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Analysing Damage from Quasi-static and Dynamic Ground Movements on Dutch Masonry Buildings via Numerical Models

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ABSTRACT

Masonry buildings in the Netherlands are especially prone to damage in the form of small cracks. This is because the masonry is unreinforced, the foundations are shallow and often also unreinforced, the bedding is composed of soft soils like peat or clay, dilation joints are missing in older or historical structures, and current loading conditions, such as earthquake vibrations, were never considered in the design of the buildings. The latter includes mining operations for salt and gas that have led to subsidence and induced seismicity. Moreover, farming policy and water management, in combination with regional subsidence, have led to varying groundwater table levels which, in turn, cause wetting and drying of sensitive soils. This process is exacerbated by more extreme seasons of precipitation and drought because of climate change, leading to swelling and compaction of the ground underneath buildings.

To understand building damage in this context, it is necessary to evaluate the combined effects of these various hazards. Their actions can be decomposed into vibrations caused by earthquakes and ground deformations. The former can be characterized by the PGV or PGA of the vibrations, and the latter by the induced curvature of the soil surface and/or by the horizontal strains at the surface because of deformations deep in the underground. Moreover, repeated earthquake events and seasonal soil subsidence or heave lead to cyclic actions.

The contribution and interaction of these loads causing progressive damage to masonry buildings have been the focus of an extensive modelling study with detailed non-linear models of the buildings and the soil. The slow soil deformations were analyzed first and served as the starting point for subsequent, repeated vibrations. For example, a horizontal strain of 0.1 mm/m caused by mining, in combination with an angular distortion of 1/2000 due to local soil compaction, can produce cracks of about 1 to 2 mm wide in a particular masonry façade. The damage is then aggravated by an earthquake vibration in the order of 5 mm/s, which is further increased by about 10% with a repeated event. The expected final damage may include multiple cracks of up to 3 mm. In this manner, the combination of all actions can lead to the establishment of conservative thresholds to prevent or limit damage to existing structures.

KEYWORDS

Deep-subsidence, Settlements, Vibrations, Numerical Modelling, Crack Damage

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INTRODUCTION

In areas where multiple subsurface activities occur, such as the Groningen region in the Netherlands, concerns about (structural) damage to buildings are becoming increasingly prominent. Activities including gas production, salt extraction, and gas storage result in both gradual ground movements and dynamic seismic vibrations. Individually, these processes may induce limited damage, but when combined, their effects can become worrisome. This cumulative impact on masonry buildings—particularly in older structures with vulnerable materials and foundations—has become a focal point for both scientific research and societal debate [5,6].

Residents of these regions, especially in Groningen and parts of Drenthe, report damages such as cracking, wall deformations, and progressive deterioration of structures. Often, these damages are difficult to trace to a single cause due to the complex nature of stacked effects. While subsidence induces static horizontal strain and curvature in the ground, seismic vibrations caused by mining-induced earthquakes generate rapid, dynamic displacements. The interaction of these two phenomena may exacerbate existing damage or initiate new cracks, particularly in unreinforced masonry walls. Moreover, structures may already exhibit existing damage related to autogenous causes.

To address these concerns, the Groningen Mining Damage Institute (IMG) and the National Mining Damage Commission (CM) have sought a deeper understanding of the mechanical processes underpinning this issue. This research, undertaken by TU Delft, aimed to quantify how combinations of soil strain (ε), curvature (β), and vibrations (PGV) contribute to building damage. The study was focused on realistic scenarios representing Groningen's buildings and soils, leveraging advanced computational methods to provide actionable insights. The goal is to develop robust tools for damage assessment and prediction, enabling better-informed decisions regarding mitigation and compensation. This paper presents a brief overview of the methodology and its main takeaways.

Mining activities induce two distinct types of ground movements: static and dynamic. Static movements occur gradually over time and manifest as ground subsidence or uplift, which causes horizontal strain (ε) and curvature (β) at the surface. These deformations are characterized by their direction and form. For example, upward curvature—known as hogging—creates tensile strain, while downward curvature—sagging—induces compressive strain. Tensile strain is generally more critical for masonry because it leads to tensile stresses that cause cracking. Boscardin and Cording [1] formulated damage thresholds associated with combinations of greenfield horizontal strain and curvatures, see Figure 1. The present study revisited these relationships with a focus on the Dutch context and on damage probability.

