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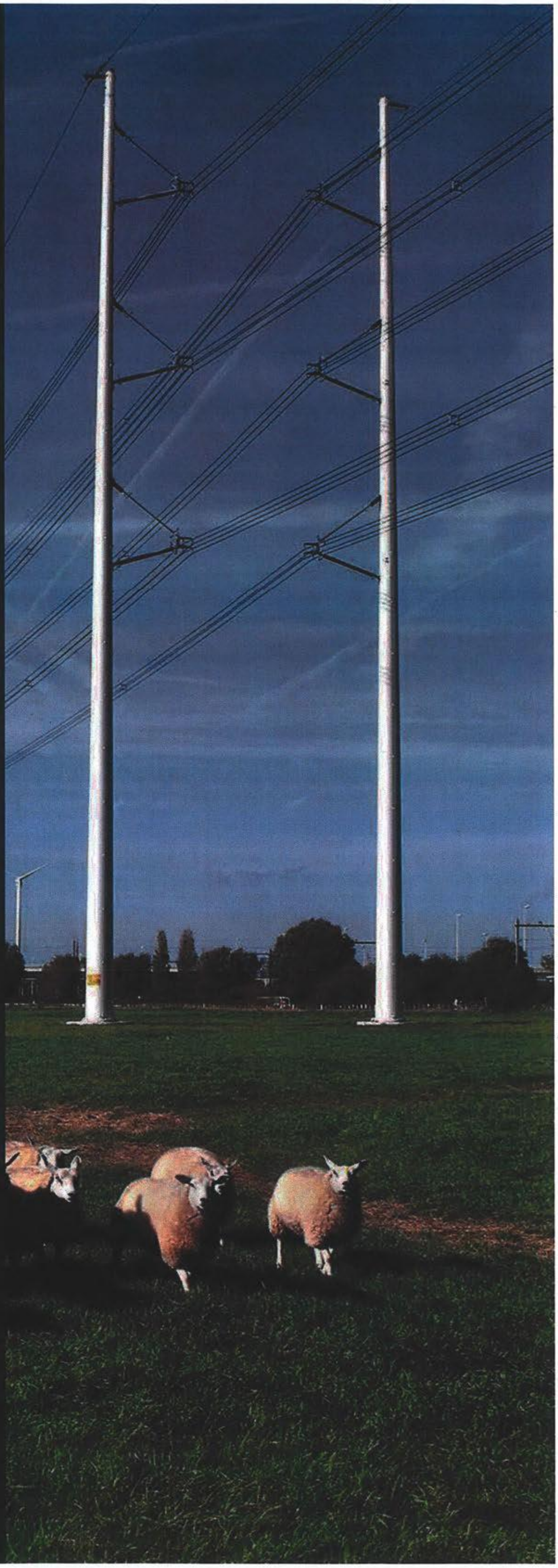
REPORT

Peer Review

Direct and indirect cause of building damages related to deep subsidence and heave



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Peer Review

Direct and indirect cause of building damages related to deep subsidence and heave due to gas extraction in Groningen and gas extraction and storage in Norg.

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Executive Summary

The Minister of EZK (Dutch Ministry of Economic Affairs and Climate) gave substance to a request from the Dutch House of Representatives from 19 November 2021, to explore whether a joined research question can be formulated in consultation with local residents, municipalities and provincial governments with the goal to clarify causes of damages in the two specific areas. Local residents raised the desire for an independent peer review of the recently conducted studies.

The current peer review focuses on the areas for which *presumptive evidence* is no longer being applied (see Figure 1) as a result of the conclusions drawn from IMG based on the studies by TNO/TU Delft and Deltares. IMG (Instituut Mijnbouwschade Groningen, independent organization tasked with handling damages to buildings due to gas exploitation) concluded that based on the studies, the physical damages to the buildings could not have been caused by deep soil subsidence and heave due to gas exploitations from the Groningen field or gas storage facility at Norg.

Residents are not only wary about the cause of the damages, but also doubt the completeness of the conducted studies and are unsatisfied about the consequences of the studies for the way of settling damages to buildings by the IMG. The change of area on which presumptive evidence is valid and the changes to assessment framework made by IMG based on the studies is not part of the peer review as it could interfere with the independent status of IMG.

The scope of the review including list of documents part of the review is shown in section 1. The review was conducted by a panel of experts selected and facilitated by Movares (see section 2).

Findings of the review
Report **01** provides the claim that deep subsidence and heave in the Norg underground gas storage (UGS) and Groningen gas field does not lead or has not led to damages to buildings.
Outcome of the review is that, albeit potentially correct, the results and conclusions are of limited credibility.
This is due to the unknown statistical significance of the calculations of the damage indicators described in **1B** and **1C**. The studies presented in **1B** and **1C** are generally well-executed within their scope, are well informed in terms of previous studies, and do not present any obvious errors. However, there are considerable factors contributing to unknown uncertainty/confidence intervals – both in the case of modelling and InSAR data analysis – that are potentially of relevance to damage indicator inferences, given these are indirect estimates based on the studies in **1B** and **1C**. In light of these uncertainties, the resulting damage indicator calculations and conclusions thereafter, albeit potentially correct, are of limited credibility due to their unknown statistical significance.
Furthermore, the review concluded that the masonry modelling and foundation modelling do not guarantee the worst case conditions or at least have not been sufficiently justified. Therefore damages can be more severe than reported. This is mainly due to:

- Façade is modelled as relatively flexible giving relative low vulnerability to differential settlements.
- Foundations are modeled relatively stiff resulting in relative low transmission of settlements to the facades.
- Orthogonal walls to facades are taken as constraints which can actually have a beneficial effect.

Report **02** provides the claim that indirect effects of deep subsidence and heave in the Norg UGS and Groningen gas fields can be excluded as cause of damages to buildings in all but several areas.
Outcome of the review is that the claim is credible and sufficiently justified.

Based on the findings of the review, it is likely that an update of the studies based on the comments given, will (locally) result in higher values for damage indicators and possibly also more stringent values of damage thresholds. Therefore, potentially increasing the inferred likelihood that deep subsidence and heave can have caused damages to buildings. However, whether these changes will be of relevant magnitude to change the conclusions made is not possible within the scope of the review and would require further investigation and most likely significant modelling, data acquisition and processing efforts.

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Introduction

The Minister of EZK (Dutch Ministry of Economic Affairs and Climate) gave substance to a request from the Dutch House of Representatives from 19 November 2021, to explore whether a joined research question can be formulated in consultation with local residents, municipalities and provincial governments with the goal to clarify causes of damages in the two specific areas. Local residents raised the desire for an independent peer review of the recently conducted studies.

