Extracted from

# International Masonry Conference 2026

## State of the Art in Masonry Research

Proceedings of the
11th International Masonry Conference (IMC 2026), Lübeck, Germany,
12–15 July 2026

Edited by Birger Gigla, Miklós Molnár and Nigel Shrive

Published by
The International Masonry Society
c/o Lucideon Limited – Stone Business Park, Brooms Road, Stone, Staffs, ST15 0SH

Link to the full conference proceedings

Fraunhofer IRB Verlag

# 3D Nonlinear Coupled Models for Unreinforced Masonry Buildings under Differential Settlement Induced by Groundwater Lowering

*Alfonso Prosperi, Michele Longo, Paul A. Korswagen, Jan G. Rots*

**Keywords:** settlements, coupled model, unreinforced masonry structures, damage, groundwater lowering

Seasonal changes, climate, and human activities can cause groundwater fluctuations, leading to differential settlements. Unreinforced masonry (URM) buildings are vulnerable to differential settlements due to low tensile strength and quasi-brittle behaviour. Damage prediction requires a better understanding of the interaction between structure, foundation, soil, and settlement causes. While previous studies focused on tunnelling or excavation, this study examines damage from progressive groundwater lowering using non-linear finite element (NLFE) modelling in DIANA FEA.

The analysis employs a two-step approach. First, a 3D ground-only model is used to calculate the free-field (or "greenfield") horizontal strain $\varepsilon_h$ and angular distortion β, well-established metrics in previous tunnelling, excavation, and mining studies, under an imposed groundwater lowering scenario (Figure 1a). This step establishes a baseline to assess how the presence of the building alters the greenfield $\varepsilon_h$ and β through soil-structure interaction. Then, a 3D coupled model incorporating the URM building and its shallow foundation is used to evaluate the effects on displacements and damage (Figure 1b). The selected building is a farmhouse with double-wythe clay brick walls, as in [1]. The analysed façade is 17.0 m long, with heights ranging from 2.4 m to 3.8 m. Assuming symmetry in the direction of the transversal walls, only half of the building and soil are modelled. The structure, on a URM foundation 0.7 m high and 0.5 m wide, rests on a compressible 6.0 m clay layer overlying sand down to about 15.0 m depth, reflecting typical soil conditions in the northern Netherlands. The initial groundwater table lies 1.1 m below the surface. The groundwater drawdown represents the uneven lowering of the originally horizontal water table. In the coupled model, after initializing stresses in the soil and structure caused by the building's self-weight and the roof overburden, the groundwater table is varied linearly beneath the building footprint: while it remains unchanged at a depth of -1.1 m on one side of the building, it is progressively lowered on the opposite side in 0.1 m increments, reaching a final depth of -3.2 m. The same groundwater lowering scenario is also applied to the ground-only model. The non-linear behaviour of the soil, soil-structure interaction, and the masonry material is modelled as follows: i) The small-strains hardening soil model is used for both the soil strata; ii) The soil-structure interaction is modelled considering gapping, slippage, and the transfer of strain and distortion from the ground to the structure using a Mohr-Coulomb interface; iii) Masonry is modelled with a continuum macro-model incorporating smeared cracking (Total Strain Rotating Crack Model), which allows for the simulation of crack initiation and propagation. The scalar index Ψ quantifies damage by combining crack width, length, and number on the whole façade [2].

Even in the absence of the structure, at the end of the analysis, the ground-only model exhibits greenfield values of $\varepsilon_h$ and β equal to $4.6*10^{-5}$ and 1/4175, respectively. The 3D coupled model highlights how the weight of the structure amplifies both the vertical and horizontal displacements obtained from the ground-only model. The structural model exhibits a damage parameter Ψ equal to 1.8 after the application of self-weight and overburden (hence, called $\Psi_G$), corresponding to light damage cracks just less than 1 mm wide. The crack pattern, starting at the wall top in the building's mid-section, progressively extends downward along the façade and into the foundation as the groundwater level decreases (Figure 1c). At the end of the analysis, the structure exhibits a final $\Psi_{Tot}$ value equal to 3.8 (damage increase $\Delta\Psi_{\varepsilon+\beta}$ equal to 2.0), with cracks up to 5 mm wide. The results indicate that $\varepsilon_h$ and β may also result from settlement unrelated to tunnelling, mining, or excavation. A comparison is presented in Figure 1c with the chart from [3], which correlates greenfield $\varepsilon_h$ and β values with contour plots of damage levels. While the chart-based prediction suggests that the building would not experience significant damage (negligible area), the 3D coupled model indicates slight damage ($\Psi_{Tot}$ = 3.8 and $\Delta\Psi_{\varepsilon+\beta}$ = 2.0). This discrepancy between the chart-based prediction and the damage from the NLFE model arises because the model exhibits deformations and damage due to the asymmetric gravity loads of the façade and the compressible soil stratum, even before the application of the groundwater lowering. The initial damage $\Psi_G$ makes the building more

https://doi.org/10.60628/9783738810400-693

vulnerable, which in the model leads to large and rapid damage aggravation induced by the groundwater lowering. These findings suggest caution against uncritically applying results from studies focused on tunnelling, mining, or deep excavations to other subsidence causes.