In contrast to quasi-static movements, dynamic movements result from seismic vibrations induced by mining-related earthquakes. These vibrations are transient but intense, their energy characterized by peak ground velocity (PGV). Even when moderate in magnitude, repeated vibrations can cause damage to buildings, especially when there is pre-existing (structural) cracking [3], which may have come from ε, β combinations.

The combination of static strain, curvature, and dynamic vibrations forms a stacked loading scenario, where damage caused by one effect can be exacerbated by another. For example, cracks initiated by static tensile strain may widen or propagate further when subjected to vibrations. This cumulative impact presents significant challenges for engineers and decision-makers tasked with predicting and mitigating damage; and, while tools to assess or predict damage from soil deformations exist in literature and guidelines, relating building damage to differential settlements or angular distortions, or even to horizontal strains, no tool evaluating the probability of damage from curvatures and strains in combination could be found. In this way, the tool presented herein will be useful in the Dutch situation.

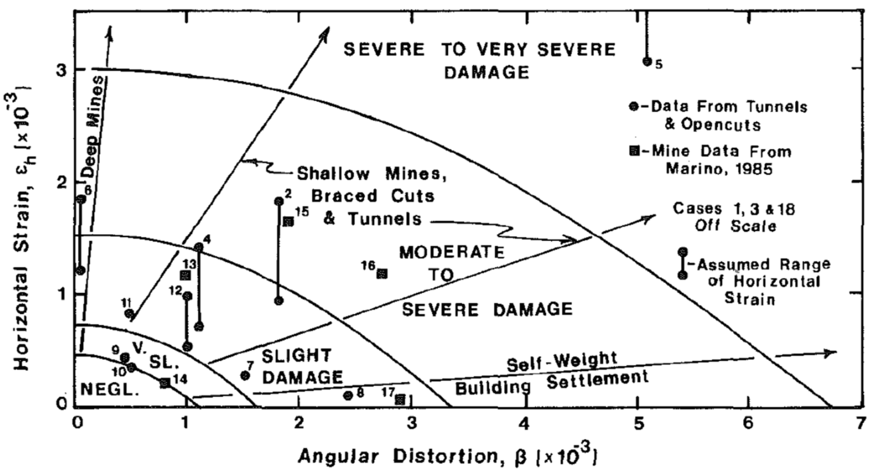

Figure 1: Diagram from Boscardin and Cording [1] with damage predictions at combinations of horizontal strain and angular distortion.

METHOD

Ground-Structure Modeling

To capture the complex interactions between ground deformations and masonry structures, the research employs 3D non-linear finite-element models, linking soil and structure interaction; see Figure 2. Unlike traditional linear models, which assume elastic material behavior, these models incorporate non-linear material properties for both ground and masonry. The models account for critical factors such as:

- Plastic Deformation in Soil: The formation of shear bands and localized plastic strains in the ground under large deformations. The small-strains hardening soil model is used in Diana FEA.
- Cracking in Masonry: Progressive damage, including crack initiation, propagation, and widening. For this, a total-strain rotating crack model is used, while comparisons are drawn against the Engineering Masonry Model [2].
- Ground-Structure Interaction: Gapping, slip, and the transfer of strain and curvature from the ground to the building are present in a soil-foundation interface based on a Mohr-Coulomb law.

The models simulate real-world scenarios where masonry walls experience combinations of static and dynamic loading. This is particularly important for Groningen, where older buildings are constructed with pre-1945 masonry on relatively weak foundations, making them susceptible to deformations.

