification factor by 40% to 60% is observed [9] but it is still significantly larger than 1.

Additional to the above three aspects, the transfer of the horizontal soil strain to the building proves to be very relevant. TU Delft carried out an additional literature study and an explorative modelling study [8]. For deep subsidence, the small horizontal soil strains (compressive strains for sagging and tensile strains for hogging) are dominant in respect to negligible curvatures at the ground surface. However, as the building is relatively stiff compared to the soil, the horizontal soil strains will only partially be transferred to the building. The stiffer building will reduce the strains in the soil close to the building. In the worse-case scenario's in [4] and the above new variations in [9] an extremely conservative

100% transfer has been applied . The results from the additional literature study and the explorative soil-structure interaction modelling [8] demonstrate that a transfer of 50% will still be a very conservative assumption for Dutch buildings with shallow foundations ; a range between 20-35% would be most likely. The margins with respect to building damage then significantly increase with respect to the unrealistic application of 100% transfer.

2.4 Quantification of the probability of building damage

The original deterministic variation studies in [4] and the additional deterministic variation studies in [8,9] addressed the following features that have an influence on the damage probability:

- the type of foundation, e.g. a reinforced concrete strip foundation, a masonry foundation, or a thin masonry foundation,
- the masonry material and connection, e.g. standard or poor material, stiff material, and a connection or disconnection to transverse walls,
- the transfer of horizontal strain from soil to building, e.g. 30% based on literature, 50% as very conservative value, 100% as unrealistically conservative,
- additional effects, including pre-existing visible damage, and cyclic seasonal effects for UGS Norg,
- the strictness of the adopted damage criterion, e.g. barely visible cracks with width 0.1 mm, or cracks of 2 to 3 mm wide,
- the location of the building, e.g. moderate strains for positions away from the center of the subsidence trough, or high strains for buildings at the center of the subsidence trough.

As a first step, multiple scenarios of decreasing likelihood have been constructed, based on these influential features and outcomes from the sensitivity studies for different assumptions regarding these influential features. For a description of these scenarios, refer to [10]. The critical building strains for these scenarios were obtained by superimposing the sensitivity outcomes of the modelling variations. Then, the relative frequency of the scenarios actually appearing in the field allowed to appraise an overall qualitative probability of masonry buildings displaying damage due to the direct effects of deep subsidence. This led to the *qualitative* conclusion that scenario E is regarded as a very unlikely worst realistic case. This scenario E represents buildings with a masonry foundation, with poor material quality. Such buildings most likely are built before 1975. For this scenario, multiple vulnerable effects have been superimposed (namely: masonry foundation, poor material, conservative 50% strain-transfer, pre-existing damage and cyclic effects included, strict 0.1 mm crack width criterion, and application at the worst geographical location with maximum horizontal strain <1% exceedance). This scenario provides a very small probability of damage for perhaps only a few buildings [10].

Next, starting from the above described scenario E, the probabilistic description has been further explored and *quantified* [11]. The probability of damage is defined as the probability that just-visible cracks, i.e. cracks with a width of 0.1 mm, will occur per building. The deterministic assumptions underlying scenario E have been augmented with probabilistic *distributions*, based on engineering judgement and outcomes of the sensitivity studies.

Distributions have been constructed for the material strength of the masonry, the foundation size, the geometry of the facades (based on the three distinct facades adopted throughout this study), the amount of pre-damage, the amount of cyclic effects, and for the percentage of strain transfer between soil and building. These distributions have been transferred to distributions for the influence factors regarding allowable horizontal strains for the buildings, based on the set of modelling variations studies.

This approach resulted in fragility functions for the probability of damage as a function of horizontal soil strain, for sagging and hogging cases [11].

Subsequently, these fragility functions have been integrated with the distribution of expected horizontal strains due to deep subsidence at a given location, as resulting from the parallel study by TNO [7]. This integration was carried out analytically and via the Monte Carlo method. The final results in terms of probability of damage are presented in the table below, for UGS Norg, Groningen South-East (Area 2) and Groningen North-West, being the three regions studied herein as indicated in Figure 2. These results lead to the quantified conclusion that the probability of damage for Norg and Groningen South-East is near zero, while the probability of damage for Groningen North-West has a maximum in the order of $2x10^{-3}$ (1:500).