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Chapter 1 presents the scope of the review. Chapter 2 elaborates on the review process used. It discusses the different parties involved, how the review was conducted and how the findings were combined into this report. Chapter 3 presents the details of the review. Lastly, chapter 4 summarizes the conclusions that can be made based on the results of the review.

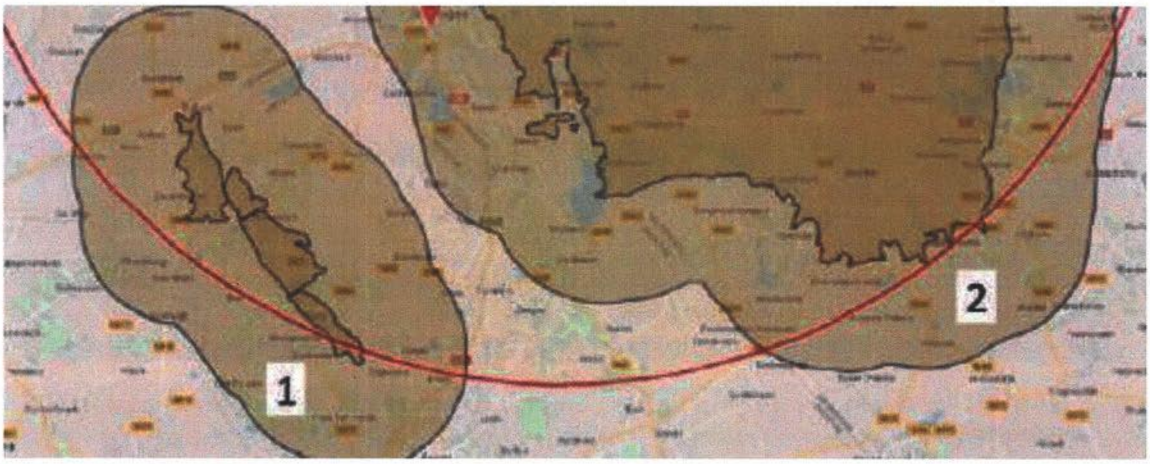

Figure 1 - areas for which subsidence and heave as cause of damage causes were investigated (areas outside circle numbered 1 and 2.

1 Scope of the review

IMG flagged the need for additional investigation mid 2020: "*Reason for additional action are multiple. This includes an increase in the number of rejected cases in the recent months in a specific area. The damages in this area cannot be caused by earthquakes but the area is affected by deep soil subsidence and heave. The rejections resulted in questions and unrest by those that reported the damages.*
The rejections were based on advice from independent experts in individual cases. These experts advised to reject the cases because the damage could not have been caused by vibrations and, based on judgment by the experts, neither by deep soil subsidence and heave. The experts judged the cause of the damage to be of autonomous nature. At this moment, the IMG would like to have more clarity before making any more rejecting decisions about these type of cases. Foremost, to ensure a uniform handling of larger number of these cases."

Based on the above, the IMG issued three studies. Only the first two studies are part of the current peer review:

1. Study regarding damage to buildings from deep subsidence and uplift conducted by TNO and TUDelft.
2. Study regarding indirect damage effects of deep subsidence and uplift near the Groningen gas field and the Norg underground gas storage facility conducted by Deltares.

Total amount of documents part of the review therefore are:

1. **01**-TNO2021-R10325B-SchadeAanGebouwenDoorDiepeBodemdalingEnStijging
   - A. **1A**-TNO2020-R12073-LiteratureReview (appendix report 1)
   - B. **1B**-TNO2020-R12068A-EffectenDiepeBodemdalingEnStijging (appendix report 1)
   - C. **1C**-TUDelft-InSAR (appendix report 1)
   - D. **1D**-TUDelft-ComputationalModelling (appendix report 1)
2. **02**-Deltares-IndirecteSchadeEffecten

(bolt code will be used to reference studies in this document)

Reviewers were asked to assess the studies using the questions below as guidance but also assess the studies based on any other aspects deemed relevant.

- Assumptions and execution of the studies:
  - Are assumptions, allowables and selected models applicable on / sufficiently representative for the specific circumstances of the area?
  - In what way are the models used validated and is the validation sufficient?
  - Do the studies use the latest insights and expertise?
  - Are the formulated research questions in the studies sufficient to answer the request for advise by IMG?
- Execution:
  - What assumptions are made to reach the conclusions? Are these assumptions valid?
  - What sources are used to reach the conclusions and what is the quality of these sources? Do other sources exist that would result in a different conclusion.
  - What soil movement data is used and is sufficiently accounted for uncertainty of this data.
  - What information regarding soil composition is used and is sufficiently accounted for uncertainty of this data? Are geographical variations in soil composition included in the studies.
  - Did the studies include the most relevant and recent data? Are other data sources available that weren't used which could lead to a different outcome of the studies?
  - Were the assumptions and used data applied in a correct manner to answer the set research questions?
  - Were cumulative effects account for and to what extent? (cumulative effects referring to effect of other mining activities in the area such as salt exploitation)
- Results:

- Does the study answer the questions of IMG?
- How did the researcher come to the drawn conclusions? Can these conclusions be drawn based on the content of the reports?
- Do any aspects or subtopic exist for which no answer can be given based on the methodology in the studies?
- Did the studies sufficiently cover how the results due to the selected methodology compare to (deviating) observations in reality?

Main goal of the review was to ensure that the conclusions/claims made in the studies were correctly justified.

It should be noted that the extend of the review was limited in that the following was excluded:

- Independent reproduction of the analyses and results
- Direct consultation/discussion with the experts who conducted the studies and produced the reports.

The latter was an active decision of Movares and EZK in order to ensure that the findings of the reviewers are not negatively influenced due to such discussions. However, reviewers were allowed to request additional information in terms of documents, modelling data used, or graphs if required.

The review was conducted on the English-text versions of the documents. Documents **01**, **1B** and **02**, were translated from Dutch to English and were provided by EZK to Movares.

2 Review process

The review was conducted at request of the Dutch Ministry of Economic Affairs and Climate (EZK). EZK requested Movares to act as facilitating party for the review. The goal of using a facilitating role in the review was to speed up the review process, ensure the review was conducted without conflict of interest, and lastly to ensure that the review will be complete and clearly presented.
The role of Movares in the review was to:

- Identify and contract a review panel that was able to review the complete study at a high level of quality without conflict of interest.
- Facilitate potential discussions between reviewer and ensure sufficient information was available for the reviewers to conduct the review.
- Combine the findings and recommendations of all the reviewers into a single document.