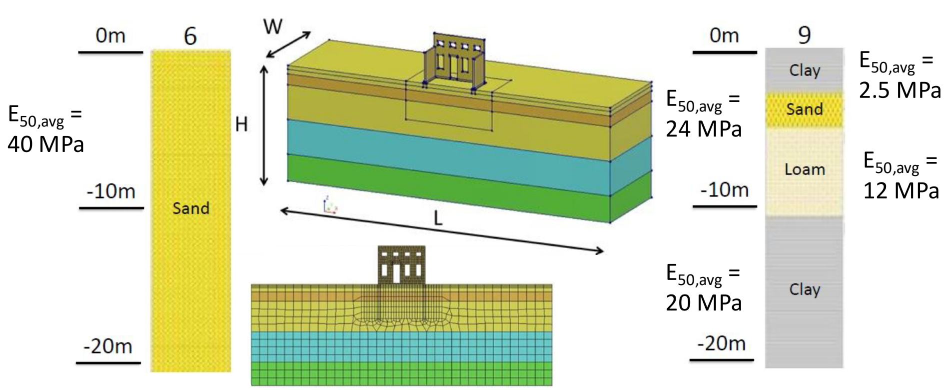

Figure 2: View of the model, symmetrical on the XZ plane, for one type of façade.

Two-Step Computational Process

The analysis follows a two-step computational approach; see Figure 3. In the first step, a ground-only model is used to calculate the boundaries required to generate free-field or greenfield ground strain and curvature under imposed static loading conditions at the location where the building would be. These deformations represent the ground's response to mining activities in the absence of any structures. In the second step, the exact boundaries which generate these greenfield deformations are applied to a coupled ground-structure model to evaluate their impact on a masonry wall. The soil model is sufficiently large that the presence of the building does not affect the boundaries of the model.

By separating the ground deformation and structure interaction phases, this approach allows for efficient exploration of different scenarios. Additionally, the two-step method aligns with geotechnical engineering practices, where greenfield deformations are often used as inputs for structural damage models. In this manner, a relationship between greenfield and building damage is established as in Figure 1 [1].

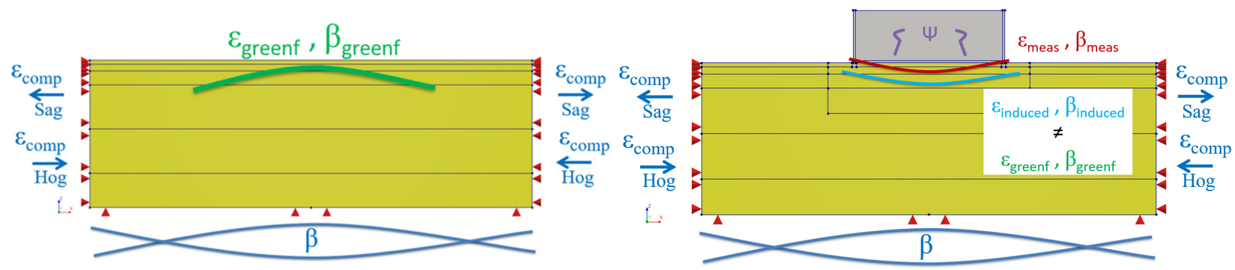

Figure 3: Two-step model: left, only greenfield, and right, soil+building.

Model Variations and Simulations

A wide range of loading and structural conditions to ensure comprehensive results were varied in the study. The key variables include:

- 22 Loading Scenarios: Combinations of pure strain, pure curvature (hogging and sagging), and mixed strain-curvature paths (see diagonal lines in Figure 1).
- Ground Types: Stiff sand and soft clay/peat profiles, representing the extremes of soil stiffness in Groningen (see profiles in Figure 2).
- Masonry Properties: Weak, average, and strong masonry to account for material variability.
- Wall Geometries: 26 façade types with varying lengths, heights, and opening configurations; see Figure 4.

This extensive set of simulations—over 3400 analyses—captures relationships between soil properties, structural characteristics, and loading conditions.

