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Aspects To Consider When Modelling the Response of Masonry Façades to Ground Movements

Lessons From A Few Studies

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Abstract: In the Netherlands, quasi-static soil movements from subsidence/consolidation are a major cause of differential settlements and crack damage in masonry façades and buildings. Recent studies have clarified where modelling gives reliable insight and where it misleads. The paper presents these insights as a checklist. Key aspects include façade geometry and its effect on crack patterns and deformation transfer, the distinction between greenfield and building deformations, explicit representation of soil–foundation–façade interaction, small-strain soil stiffness and progressive nonlinearity, masonry cracking and stiffness loss, and the role of initial damage and foundation behaviour. Systematic variations are needed to quantify uncertainty.

Keywords: Masonry façades, ground movement, numerical modelling, soil-structure interaction, cracks, damage.

1 Introduction

Quasi-static ground movements are a common cause of serviceability damage in masonry façades. In the Netherlands, shallow drivers such as groundwater-related consolidation and peat–clay behaviour are dominant, whereas in other contexts long-wavelength subsidence, excavations and tunnelling may govern the deformation field [4, 12]. Regardless of origin, damage is controlled less by settlement magnitude than by angular distortion β and horizontal strain ε, and the ability of the soil–foundation system to transmit or attenuate these (see Fig. 1).

Recent research has shown that modelling can mislead when greenfield deformations are directly imposed on the building, or when soil and masonry stiffness is

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treated as fixed. The key aim is to obtain a realistic response (neither systematically conservative nor optimistic) by representing (i) deformation transfer through soil-structure interaction (SSI), (ii) small-strain soil stiffness and its nonlinearity, and (iii) stiffness loss of masonry and foundations as damage develops. This paper summarises four modelling campaigns and gathers the main lessons in a concise overview.

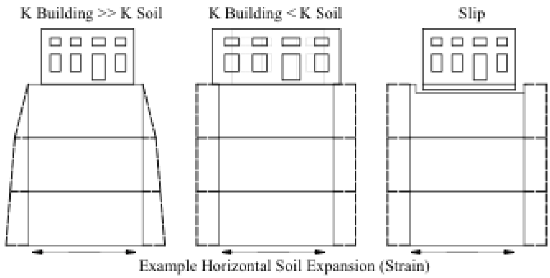

Fig. 1 Effect of soil–structure interaction due to soil and structural stiffness (K) for horizontal-strain deformations originating from underneath a shallow soil block.

2 Reference studies

This section briefly describes four studies that underpin the checklist in Section 3, focusing on what each study contributed to modelling choices and why the adopted approach was appropriate.

2.1 Prescribed-movement model checks

This campaign used “controlled-input” nonlinear analyses to understand how masonry façades respond when horizontal ground strain from deep mining is a primary driver of demand. Nonlinear finite-element façade models with smeared cracking were subjected to prescribed base movements consistent with extension/compression actions representative of deep subsidence; see Fig. 2 [25]. Demand was tracked in terms of ε and crack development, quantified with a crack-based damage measure (Ψ). The programme was structured as a sensitivity study: alternative masonry parameter sets, façade typologies (including openings), and assumptions on strain transfer (from the recommended 30% up to 100%) were compared. The predicted damage state may change by more than one class under the same nominal greenfield ε depending on transfer assumptions, making these a first-order uncertainty.

The main lesson is that horizontal-strain dominated checks are a fast way to isolate the structural side of the problem before adding soil-modelling uncertainty. They also clarify why initial condition matters: once cracking has reduced stiffness, the façade admits a larger fraction of the imposed ε, so transfer factors inferred from elastic assumptions can become non-conservative for already-cracked stock [25]. These findings motivate the emphasis on explicit SSI filtering and sensitivity bands in subsequent studies (Sections 2.2 and 2.4).

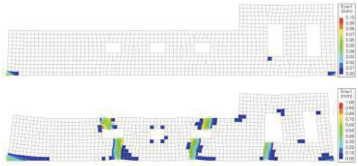

Fig. 2 A FEM-model of a long masonry façade subjected to extension at the foundation and showing smeared cracking (Ecw1).

