

# Geotechnical sensor monitoring towards digital twin application

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**ABSTRACT:** The geotechnical industry is gradually moving toward digital twin applications to enhance infrastructure lifecycle management and risk mitigation. This paper outlines the development and implementation of a geotechnical digital twin using the GeoBIM concept, a platform for structured integration of multidisciplinary subsurface data, including geotechnical, hydrogeological, environmental, and geophysical datasets. Emphasis is placed on incorporating geotechnical structures and time-dependent sensor monitoring data—elements crucial to simulating ground behavior under various load conditions.

A major challenge addressed is the lack of standardized data formats across disciplines and sensor types. This has been mitigated through the development of quality-assured delivery specifications compatible with a centralized database environment. Use cases demonstrate the successful application of this system in diverse projects: Nyhamnen city development (urban contamination and underground structure mapping), Assmåsa road reestablishment (peat ground reinforcement monitoring), landfill displacement tracking (slope stability analysis), Spårväg South subway depot (groundwater and settlement monitoring), and the Korsvägen, West Link rock tunnel (displacement monitoring in complex geology).

These examples illustrate that despite format heterogeneity, consistent data integration is achievable, enabling digital workflows and paving the way for real-time scenario modeling. The paper argues that, while traditional geotechnical modeling tools are often limited in scale and speed, the integration of AI and machine learning with digital twins can accelerate analysis and improve predictive capabilities.

In summary, the GeoBIM concept demonstrates how a comprehensive geotechnical digital twin can be realized at a national or organizational level, even in the absence of universal standards. This approach supports better-informed decision-making, long-term data access, and enhanced resilience in geotechnical engineering.

**KEYWORDS:** Digital twin, geotechnics, GeoBIM, data format, sensor monitoring, sustainability

## 1 INTRODUCTION

Heading towards the concept of a geotechnical digital twin, a database originally holding fundamental field and laboratory data and interpreted physical properties, has to be complemented with design phase geomodels, installed geotechnical structures during construction, and also adding monitored data from geotechnical sensors from the construction phase.

To fulfill the definition of a digital twin, ideally an automatic procedure predicting geotechnical/construction scenarios – slope stability, settlement, sheet pile wall movements – based on sensor data should also be implemented (Ninic et al., 2021). However, still very few geotechnical digital twin cases has been presented. Most probably due to lack of the extensive and complete geotechnical datasets that are required.

This paper describes a few challenges on the road to a geotechnical digital twin in the daily design life, ways to overcome them and discuss future applications. Also, a few use cases are shown, focusing on adding sensor monitoring data to complete the geotechnical dataset.

## 2 GEOBIM CDE CONCEPT

The GeoBIM concept has systematically been developed for structured database handling of a large number of geotechnically related properties within the subsurface disciplines geotechnics, environmental, rock engineering and hydrogeology, and also holding interpreted geomodels and geotechnical structures (Svensson & Friberg, 2024) in the database. With the vision of full transparency between all project phases and all stakeholders from idea to demolition of a structure the GeoBIM concept enable:

- Easy access to all data (geotechnical, environmental, geology/rock, groundwater, geophysics) for all stakeholders always.
- Design managed by known geotechnical uncertainties

- Flexible workflow and quick adaption to the user needs and specific software.
- Lifetime storage and access to all geotechnical data for facility management purposes.

This not only allows a smooth, quality assured and efficient workflow for any geotechnical design applications, it also enables a significantly updated geotechnical process.

Considering all the subsurface disciplines – geotechnics, hydrogeology, geology, rock mechanics, environmental, geophysics – and both field and laboratory data, the number of data types could be >100, see Figure 2.

Having all data in good order in a professional and well-structured database is fundamental for applying a digital workflow. It is also crucial for making use of the new universe that has opened with IoT and AI methodologies.

Aiming at reaching a full geotechnical digital twin, the GeoBIM concept has recently been further developed by implementing hosting of sensor monitoring data in time series in a structured way in the database, see Figure 1.

