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Citation for the original published paper (version of record):
Wikby, P., Haaf, E., Karstunen, M. (2025). Modeling subsidence and building damage in central Gothenburg using machine learning. [Source Title missing], 1: 375-378.
http://dx.doi.org/10.3850/9789819440757

Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
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doi: 10.3850/GRF-25280825_isgsr-080-P041-cd

MODELING SUBSIDENCE AND BUILDING DAMAGE IN CENTRAL GOTHENBURG USING MACHINE LEARNING

Pierre Wikby[1,*], Ezra Haaf[1], Minna Karstunen[1]

[1]*Architecture and Civil Engineering, Chalmers University of Technology, Sweden.* [*]*E-mail: pierre.wikby@chalmers.se*

Subsidence is an important consideration affecting many cities around the world. It leads to an increased risk of flooding and may cause damage to buildings and other infrastructure, especially in low-lying urban areas on soft clays. Physics-based numerical models can provide estimates of ongoing and future subsidence, caused by the combined time-dependent processes of creep and consolidation, thereby increasing our understanding of when and where deformations will arise and at what magnitude. However, such models are computationally expensive and generally not feasible at a large scale with varying stratigraphy. To address these challenges, we apply a recently developed modeling approach that uses the data from a physics-based model to train a machine learning-based metamodel for subsidence prediction and a consequent building damage model. The approach was applied to an area within City of Gothenburg, Sweden, simulating ongoing background creep subsidence over a 30-year period. The predicted subsidence is validated against observed settlement rates from interferometry (InSAR) and point-based depth-integrated measurements from a bellow-hose. The building damage is calculated on a large scale using the limiting tensile strain method. The results demonstrate that the metamodel effectively represents subsidence as a function of time and space. The areas with discrepancies in comparison to InSAR are explained by ongoing construction and the effects of relative soil-foundation stiffness.

Keywords: Subsidence, metamodeling, building damage, large-scale modeling, soft soils, creep.

1. Introduction

Subsidence affects millions of people globally through increased risk of flooding and damage to infrastructure and buildings. Subsidence often occurs in metropolitan areas situated over thick deposits of soft soils, including Mexico City (Chaussard et al. 2021), Venice, Italy (Teatini et al. 2006), Shanghai (Shen and Xu 2011), and Las Vegas (Burbey, 2002). Subsidence can be caused by natural phenomena, such as long-term creep, but most importantly by anthropogenic factors such as fluid extraction, fills and other loads applied by construction activities. Hydro-mechanical (HM) numerical models with coupled flow-stress-strain formulation can estimate subsidence, by modeling the coupled time-dependent processes of creep and consolidation. This will deepen our understanding of the timing, location, and magnitude of deformations. However, three-dimensional HM models are computationally expensive and generally impractical for large-scale applications where timely mitigation decisions are required.

To overcome this challenge, we apply two recently developed models. The first is a computationally efficient Machine Learning-based metamodel (Haaf et al. 2024). The metamodel emulates the time-dependent subsidence of the Creep-SCLAY1S model (Gras et al. 2017), developed for simulating the response of soft sensitive clays. This advanced time-dependent constitutive model is adopted for a coupled HM finite element (FE) model in Plaxis 2D. The computed subsidence at a given time of interest is used to train a metamodel with the decision tree-based ensemble learner, random forest (RF), with hydro-stratigraphic data as predictors (Haaf et al. 2024). After cross-validation and tuning, the subsidence (i.e. vertical settlements) is computed on a 3D grid (along x- and y-directions) using the metamodel over a large area with variable hydro-stratigraphy. The second model is a building damage model by Wikby et al. (2024), which is used to estimate the building damage from spatially distributed, non-Gaussian settlement data, produced by the metamodel, by employing typical 2D damage parameters on settlement profiles and comparing them with intelligible damage criteria.

The novel modelling approaches above were applied to an area in central Gothenburg, Sweden, simulating ongoing background creep settlements over 30 years. The settlements predicted by the FE model were validated against depth-integrated bellow-hose measurements, and the results of the metamodel were compared against InSAR measurements. Finally, the severity of subsidence was assessed through temporal building damage mapping in the model domain. Both settlement and damage simulations due to background creep only are presented.

