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DIGITAL TWIN-BASED REAL TIME BACK ANALYSIS OF SYSTEM BEHAVIOUR IN SUPPORTED EXCAVATIONS

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Digital twins are receiving increasing attention for geotechnical projects (e.g., for storing monitoring data, ground models) but are often limited to either digital models (digital representation of the physical asset) or digital shadows (real-time data from monitoring the physical asset). We use the term digital twin, as we present a case study of a project where a digital shadow's functionality is enhanced with real time system behaviour simulation capabilities. So far, digital twins are not commonly used for improving the design and execution of geotechnical activities (e.g., deep excavations), although commercial software exists for specific excavation problems. The case study addresses the construction of the new office for the Norwegian Geotechnical Institute in Oslo, featuring an up to 7 m deep excavation pit in marine clay ground conditions in a densely populated urban environment. The construction pit is equipped with several inclinometers, load cells and fibre-optic sensors to monitor soil and structure response at different stages of excavation. Most sensors were installed in the first half of 2023, providing continuous monitoring data since then. This paper presents a workflow for using monitoring data to continuously update the digital twin (numerical 2D/3D model), thereby enabling more realistic prediction of the system behaviour and optimizations in the design (e.g., adaption of strut forces during construction, calibrate soil parameters). The project's design phase provides the starting point of the simulation. The digital twin case study highlights the challenge of integrating multiple different geotechnical data sources within one model, while also demonstrating the potential of real time back analysis to improve system behaviour predictions during construction. Given a suitable contractual framework, digital twin based real time back analysis improves geotechnical work and is the next step in the evolution of the observational method.

Keywords: Digital twin, sensor data.

1. Introduction

Present-day digital twins (DT) have come a long way since the first implementations of NASA in the 1960s to simulate systems used in space via complex physical replicas on the ground. Since then, we have the technical advances that enables digital twins, and as a result, we see a booming market for digital twins. The concept is well-established in fields such as manufacturing, but is relatively new in construction and geotechnical engineering. With DTs first gaining traction in fields like manufacturing and process engineering, some definitions and use cases of DTs are not directly transferrable to geotechnical engineering and the construction industry. Assets are unique, and the geotechnical construction phases are relatively short-lived. Saback et al. (2024) therefore highlights the need to focus on "what makes sense to the industry (…) regardless of trends and buzz-words". With this in mind, we need to assess what the geotechnical engineer would want from such tools. While a complete 3D-model that updates every millimeter of measurement from the installed sensors, is futuristic and interesting by its own, it might not hold that much practical use, as also emphasized by Fuller et al. (2020).

A digital twin is a digital copy of a physical asset, on some level of maturity. There is no clear consensus on what defines a digital twin; a digital model might be classified as a digital twin by some, while others require it to meet specific criteria. The criteria would also vary by field.In this work, we assume the 3 levels ofFuller et al. (2020), which describe the integration of the technology with the real world, where the distinction lies in the ability to exchange data between the digital model and the physical asset. The levels are defined as follows:

1. Digital Model: Manual data exchange from the physical asset to the digital model. Any state changes are
unrelated to each other.
2. Digital Shadow: Automatic flow of data from the physical asset to the digital model only.
3. Digital Twin: Automatic flow of data from the physical asset to the digital model and back again. The physical asset may influence the digital model, and vice versa.

There are several methods for calibrating material parameters in finite element (FE) analysis using measurement data, for instance from triaxial tests (Calvello and Finno 2004, Rouainia et al. 2017) or a combination of laboratory tests and on-site measurements(Tornborg et al. 2021).However, these calibration approaches are not automated, andthe sensitivity analyses are manually adjusted.

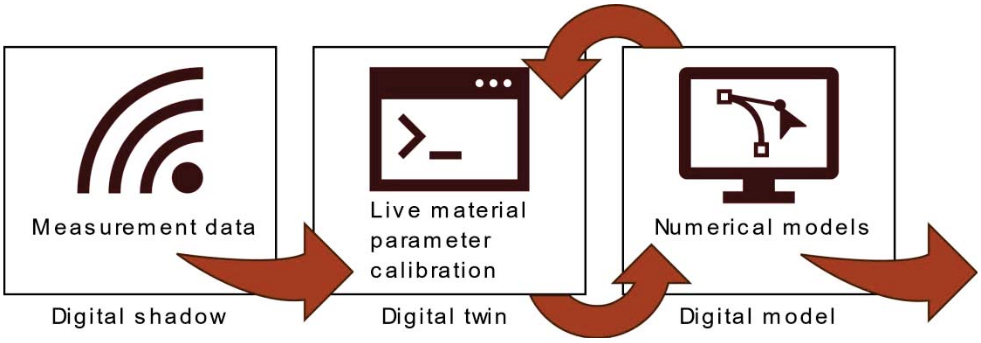

Figure 1. Flowchart of the components of the digital twin-based real time back analysis workflow. The digital shadow provides the digital twin with live measurement data used to calibrate material parameters against. The digital model is repeatedly run with altered material parameters and its output compared with the measurements, until the fit is good enough. The output from the iterations is then used in decision-making by the engineer.