Table 1 Summary of results showing the computed maximum probability of damage (defined as the probability that just-visible cracks occur per building), for the three regions of interest, Groningen North-West, UGS Norg, and Groningen South-East. The regions are indicated in Figure 2. The value $<<10^{-10}$ in the table refers to a negligible probability of damage. For calculated values, refer to Table J.2 in [10]

Calculation	Distribution	Groningen NW (see Fig 2)	Norg 1995 (incl. Area 1)	Groningen SE (Area 2)
Analytical Numerical	Normal	$2.0 \cdot 10^{-3}$	$<<10^{-10}$	$<<10^{-10}$
	LogNormal	$2.23 \cdot 10^{-3}$	$<<10^{-10}$	$<<10^{-10}$
Monte Carlo (10^{+8} samples)	Normal	$2.0 \cdot 10^{-3}$	0	0
	LogNormal	$2.19 \cdot 10^{-3}$	0	0

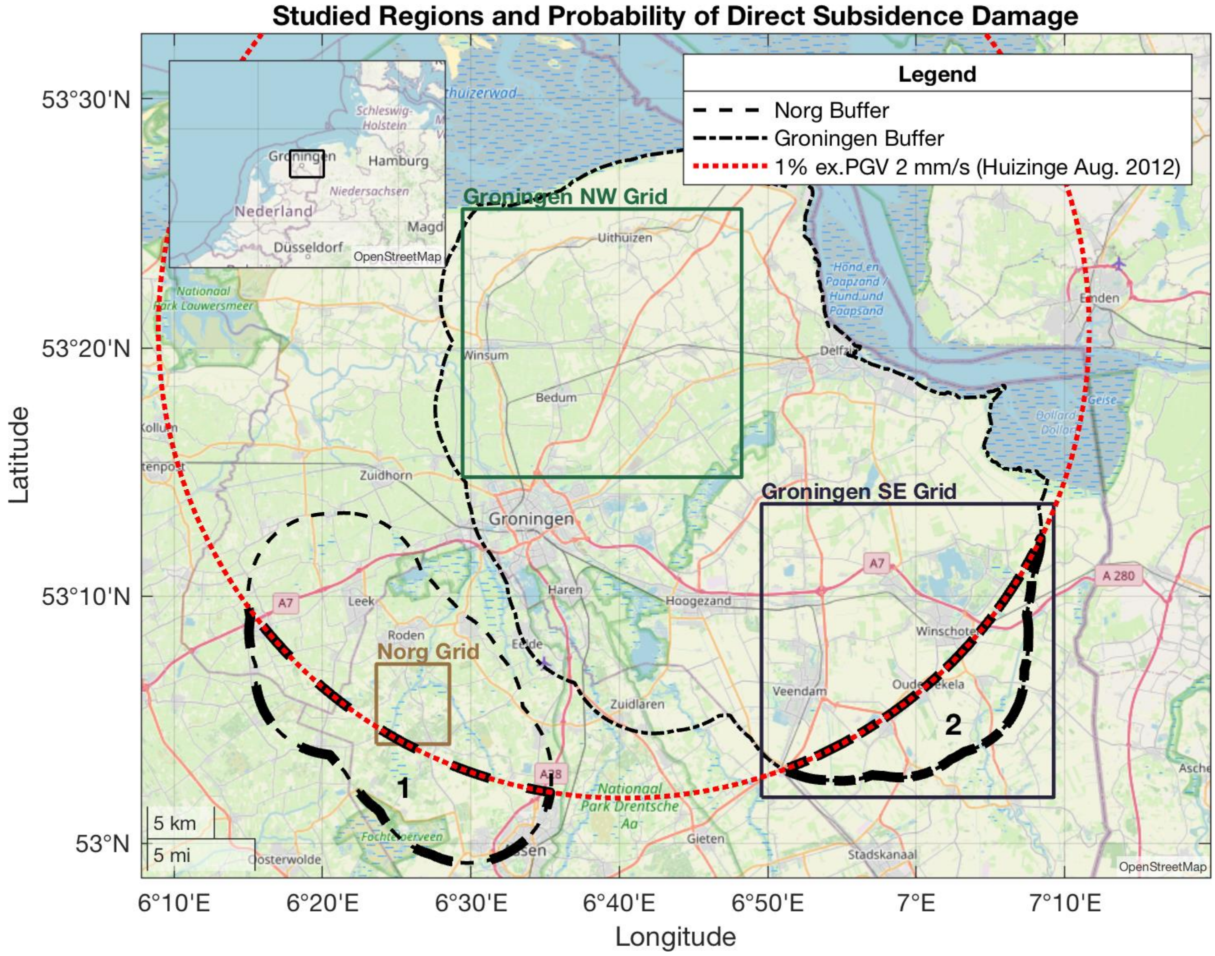

Figure 2: Map of the Northeast of the Netherlands with the three regions studied, Groningen North-West, Norg and Groningen South-East. Also indicated are the 6 kilometer buffer zones of the Groningen gas field and the Norg gas storage field, and the contour line of the 2 mm/s PGV value associated with the 1% probability of exceedance from the historical maximum for earthquakes (the 'Huizinge circle'). In addition, the effect areas 1 and 2, as introduced in Figure 1, are indicated.