2.2 Curvature with interface SSI

This campaign focused on curvature-dominated settlement cases, asking how much of a nominal curvature demand is actually experienced by the façade once soil–foundation–façade interaction develops [5,6, 8, 20]. Instead of enforcing a deformation profile directly, curvature demand was introduced through a calibrated interface idealisation representing near-foundation soil compliance and loss-of-support mechanisms. This enabled a systematic distinction between an applied ("greenfield-like") angular distortion βA and the measured distortion βM, with the ratio βM/βA emerging from the interaction rather than being assumed [14]; see Fig. 3. The interface allowed gapping/sliding tendencies essential for realistic crack localisation at the base [9–11].

The main outcome is that "applied curvature" is not a reliable proxy for "experienced curvature". The same imposed settlement shape can produce markedly different βM, and thus different cracking and Ψ-based damage levels, even when βA is constant [14, 15]. This makes an explicit transfer mechanism crucial for assessment-grade modelling and provides a practical middle ground between prescribed-profile checks (Section 2.1) and fully coupled soil-block analyses (2.4).

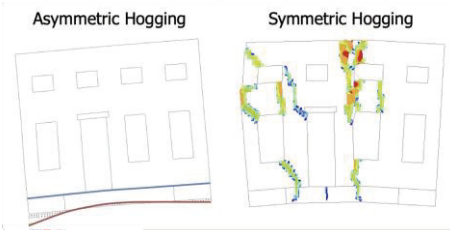

Fig. 3 Model of a façade subjected to, left, hogging but without damage due to the applied distortion (red line below) being attenuated by the interface, and right, smeared cracks due to the application of a more intense symmetric hogging shape.

2.3 Curvature sensitivity

This study concentrates on aspects easily overshadowed when the focus is on deformation transfer: façade geometry, crack localisation, and the difference between 2D and 3D idealisations. Using curvature-dominated settlement cases, a structured set of façade configurations was analysed to show how opening layout, pier/slenderness and restraint can shift the governing mechanism and crack pattern even for similar nominal β [1, 9–11], framing geometry as a first-order source of scatter in curvature–damage relationships [23]. By comparing 2D façade and 3D building modelling strategies, the work highlighted when simplified idealisations are adequate and when 3D restraint effects become decisive [22], and documented sensitivity to modelling details that influence localisation and crack-width predictions [18, 19, 24]; see Fig. 4. The main takeaway is that curvature analyses should be accompanied by systematic variations in geometry and boundary/contact idealisations, and, when restraint is uncertain, at least a targeted 3D check to avoid drawing conclusions from an overly idealised model [22, 23].

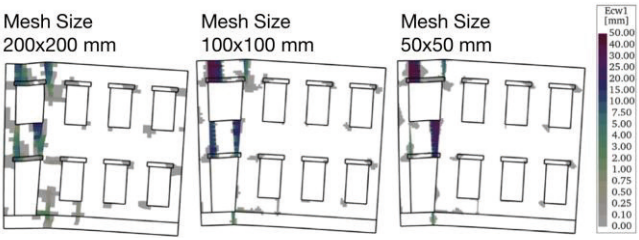

Fig. 4 Nominally identical models at the same loading stage differing only in mesh size.

2.4 Strain+curvature SSI

These studies provide the main reference for representing deformation transfer explicitly and capturing the combined effects of horizontal strain ε and angular distortion β. The work adopted an ε–β framework and constructed a workflow that links greenfield deformation descriptors to façade-level demand and damage through SSI.

A key methodological feature is a two-tier approach. In Tier 1, a soil model realises controlled "greenfield" deformation states at the building location in terms of target (εGF, βGF) combinations. In Tier 2, the façade and foundation are placed in a soil domain (see Fig. 5) so that the deformation conveyed to the structure arises from equilibrium and compatibility, rather than being imposed [16, 17]. This separation makes the SSI filter quantifiable as the difference between greenfield and measured deformation at the building [5, 8].