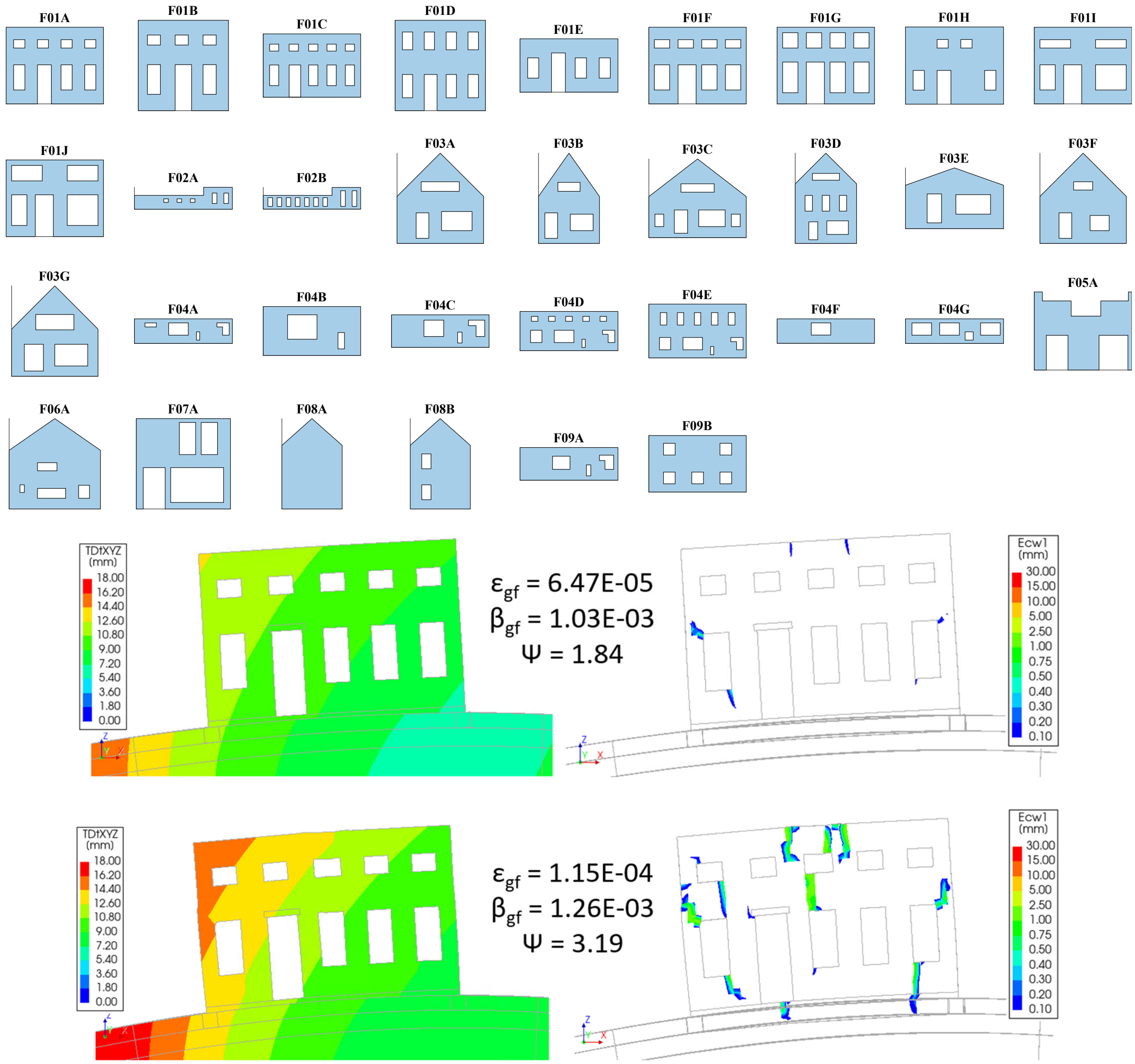

Figure 4: Variations of façade geometries and deformation of façade F01C subjected to strain/curvature and its measured damage.

Damage Metric (Ψ)

To quantify damage objectively, the Ψ-damage metric, a scalar index that combines crack width, crack length, and the number of cracks into a single value [7] was used. Unlike traditional damage classifications, which rely on subjective thresholds, the Ψ metric provides a continuous and consistent measure of damage severity which can be automatically determined for each model throughout the analyses; see Figure 4. A Ψ value of 1.0 corresponds to barely visible cracks, while higher values indicate more severe damage. This metric enables direct comparisons between different scenarios and can be automatically extracted from the models.

Key Findings and Insights

Damage Due to Strain and Curvature

The simulations reveal clear trends in how masonry structures respond to static ground deformations. Hogging profiles, which induce tensile strain, are significantly more damaging than sagging profiles, which cause compression; see Figure 5. Cracks in masonry walls initiate at lower strain levels under hogging conditions and propagate more extensively as deformation increases. This result highlights the importance of horizontal ground strains as a critical parameter for damage initiation.