As a final step, for Groningen North-West the sub-areas where the probability of damage is higher than 10^{-4} (1:10000) have been identified. This results into two small areas near Warffum and Bedum. Within these areas, the probability of damage is between 1:10000 and 1:500. Using the BAG building database, approximately 30 buildings from before 1975, which may be characterized by the poor masonry foundations as represented by scenario E are expected to be present in these areas [11]. Please note that the appendix J [11] also includes contours and counts for threshold probabilities different than 10^{-4}. Here, we only included the results for the 10^{-4} threshold, as that threshold complies with the a posteriori interpretation of the critical peak ground velocity selected by the TCMG panel [15] as criterium to define the effect area for the presumption-of-evidence regarding vibrations; see also chapter 3 for further discussion.

In [11] also a discussion on the assumed distributions for the influential features is included and a number of sensitivities is shown. As an example of the sensitivities, the assumed distribution for the percentage of horizontal strain transfer from soil to building was found to be highly influential; if the mean of that distribution is reduced from 30% to 20%, a 40% reduction in the number of buildings exhibiting a damage probability of 1:10000 is found. Also, reinforced concrete strip foundations, assigned to buildings after 1975, have a positive impact; the probability of damage then reduces by three further orders of magnitude as compared to the probability of damage for the buildings with masonry foundations (from the period before 1975).

3 Considerations for an acceptable probability of damage

The calculations performed by combining the distributions of subsidence and the fragility functions lead to a probability of damage, given a certain location in the area of interest, as presented in [11]. These probabilities are presented in the form of maps with iso-contours, i.e. lines with the same probability of damage.

A decision on the *acceptable* probability of damage is in the hands of the responsible governing institutes, including IMG and the Ministry of EZK. In our study, we do not define such threshold for damage probability. In section 2.5, based on [11], we adopted 10^{-4} (1:10000) as an example for such a threshold and elaborated the areas and number of buildings that would not comply for that threshold. Different thresholds, leading to different areas where the threshold is exceeded and different numbers of buildings where damage is expected, have also been elaborated [11].

In order to support IMG and other concerned stakeholders to decide upon the application of the outcomes of our study, we herewith provide some considerations:

1: For mining-induced earthquake vibrations the TCMG panel [15] has proposed a criterium in terms of an exceedance probability of a peak ground velocity. This criterium defines the effect area (the Huizinge Circle) within which the 'presumption-of-evidence' law applies (in Dutch: '*het effectgebied voor het bewijsvermoeden betreffende aardbevingstrillingen*'). The applied criterion implicitly complies to a probability of damage of 10^{-4} or higher within the effect area [15].
Given that approach, it would be consistent to also adopt a damage probability of 10^{-4} as criterium to define effect areas for damage caused by from deep subsidence. It is noted that, based on the results, also the probability of unjustly overlooking one or more buildings that may experience damage, can be quantified, for specific regions. It is very likely that these probabilities are very small and may be relevant only for Groningen Northwest.

2: Regarding the assessment of safety (ultimate limit state, collapse) the National Government has set the Meijdam-norm for acceptable individual risk as 10^{-5} (1:100000). This norm is associated with life safety and is roughly decomposed into a 10^{-4} probability of collapse and a 10^{-1} probability of fatality given such collapse. It is not unreasonable that a norm for damage in terms of cracks with a width smaller than 0.1 mm is at least one order of magnitude larger than the norm for life safety, provided that the damage is handled in a generous way and includes the presumption-of-evidence principle.

3: The damage probability is for initiation of damage with cracks of 0.1 mm width. This is seen as a strict criterion as cracks with a width of 0.1 mm are hardly or only just visible to the naked eye. So the values presented here are a conservative estimate of the probability of actually observed damage. The probability of exceeding the so-called light damage state (also denoted as a serviceability limit state), often associated with crack widths above 2 to 3 mm, is significantly smaller.

