Subsidence-induced damage to the built environment: a new research program focusing on challenges and needs

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Introduction

Damage inflicted to the built environment as a result of anthropogenic induced subsidence is a hazard that has been reported all over the world. This primarily occurs in low-lying urbanized coastal zones such as Venice, New Orleans, and Jakarta, but has also been observed in upland urban conglomerates like Tehran and Mexico City.

In the Netherlands, subsidence induced damage is estimated to exceed over €20 billion in the coming decades (Van den Born et al., 2016). Besides damage to buildings, subsidence can compromise the integrity of critical infrastructures, such as flood protection structures, (rail)roads, pipelines, and underground cables. The built environment can be damaged by subsurface activities ranging from groundwater level management to deep resource extraction. Besides existing subsurface activities, there are multiple anticipated changes that can exacerbate subsidence-induced structural damage in the Netherlands: (i) housing shortage, forcing to build in our most subsidence prone areas; (ii) the transition to renewable energies (geothermal and Aquifer Thermal Energy Storage, ATES) which can lead to additional subsidence; (iii) the closing of the Groningen gas field, forcing gas production at other locations; and (iv) increased drinking water extraction accelerating local subsidence processes.

At present in the Netherlands, damage induced to the built environment is dealt with only after its occurrence. This leads to often unresolved issues with respect to the contribution of subsidence to the damage which has been observed. This reactive approach stems from the lack of knowledge and lack of tools to accurately assess the causal relationship between subsidence and damage. In this contribution, we present the outline and preliminary results of a new multi-disciplinary research program 'Subsidence and Building Damage' currently in progress at TNO, which aims to fill in these gaps to predict subsidence and the related damage to the built environment.

From subsidence to building damage: the Model Chain approach

The main goal of the 'Subsidence and Building Damage' research program is to establish causal relationships between the sources of subsidence and inflicted damage to the built environment. The core of the research program is to develop the know-how necessary to generate a model chain for subsidence induced damage to the built environment. The aim of this model chain is to identify per subsidence cause the probability of damage, given the type of construction and given the location. To achieve this goal a number of knowledge gaps need to be overcome, which are illustrated in Figure 1.

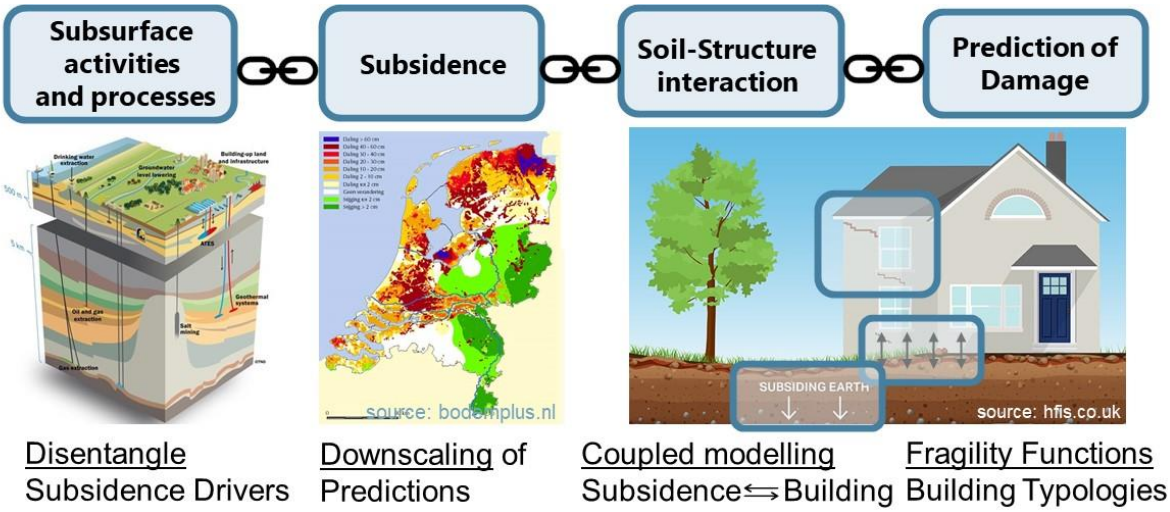

Figure 1 From subsidence to building damage prediction. The chain in the upper panel of the figure illustrates the different steps in the model chain. The lower panel indicates the knowledge gaps within each model step.

The chain of models starts with the description of the subsurface activities which form the drivers behind subsidence (Candela and Koster, 2022). Based on these drivers, probabilistic predictions of subsidence are made. The next step deals with the description of the interaction between soil and structure. Soil behavior influences the structure on top, and vice versa. Finally, the damage risks should be assessed. This is conducted by developing fragility functions for a range of selected typologies. These typologies are defined such that they properly describe the building behavior under subsidence loads and so that these are representative of a large group of buildings.

Research lines

This section delineates the key research questions to be answered within six research lines.

Research line 1: Subsidence predictions

This research line answers the research question: *How to disentangle multiple sources of subsidence and downscale our subsidence predictions to the building-scale?* Physics-based models fed by laboratory-derived constitutive equations and coupled with AI algorithms are developed to disentangle the contribution of each superposed source of subsidence and to downscale our subsidence predictions.

Research line 2: Soil Structure Interaction

This research line answers the research question: *What is the influence of soil-structure interaction on the subsidence induced damage of the built environment?* To provide answer(s) first we develop physics-based coupled models of the soil-structural interaction (finite element models). Ultimately the goal is to create accurate and computationally cheap models (i.e. surrogate models) that are used as components in the structural modelling of civil engineering assets and their damage.