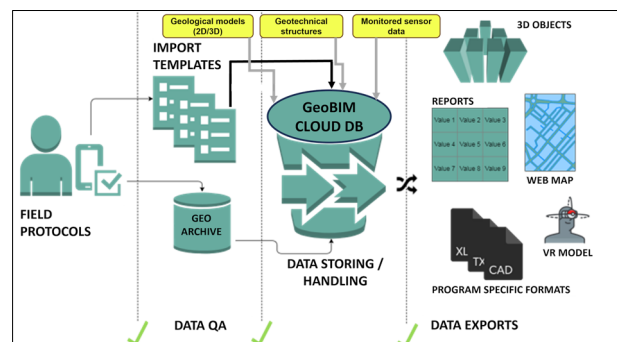


Figure 1. Schematic of the GeoBIM concept. All data is saved using standards if available or otherwise open delivery specifications. Recently, the concept was complemented with also hosting both geomodels and geotechnical structures for facility lifetime maintenance purposes.

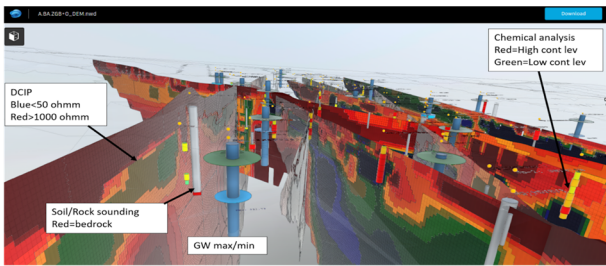


Figure 2. A powerful full geotechnical dataset visualized in the same digital environment. The dataset consists of data from the disciplines environmental, geophysical ERT/DCIP, groundwater and geotechnical sounding and sampling.

In Sweden only the geotechnical data collected with drill rigs are standardized (SGF, 2012). Also internationally, only a small proportion of all geotechnically related data types are standardized.

Beginning with developing standardized delivery specifications for geotechnical sounding and sampling methods for which there were already standardized data formats, see Figure 3, the GeoBIM concept has been systematically developed with most other methods used in large infrastructure projects within the geotechnically related subsurface disciplines - hydrogeology, geology, rock mechanics, environmental, geophysics, see Figure 2.

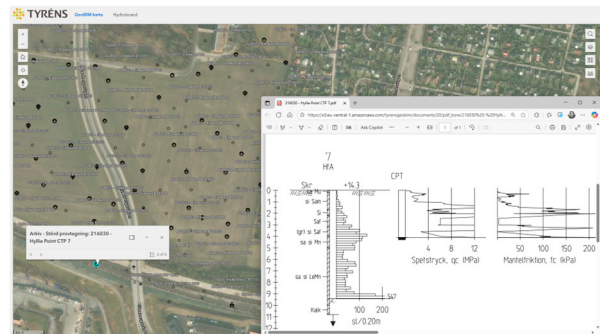


Figure 3. The GeoBIM CDE map interface from which all data could be visualized and downloaded. In this case one of the soil-rock sounding logs is visualized. All traditional geotechnical investigation methods are collected using a standardized data format defined by the Swedish Geotechnical Society (SGF, 2012).

### 3 USE CASES

With the aim of visualizing the application of the recently developed ability to handle also geotechnical structures and time monitored sensor data in the same digital environment a few use cases are presented. The different data types are all based on delivery specifications defined by Swedish discipline experts.

#### 3.1 Nyhamnen city development, Malmö

The city development area Nyhamnen, Malmö, south Sweden, is transforming from an industrial harbor into a vibrant urban district. Historically, it served as a bustling port and industrial area, with activities ranging from shipping and trade to food processing and emigration. This industrial past has left a legacy of potential soil contamination, posing challenges for redevelopment. The project includes new housing, offices, parks, and public amenities, with a focus on green and blue infrastructure.

##### 3.1.1 Geotechnical structures – data format

In the early planning process, given the industrial legacy, the client looked for a tool to map and digitally organize and

visualize all underground facilities, including contaminants and geotechnical structures. No digital standards for geotechnical structures were found. Therefore, in a client-designer common R&D project (Svensson, Friberg and Hagerberg, 2023) delivery specifications for a number of geotechnical structures were developed – sheet pile walls, anchors, piles, wells, lime-cement columns and also a generic volume.