It should be noted that Movares had no previous involvement in the reviewed studies or affiliation with the people that have conducted the reviewed studies.

The role of Movares in the review was to identify and contract a review panel consisting of a minimum of 3 qualified reviewers. Reviewers were identified and selected based on the following criteria:

- No previous involvements with the studies to be reviewed.
- High level of expertise in the area of knowledge relevant for (parts of) the review.
- Availability.

Each of the reviewers was assigned parts of the studies based on their respective area of expertise in which several reviewers had some overlap in parts to review. The final number of reviewers was the required number in order to cover all area of expertise. Furthermore, reviewers were free to comment on other parts of the studies if deemed relevant.

At the start of the review, an online kick-off meeting was held with Movares and the reviewers. The goal of this kick-off was to introduce each other and to clarify the scope of the review if necessary. The reviewers were free to request more information from original authors of the studies to be reviewed. Lastly, in the case reviewers would come to conflicting conclusions, Movares would facilitate a discussion in order to clarify this conflict. However, none such discussion was required in the end.

All reviewers submitted their findings in written form. Movares combined these separate results into a single document (this document). All reviewers have reviewed the final document and agree with the content as a correct representation of their findings.

2.1 Selected review panel

The selected panel for the review including area of expertise on which members were selected for this review:

- Ivan Vasconcelos - geotechnical
- Iunio Iervolino – building damage mechanisms / geotechnical
- Pietro Teatini – geohydrology
- Claudia Zoccarato - geohydrology

3 Results

In the following sections, review results are given per document starting with sub-documents (**1A, 1B, 1C, 1D)** leading towards the main documents (**01** and **02**). It should be noted that this text is a combination of the findings as submitted by the different reviewers. The findings were combined and clarified to a level deemed necessary by Movares. The amount of textual changes are minimized in order to best represent the findings and conclusions of the reviews.

3.1 Literature review (1A)

Document **1A** presents results of a literature survey for assessing damage on buildings induced by subsidence, resulting in a criteria and threshold values that can be used in assessing building damaged due to subsidence.
The literature review was deemed exhaustive by the review to come to representative damage threshold.

3.2 Subsidence modelling (1B)

3.2.1 General review

In the case of modelling surface deformation for both Norg and Groningen fields, **1B** relies on the same workflow, with the following aspects:

- *Input 1 – reservoir compaction models.* The study relies on a linear compaction model (Fokker and Orlic, 2006), that assumes a piece-wise constant reservoir. In the Norg case there are four homogenous compartments (**1B** Table 2), whereas the Groningen model relies on a previous, more laterally heterogeneous reservoir model (**1B** Table 3, see refs in **1B**). Norg is treated in the purely linear compaction regime, while Groningen compaction is based on the compaction model by Pruiksma et al. (2015) to be used as input in the modelling scheme. The reservoirs appear to be treated as a fixed-thickness horizontal layer, with varying compaction properties as per the Tables mentioned above.
- *Input 2 – overburden poro-elastic properties.* Relying of the semi-analytical deformation modelling (SADM) of Fokker and Orlic (2006), it is implicit that the studies model the subsurface as potentially a 3-layer model with: i) reservoir layer, ii) overburden (rock volume from top reservoir to surface) and iii) underburden (infinite half-space below bottom reservoir – allegedly implemented as a rigid boundary condition). Each of these requires elastic quantities (elasticity and Biot parameters) as input. In particular, it is key to note the overburden elastic properties are assumed to be constant – see discussion below.
- *Subsidence calculations by SADM.* The SADM method used is strictly valid for laterally homogeneous media. For the purposes of **1B**, to accommodate for the case of lateral variations in compaction properties, it appears that what is done is simply a superposition of SADM results for separate evaluations over, e.g., reservoir blocks – this is inferred here, as neither **1B** nor the original SADM paper detail how the calculation is conducted for laterally heterogeneous compaction parameters. One important detail is that while the SADM paper accounts for 3D media and shows a gridded 2D deformation result as an output (Fig 14 of Fokker and Orlic), for unspecified reasons **1B** contains only 1D transects of deformation results from SADM – see further discussions below. The desired estimates of soil curvature are derivatives of strain estimates.

With these being key aspects on how the modelling studies were designed and conducted, there are a few assumptions and choices in these studies that raise questions to be considered:

- *On the use of SADM.* The state-of-the-art in production-related geomechanical modelling are 3D numerical solvers for coupled poro-elastic partial differential equations (e.g, Berard et al., 2015, Koutsabeloulis and Zhang, 2009, Pan et al., 2009, RVO 2022 Report) – industry-standard examples of such software are VISAGE (under the Petrel platform), or COMSOL in a more general context of numerical simulations (e.g., Gong and Wang, 2013). Such software packages entail a licensing cost and are generally numerically more demanding than a choice such as SADM. It is likely SADM was chosen for simplicity and numerical convenience – it being a by-product of TNO's own technical work. However, this choice seems to come at the cost of accuracy in the presence of lateral heterogeneity. Clear evidence of this issue appears in the case of both fields – see Figures 6B and 16B of **1B**. In both cases there are several instances where the line transects cross and the inferred Curvature values show notable discrepancies. Because the medium above the reservoirs in these models is constant, deformation and associated stress and strain on the surface should be continuous - according to the underlying equations in the case of a homogeneous overburden volume. As such, the discrepancies seen in Figs 6B and 16B of **1B** are artefacts of conducting separate 2D calculations at the transect locations – each of these already approximated to accommodate lateral heterogeneity in reservoir compaction properties with the SADM designed for laterally homogenous medium. It is important to note that the original SADM paper provides independent numerical validation in the case of a laterally homogeneous medium, but this review has not found a similar benchmark in the case of laterally heterogeneous media. Thus, there are two potential issues at play:

- Discrepancies caused by separate 2D transect calculations as opposed to full 3D geomechanical simulation – aside from a different geomechanical modelling approach, it is unclear why the SADM was not employed to produce 2D-gridded maps;
- Heterogeneous compaction properties approximated via the SADM, in turn designed for laterally homogeneous media.