The geometry of the wall also plays a significant role in determining damage severity. Longer walls and walls with larger height-to-length ratios are more vulnerable because they are less stiff and more prone to deformation; see Figure 6. Additionally, the presence of openings—such as windows and doors—intensifies stress concentrations near the corners, accelerating crack formation.

Soil stiffness further influences the extent of damage. In soft soils, such as clay and peat, the transfer of ground strain to the building is significantly reduced compared to stiff sand. As a result, buildings on soft soils experience less damage under the same loading conditions. This finding underscores the importance of considering ground-structure interaction in damage assessments.

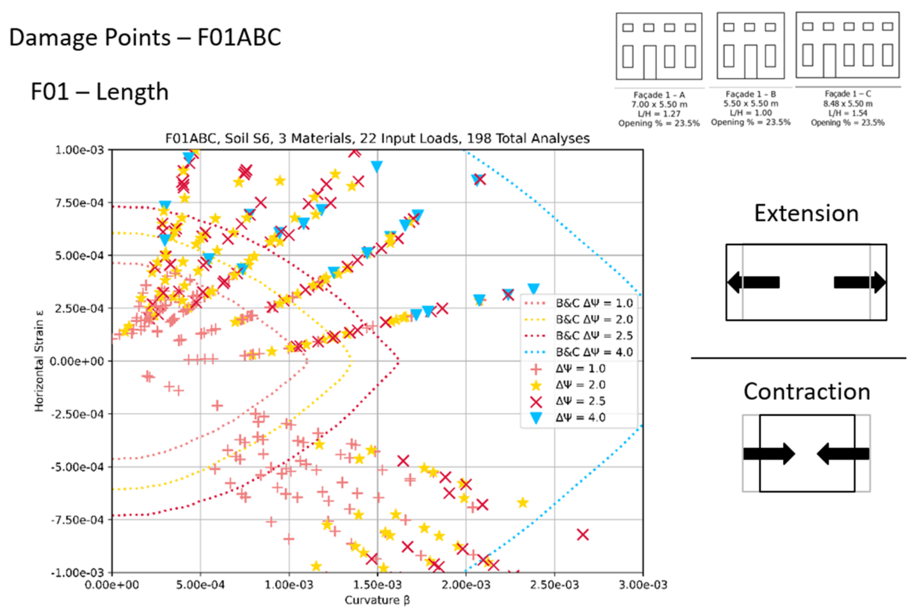

Figure 5: Damage intensity due to ε (vertical axis) and β (horizontal axis) for three example façades (F01 A, B and C), depicted top right.

Figure 6: Example cracking patterns and automatic Ψ for two façades.

Updated Boscardin & Cording Framework

The results were used to update the well-known Boscardin & Cording damage chart, which relates strain and curvature to damage levels. The original chart does not distinguish between hogging and sagging effects, but the current study demonstrates that this distinction is critical. The updated framework introduces separate curves for hogging and sagging, reflecting the greater vulnerability of masonry walls to tensile strain.

Probabilistic Analysis and Iso-Contours

Building on the deterministic results, a probabilistic analysis, to account for variability in input parameters, was performed. By weighting the results according to realistic distributions of soil properties, masonry strength, and wall geometries, iso-contour plots were developed to represent the expected damage level (Ψ) as a function of strain and curvature; see Figure 7.

These surfaces highlight the distinction between hogging and sagging effects and provide confidence in the updated framework. Notably, the results align well with Eurocode limits for angular distortion (β=1/2000 to 1/300), which provides further validation to the approach in the study. For instance, Eurocode limits of angular distortion for light damage align closely with the damage thresholds identified for Ψ values around 1.0 and 2.5. Other contours, showing the probability of exceeding specific damage thresholds could also be generated but are not included here due to brevity.