4: Damage to buildings can be caused by multiple causes, which may have much larger probabilities than those related to deep subsidence, as calculated in this study. The strain values associated with the damage need to be put in perspective with respect to other loads which can cause damage. As an example, a temperature difference of 30 degrees, frequently occurring between a masonry wall and the bottom of its foundation, leads to a strain difference of *two to three times* the maximum horizontal strain difference from deep subsidence. The likelihood of damage having been caused by such regular temperature or shrinkage effects, more frequently occurring during the service life of the building as compared to deep subsidence effects, has not been studied.

4 Conclusions

4.1 Effect areas 1 and 2, outside the Huizinge circle

Based on the additional studies carried out by TNO and TU Delft, it is confirmed that in the effect areas for deep subsidence, and particularly the areas 1 and 2, which lie outside the Huizinge circle, as indicated in Figure 2, deep subsidence does not directly lead or has led to damage to buildings. The probability of damage as a direct result of deep subsidence per building is much smaller than 1 in 10,000. The expected number of buildings with damage as a direct result of deep subsidence is smaller than 1 in these areas.

For these effect areas 1 and 2, this conclusion applies to both (vulnerable) buildings with a masonry foundation (these usually have a year of construction before 1975) and to (much less vulnerable)buildings with a reinforced concrete foundation.

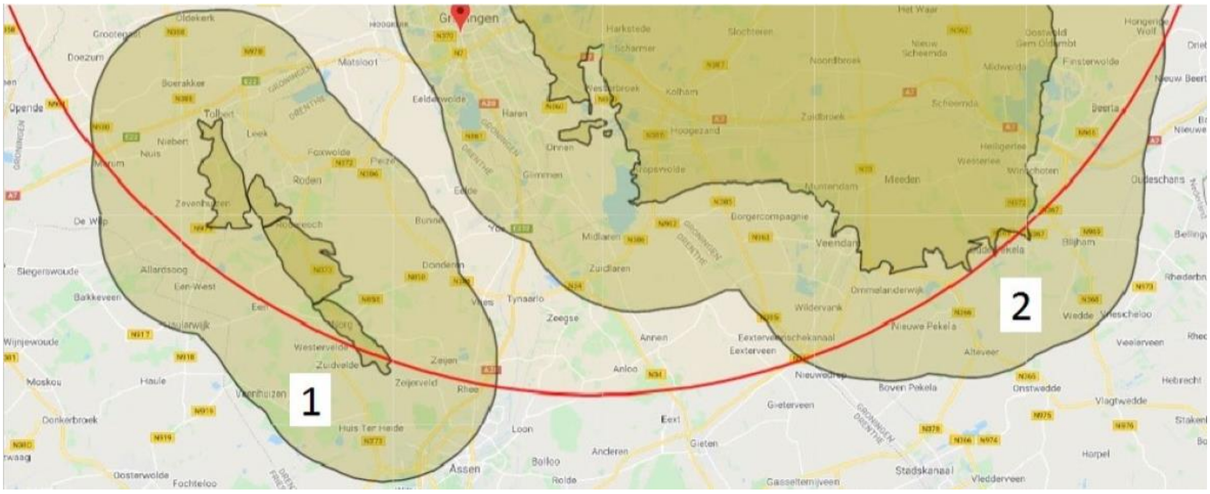

Figure 2: Effect area defined in the TCMG advice [15]. The red circle (Huizinge circle) encloses the area where the probability of damage to a building due to vibrations is greater than 10^{-4} (1:10000). Area 1 (southwest of the Norg gas storage facility) corresponds to the area outside the red circle but within 6 km around the Norg gas storage facility. Area 2 (south-east of the Groningen field) corresponds to the area outside the red circle but within 6 km around the Groningen field.

4.2 Effect area within the Huizinge circle

Within the red circle (the Huizinge circle) in Figure 1, which is the effect area for the influence of earthquake vibrations, a distinction is made between buildings with a masonry foundation and buildings with a reinforced concrete foundation:

- For buildings in this area with a reinforced concrete foundation, it is confirmed that deep subsidence does not directly lead or has led to damage. The probability of damage as a direct result of deep subsidence per such building is considerably smaller than 1 in 10,000. In this area the expected number of this type of buildings with damage as a direct result of deep subsidence is less than 1.

- For buildings with a masonry foundation, there are two small areas within the Huizinge circle, near Warffum and Bedum, where there is a slightly greater, but still very small probability (between approximately 1 in 500 and 1 in 10000) that deep subsidence can have led directly to minor damage to such a building. These two small areas are shown in Figure 3. They cover a total of approximately 4 square kilometers, located outside the built-up area. It is estimated that in these two sub-areas there are approximately 30 buildings with masonry foundations.