2. Method

The model approach is shown in Fig. 1. The hydro-stratigraphy, i.e. local soil and bedrock layering and initial piezometric levels, was modeled for an area of 1.5x1.5 km^2 using the approaches by Sundell et al. (2016) and Sundell et al. (2019), as well as available data from boreholes and piezometric levels, respectively. The other models are described briefly in the following subsections.

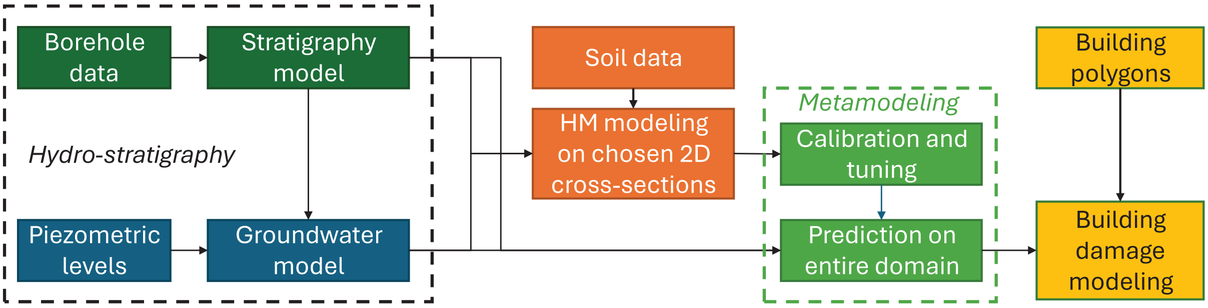

Fig. 1. Flowchart of the model approach (adopted from Wikby et al. 2024).

2.1. *2D hydro-mechanical (HM) finite element (FE) modeling on cross-sections*

This sub-section is further described in e.g. Wikby et al. (2023) and Haaf et al. (2024). HM analyses were performed using PLAXIS 2D FE software. The hydro-stratigraphy was extracted for three cross-sections, BB, DD, and FF (outlined in Fig. 2C). To represent the soft sensitive clays, an in-house implementation of the rate-dependent Creep-SCLAY1S model (Gras et al. 2017) was used. The model features e.g. non-linear recoverable and irrecoverable rate-dependent (creep) strains. It also features initial and evolving anisotropy and degradation of bonding. The latter two features are important for realistic deformation predictions in sensitive clays.

2.2. *Machine-learning-based metamodel*

A metamodel is an approximate mathematical model of the outcome that is more computationally efficient than a more detailed numerical model. For this study, the metamodel uses Random Forest (RF) as a training regression model with hydro-stratigraphic input as predictors. A cross-validation and tuning strategy is used to improve model performance and to limit metamodel under- or overfitting, the Leave-One-Cross-Section-Out (LOCSO) strategy is employed, where one of the available cross-sections is held out from model training for validation. Before model fitting, hyperparameter tuning is performed using the computationally efficient Latin hypercube grid search based on Root Mean Squared Error (RMSE) as an objective function. For more details on the metamodeling, see Haaf et al. (2024).

2.3. *Building damage model*

The building damage model was developed by Wikby et al. (2024) to assess the possible building damage by considering differential settlements. The regional settlements from the metamodel, aligned as a grid (along constant x- and y-directions, were extracted to calculate damage parameters on building-specific profiles. The buildings represented as polygons define the boundaries of those profiles (Fig. 2B). For this study, the Limiting Tensile Strain Method (LTSM), e.g. Burland et al. (1977), is used to calculate damage with max. tensile strain. The max. tensile strain was compared with parameter thresholds for four damage classes (negligible (N), very slight-slight (V), moderate (M), and severe (S) damage) according to the classification system by Burland et al. (1977). Thereafter, each building was assigned an expected damage class, visualized on maps.

