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Building the future of geotechnics: A focus on data management and utilization

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ABSTRACT: Over recent years, data management has become an increasingly central topic across multiple sectors, including geotechnical engineering. While it is already the economic backbone of many technology companies and essential for the operation of AI platforms, efficient and structured data management is equally critical in engineering contexts. In geotechnics, engineers routinely integrate data from various sources, formats, and time periods. However, fragmented data handling methods often lead to inefficiencies, lost opportunities for reuse, and reduced data quality. This paper examines the importance of robust data management in geotechnics, outlines current challenges, and shows how the Norwegian Geotechnical Institute (NGI) has developed structured solutions for improved data handling.

KEYWORDS: Data management, digital geotechnics, data utilization

1 INTRODUCTION

In recent years, data management has proven to be a catalyst driving innovation across industries, fundamentally reshaping how organizations approach data-driven decision making. The European Commission highlights how the convergence of green and digital transitions creates unprecedented opportunities for technological advancement and sustainable development (European commission, 2023)

In geotechnics, as in all other industries, the development, training, and operation of digital tools, including artificial intelligence applications, rely on well-structured and high-quality datasets. Poor data governance increases the risk of biased, incomplete, or erroneous datasets, which can result in unreliable analyses and flawed decision-making.

Geotechnical engineers are used to combine information from diverse sources, such as field investigations, laboratory testing, instrumentation, and monitoring, and these data are often collected at different times and stored in incompatible formats. While these datasets provide valuable insights, their handling is frequently fragmented, involving multiple software platforms and dispersed file storage. Such conditions hinder both project efficiency and long-term data reuse.

This paper discusses why improved data management is vital for the geotechnical sector, highlights specific challenges, and presents NGI's recent initiatives to develop integrated and reusable data infrastructures. The paper also shows examples of improved workflows or assessments due to the data management we have established.

2 NGI'S EXPERIENCE AND APPROACH WHEN IT COMES TO DATA MANAGEMENT

At NGI, we have purposefully worked over recent years to improve our data management for all geotechnical data. This effort has encompassed solutions for data from laboratories, field investigations, and instrumentation/monitoring. As a result, all data production within these disciplines is now fully digitalized, enabling easier access to the data and allowing NGI to gradually build a comprehensive database for laboratory, field, and instrumentation data from completed projects. We have also begun integrating historical data, having already digitalized and implemented most of the field investigation data dating back to approximately the mid-1990s.

The current components of this data management system include mainly:

- AutoLab: Digitalizes all laboratory tests, meaning that results from both routine and advanced tests are now available in digital form.
- Field Manager: Provides an improved process tool for conducting ground investigations and serves as a visualization platform, reporting tool and database for all field and laboratory data.
- NGI Live: Functions as both a database and a visualization platform for all instrumentation and monitoring data.

A crucial part of the data management at NGI is that all data is accessible and can be supplemented or extracted via APIs (application programming interfaces). This enables systematic and significantly easier data reuse.

While these programs were initially developed as internal tools at NGI, over the past few years some have also been offered as a SaaS (software as a service) solutions to the industry. This has made Field Manager an industry standard in Norway and it has started to be used in Sweden as well as in the offshore market.

So, why did we choose to build our own geotechnical software instead of buying an off-the-shelf solution?

Over time, we saw that our existing approach to managing geotechnical data was inadequate. The software we used limited digital innovation, and parts of the data handling relied on server folder structures, leading to poor organization.

We evaluated available solutions but found none that met our needs for flexibility and integration. Key challenges included:

- Closed ecosystems: Most tools restricted further use of geotechnical data. We needed a solution with easy two-way API communication.
- Poor data transparency: Extracted files were hard to interpret, and some tools even degraded data quality from raw field files.
- Clearly defined data models: We needed standardized parameters to ensure consistency and enable efficient reuse of data.
- Limited data sharing across organizations: Many existing tools make cross-organizational data sharing difficult. From several landslide incidents over the years, we have seen that efficient data sharing among all involved personnel is critical
- Workflow integration: Existing tools didn't fit the daily routines of NGI's geotechnical engineers.

- Lab digitalization: With three labs in different countries and a mix of off-the-shelf and in-house equipment, adapting external software would have been as complex as building our own—likely with worse results.
- Instrumentation and monitoring: These departments also rely heavily on internally designed systems, making external software impractical.

While we build our own data management systems, we leverage external services for security. All databases are cloud-based on Norwegian servers, and access is managed through Azure single sign-on.