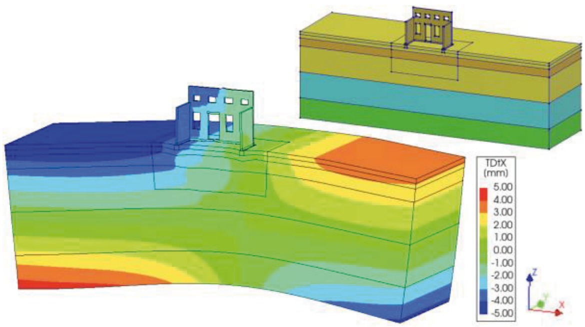

Fig. 5 Model of a façade including transversal walls with foundations embedded in a shallow soil block with multiple layers. Below, horizontal displacement of a hogging profile with the deformed picture magnified 200 times.

The soil was modelled with constitutive formulations capturing high small-strain stiffness and progressive nonlinearity. Masonry was modelled as nonlinear so that cracking and stiffness loss feed back into transfer; in many cases, horizontal strain transfer substantially exceeds 30%. Foundations were represented explicitly, and soil–foundation contact was modelled so that gapping and frictional slip can develop. The studies were executed as a large parametric analysis over soil profiles, façade geometries, foundations, material properties, and 3D effects, providing the strongest evidence base for the checklist in Section 3.

3 Modelling aspects governing settlement response

The aspects that repeatedly governed whether settlement models produced realistic predictions of deformation demand and cracking are summarised in Tab. 1. The common thread is that façade damage is controlled by the interaction between (i) the deformation field imposed by the hazard, (ii) how that deformation is filtered by soil–foundation–structure interaction, and (iii) how the structural stiffness evolves as cracks develop. The following discussion expands the table into practical modelling guidelines.

Tab. 1: Overview of selected aspects and reasoning.

Aspect	Reason
Hazard type	Sets ε–β shape/wavelength.
Greenfield ≠ building	SSI filters demand.
Small-strain soil E	Controls transfer at light damage.
Early soil nonlinearity	Needed when soil drives response.
Geometry & openings	Governs stiffness and cracking.
Transverse walls	Change restraint and SSI.
Initial damage	Stiffness reduction raises transfer, affects crack development.
Masonry nonlinearity	Captures cracking/softening.
Contact/interface	Enables gapping/sliding; base cracks.
Foundation type	Reinforcement changes transfer.
Staging/sequence	Gravity/pre-damage affects stiffness and cracking.
Sensitivity study	Uncertainty is dominant.

3.1 Hazard characterisation and deformation transfer

The first modelling decision is to describe the ground movement consistently with the underlying driver. Shallow consolidation processes often introduce shorter wavelengths and stronger curvature gradients, whereas deep subsidence tends to be longer-wavelength and more strain-dominated. Demand should be characterised in terms of horizontal strain ε and angular distortion β, keeping the settlement shape/wavelength explicit rather than relying on a single scalar descriptor [4]. A recurring source of bias is to treat greenfield deformation as the deformation experienced by the façade. In reality, the building and its foundation modify the deformation field; the experienced ε and β depend on relative stiffness, contact conditions and constraint. Deformation profiles should not be imposed directly on the façade; instead, the deformation should be introduced through a mechanism that allows the structure to find its compatible deformation state (e.g., soil domain, interface, or calibrated transfer model), so that the SSI "filter" emerges rather than being assumed [1]. Prescribed-profile analyses can still serve as controlled checks, provided they are paired with sensitivity bounds.

3.2 Soil, foundation and structural modelling

Light-damage settlement problems often operate at very small strains, where soil stiffness can be significantly higher than values derived for larger-strain problems. If this high small-strain stiffness is not represented, the model may systematically mispredict the deformation transmitted into the foundation–façade system [13]. As demand increases, strain-dependent stiffness decay can change both the magnitude and shape of the transmitted deformation; nonlinear soil modelling then becomes part of representing the governing transfer mechanism.