3. Case study

The method was applied to buildings in three districts of Central Gothenburg, Sweden (*Haga*, *Vasastaden*, and *Inom Vallgraven*). The area consists of deposits of soft sensitive marine clay formed during and after the last Ice Age (glacial and post-glacial clay). The clay was deposited on top of glacial till, occasional glaciofluvial coarse-grained sediments (sand-gravel), and hard crystalline rock, which at the top may be heavily weathered and fractured. Due to a strongly undulating bedrock surface, clay deposits reach depths of up to 70 m in some locations, whilst at other locations the bedrock is exposed. Thus, non-uniform settlements are expected. On top of the clay deposits, there are beach deposits and fill materials. The top five meters of clay (fill) have been heavily altered, due to urbanization processes, e.g. induced loads from land reclamation and construction. Thus, both natural and anthropogenic loading situations have led to ongoing background creep settlements. Following the method of Sundell et al. (2016), the modeled stratigraphy is shown in 3D in Fig. 2A and is represented by clay thickness on the map in Fig. 2B.

Constant rate of strain (CRS) oedometer and consolidated undrained triaxial tests were performed to derive relevant model parameters for the soft clay. The tests were performed on soil samples taken from boreholes near a construction site in the center of the study area (Fig. 2B). Fig. 2D shows the apparent over-consolidation ratios, OCR (1.1-1.5) derived based on the CRS test. The results from depths greater than 30 meters indicated poor sample quality and were therefore disregarded (omitted from Fig. 2). Instead, the OCR values at those depths were calibrated through bellow-hose measurements located centrally in Fig. 2C. A bellow-hose measures depth-integrated absolute settlements similar to the extensometer. The bellow-hose method has been developed in

Sweden and is expected to give high accuracy (+/- 1 mm) at greater depths. These results were used to calibrate the OCR values at deep layers.

Fig. 2C also plots the surface vertical subsidence velocity provided by interferometric synthetic aperture radar, InSAR, (TreMAPS, 2024) measured 2023-2024. These values were used for validating the modeled subsidence in the entire model area. It should be noted that the available InSAR time series are relatively short (about 1.5 years) and generally have a low signal-to-noise ratio due to atmospheric noise and other factors. It is also likely that isostatic uplift (reported ca 3 mm/year in the Gothenburg area but not known on a local level) also adds to the uncertainty.

215 buildings with detailed inventories were identified in the model area (Fig. 2B). To estimate the tensile strains, the relative flexibility of each building had to be assumed. Based on structural information from the inventories, each building was therefore categorized as “stiff” (112 in total) or “flexible” (103).

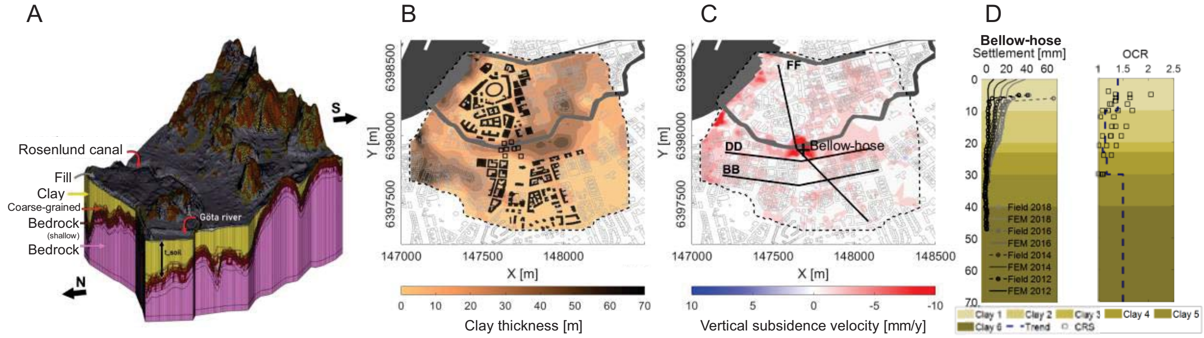

Fig. 2. A. Stratigraphy model B. The clay thickness, boreholes (open squares), and assessed buildings (black). C. Cross-sections for finite element modeling, InSAR measurements (red to blue), and the location of the bellow-hose. D. Bellow-hose measurements, simulations, and OCR (adopted from Wikby et al. 2024 and Haaf et al. 2024).