3 WHY WE NEED BETTER DATA MANAGEMENT

In his keynote for the 5th International Conference on Information Technology in Geo-engineering, Erharter (2024) did an objective assessment of several geo-engineering technologies and their position in Gartner's Hype Cycle (Gartner, 2018). The assessment is shown in Figure 1.

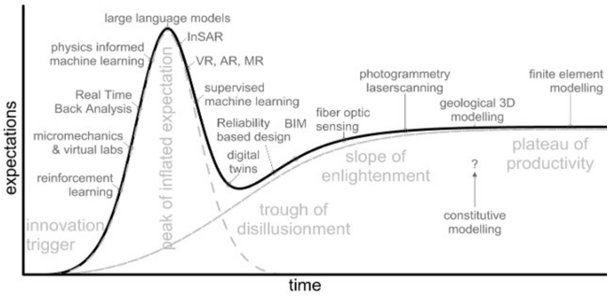

Figure 1. Geo-engineering technologies in Gartner's Hype Cycle (Erharter, 2024).

The key for moving almost all of these technologies to the right in the Hype Cycle, making them more mature and ready to useand hence get a better development of these technologies, is better data management of the geotechnical data.

In the following chapters the importance of data management is explained further, related to the advantage for the geotechnical engineer and linked to some of the technologies given in Figure 1. We also show some examples of how better data management over recent years have improved the daily work of the geotechnical engineer.

3.1 *Time efficiency and data reusability*

As mentioned, the geotechnical engineer is used to combining data from different sources and in different formats in their projects. This data must often be gathered and interpreted before making some sort of interpretation-plot or similar for different locations or even projects.

Experience from NGI shows that this gathering and interpretation is very time-consuming work. For example, during one specific project approx. 10 years back, one had to combine data from one specialized software and 60 different excel-files to make one given plot for one location (se example in figure 2). And this was only one of many plots for each location, in addition there were approximately 170 different locations. This makes the process of understanding and interpreting the data on especially large projects extremely time-consuming, which is a waste of the time of good geotechnical engineers. These engineers should use their time on doing a good assessment of the geotechnical data, they should not use time on searching through endless amounts of PDF's or excel-sheets, gathering data manually. This is both time-consuming and has a high risk of errors.

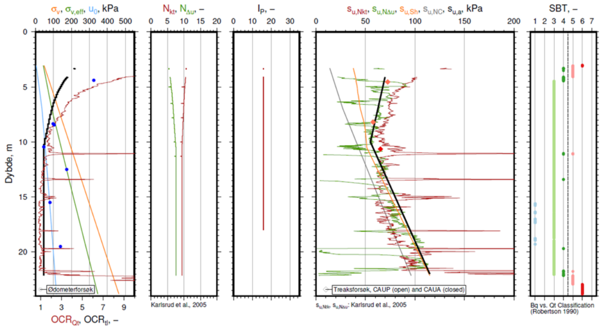

Figure 2. Example of combined plot with both field and lab.data

The consequences extend beyond inefficiency and potential errors: poor data management also reduces the ability to reuse historical datasets in future projects. In practice, retrieving and processing archived geotechnical data can be so cumbersome that organizations either proceed with suboptimal datasets or repeat costly investigations. Furthermore, if projects change consultants or contractors between phases, the full set of geotechnical data is not always transferred, potentially compromising the quality of subsequent project stages.

At NGI, we have already experienced positive effects on both project efficiency and the ability to reuse data as a result of the improvements made in geotechnical data management. Firstly, it has become significantly easier to produce compilation plots, such as the one shown in figure 2, as well as to generate the standard summary tables that are routinely included in interpretation reports for geotechnical investigations. As long as all data are digitally available, the process of compiling them becomes considerably more straightforward.

Secondly, we now find it easier to reuse data from previous projects, which provides better control of ground conditions at early stages of new projects. This capability will potentially save both time and costs associated with the execution of new site investigations for our clients.

3.2 *Development of new and improved correlations*

Correlations from field measurements and laboratory test form a cornerstone of geotechnical engineering practice. They are widely used for amongst other soil classification and interpretation of parameters. Well known examples include Robertson's CPT-based soil behavior type charts (Robertson, 1991; Robertson, 2010) and the CPTU correlations for clays developed by Karlsrud et al. (2005) (example in figure 3) and Paniagua et al. (2019), which are particularly influential in Norwegian practice. Such correlations facilitate rapid, cost-effective interpretation of large datasets, enabling engineers to make informed decisions with maybe limited site-specific laboratory data.