■ *On the potential importance of near-surface properties.* In this study, the overburden medium above the reservoir is treated as a single, homogenous rock volume. As a result, lateral variations in the modelled results are controlled by the lateral variations in the model-supplied compaction properties. However, in reality the subsurface is heterogenous, and particularly so with the so-called 'near-surface' i.e. the first few hundred meters below the surface. This implies that near-surface changes in properties yield potential variations in elastic properties, thus also influence the surface characteristics of deformation and, in particular, of horizontal strains (Malehmir et al, 2016; Medwedeff et al., 2022). The absence of treatment of near-surface heterogeneity in modelling may lead to potential blindspots:

- Underestimation of strain magnitudes: because the near-surface is always more compliant then the deeper overburden rocks, given the same input stress the resulting strains may be higher;
- Unknown scale of lateral strain variations at building scales: the models presented represent only reservoir-depth compaction-variation trends on the surface, thus yielding smooth variations over relatively long length scales. The models simply do not contain any near-surface geology information thus the importance and extent of near-surface effects is unknown.
- Absence of discontinuous scenarios. Lateral discontinuities in near-surface properties – e.g., due to building vs natural areas or other reasons – would incur discontinuities in surface strain, indicating potential extreme scenarios for the purposes of the study. For the same reasons as above – these are not included in the study.
- Unknown potentially local contributions to geographically-dependent variations on subsidence-related damage risk. Since the near-surface could further change horizontal strain values and thus the subsequent damage thresholds, the current analysis only relates to compaction variations at depth, so the extent of near-surface-related contributions to the question is simply unknown.

■ *On the absence of uncertainty quantification*. In both the Norg and Groningen cases, the results correspond to fixed set of model parameters – for all parameters concerned. On the one hand, it is clear that the values proposed are sensible in light of several previous studies – this is supported by the references provided in **1B**. On the other hand, there is a very notable absence of uncertainty considerations. Uncertainty studies in reservoir simulations are notoriously challenging given the numerical cost of 3D simulators, however, in the case SADM – and in particular in the calculation of 2D transects – this may be more tractable as the simulation is significantly more efficient numerically. Ideally, the input parameters in Tables 2 and 3 would have been provided with some uncertainty – even if from educated/conservative guess estimates. Those could have then supplied multiple simulations to yield confidence intervals for resulting surface deformations. Though this may well have been beyond the resources/scope of the project, the absence of uncertainty analyses does lead to important considerations:

- Unknown range of extreme deformation values. As is, without confidence intervals, it is not possible to determine the range of likely-vs-extreme vertical deformation resulting from uncertainties in the input parameters. This is particularly relevant to curvature estimates, because these are derived from strain calculations and thus amplify errors/uncertainty inherently present in deformation estimates.
- Unknown statistical significance of final results. Damage indicators are provided in **1B** as a series of Figures in sections 2.4 and 3.4. These figures do not contain error estimates – which would appear on both axes – and as such their statistical significance in light of the chosen input parameters is unknown.

These being the general points regarding the modelling studies for both fields, next a brief assessment of the results is presented for each field.

3.2.2 Norg field modelling

Aside from the assumptions and considerations discussed in the previous section, the input model parameters chosen (**1B** Table 2) are reasonably chosen and indeed consistent with those referenced by the authors. The SADM results presented along transects (e.g., **1B** Figs 4 and 5) show appropriate physical behaviour and display sensible deformation magnitudes. As mentioned above, the modelled estimates over transects do not necessarily coincide at the transect crossing points (see **1B** Fig 6), likely as a result of the underlying SADM assumptions on lateral homogeneity and of how the method was adapted to approximate heterogeneous compaction properties. It is important to remember that lateral variations in the modelled values are due to lateral variations at compaction properties at depth, and do not incorporate information of overburden or near-surface variations. Finally, the SADM for the scenarios of a full vs depleted reservoir, in line with the previous results shown, displays correct physical behaviour and sensible magnitudes for deformation and curvature/tilt.

The damage indicator results based on the SADM estimates are shown in **1B** Figs 10-14. From a qualitative perspective, and given the assumptions and subsurface model supplied, the values and trends presented in these Figures seem reasonable and indicate all calculations to be self-consistent. As per the discussion above:

- Without uncertainty/confidence interval estimates, the statistical significance of the damage indicator results is unknown;
- The curvature and horizontal strain values in the results correspond to a homogeneous overburden without information on near-surface properties, leading to potential underestimation of these values as the actual near surface is likely more compliant then the medium used as reference in the calculations. Note that the Poisson's ratio listed on **1B** Tables 2 and 3 is 0.25, which corresponds to a relatively stiff rock material (akin to e.g., cast iron), whereas the near-surface is significantly more compliant, with a Poisson's ration likely greater than 0.35.

The overall conclusion drawn from the results is that the predicted damage indicators are well below the damage thresholds (**01** Figure 5), which range between 10^{-4} and 10^{-3} in both strain and deformation. Noting that the maximum magnitudes in Figs 10-11 reach 10^{-5}, the questions of both confidence intervals in light of both provided parameters as well as near-surface conditions is relevant. In the case of rotation estimates, predicted values are significantly lower than the thresholds at around $10^{-8} – 10^{-7}$: this is not entirely unexpected because rotation estimates are connected to stress/strain on the plane of the ground surface, and seeing that the reference overburden model is relatively stiff, the resulting strains will be accordingly small at fixed stress conditions. Again, the use of more compliant near-surface models might result in larger rotation values, but without corresponding calculations it is not possible to determine by how much rotation values would be affected.

3.2.3 Groningen field modelling

In **1B**, the SADM approach and subsequent damage indicator calculations essentially follow the same procedure as that for the Norg field case. Aside from the larger grid size to accommodate a larger modelling volume than that of the Norg case, some notable differences in the case of Groningen are:

- The compaction model is based on that of Pruiksma et al. (2015). While this means a higher degree of realism and calibration behind the compaction model, it also implies more complexity in terms of lateral heterogeneity – which could in turn imply that the use of the SADM is more approximate in this case than that of Norg where only 4 piece-wise constant compartments are considered; see the General Review section above for the discussion on the limitations the SADM approach in the presence of lateral heterogeneiy.
- The reservoir layer is thicker than that of Norg, thus the effects can be of greater magnitude (though this is of course entirely dependent on production/injection rates): this can be observed by comparing the values in **1B** Figs 6 (Norg) and 16 (Groningen).

The results from the Groningen SADM are similar to those of Norg, however, **1B** Fig 16 shows more pronounced discrepancies between modelled values at transect crosspoints, likely due to the SADM method performing poorer in the Groningen case due to its limitation in handling the greater complexity of lateral variations in compaction parameters – see discussion above.

When it comes to the final damage indicator estimates and conclusions thereof, the overall outcome stated **1B** is that horizontal strain and rotation are well below damage thresholds. These estimates and associated conclusion are subject to the same assumptions and uncertainty considerations as with the Norg case – see discussion above. Although there is a brief mention of vertical deformation uncertainty in the case of the Groningen study (for total subsidence), that information is not translated into the context of the specific study in **1B**.