In Figure 4 an example of how both geotechnical structures and contaminants could be visualized, complementing all traditional sounding and sampling data stored in the same database. Drawings from historically installed sheet pile walls were digitized and data was applied to the delivery specification to be database compatible. After early phase investigations for contaminants the interpreted polluted volumes were also fed into the database following the delivery specifications that were developed, allowing a smooth and quality assured process.

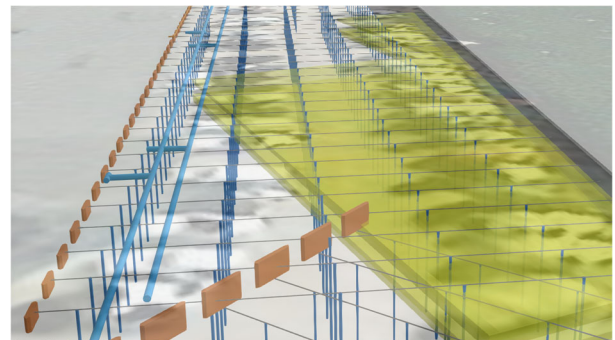


Figure 4. Visualizing both contamination levels (yellow) and geotechnical sheet pile walls with anchors in the Nyhamnen area, Malmö, Sweden. All information is kept in the same database (Svensson, Friberg and Hagerberg, 2023).

#### 3.2 Assmåsa road reestablishment, south Sweden

Parts of a 2,6 km rebuilding of a regional road (985) in the south of Sweden consists of peat. Across the peat area the new road will be established through various reinforcement methods, see Figure 5. A new bridge will also be built over the existing watercourse.

In a collaboration with the Swedish Transport Administration the area was used for pilot studying the application of delivery specifications developed for piles and pile decks, sheet pile walls and a generic volume defined for soil mass exchange, in the design phase. In the project, information about all the geotechnical reinforcement structures were imported to the database using the standardized delivery specifications.

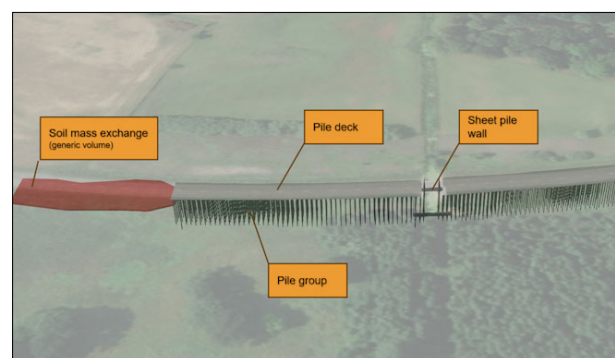


Figure 5. Digital model overview of the different geotechnical reinforcements used in the Assmåsa road reestablishment project.

The database also store document information produced in each project. Typical information reported for piles is the pile driving reports. These are accessed via the map interface and even if they are not available in fully digital format (most often pdf)

they could still add a lot of information, especially in the lifetime maintenance perspective.

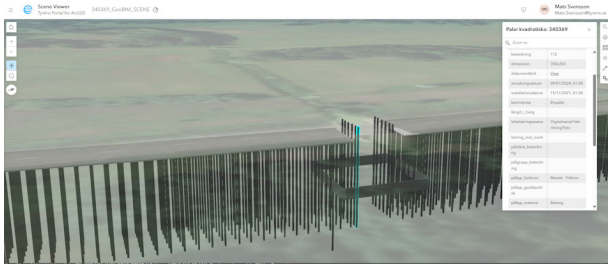


Figure 6. For each digital object there is additional object information, typically length of pile, pile material (steel, concrete), if it is tested (Y/N) etc. If available, there is also a link to pdf documents, for example pile driving protocols.

### 3.3 Landfill displacement monitoring

At a landfill located approximately 100 km south of Stockholm, significant ground displacements were observed. Consequently, the site was selected for pilot testing of delivery specifications for soil displacement monitoring, aiming at a streamlined data import into the central database.

In accordance with the Swedish landfill closure strategy, a final clay top cover will be constructed to minimize rainwater infiltration and, thereby, reduce the risk of contaminated leachate escaping into the surrounding environment.

Simultaneously, all slopes must be evaluated for potential stability issues. Where necessary, slope angles will be reduced or alternative stabilization methods will be implemented. To support stability assessments, a monitoring program was established, incorporating sensors to track displacements in the X, Y, and Z directions.