Façade geometry controls stiffness distribution and tensile concentrations, directly governing crack localisation. Openings and pier/lintel proportions can shift the mechanism from global bending to localised cracking, even under similar ε–β demand; opening layouts should not be treated as cosmetic detail [21]. Transverse walls further modify both façade flexibility and SSI response; where full 3D modelling is not feasible, restraint from perpendicular walls should still be represented explicitly. Foundation typology and contact mechanics strongly influence how curvature and strain reach the superstructure. The potential for gapping/sliding at the soil–foundation interface can dominate transmitted β and ε, particularly for curvature-driven cases [12]. If foundations are idealised as rigid or purely elastic, the model can enforce a transfer assumption not supported by the system.

Nonlinear masonry behaviour is central whenever the objective is to predict crack development, widths, or stiffness degradation. As cracking develops, stiffness reduces and the façade becomes more deformation-compatible, increasing transfer and altering crack localisation. Modelling with an "intact" elastic modulus can be misleading for existing stock where pre-existing cracks may have already substantially reduced stiffness. The initial condition should be treated as an input scenario with its associated uncertainty, and stiffness reduction should be explicitly explored [25, 26]. The constitutive model for masonry cracking also affects results: isotropic, total-strain-based, or orthotropic models will render substantially different crack patterns.

3.3 Sensitivity and dimensionality

In settlement problems, the most important modelling parameters interact non-linearly: soil stiffness level, settlement shape, geometry/openings, restraint, foundation nonlinearity and the damage-dependent stiffness of masonry can reinforce or counteract each other. Consequently, single "best-estimate" runs are rarely sufficient for objective conclusions. A proportional approach is to vary the parameters that control transfer and stiffness most strongly, report response bands rather than point values, and use sensitivity runs to identify which assumptions the conclusions depend on [7]. Uncertainty is thereby handled explicitly instead of being hidden inside a single set of choices.

In coupled soil–foundation–façade analyses, a first-order choice is the stress state and dimensionality. Common options (plane-strain soil with plane-stress façade ("2.5D"), or fully 3D models) are not interchangeable because they imply different confinement and stiffness, and therefore different deformation transfer and crack localisation [2, 3, 8, 22]. In the two-tier coupled soil-block approach of Section 2.4, the transfer mechanism is placed in a 3D soil domain with explicit foundations and soil–foundation contact, so deformation is transmitted through equilibrium at the foundation rather than imposed on the façade; the façade can then remain proportional (often plane stress for in-plane cracking).

4 Discussion and conclusions

The studies reviewed in this paper converge on a clear message: realistic modelling of settlement-induced façade damage depends on a small set of decisive modelling choices rather than maximum model complexity. The deformation that drives cracking is that experienced by the structure after SSI has filtered the greenfield field, and this filtering evolves as cracking reduces stiffness. Models become misleading when they bypass that mechanism, for example by imposing a settlement profile directly on the façade, using soil stiffness levels inconsistent with the small-strain regime, or assuming intact stiffness for already-cracked masonry.

Modelling should be proportional to the decision context. Prescribed-movement analyses remain valuable as controlled checks; however, once conclusions depend on deformation transfer magnitude, an explicit SSI representation is required. Soil modelling choices should match the relevant strain range, and masonry nonlinearity and stiffness loss are essential when predicting cracking. Initial damage state should be treated as a variable with explicit uncertainty bounds, and sensitivity studies should be part of the method. The present work focuses on in-plane façade response on shallow foundations under quasi-static movements; dynamic effects and mechanisms difficult to represent in 2D remain underexplored. Similarly, deep, piled foundations have not been investigated (yet).

In summary, the checklist in Table 1 provides a concise guide to what must be considered when modelling settlement response of masonry façades. The main recommendations are to (i) distinguish hazard types and deformation shapes, (ii) avoid imposing greenfield profiles directly and instead represent transfer mechanisms, (iii) model soil stiffness consistently with small-strain behaviour and include nonlinearity when relevant, (iv) represent geometry, restraint, foundations and contact explicitly, (v) account for masonry stiffness loss and initial damage, and (vi) use systematic variations to quantify uncertainty and avoid biased conclusions.

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