3.3 InSAR data analysis (1C)

With the objective of providing observational support to the numerical modelling results within **1B**, **1C** aims at using InSAR data over the interest area above the Norg field. In particular, **1C** provides a fair amount of technical detail over the dataset, processing steps, and calculations that were undertaken in a clear and consistent manner. Here are some of the relevant characteristics of the InSAR study:

- The full data set is a combination from 2 datasets from 2 satellites (Sentinel-1a and -1b, descending and ascending trajectories): these have partial spatial overlap (shown clearly in **1C** Figs 2a and 2b), and likely different signal-to-noise and orbital-angle resolution characteristics (e.g., Zhenhong et al., 2004; Reeves et al., 2014; Fattahi and Amelung, 2014). The four datasets are merged into a single set of results through the data processing;
- The processing flow-chart is clearly displayed in **1C** Fig 6. Each dataset is processed individually then subjected to further processing during the data merging process. There are 2 key points for the sake of this review:
  - The data are subject to 2 steps of nonparametric fitting – using the well-established LOWESS method. The first of which seems to have the purpose of extracting smooth time series per grid point from each of the four datasets (e.g., **1C** Fig 3). The second step seems to serve the purpose of spatial averaging toward extracting smooth vertical deformation maps at scales comparable to those of the SADM study (e.g., **1C** Figs 4 and 5);
  - The final outputs of curvature and horizontal strain are indirect estimates based off vertical deformation fields inferred from the InSAR data. Curvatures are the output of 2nd order spatial derivatives of vertical deformation, and horizontal strains are inferred from curvatures by means of a canonical Euler-Bernoulli beam model.
- To provide validation to the processing of InSAR data, a comparison between InSAR and ground-based GPS deformation is presented (**1C** Fig 9).

Overall, the InSAR study in **1C** contains no obvious errors and is executed with a professional degree of expertise. However, there are important points to be considered:

- <u>*On the absence of uncertainty analysis.*</u> At the bottom of **1C** page 3, the authors of the study acknowledge variability in the input data leading to unknown uncertainty, and that a probabilistic approach was beyond the scope of the study. Indeed, this would have been a highly desired analysis, given the various error sources in InSAR data observations (e.g., Zhenhong et al., 2004; Reeves et al., 2014; Fattahi and Amelung, 2014). It is worth noting that, aside from InSAR-specific error analysis, variance estimates in the context of goodness-of-fit can be a by-product of LOWESS fitting (e.g., Higgins, 2004; Andersen, 2009) and could have potentially been employed on the time-series and later spatial smoothing steps applied in processing. Here are some observations on the chain of dependence of uncertainty estimates in this study:

- **1C** Fig 3 shows that the variance associated with time-series smoothing is non-negligible, taking the data spread around the fit to be a proxy for approximately 1.5 standard deviations in goodness-of-fit. In fact, it is possible that this variance is in the order of variations observed in the fit;
- If time-series variance were available, these could be propagated to the LOWESS spatial smoothing, and could provide confidence intervals to the vertical deformation that would carry spatial variability, because the data are highly irregularly sampled (**1C** Fig 2b);
- Because curvature estimates are based on 2nd order derivatives of vertical deformation, uncertainties in the latter may be greatly amplified into curvature uncertainties – this would equally amplify uncertainty in horizontal strain estimates.

■ Regarding the output deformation maps in **1C** Fig 5, there is a statement that the contours are "almost identical" based on visual inspection of the maps. In this reviewer's observation, though the maps in Fig 5 indeed display similar spatial patterns, it appears that if one produced a difference map, that result would have spatially variable fluctuations in the order of 1 mm or greater in some locations. Thus implying that the identity of the results is quantitatively questionable – particularly so in the absence of confidence intervals to aid in interpreting the statistical significance of the observed differences in values. Moreover, visual inspection of the maps in Fig 5 shows notable differences in spatial patterns of deformation gradients, thus, likely in subsequent curvature estimates.

■ While the comparison with ground-based GPS is an important addition to the study, what **1C** Fig 9 appears to display is agreement between local InSAR and GPS observations (noting that the red line is within range of the light gray lines displaying local variability), but a potentially statistically significant bias in the spatially-smoothed InSAR – because the black line systematically lies outside the area implied by light gray lines. Again, the statistical significance of this bias cannot be assessed without confidence interval estimates. More importantly, it is key to note that:

- The GPS comparison yields information over the time-series processing of the InSAR data at the observed location, and can neither support nor discredit the overall spatial information displayed and discussed over the full InSAR dataset;
- Consequently, and because the GPS comparison speaks to local vertical deformation only, this comparison is of little value in support of curvature and horizontal strain estimates.

■ Importantly, visual inspection of **1C** Figs 8a and 8b, to this reviewer, implies the following:

- InSAR-based results only show some correspondence in spatial patterns in 2 out 6 displayed transects, with notable magnitude discrepancies. In particular, curvature profiles visually differ fairly significantly between InSAR-inferred versus SADM-based estimates;
- The absence of confidence intervals makes the comparison between results difficult: the statistical significance of the differences between the curves presented is simply unknown.

■ Because InSAR-based deformation was produced over the area of interest, it is not clear why the curvature and horizontal strain calculations presented are limited to the modelled transects, as they could have been supplied over space. Those observation-based maps could provide information about whether the SADM transect locations/sampling needed revising or if spatial patterns indicated a potential influence of near-surface effects not contained in the SADM results.

In closing, while the data processing is expertly-executed, the claim that InSAR-based results compare "well" with SADM results – though possibly true – is of unknown statistical significance, which is of particular importance in evaluating the significance of resulting curvature and horizontal strain estimates. Moreover, in spite of the uncertainty considerations, it is not clear why the spatial coverage of the InSAR results was not explored further into the damage indicator studies, being restricted to the limited locations of the SADM transects.

3.4 Building damage modelling (1D)

The report does not contain a thorough discussion of the masonry model considered with respect to the typological characteristics in the area, although masonry buildings of Groningen have been widely studied numerically and experimentally, beyond refs [14,15] reported in the paper (e.g., Sarhosis et al. 2019; Blanco et al., 2018; Kallioras et al. 2018; Graziotti et al., 2016; Bal et al., 2021; Graziotti et al. 2019, etc). However, it is discussed that the chosen masonry is relatively flexible (**01** §3.1), which generally should indicate a relatively low vulnerability to differential settlements. On the other hand, the foundations appear to be relatively stiff; i.e., relatively less prone to transmit settlements to the facades. In fact, it may be that the foundations of Groningen masonry buildings are basically only walls enlargements. Furthermore, the parametric analysis goes towards even more rigid or sliding foundations; i.e., even less transferring the settlements. Finally, the walls orthogonal to the facades are taken as constraint, which could have a beneficial effect, while it seems to be ignored that if these walls suffer settlements these may affect the studied facades with further damages out-of-plane in addition those in-plane discussed in the documents. Also, the use of calculated deformations at greenfield without façade is claimed to be worst case but is not necessarily so. The buildings can induce settlements due, for example, to their different weight distributions, soils with aquifer, soil profiles with non-homogenous layers.
The study uses the latest insights and expertise with for the masonry numerical model, while the geotechnical model appears linear, while it could be questioned the use of a non-linear numerical geotechnical model, which could lead to concentration of deformation and therefore larger differential settlements, possibly detrimental for the buildings (also see review results of **1B,** section 3.2).
In conclusion, the choice of the masonry model, the foundation type, and the constraint of the orthogonal walls, could have been better justified as they do not seem to represent the worst-case conditions.