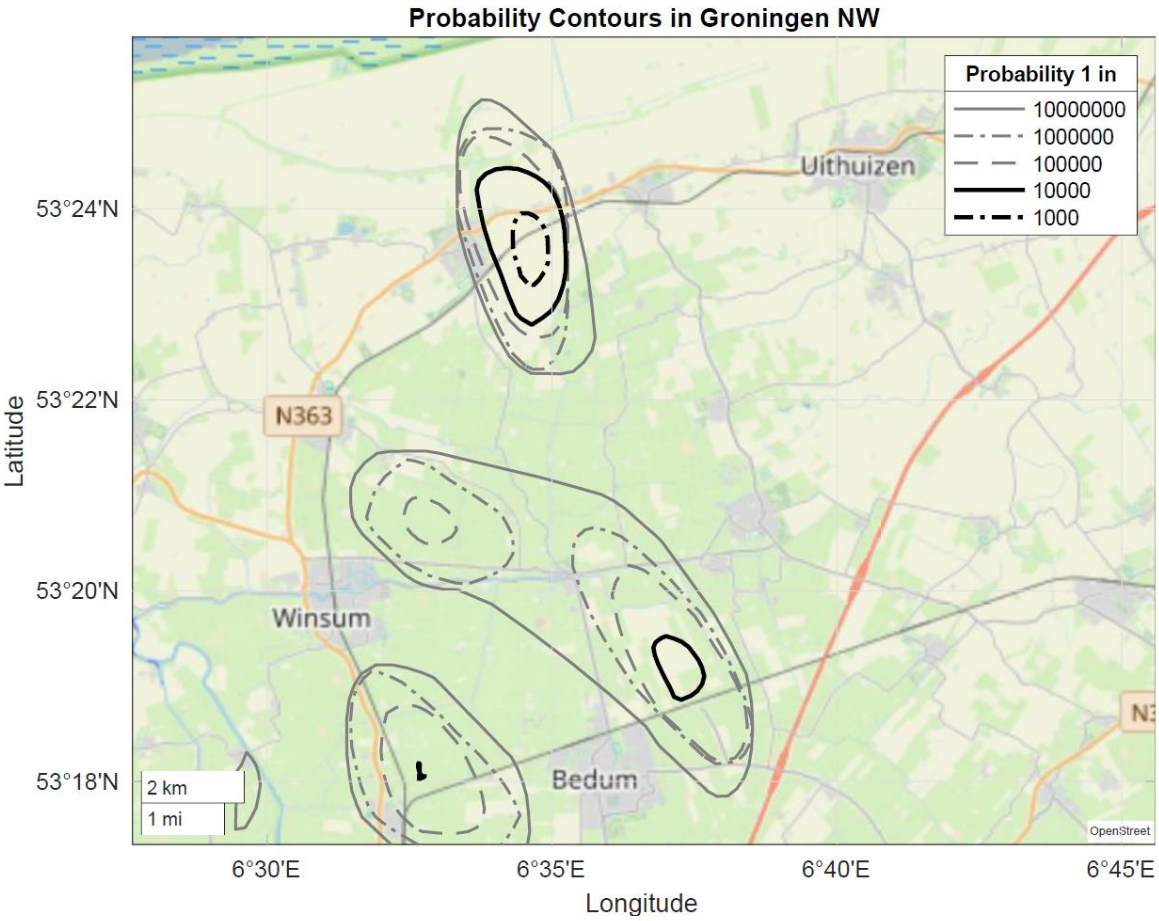

Figure 3: The solid lines envelope the areas in which the probability of minor damage (crack widths below 0.1 mm) for a building with a masonry foundation, as a result of deep subsidence, is greater than 1 in 10,000 (figure is equal to figure J.13)

4.3 Summary

With respect to the UGS Norg, the conclusion of the additional studies complies with the conclusion from the original study in 2021.
With respect to the Groningen field, there is a minor difference between the conclusion of the additional studies and the conclusion from the original study in 2021. The original study did not detect the two small areas in Groningen North-West, whereas the current study does. Please note that these two small areas in Groningen North-West already fall within the presumption-of-evidence because of the criterium for vibrations.

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[15] Beantwoording vragen Tijdelijke Commissie Mijnbouwschade Groningen, Panel van deskundigen, document TCMG 22 januari 2019

6 Signature

Delft, 13 November 2023

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For: Dr.Ir. C.P.W. Geurts
Author

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Author

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