Research line 3: Damage predictions

This research line answers the research question: *How to derive fragility functions that predict structural damage under subsidence?* To answer this question, we develop physics-based structural models (finite element models) fed by the subsidence predictions. The nonlinear finite element models are parametric, which allows to programmatically vary parameters and to couple them with probabilistic models that represent uncertainties in material properties, loading, dimensions, etc. Finally, we devise novel methodologies to derive fragility functions.

Research line 4: Model validation and calibration
To trust models, they must be validated against real world observations. This validation/calibration step is performed for each model component and the entire model chain as well. The main research question is: *How to satisfactorily validate a model when existing observations can be scarce and/or attached to a low signal-noise ratio and collecting new observations can be time consuming?*

A combination of diverse type of data (satellite-based such as InSAR; cone penetration tests; damage assessments by experts; etc.) coupled with adapted data assimilation procedures and conformance methodology is developed.

Research line 5: Software development
Within this research line we develop software that implements the model chain. The research question is: *How to effectively link models which describe different physical processes, and how to account for uncertainties, to allow for model calibration, to be maintainable and expandable when new knowledge is obtained?* The software should be fast enough to allow scenario studies, sensitivity studies, and probabilistic forecasts.

Research line 6: Societal impact and user involvement
This research line answers the research question*: How to increase the societal impact of the model chain and to connect it to the relevant users and their contexts*? A knowledge brokerage process is set up between potential users of the model chain and researchers who are involved in its development. AI learning capabilities to assist planning and decision making are explored. The objective is to enhance the understanding and use of the model in the selected user contexts. Finally, guidance are developed for different user groups, such as policy makers, banks, insurance companies, and house owners.

Outlook

Figure 2 illustrates the level zero model chain which enables:

(A) to provide probabilistic predictions of differential settlement at the building scale;
(B) to use (A) to estimate probabilities of damage for existing masonry buildings.

The large-scale subsidence is computed combining geological and groundwater realizations with InSAR observations. The small-scale differential subsidence is computed combining large subsidence predictions with spatial correlations of lithologies. The probability of damage is computed combining the small-scale differential subsidence with fragility curves.

Although not all uncertainties and complexities were accounted for, as until now only a single source of subsidence (phreatic groundwater level lowering) was considered, this proof-of-concept has shown its value: we are able to couple our subsurface and structural modelling capabilities with the potential to model the causal relationship between subsidence and building damage.

The success of this 'Subsidence and Building Damage' research program will be supported by the active interaction between TNO and external parties.

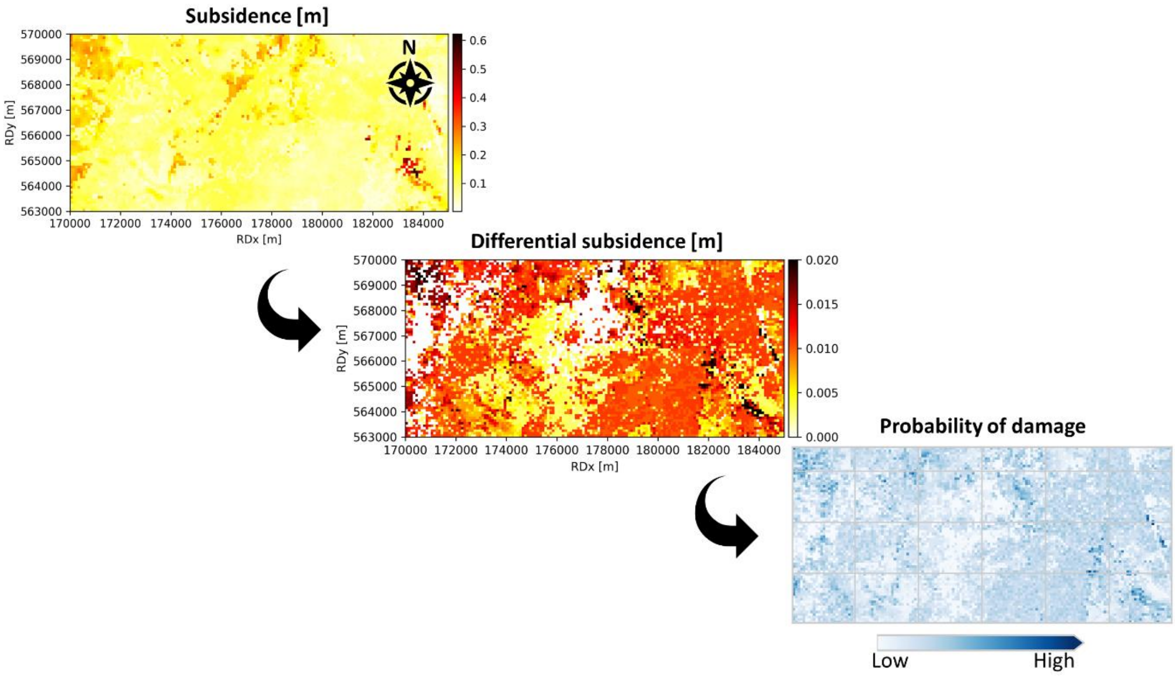

Figure 2 From large-scale subsidence to differential subsidence at the building scale to building damage prediction. These results of the level zero model chain correspond to an arbitrary area of interest in the Netherlands. The large-scale subsidence map (top) corresponds to the mean of the ensemble of multiple realizations. The small-scale differential subsidence (middle) corresponds to the P90 of the ensemble of multiple realizations.

References

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