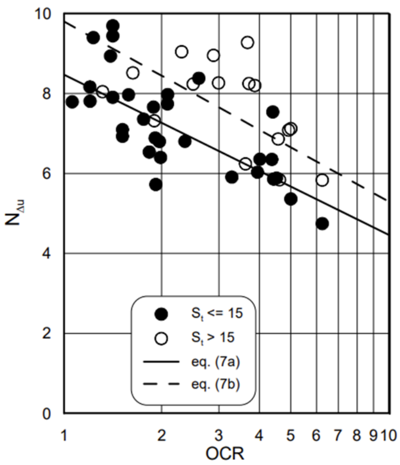

Figure 3. Example of CPTU correlation from Karlsrud (2005).

Historically, these correlations have been established using manually compiled datasets, often assembled over many years from multiple projects. While effective in their time, this approach inherently limits the scope, size, and representativeness of the underlying database. The manual nature of data compilation also means that updates, whether to incorporate new measurements or to refine statistical relationships, are labor-intensive and infrequent. As a result, some widely used correlations today may be based on datasets that are not only small by modern standards but also skewed toward certain geographic regions, soil types, or investigation methods.

The transition to structured, centralized geotechnical databases opens entirely new possibilities for correlation development. By integrating extensive archives of field and laboratory results, potentially including hundreds of thousands of data points across multiple soil types and climatic regions, it becomes feasible to develop correlations that are more robust, statistically representative, and adaptable to specific geological contexts. Moreover, such datasets allow for the exploration of parameter relationships previously obscured by small sample sizes or fragmented record-keeping.

So far, NGI has not yet fully realized the potential for further development or the establishment of new geotechnical correlations. This is largely because the work on data management for laboratory data has only recently been completed, and we have not yet had the opportunity to explore this area in detail.

3.3 *Interpretation of site investigations*

Interpretation of field investigations, laboratory tests, and instrumentation/monitoring constitutes a critical part of a geotechnical engineer's work. This stage establishes the basis and preconditions for subsequent analyses and calculations, and it is essential to accurately interpret stratigraphy and determine the most reliable and representative design values for strength and stiffness.

To achieve sound evaluations, high-quality field and laboratory investigations are indispensable. Equally important, however, is the ability to efficiently compile these datasets and assess them in relation to one another, enabling a more robust interpretation of the ground conditions in the project area. This is where effective geotechnical data management becomes crucial: when all relevant information is well-organized and readily accessible, the engineer's ability to make informed assessments is greatly enhanced.

In recent years, NGI has improved our procedures for interpreting geotechnical field and laboratory investigations by developing software tools that leverage the datasets we have compiled through dedicated data management efforts. Our first initiative was the development of a CPTU interpretation program, designed to facilitate the evaluation of CPTU soundings based on, amongst several other, the correlations mentioned in chapter 3.2.

Additionally, we have developed software for the interpretation of offshore CPTU soundings in combination with laboratory test data. This tool not only allows for the evaluation of individual locations but also supports the analysis of groups of sites, thereby enabling large-scale interpretation of both stratigraphy and geotechnical parameters. While the underlying methodology has been applied at NGI for many years, it was only with the foundation of robust data management that we were able to fully digitalize the process. The software retrieves relevant datasets via APIs developed within our data management systems, enabling an efficient and integrated workflow.

3.4 *Data exchange with national databases*

In many countries, national geotechnical databases have been established to centralize the storage and accessibility of subsurface investigation data. These platforms vary significantly in terms of maturity, data structure, and legal or contractual requirements for reporting. As discussed in Daktera and Janodet (2024) and in the webinars arranged by ISSMGE TC222 (ISSMGE TC222 2024-1 and 2024-2), the level of standardization and integration into engineering practice differs widely between jurisdictions. Some databases act primarily as passive archives, while others offer interactive interfaces, standardized formats, and APIs that enable direct integration into project workflows.

In Norway, as of 1 January 2025, it has become mandatory to report all geotechnical site investigation results to the NADAG database (NGU, 2024). This includes a formal requirement to submit data through a dedicated API using predefined data schemas, ensuring compatibility and uniformity. The reporting obligation is assigned to the company responsible for the investigations, and failure to comply can result in financial penalties. While the initial scope of the mandate covers only field investigation results—such as CPT, borehole logs, and in-situ testing—plans are already in place to extend the requirement to include laboratory results, both from standard routine testing and advanced geotechnical laboratory procedures.