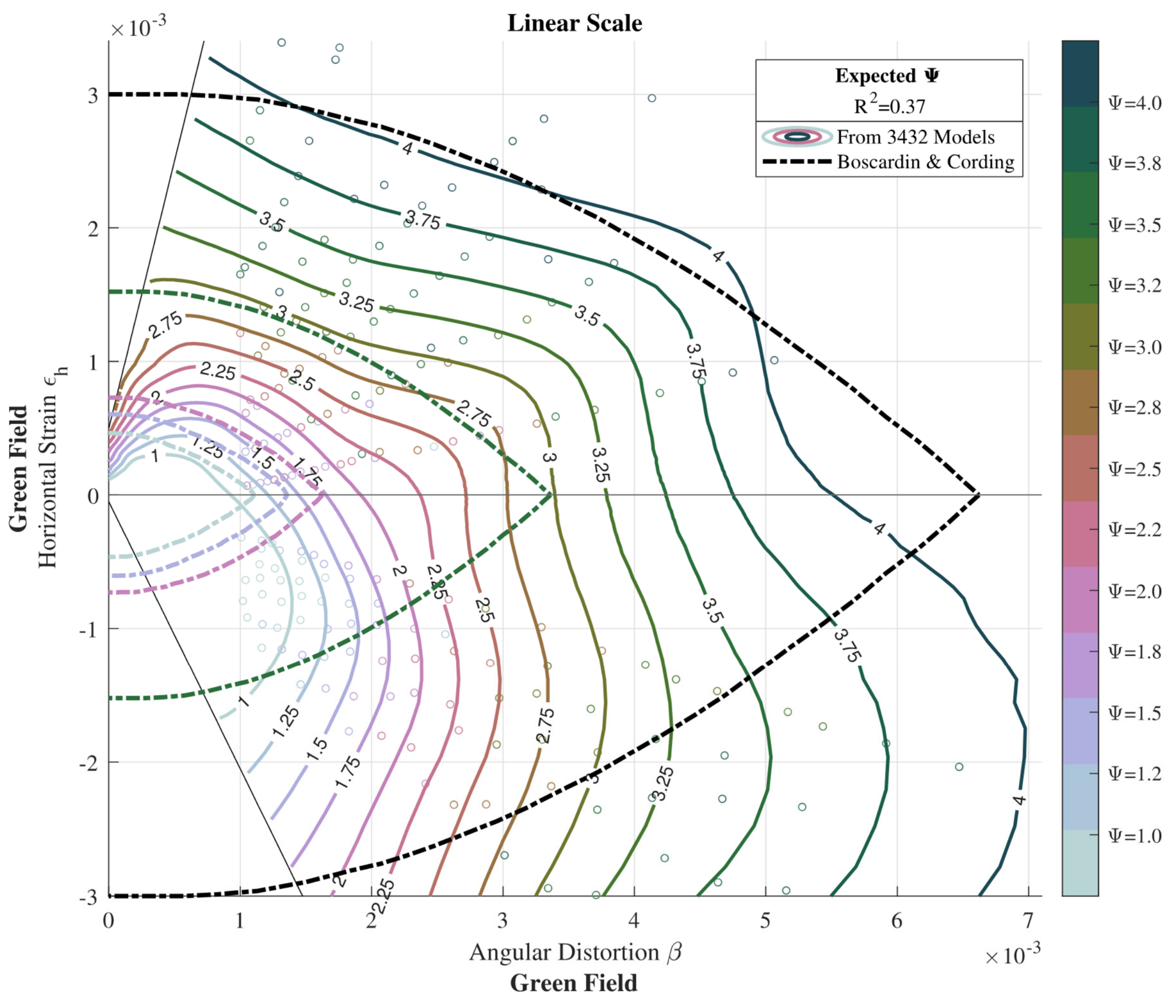

Figure 7. Iso-Ψ contours showing the expected value of Ψ at combinations of ε and β.

The iso-contour plots also reveal how damage probabilities change with increasing strain and curvature. For hogging scenarios, even small tensile strains can initiate damage, whereas sagging profiles demonstrate greater tolerance due to the compressive strains. The probabilistic analysis further confirms that soft soils reduce the transfer of ground deformations to buildings, providing a natural mitigation mechanism [8]. These findings are crucial for decision-makers tasked with assessing damage risks and prioritizing mitigation measures.

While the revised curves show slightly more conservative thresholds for damage initiation under hogging conditions, they also indicate greater tolerance for moderate to severe damage compared to the original chart for the case of Dutch unreinforced masonry buildings.