To facilitate effective analysis of soil movement data, a digitized and structured workflow was developed. This includes a web-based graphical interface integrated into the GeoBIM platform, see Figure 7.

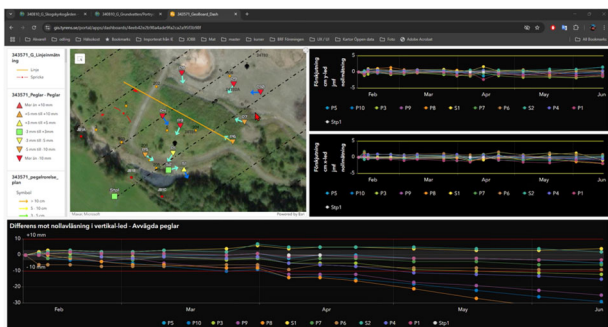


Figure 7. The web based graphics interface was developed visualizing time dependent soil displacement data stored in the database. First, a delivery specification for soil displacement sensor data was developed, taking care of both manually and automatically logged read data. Data is monitored in all directions (XYZ). The number of sensors and time period is interactively chosen by the engineer.

### 3.4 Spårväg South, Stockholm – groundwater monitoring

In the NW area of Stockholm, the subway depot in Rissne is being developed to accommodate multiple types of trains. The depot will also be expanded with a new workshop hall that can handle several types of subway trains. The construction include deep structures and blasting.

Since it is an urban area, the building activities had to be carefully carried out. Also, for environmental reasons, a certain groundwater monitoring program was followed. Both manually and automatically monitoring pressure gauges of various technical generations and manufacturers were used, which had to be taken care of when designing the delivery specifications.

In order to get the best possible tool for analyzing all the hydrogeological data, a digitized structured workflow was also developed, including a web based Hydroboard graphics interface (GUI), implemented in the GeoBIM platform.

During pilot testing of the groundwater sensor monitoring functionality it was realized that it would be of great value if also the settlement sensors installed in the area could be visualized in the same digital environment. Since the delivery specifications for that type of sensors were recently developed in the previous landfill project this was applied to the Spårväg Syd settlement monitoring data and added to the Hydroboard.

In urban areas, settlements are often the result of groundwater lowering (increased effective stress). Being able to follow both groundwater and soil settlement behavior is of great value to understand the whole geotechnical system during construction activities. Sometimes for validating, sometimes for excluding possible explanations for a certain behavior.

### 3.5 Station Korsvägen, West link – rock tunnel displacement

Project West link is a railway tunnel under central Gothenburg, Sweden, that improves commuter and regional train traffic. The project includes eight kilometers of railway, six of which are in tunnels, and three new stations at Korsvägen, Haga, and Gothenburg Central Station.

Station Korsvägen is located in granitic/gneissic rock with a generally low rock cover, often < 10 m, a span of up to 30 m and a complex geometry. Due to the complex geometry an extensive monitoring program was established prior to the rock excavations. Various displacement sensors were installed, including extensometers, prisms for convergence monitoring, and fiber optic cables and inclinometers for displacement monitoring, see Figure 8.

#### 3.5.1 Challenging datasets

The project utilizes a large number of different sensors and also from different manufacturers, most of them automatically monitoring and updating with a frequency of minutes. This results in very large datasets, in various data formats. Due to server requirements a decision was made not to download full datasets to the project database. Instead, the data was downloaded to a separate database, where it was filtered and analyzed in relation to alarm levels, see Figure 9, and then visualized in the design model where all other geological information and photogrammetry data was accessible. If any alarm levels were exceeded the specific sensor was colored in yellow or red in the as built model, see Figure 8.