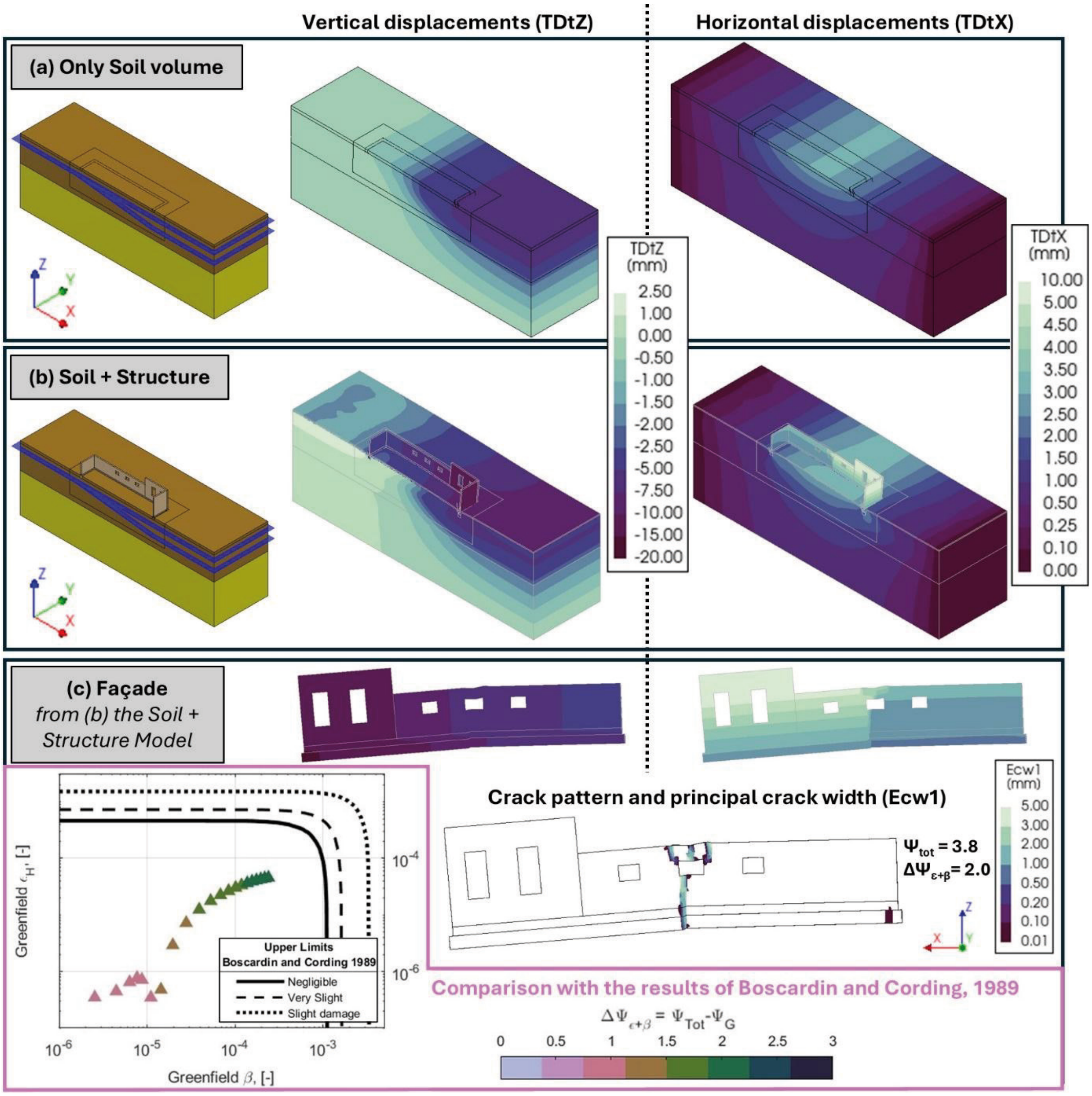


Figure 1: The results of the 3D NLFE models and the comparison with the chart proposed by [3]. Axes in (c) in a logarithmic scale. Damage levels: $\Psi = 1$ (negligible), $\Psi = 2$ (very slight), $\Psi = 3$ (slight). $\Psi_{Tot}$ is the total damage, $\Psi_G$ the initial damage due to gravity loads, and $\Delta\Psi_{\varepsilon+\beta}$ the damage aggravation due to the groundwater lowering.

[1] Korswagen, P.A., M. Longo, and J.G. Rots (2024), Research into the combined effects of soil strains, soil curvatures and earthquake vibrations from multiple mining activities on damage in masonry. Report Number 01, Final (v08), September 13, 2024. *https://www.schadedoormijnbouw.nl/media/1dvjkqum/tudelft-onderzoek-gecombineerde-mijnbouwactiviteiten.pdf*

[2] Korswagen P.A., Rots J.G. (2020). Monitoring and quantifying crack-based light damage in masonry walls with Digital Image Correlation. 1st International Conference on Structural Damage Modelling and Assessment (SDMA), Gent, Belgium 2020.

[3] Boscardin, M.D. and E.J. Cording, Building Response to Excavation-Induced Settlement. Journal of Geotechnical Engineering-Asce, 1989. 115(1): p. 1-21.