Dynamic Amplification of Damage

To assess the impact of seismic vibrations on pre-damaged structures, non-linear time history analyses (NLTHA) were conducted; see Figure 8. These simulations revealed that at low PGV levels—up to 4 mm/s—the additional damage caused by vibrations is minimal, even in walls with pre-existing cracks. In most cases, the increase in the Ψ-damage index (ΔΨ) remains below 0.2, which corresponds to just visible changes. However, as PGV levels increase to 8–16 mm/s, the amplification of damage becomes significant, particularly in walls already weakened by hogging-induced tensile strain. At these levels, ΔΨ values of 2.0 or higher are observed, indicating visible cracks that affect repairability.

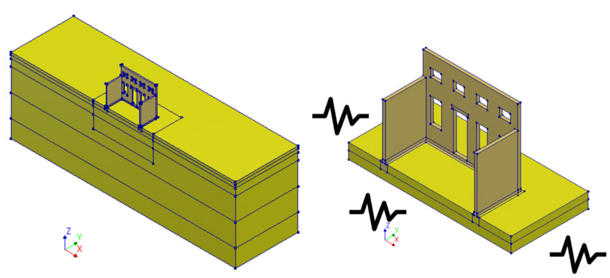

Figure 8. Model simplification for NLTH Analyses.

The effect of repeated vibrations, using a power-law approximation validated against experimental data [4], was explored. Results suggest that repeated seismic events increase damage incrementally by approximately 10–20%. The rate of progression depends on the intensity and sequence of the vibrations, with lower-intensity events causing less additional damage.

Combined Effects of Static Deformations and Seismic Vibrations

The cumulative effects of static ground deformations and seismic vibrations were explored to understand how vibrations amplify pre-existing damage. In the limited number of simulations, buildings subjected to strain and curvature first developed a baseline damage level, represented as Ψ_0. Subsequently, seismic vibrations were imposed to evaluate the incremental damage (ΔΨ). Models with similar value of damage but caused by different combinations of strain and curvature were subjected to identical earthquake vibrations of increasing intensity. Figure 9 shows the results. The graph shows that the increase in damage can be approximated using a power law. Moreover, most of the damage increase is captured by a 95% confidence margin of about 10% of Ψ, suggesting that the cause of the damage has little but not insignificant importance. Because of the expense of the models, only 270 cases were analysed.

Indeed, the fact that the origin of Ψ_0, be it from pure horizontal strain, pure curvature, or anything in between, did not lead to a strong variation for $\Delta\Psi$, is a useful observation. It means that existing fragility curves for earthquake vibrations, which consider an initial value of Ψ_0, can be directly applied considering a small uncertainty value [3]. Nevertheless, additional insight into the effect of the initial cause on further aggravation of damage is still required. Causes other than strain/curvature combinations, such as temperature or shrinkage effects, should be explored.