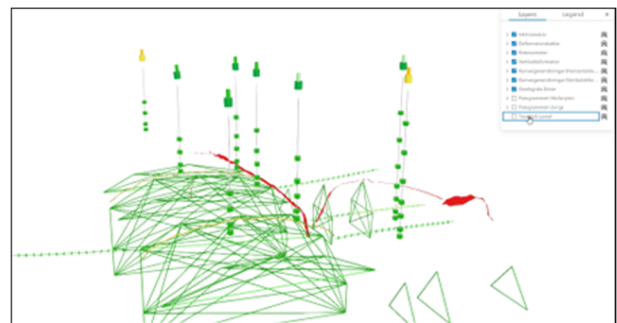


Figure 8. The sensor set up at station Korsvägen, West link, Gothenburg. An extensive displacement sensor set up was established, including extensometers, prisms for convergence monitoring, and fiber optic cables and inclinometers for displacement monitoring. Due to the large amount of data that was extracted no full sensor datasets were stored in the general project database. Each sensor was visualized as color coded in relation to the defined alarm levels.

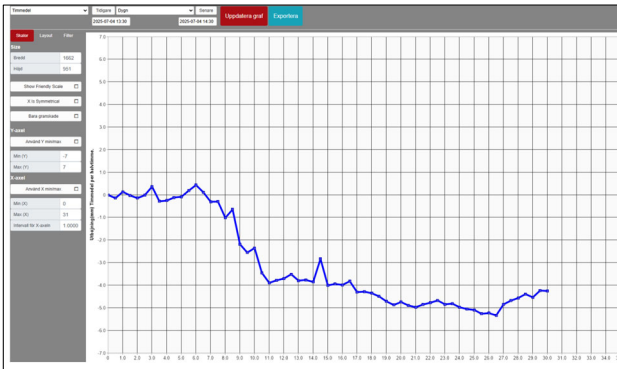


Figure 9. A single convergence graph visualizing the displacement in one of the sensors shown in Figure 8.

## 4 DISCUSSION

Digital twins are widely used in other industries, such as property management, for scenario simulation. In geotechnics, if sufficient knowledge about the subsurface environment and its behavior under various loads is stored digitally and complemented by sensor monitoring, scenario modeling becomes feasible. This is valuable for risk management and infrastructure maintenance, enabling real-time modeling based on online sensor data. Digital twins may complement or even challenge traditional numerical modeling, which often requires time-consuming calibration.

This paper demonstrates that, despite the lack of universal data formats, compatibility across datasets in infrastructure planning is achievable using best practice delivery specifications. Thus, the foundation for digital twin applications in geotechnics is established.

### 4.1 Challenges

The presented functionalities were first developed in R&D projects and pilot tested. While it is possible to digitally integrate all necessary data types, challenges remain in scaling up for daily design work. Key issues include ensuring all stakeholders deliver data in specified formats and managing the increased data volume from sensor monitoring.

Further questions arise: What are the optimal uses for a geotechnical digital twin? How do we assure quality, determine data requirements, and manage long-term operation and maintenance?

#### 4.1.1 Data formats

Applying a geotechnical digital twin in practice requires handling diverse data types from all subsurface disciplines. The challenge of multiple formats is significant, especially when adding sensor data. While standardization efforts are ongoing, a practical solution is to use well-prepared, quality-assured delivery specifications tailored to specific platforms.

#### 4.1.2 Large datasets

The GeoBIM database holds about 500,000 geotechnical boreholes, mostly 1D data. Incorporating sensor monitoring adds complexity in terms of data storage and analysis, requiring new methodologies.

### 4.2 Use of a geotechnical digital twin

Current tools in geotechnics often rely on simplified models to keep computation reasonable. There is a need for new approaches. AI and machine learning, combined with digital twins, can enhance analysis and prediction of ground behavior, helping to identify risks and optimize construction. The

required data volume for effective AI use remains a topic for further discussion.

## 5 CONCLUSIONS

This paper shows that full compatibility between geotechnically related information—physical properties, geophysical profiles, interpreted models, geotechnical structures, and time-dependent sensor data—can be achieved in a unified digital environment. The GeoBIM concept is a strong candidate.

Large infrastructure projects often require handling over 100 data sources, with the main challenge being diverse data formats, especially from sensors. The proposed solution, pending international standards, is to use quality-assured delivery specifications adapted to specific platforms at national or organizational levels.

By continuously developing the GeoBIM concept to integrate 1D/2D data, 2D/3D models, geotechnical structures, and sensor monitoring data, it now serves as a communicator and toolbox for data management. The GeoBIM concept is ready to support geotechnical digital twin applications.

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