Validation of the model is not completely clear. It appears the deep soil model is validated using **1B**. Therefore, apparently a model vs model validation is used, while one with respect to comparable real structural cases would have been preferred.
Furthermore, for the validation a comparison to the studied reservoir area (Norg) from 1B is used which is not the case with the highest (and therefore worst) curvatures. See for example Figures 42, 43, 46, 47, 53, and especially 56-bottom.
It is claimed that different sources contribute to the settlements, however only one seems to be considered. It is not clear how it is excluded that the interaction between different sources does not determine a pejorative case. Validation with respect to the structures (including foundations) is not clear and appears not fully exhaustive and only seems to refer to horizontal strains. It is not clear why the vertical strains are not relevant as well (if not the most relevant). This issue is even most relevant if the foundations decouple horizontal displacement how it is discussed at some point in the document. Emphasis seems to be given to horizontal deformations, while those vertical can cause significant damage, although apparently considered as secondary in the study. Soils-structure interaction is missing, although the vertical loads can induce differential settlements that would add-up to the effects of mining activities.

It is not clear whether further settlements are expected after the dismissal of the field; if so, it is not clear how future evolution of settlements in Groningen area is accounted for.
In one year, the settlements go from minimum to maximum cyclically due to mining activities, so there is also an effect of cumulative damage and cyclical action, which is not clearly taken into consideration. Cumulative effects were not fully accounted for. Only cyclic effect is mentioned in Appendix C, but the masonry hysteretic model used is unclear, as well as that of interfaces with soil. Moreover, the effect of ten cycles seems almost null, which let the reviewer think that cyclic modelling may be not adequate (this may be a limitation of DIANA or the reduced number of cycles).

It appears that the studied settlements are much lower than those that would cause visible damage, given that the study of the effects of settlements is very sensitive to the properties of the masonry, internal constraints between the walls, design and configuration of the foundations. It is not clear whether the settlements detected in situ were used, or if the model has only been calibrated on horizontal strains neglecting the vertical ones. Therefore, the questions of IMG were answered, but the assumptions made are often on the side of reducing vulnerability and the parametric analysis are not necessarily on the safe side, while a wider variability should be explored, and as close as possible to in-situ reality.

It seems there's no field monitoring of the actual settlements, no evaluation of the real features of the structures (both mechanical and geometric, except refs [14,15] in **1D**), but only very simplified models with ideal properties (probably not the most critical for the investigated problem). Also the effect of previous damage, as it is treated, can only lead to showing that it is beneficial compared to the case that there is no previous damage because the damage is considered minimal and only as seen as reduction of stiffness.

Smaller comments which would require clarifications but do not directly influence the outcome of the study:

- Stresses and damages in the foundations are never shown, is there any damage inferred from the FEM analysis?
- It is claimed: "Note that no damage is found for any of the cases; the stresses remain in all cases, below the assumed masonry tensile strength". Then, should a linear analysis lead to the same results? If yes, why all the hypotheses on the nonlinear modelling?
- Figures 20-22 show tensile stress reducing with respect to the principal stresses, which seems impossible in principle. Same for figures 27-29. Perhaps these are different loading steps. This should be clarified.
- Could there be any interaction with earthquake vulnerability after damages due to settlement?

3.5 Main document (01)

This document presents the overall findings of the combination of all sub studies. The overall findings stating 5 Claims:

- Based on the literature study in **1A**, Section 3.1 presents threshold values based on horizontal strain and relative rotation are selected for masonry which can be considered the lower limit for the occurrence of visible cracking (Claim 1);
- Regarding subsidence modelling, Section 3.2 presents the estimates off of **1B** for both Nord and Groningen, essentially concluding that the associated damage indicator estimates are below damage thresholds for both fields (Claim 2);
- Regarding the analysis of InSAR data, the **01** (supported by Section 3.3) relies on the results of **1C** to conclude the InSAR observations largely support the modelling results (Claim 3), while also suggesting that the modelled curvature and horizontal strains may be overestimated because the results from the InSAR analysis are of smaller magnitude over the compared transects (Claim 4).
- Regarding the modelling of the effect of subsidence on buildings relies on results of **1D** and concludes that effects of deep subsidence and uplift above the Norg underground gas storage would not lead to damage in the façades. Even when assuming a previously damaged façade, or when calculating the cyclic behaviour above the underground gas storage, no visible damage was observed (Claim 5).

With regards to Claim 1, review concludes that claim is justified based on the presented report in **1A.**

Concerning Claim 2, review concludes that the SADM calculations were appropriately conducted, with reasonable model parameter choices, giving a certain amount of credibility in support of the conclusion made in **01**. However, given the uncertainties surrounding the modelling study – predominantly due to modelling approximations, no inclusion of near-surface information and absence of uncertainty estimates – the final uncertainty surrounding the damage indicators remains unknown. Given the various factors influencing these estimates, the degree to which Claim 2 would be affected by including these uncertainty-related factors is also not known.

Concerning the InSAR data analysis, given the professional level of expertise/quality employed in the data processing, there is credibility to Claim 3 – that the InSAR observations corroborate the modelling result – albeit this credibility is undermined by the absence of uncertainty quantification. For the most part, it is the reviewer's opinion that while the InSAR data can reasonably be taken as support for the SADM mainly toward validating overall vertical deformation magnitudes, uncertainty may be considerably greater concerning the by-product calculations of curvature and horizontal strain – used to inform the damage indicator calculations. With regard to Claim 4, the absence of reliable confidence intervals in the presence of data noise (see discussion above) makes the InSAR curvature and horizontal strain results difficult to evaluate – so whether those values are indeed small in a statistically-significant manner is simply unknown and not supported by the data and analysis presented. Consequently, the claim that the InSAR results suggest the modelling results are overestimates is also not well supported by the data and analysis presented in **1C**.