The implications of such a system are twofold. On the compliance side, firms must ensure that their data management workflows are compatible with NADAG's formatting and submission requirements. This entails the adoption of structured data storage, clear metadata protocols, and quality control measures to verify data integrity before submission. On the opportunity side, a national database of this scale offers engineers unprecedented access to historical and geographically relevant datasets. By retrieving existing NADAG data before commencing fieldwork, practitioners can in many cases reduce the need for redundant investigations, optimize the design of site-specific exploration campaigns, and improve the accuracy of preliminary ground models..

For our own integration with NADAG, we have prepared our software to enable both the efficient retrieval of available data and, importantly, the uploading of data that is required to be reported to the database. At present, however, the NADAG API has not yet been completed, and we are awaiting its implementation with great interest.

3.5 *Uncertainty in geotechnical data*

Effective data management plays a foundational role in geotechnical engineering, where decisions are often made under significant uncertainty. As emphasized by Bozorgzadeh and Feng (2024), the field faces persistent challenges related to limited, fragmented, and context-dependent data, which hinder both reliable analysis and the transferability of findings across projects. In this context, managing uncertainty is not just a statistical exercise but a core aspect of responsible engineering practice. Sources of uncertainty, ranging from natural variability in soil and rock properties to inconsistencies in data collection methods, must be explicitly identified, quantified, and communicated.

A robust data management framework should therefore include standardized protocols for documenting data provenance, assessing data quality, and capturing uncertainty at each stage of the data lifecycle. Without such practices, geotechnical interpretations risk being overly confident or misleading, ultimately affecting the safety and cost-effectiveness of engineering solutions.

3.6 *Optimized workflow in design/engineering*

Improved data management, and consequently more robust databases for geotechnical data, can streamline and enhance certain aspects of the design process. In Norway, recent years have shown that when data are structured and made more accessible, various companies have developed internal applications or software that retrieve information directly from these databases and do initial assements related to the project. Such applications also can assist geotechnical engineers in for example specifying the need for supplementary investigations, identifying critical locations for stability assessments, and potentially determining the conditions required for a project to be feasible.

This enables the geotechnical engineer to gain early and more accurate insight into the actual site conditions, allowing for more reliable early-stage assessments than has previously been possible. In some cases, this also extends to evaluating and communicating the overall feasibility of a project, something that is, naturally, desirable for the client to quantify as early as possible in the project lifecycle.

In this area, both NGI and several other companies using our site investigation solution have made significant progress in recent years. Several Norwegian companies have developed systems that utilize API access to site investigation data, integrating them into automated early-phase assessment workflows. The example shown in Figure 4 (NVE 2025) was developed by geotechnical engineers at the Norwegian Water Resources and Energy Directorate (NVE) and provides an evaluation of quick clay hazards, including the potential retrogression distance of a quick clay landslide and an initial interpretation of the presence of quick clay. All these are essential considerations for geotechnical engineers working on projects in marine sediments in Norway.

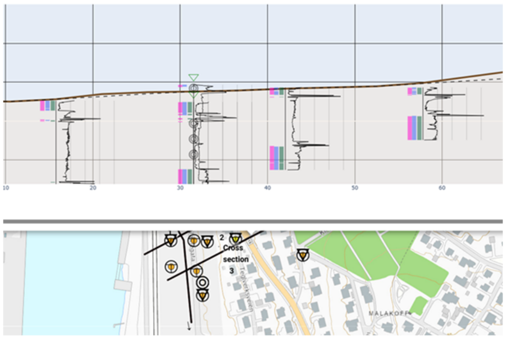

Figure 4. Example from NVE on software for optimized workflow (NVE 2025).

At NGI, we are developing a solution that, based on our own datasets in combination with publicly available information, delivers initial project assessments, identifies critical areas for the project, and indicates where additional site investigations are most important. This, however, is only the beginning. As the threshold for developing small-scale software tools to perform repetitive evaluations continues to decrease, the scope and prevalence of such applications will increase in the coming years. Nevertheless, achieving this requires that the data used in these assessments to be structured in a robust and consistent manner.

3.7 *Eurocode 7, Second Generation: Ground Models*

The second generation of Eurocode 7 introduces a fundamental shift in geotechnical project documentation by requiring the development of a Ground Model for every project. This model is defined as a "site-specific outline of the disposition and character of the ground and groundwater, based on results from ground investigations and other available data" (Garin et al., 2024). Unlike a static deliverable, the ground model is conceived as a dynamic framework that evolves throughout the project lifecycle. Its scope extends beyond the immediate construction site to include the broader Zone of Influence (ZOI), this means areas that may affect or be affected by future construction works.