This paper proposes an automated workflow for coupling the most recent measurements with the updated construction stage. We focus on the automation of live measurement data combined with finite element models to continuously update and calibrate material parameters for the FE model, as that will aid in the design and construction phase of an excavation pit. However, the principle of the workflow also applies to any representative model of the physical asset, not just limited to FE models.

2. Digital twin workflow

To set up a digital twin for combining the live monitoring data and a physical numerical FE model with calibration of parameters, we suggest the iterative workflow illustrated in Figure 1. The aim is to get good estimates or predictions of the system response by automatically calibrating and updating the physics-based numerical model. In order to calibrate and improve this numerical model, live measurements obtained from an API are inserted into a digital twin that combines the output from the numerical model with the actual response, and from there suggests a new set of material parameters to fit with the actual response.

The numerical model will therefore have the best estimate of material parameters of the current state and so the analysis of future construction stages may be more reliable. Note that we are not considering the uncertainties listed in Section 3.3 in this study, but with automating this process, a future step could be to generate results for several combinations of material parameters that all fit reasonably well with the measurements at that point.

The way to incorporate such a workflow into a real design problem, is:

i) Develop a numerical FE model of the problem
ii) Run an updating script when a new analysis should be made
iii) The script takes in newest measurements
iv) The script runs the existing numerical model and get the outputs from it
v) The script uses any method of choice to find better calibrated material parameters
vi) Update and save FE model with new material parameters
vii) If wanted, one can iterate this process from step iii)

This workflow is tooling agnostic, meaning that any measurements can be used, any FE or numerical model can be used, any material model can be used, any parameter calibration method can be used.

3. Case study

To demonstrate the iterative DT workflow, the excavation pit for Campus Ullevål in Oslo has been selected. Excavation was carried out during 2023. The excavation was up to 7 meters deep in marine clay and supported with sheet pile walls (SPW) and lime cement reinforcement (LC).

3.1 Construction phases

See Figure 2for an overview of the construction sequence. The construction is partitioned into 7 phases:

i) Installation of SPW
ii) Installation of ground improvement with LC to support the SPW
iii) Excavation of most of the pit. A temporary berm is left along the perimeter of the pit to support the SPW
iv) Casting of a concrete slab and installation of temporary struts between slab and SPW
v) Final excavation of the berms, performed section-wise
vi) Concrete slabis extended to sheet pile wall
vii) Removal of struts: SPW is cantilevered from the concrete slab

3.2 Monitoring setup

The excavation pit is equipped with with several monitoring instruments. In this case study, only the inclinometer data is used, but as discussed in Section 2. the workflow and models can be expanded to include any type and amount of monitoring data. In this example, data from the 2 inclinometers that are installed on the SPW are studied during the stages of construction.

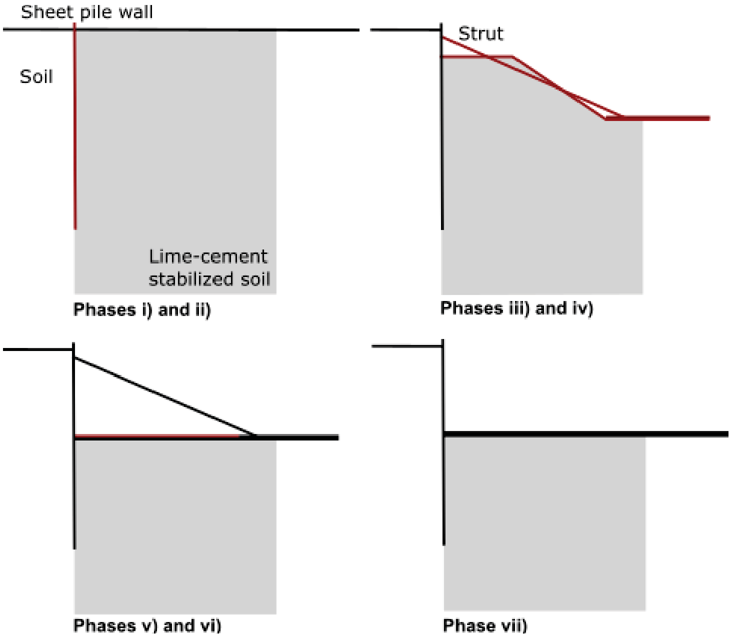

Figure 2. Construction sequence: i) SPW installation, ii) LC soil improvement, iii) excavation to final level, leaving a soil berm to support the SPW, iv) installation of struts and casting concrete slab, v) final excavation of berms, vi) extension of concrete slab to SPW, vii) strut removal.