4. Application to the case study

In general, the metamodel shows acceptable to very good predictive skill on the unseen cross-sections based on the cross-validation. For the 1- and 30-year results, the predictive skill was 0.24 and 0.86, respectively, based on Pearson correlation. These values are lower than those reported by Haaf et al. (2024), most likely due to the low contrast in settlements compared to those caused by consolidation from large pore pressure drawdowns. For this scenario, the errors are mostly due to small shifts along the subsidence profile. By graphical comparison, however, the trained profiles are still similar to the unseen ones.

Fig. 3 shows the subsidence results (negative values) from 1- and 30-year simulations with the FE-fed metamodel, where the settlement range was computed as +1 to -1.5 cm and -1 to -13 cm, respectively. The results are highly correlated to the clay thickness, where the smallest magnitudes are predicted next to bedrock outcrops (see Fig. 2C). Hence, the hydro-stratigraphic information is highly relevant for large-scale subsidence simulations.

Moreover, Fig. 3 shows that the metamodel overestimates subsidence due to creep up to 5 mm/year (blue colors). This discrepancy is primarily due to the neglect of relative soil-structure stiffness from existing foundations resisting subsidence, but also due to the calibration process. The latter refers to the location of the single bellow-hose and the evaluated boreholes lacking representativeness of the entire model area. More data points with high areal coverage would improve the modeling results. Another reason for the discrepancy is the isostatic uplift, which the InSAR data has not been corrected for. This is especially seen in regions with thin soil layers, shown with white to slight blue coloring. When corrected for a value of 1mm/year, a better match at these regions was found. Nonetheless, the assessed building damage, based on differential settlements, would not be affected. In some areas, the InSAR data shows larger subsidence, explained by significant excavations and high-rise construction sites. This comparison indicates that other than the discrepancies explained by the data and ongoing projects in the study area, there is no systematic error in the metamodel. However, the results could benefit from considering soil heterogeneity in the metamodel through a probabilistic approach, see e.g. Sundell et al. (2019) and Wikby et al. (2023).

Finally, Fig. 3 shows that 143 (66%), 57 (27%), 13 (6%), and 2 (1%) buildings resulted in negligible (N), very slight-slight (V), moderate (M), and severe (S) damage, respectively, based on the classification system by Burland et al. (1977), for 30 years of creep. Meanwhile, only 1 and 214 buildings resulted in slight and negligible damage respectively for 1 year. It is worth noting that no previous damage has been considered, and thus the true damage propagation may be different. Comparison with InSAR generally shows that the subsidence calculations are conservative. Larger absolute settlements are associated with larger differential settlements, although the correlation is relatively low (see Wikby et al. 2024). Therefore, the computed tensile strains are generally overestimated, which has led to higher damage predictions. On the other hand, damage assessment through absolute settlements would result in much greater damage, which is unlikely due to uniform settlements not being related to façade cracking or tilting floors (Wikby et al. 2024).

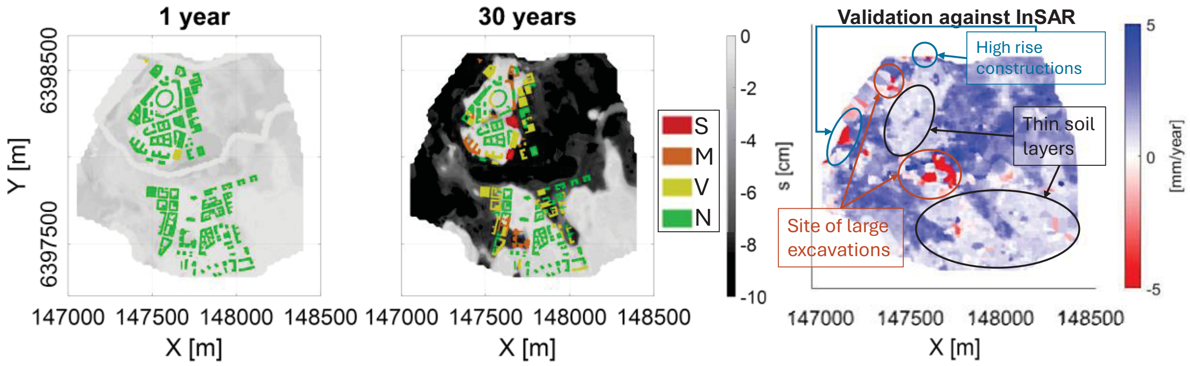

Fig. 3. Metamodel and building damage model results after 1 (left) and 30 years (middle) of background creep. The difference between the InSAR average yearly settlement rate (2023-2024) and the creep rate estimated by the metamodel as average from the 30-year simulation (right), adopted from Wikby et al. (2024) and Haaf et al. (2024). S=Severe, M=Moderate, V=Very slight-slight, N=Negligible according to Burland et al. (1977) classification system.