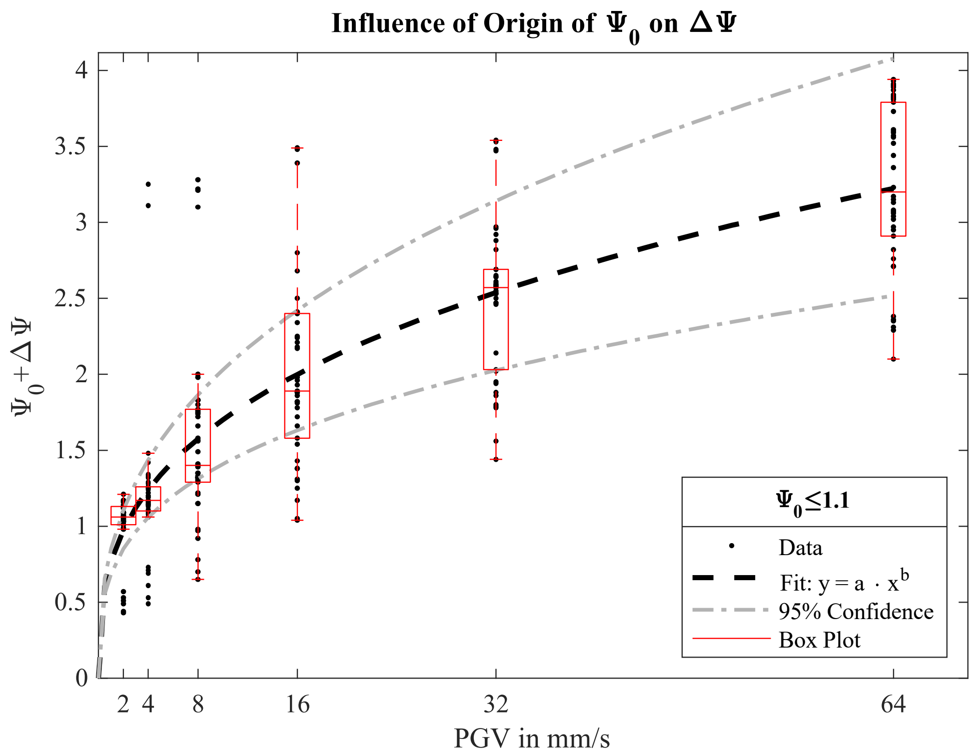

Figure 9. Increase in damage ($\Delta\Psi$) due to vibrations for various initial values of damage.

Limitations and Future Directions

While this study represents a significant advancement in understanding mining-induced damage, certain limitations remain. The analysis focused primarily on masonry walls, and further research is needed to extend the findings to complete buildings. Multi-wall systems, connections, and roof-structure interactions may introduce additional complexities that require investigation. Cyclic effects can benefit from a more robust material model such as the EMM [2].

Additionally, only two extreme soil profiles—stiff sand and soft clay/peat—were considered. Although these profiles provide valuable insights, intermediate soil conditions may exhibit different behaviors. Future studies should explore a broader range of soil types to refine predictions of strain transfer and damage severity.

Proportional loading paths in the strain-curvature space, where strain and curvature were scaled simultaneously, were used in this study. In reality, non-proportional loading scenarios—where strain and curvature evolve at different rates—may occur, particularly in complex subsurface conditions. Similarly, deformations are applied on a plane parallel to the main façade, 3D deformations could lead to differing damage intensity.

Furthermore, quasi-static deformations on buildings occurring over a long-time span could be adopted by the structure without causing cracks. This time-dependent phenomenon, called creep, has not been considered in the models and requires further study.

Despite these limitations, a strong foundation for future research is provided with this study. Key recommendations include extending the models to full buildings, incorporating additional soil profiles, and validating predictions through in-situ measurements and manipulative testing. Such efforts will further improve our understanding of ground-structure interactions and support the development of practical guidelines for damage assessment and mitigation.

CONCLUSIONS

This study provides a comprehensive understanding of the potential effects of mining-induced ground movements on masonry structures, focusing on a tool or instrumentarium to analyse the combined impact of strain, curvature, and seismic vibrations. By leveraging advanced non-linear 3D finite-element models, the research quantifies damage initiation and progression under realistic scenarios representative of Groningen's conditions.

The key findings can be summarized as follows:

- Static Ground Movements:
  - Hogging (tensile strain) is significantly more damaging than sagging (compressive strain).
  - Longer walls, walls with openings, and weak masonry are particularly vulnerable to tensile strain.
- Dynamic Amplification:
  - Seismic vibrations at PGVs up to 4 mm/s have minimal impact on pre-existing damage.
  - At PGVs of 8–16 mm/s, vibrations significantly amplify damage, particularly in walls weakened by tensile strain.
  - Repeated vibrations increase damage incrementally, with slower progression for lower-intensity events.
  - The small influence of the cause of pre-damage allows use of existing fragility curves.
- Ground-Structure Interaction:
  - Soft soils reduce strain transfer to buildings, mitigating damage severity.
  - A distinction between hogging and sagging effects has been incorporated into the updated Boscardin & Cording framework, enhancing its accuracy as a predictive tool.
- Ψ-Damage Metric:
  - The Ψ metric offers an objective and continuous measure of damage severity, combining crack width, length, and number into a single index.

By refining existing frameworks and employing coupled modeling techniques, the research equips decision-makers with practical tools for predicting damage and informing mitigation strategies. Moving forward, continued efforts to validate these models through in-situ measurements and manipulative testing will be essential for further improving reliability and acceptance.

As subsurface activities expand to include energy transition technologies—such as deep geothermal systems and underground storage—the methods and findings developed in this study will play a critical role in safeguarding structural integrity and addressing societal concerns.

ACKNOWLEDGEMENTS

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