Given the scope of the technical work presented in **1B** and **1C**, it is evident that those studies were conducted with limited resources, both in terms of time and budgetary/technical resources. In case of **1B**, this is likely the reason behind the choice of the SADM approach – given its simplicity and numerical efficiency – over more state-of-the-art 3D numerical geomechanical modelling tools. Likewise, it is likely that the time constraints of the projects did not lend themselves to more thorough analysis on uncertainty and model parameter sensitivity (in the case of modelling) – this is explicitly raised by the authors of **1C**.

It is important to note, that in the case of subsidence modelling and damage prediction, proper inclusion of more complex models, including realistic near-surface parameters informed by geophysical observations would be a rather significant technical undertaking. Though possible, this kind of work would likely require significantly greater resources – budget, time and technical experts – than those employed in the studies currently available. Likewise, the use of state-of-the-art 3D geomechanical modelling, together with a reasonably-designed approach to uncertainty quantification across the various components of these studies - both in modelling and data processing – would also require greater computational resources together with time for appropriate calculations and validation. Finally, it is also key to note that the studies in both **1B** and **1C** provide indirect inferences on soil curvature/strain information needed for damage-prediction studies. As such, these indirect measures will always be significantly more uncertain than more direct strain observations obtained, for example, from fibre-optic-based strain monitoring (Huntley et al., 2014, Webb et al., 2017). This again, would also require significant technical investment and time, but would also yield observational data directly tied to building damage prediction and monitoring.

Lastly, concerning Claim 5, the study presented in **1D** contains a large number of variations including complex modelling but fail to represent the worst-case conditions or at least fail to sufficiently justify the assumptions made. This is mostly with regards to the stiff foundations used and relatively rigid masonry.

3.6 Indirect causes (02)

The reviewed document deals with indirect effect of deep subsidence caused by gas production activities in the Groningen field and underground gas storage in the Norg field. The effect of subsidence and uplift is investigated in relation to damage to buildings. Indirect damage depends on (differential) deformations occurring underneath the foundations due to changes in groundwater levels relative to foundations. Conclusions of the study are drawn based on investigation of three **processes** ("pathways") possibly causing changes of the depth to the water table and, in turn, damages to buildings: (i) water level variation in the drainage canals relative to the surface level, (ii) freeboard variations within a polder due to differential deep subsidence/uplift, (iii) changes to the regional groundwater flow. All of them are related to changes/fluctuations of the groundwater level near foundation elements due to deep subsidence (i.e., indirect effect). These changes may be 'autonomous' (i.e., induced by deep displacements only) or related to the management of the water systems in response to land displacements ('human response').

Damage **mechanisms** to buildings due to groundwater level change are investigated for shallow and pile foundations. For pile foundations, the potential damages occur only when the groundwater level drops below the level of the wood material. For shallow foundations combined with a rise of the groundwater table (i.e., the depth to the water table decreases), potential damages are related to reduced bearing capacity of the soil, flotation of the basement, and swelling of unsaturated clays. If groundwater table is lowered (i.e., the depth to the water table increases), potential damages are caused by settlement due to a larger intergranular stress, peat oxidation, and shrinkage of clays. Limit values for the admissible groundwater level change are assumed based on previous literature (manly developed in The Netherlands). A value of 0.05 m is assigned to maximum groundwater level rise/lowering in relation to bearing capacity of the soil, flotation of the basement, and movement due to intergranular stress change. A value of 0.02 m is assumed if additional mechanisms such as clay swelling or shrinkage, peat oxidation, and degradation of wooden pile foundations must be accounted for. Based on available knowledge and experience these two values must be considered as conservative.

For each area of interest (Norg and Groningen fields), the study investigates whether deep subsidence could cause a variation of the depth to water table larger than the mentioned limits in relation to the three processes listed above.

Quantification of processes and assessment of the possibility of occurrence of damage mechanisms are carried out in the two areas of interest based on the available dataset (which are listed in the following) and the use of simple conceptual models and assumptions characterized by "large safety margins". The report outcomes point out that:

- in the Norg area, the possibility of indirect damage hazard due to deep subsidence/uplift can be excluded apart from two subareas where the limit 0.02 m can be slightly exceeded due to process (ii). Clay shrinkage/swelling, peat oxidation, and degradation of pile foundation are possible mechanisms causing building damages although the subareas are not sensitive to these mechanisms;
- in the Groningen area, the hazard of indirect damage due to a lowering of the water table of more than 0.02 m cannot be excluded in several subareas. Not exceeding the 0.05 m safe bound cannot be excluded in two fixed drainage-level subareas to the northeast. Available data suggest that the four westernmost detected subareas are not sensitive to the detected damage mechanisms (lack of shallow clay and peat, low settlement potential due to increase of the effective stress, and low sensitivity for wooden pile degradation). Conversely, to the northeast, the sensitivity increases in relation to all four mechanisms. Here, the processes of (i) water level variation in the drainage canals relative to the surface level and (ii) freeboard variation within a polder due to differential deep subsidence/uplift superpose increasing the probability of damages.

Globally, the research approach is properly set-up to provide a reliable answer to the request for advice by IMG. The report identifies the change of the depth to water table the (sole) indirect effect of deep land subsidence (uplift) that possibly causes damages in buildings. Review agrees with this key starting point of the analysis. In relation to deep displacements, the report states that depth to the water table can change as a result of three physical processes. The review agrees, no other process can be envisaged. Because of a variation of the depth to the water table, the report identified four mechanisms that can cause damages to buildings. The review agrees, no other mechanism can be envisaged.

Simple and conservative conceptual models are used to quantify the three processes in the study areas. They are reasonable, effective, and representative for the specific hydraulic/hydrologic setting of these flat lowlying areas.

Conservative assumptions and a simple rationale on the behavior of the subsurface flow are used (e.g., the change of the water level in a drainage canal equally affect the depth to water table in the drained unit). This implies that the conceptual models , which were used to investigate if the three identified processes can cause a variation of the depth to the water table larger than the two limits (0.05 m and 0.02 m), do not require a validation phase (which is typically needed in more complex modelling approaches). Notice that also the limit values, which are selected based on the previous technical and scientific literature, are stringent. This respects the request of using the worst-case scenarios in the assessment suggested by IMG.

The analyses are carried out based on the conspicuous dataset. The majority of the used data are state-of-the-art information (reports and maps published in 2021). The need of info about the hydraulic drainage network in the mid-1970s (far back in the past when digital files lack) has required the use of some assumptions. The operative way to overcome these problems have been justified by the statement "Considering the time available for this study, we therefore assumed that ..." which are not scientifically sound. However, the review is persuaded that the use of very stringent limits concerning the variation of the depth to water table (0.05 and 0.02 m) ensures that, most likely, updated information on the hydraulic network would not change the report outcomes.