3.3 Numerical model

A FE model of the excavation was established in PLAXIS 2D, see Figure 3, with construction phases as described in section 3.1

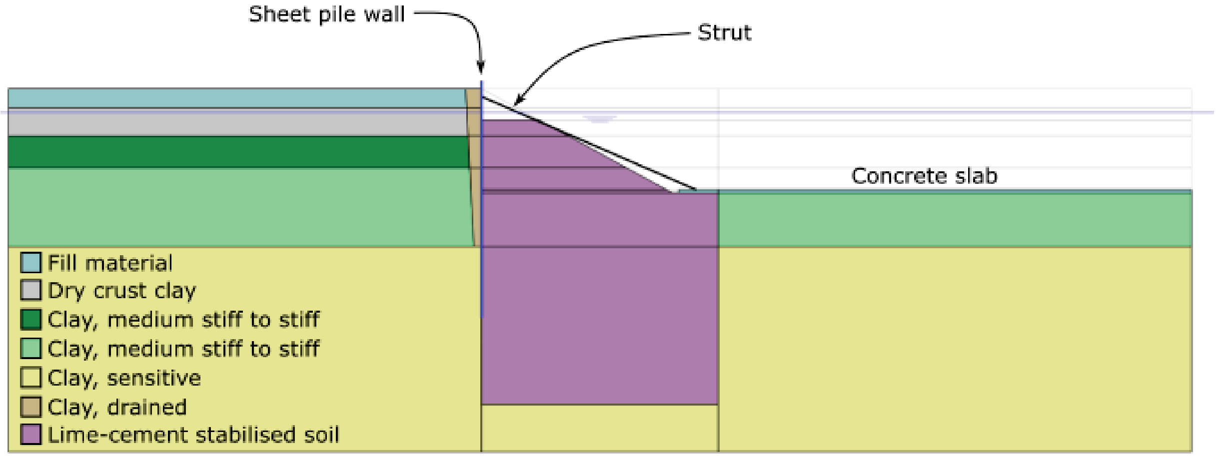

Figure 3. Geometry of the Plaxis 2D model of the sheet pile wall and excavation pit of phase 6, where the main excavation is performed and the concrete slab and struts installed.

4. Discussion

4.1 Application of digital twin workflow

This preliminary study tested the integration of fetching sensor data from an API, automated running of a numerical model, and the ability to update the numerical model with material parameters of choice. The only material parameter that was adjusted in this preliminary study, was the stiffness of the lime-cement improved soil. However, there are several other model parameters that should be adjusted in order to calibrate the model, for instance other material parameters, geometry, etc.

4.2 Benefits

According to Eurocode 7 (Standard Norge 2020b)the observational method is an appropriate approach when predicting the geotechnical behaviour is difficult. The proposed workflow allows for such adjustments, as the latest measurements are used to update the design model, thereby aiding in reviewing the design during construction. The Eurocode also lists certain requirements that should be met in order to apply the observational method, such as a plan of monitoring and that "the procedures for analysing the results shall be sufficiently rapid". Automating the pipeline from live measurements through adjusted calculations fulfills the requirements.Sensitivity analyses and material parameter calibration processes are often performed manually and are time-consuming. With an automation of this feedback loop, this work will be smoother.

The ability to adjust the design during the construction is beneficial in both worst and best cases. In scenarios where the system performance is worse than intially designed for, this allows for crucial adjustments. But also, in the other case, there is a possibility to lower dimensions, leading to less material use and CO2 emissions and consequently also lower the price. Another option is to optimize the progress, as in this case, that the excavation process may be sped up. In order to accommodate such changes, they should be included in the initial plan.

4.3 Limitations and uncertainties

As with any representative model, there are several uncertainties with regards to the modeling:

- modeling uncertainties (i.e. true geometry, idealisations, boundary conditions, numerical accuracy)
- material uncertainties (i.e. selections of constitutive models, material parameters, interface behaviour)
- physical uncertainties (i.e. spatial variability, stratigraphy, ground water level, climatic factors, stress history and initial state)
- execution uncertainties (i.e. quality of works, impact from other activities and traffic)

By incorporating field measurements and model validation into the workflow, uncertainties related to data collection and analysis is introduced. Such uncertainties can include:

- limitated quantity and/or quality of field measurements
- poor processing/analysis of field measurements
- model validation based on innacturate system behaviour assumptions
- overfitting the wrong parameters during model validation
- converging to local minimas of the chosen validation function, i.e. not finding the truly optimized set of model parameters

In this case, the discrepancies between the physical asset and the 2D numerical model are for instance that a small section of soil closest to the sheet pile wall was not stabilized due to difficulties with the machinery.Furthermore, the numerical model was a 2D model, hence 3D effects are not captured.

Limitations with regards to unforeseen future events cannot be captured by any model. In this case, Oslo experienced an extended freezing period the winter of excavation, which influenced deformations considerably.

Another important uncertainty is the optimization problem as a whole: there is no perfect model that captures reality. We can link deformation to stiffness material parameters, as done in this work, but there are many more input parameters that may influence the actual deformation, as listed above. It is crucial that the observational method (combining measurements with numerical models) is used in a physically founded way, and fit parameters that are linked to the response. (Strength parameteres for forces, stiffness parameters for displacements, etc.)

5. Conclusion

Digital twins might have limited use in construction due to the bespoke nature of construction projects. In this paper we suggest a workflow that combines measurements and digital models continuously, to get better estimates of later stages of the construction phases. Such a workflow is relatively easy to set up and is agnostic to type of physical model. However, it does require a monitoring setup to get the real time data, which is expensive.

Further work is to implement automated sensitivity analysis methods for material parameter calibration.

Acknowledgements

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