5. Conclusions

The following conclusions can be drawn from the study:

- A novel efficient modeling approach to calculating subsidence and consequent building damage on a large scale is applied here to time-dependent pure (background) creep scenarios in an urban setting.
- The modeled background creep is compared against InSAR data. Differences in the measured and calculated subsidence highlight the need for accurate modeling and monitoring tools to replicate, understand, and predict subsidence. Further metamodel development should account for soil heterogeneity, e.g. Sundell et al. (2019), Wikby et al. (2023).
- Modeling results suggest that severe damage to some buildings due to differential settlements will occur after 30 years, which would require either more detailed modeling and/or decision support for damage mitigation.

Acknowledgment

The research presented is financed by the Swedish Transport Administration (*Trafikverket*), grant number TRV 2020/54637. The work is done as part of the Digital Twin Cities Centre supported by Sweden's Innovation Agency VINNOVA under Grant No. 2024-03904.

References

Burbey, T. J. (2002) The influence of faults in basin-fill deposits on land subsidence, Las Vegas Valley, Nevada, USA. *Hydrogeology Journal 10*, 525-538.

Burland, J. B., Broms, B. B., & de Mello, V. F. B. (1977). Behaviour of foundations and structures. *Proc., 9th Int'l. Conf. on Soil Mech. and Found. Engr.*, 495–536.

Chaussard, E., E. Havazi, H. Fattahi, E. Cabral-Cano, and Solano-Rojas, D. (2021). Over a Century of Sinking in Mexico City: No Hope for Significant Elevation and Storage Capacity Recovery. *Journal of Geophysical Research: Solid Earth 126*, 1-18.

Gras, J. P., Sivasithamparam, N., Karstunen, M., & Dijkstra, J. (2017). Strategy for consistent model parameter calibration for soft soils using multi-objective optimisation. *Computers and Geotechnics 90*, 164–175.

Haaf, E., Wikby, P., Abed, A., Sundell, J., Mcgivney, E., & Rosén, L. (2024). A metamodel for estimating time-dependent groundwater-induced subsidence at large scales. *Engineering Geology 341*, 107705.

Shen, S.-L., Wu, H.-N., Cui, Y.-J., & Yin, Z.-Y. (2014). Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai. *Tunnelling and Underground Space Technology 40*, 309–323.

Sundell, J., Rosén, L., Norberg, T., & Haaf, E. (2016). A probabilistic approach to soil layer and bedrock-level modeling for risk assessment of groundwater drawdown induced land subsidence. *Engineering Geology 203*, 126–139.

Sundell, J., Haaf, E., Tornborg, J., & Rosén, L. (2019). Comprehensive risk assessment of groundwater drawdown induced subsidence. *Stochastic Environmental Research and Risk Assessment 33*, 427–449.

Teatini, P., Ferronato, M., Gambolati, G., & Gonella, M. (2006). Groundwater pumping and land subsidence in the Emilia-Romagna coastland, Italy: Modeling the past occurrence and the future trend. *Water Resources Research 42*, 1–19.

TreMAPS (2024). Gothenburg TSX VERT MAY 2024. *Available at: https://tremaps5.tre-altamira.com/.*

Wikby, P., Abed, A., Karlsson, M., Karstunen, M. (2023). The influence of parameter variability on subsidence. *Proceedings 10th NUMGE 2023*, 1-6.

Wikby, P., Haaf, E., Abed, A., Rosén, L., Sundell, J., & Karstunen, M. (2024). A grid-based methodology for the assessment of time-dependent building damage at large scale. *Tunnelling and Underground Space Technology 149*, 105788.