Specific assumptions are made both in the processes leading to changes of depth to groundwater level and damage mechanisms. In relation to the three pathways, the assumptions of the analysis are:

- the relative drainage canal water level change due to deep subsidence cannot exceed the maximum lowering of the subsidence bowl (process i);
- groundwater level change equals the change of the freeboard (process ii);
- uniform water level is assumed in watercourses that drain into a course between two weirs (process ii);
- freeboard change is zero in the upstream side of a weir (process ii);
- freeboard change is equal to subsidence variation with respect to the subsidence at the weir (process ii);
- the simple models develop to estimate the groundwater regional flow are based on conservative values of the hydrogeologic parameters (process iii);
- the effect of land uplift associated to Norg UGS activities is neglected. Uplift is stated to be much smaller than land subsidence occurred in the past during primary production (process i).

Concerning the damage mechanisms, the basic assumptions for the hazard calculation are the following:

- sensitivity to settlement is based on a quantification of the settlement of the land surface after 30 years when filling up 1 m of sand;
- sensitivity to clay shrinkage/swelling is related to clay thickness;
- sensitivity to peat oxidation is based on a prediction of subsidence due to peat oxidation over the period 2020-2050;
- sensitivity to wooden pile foundation is based on a map of exposure over the period 2020-2050.

To the reviewers judgement, the study assumptions are reasonable and generally valid. The assumptions are formulated to maximize the principle of preventing any underestimation of the indirect effect of deep subsidence.
Data sources available to the study are estimates of deep subsidence, historical and current information about the water system and the in-house (Deltares) knowledge about soil heterogeneity and building foundation:

- estimates of deep subsidence from TNO models;
- current location of fixed drainage level areas, polder water level, and the drainage outlet canals from National Hydrological Model;
- historical boundaries of fixed drainage level areas and water level information as of 1975 are taken from the archive of the Directorate-General for Public Works and Management;
- land elevation from AHN.

The above-mentioned sources are characterized by high relevancy and a discrete reliability.
In Section 3, the authors of **02** stated "In cases where the conclusions about the effects of deep subsidence greatly depend on this information, we would recommend verifying this information through the water boards in question. The review was unable to carry out this verification for the performance of this study." This consideration would be specifically related to the historical boundaries of fixed drainage areas and water level information dated 1975. Reviewers are not aware of additional and more precise information about this aspect, being specific (local) data not available at the international level. The reviewers agree that data, dating back 50 years ago, cannot be characterized by the same level of accuracy and reliability of recently collected information. The point is: can the uncertainty associated to this information significantly affect the report outcomes (i.e., the extension of

the sub-areas for which the hazard of indirect effect of land subsidence on building damages is negligible)?
Moreover, the whole dataset used in the analysis is not supported by uncertainty quantification. Despite these shortcomings, the review can conclude that because of the conservative assumptions adopted in the study on a) the safe limits of groundwater level change and b) the rationale behind the simplified models used to investigate the pathways, the robustness of the study outcomes is generally ensured.

The document presents a workflow and analysis performed to assess which sub-areas cannot be affected by indirect effect of deep subsidence in terms of damages to buildings. Mechanisms that potentially damage buildings have been identified at the 'polder' spatial scale. This result comprehensively answers the first request advised from IMG. The proposed methodological approach also provides a partial response to the second request. However, the application of this methodology has not been carried out at the scale of a single building ('individual case'). As stated by Deltares, this detailed application is much more challenging and requires an in-depth knowledge of soil composition (soil compressibility, peat and clay thickness), construction type (deep or shallow foundations), and local changes of depth to groundwater table. A proper procedure to be used by an expert to carry out the surveys needed at the building scale will be advised by Deltares to IMG in a separate document.

The conclusions drawn in the report are appropriately based on the methodological approach proposed and implemented in the study. Generally, methods and outcomes are clearly described in the report, including a detailed discussion on the underlying assumptions. Possibly, a couple of procedural steps could be supported with a clearer description for a better comprehension. First, the description of the model set-up for pathway related to regional groundwater flow is too concise to provide an added value to the report conclusions. Nonetheless, the review agrees with the authors that such low settlements in the areas of interest support the thesis for which indirect effects of deep subsidence due to regional groundwater flow are negligible. Second, the review suggests increasing the level of explanations for the assumptions on calculation related to process ii) ('changes to the freeboard in drainage units'). The comprehension of the final results shown in the report figures might be improved by providing 'intermediate' calculations or a sketch on a simple case.

4 Conclusions

Report **01** provides the claim that deep subsidence and heave in the Norg underground gas storage (UGS) and Groningen gas field does not lead or has not led to damages to buildings.
Outcome of the review is that, albeit potentially correct, the results and conclusions are of limited credibility.
This is due to the unknown statistical significance of the calculations of the damage indicators described in **1B** and **1C**. The studies presented in **1B** and **1C** are generally well-executed within their scope, are well informed in terms of previous studies, and do not present any obvious errors. However, there are considerable factors contributing to unknown uncertainty/confidence intervals – both in the case of modelling and InSAR data analysis – that are potentially of relevance to damage indicator inferences, given these are indirect estimates based on the studies in **1B** and **1C**. In light of these uncertainties, the resulting damage indicator calculations and conclusions thereafter, albeit potentially correct, are of limited credibility due to their unknown statistical significance.

Furthermore, the review concluded that the masonry modelling and foundation modelling do not guarantee the worst case conditions or at least have not been sufficiently justified. Therefore damages can be more severe than reported. This is mainly due to:

- Façade is modelled as relatively flexible giving relative low vulnerability to differential settlements.
- Foundations are modeled relatively stiff resulting in relative low transmission of settlements to the facades.
- Orthogonal walls to facades are taken as constraints which can actually have a beneficial effect.

Report **02** provides the claim that indirect effects of deep subsidence and heave in the Norg UGS and Groningen gas fields can be excluded as cause of damages to buildings in all but several areas. Outcome of the review is that the claim is credible and sufficiently justified.

Based on the findings of the review, it is likely that an update of the studies based on the comments given, will (locally) result in higher values for damage indicators and possibly also more stringent values of damage thresholds. Therefore, potentially increasing the inferred likelihood that deep subsidence and heave can have caused damages to buildings. However, whether these changes will be of relevant magnitude to change the conclusions made is not possible within the scope of the review and would require further investigation and most likely significant modelling, data acquisition and processing efforts.

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