In practice, a ground model integrates diverse datasets, field investigation results, laboratory analyses, monitoring data, and relevant historical records, into a coherent spatial and interpretative representation. Its development requires iterative refinement as new data become available, with uncertainties explicitly identified, quantified, and progressively reduced. This iterative nature ensures that the model remains an accurate and up-to-date reflection of subsurface conditions, serving as a central decision-support tool for design, risk assessment, and construction planning.

A key implication of the new Eurocode requirement is that geotechnical engineers will need to adopt more systematic and standardized approaches to data handling. Without robust data management, the process of compiling and updating the ground models risks becoming fragmented, time-consuming, and prone to errors. Well-structured databases enable direct integration of newly acquired results, rapid comparison with historical datasets, and automated generation of model updates. It will also make it easier to combine different datasets, adding the value of data from for example geophysics or InSAR together with the geotechnical data. This not only improves efficiency but also supports compliance with the Eurocode's requirement for transparent documentation of data sources, quality assessments, and uncertainty quantification.

Since the new version of Eurocode 7 has not yet been released, progress in this area has so far been limited. However, as the industry is already aware that its implementation is approaching within a few years, it will be prudent to begin preparations well in advance to improve workflows related to its adoption

3.8 *BIM models*

Building Information Modeling (BIM) of the subsoil can generally be divided into two categories: factual data models and interpretation models of stratigraphy or layering (Rømoen, 2024).

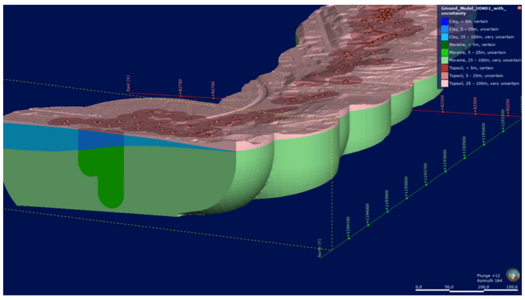

Figure 5. Examples of a subsurface BIM model, with both factual and interpreted data.

Factual data models represent direct data from measurements or investigations. These models combine spatial information, whether in 1D, 2D, or 3D, with results from field tests, laboratory analyses, or instrumentation. For effective production of such BIM models, it is essential that the underlying data is well-structured and digitally accessible. Without proper data management, creating accurate factual models becomes difficult and time-consuming.

Interpretation models, on the other hand, involve creating representations of subsurface layering and soil properties by interpreting the factual data. These models often include parameters estimated or interpolated between data points to provide a continuous understanding of the ground conditions. Good data management is crucial here as well, as poorly organized data limits the ability to generate reliable interpretation models.

Furthermore, interpretation models can be enhanced using machine learning (ML) techniques, which rely heavily on large, structured datasets to identify patterns and improve predictions. More about ML applications in the next chapter.

Creating BIM models based on databases of site investigation data is relatively straightforward and has been implemented by several companies in Norway, including NGI. One of the early adopters was COWI Norge AS, which, through the use of parametric programming in Rhino/Grasshopper, see Figure 6, developed a tool that connected to the API in Field Manager and generated an IFC model containing all site investigation data for a defined project. For each individual borehole, the model also included a link back to Field Manager. This allowed users viewing the results in an IFC-based platform to simply click on a borehole and be redirected to the original system to examine the underlying data.

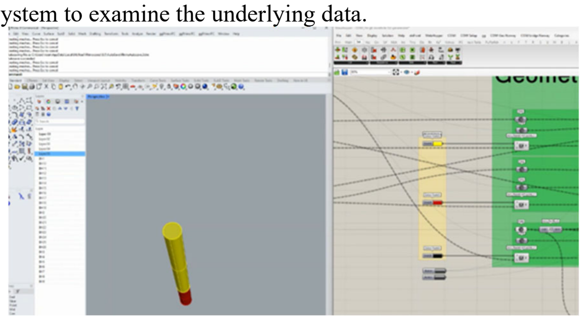

Figure 6. Examples of a subsurface BIM model generated through API of Field Manager (Engebretsen 2024)

3.9 *Machine learning application*

The effective use and full potential of ML within geotechnical engineering heavily depend on having a robust and well-structured dataset for training ML models. As emphasized by Phoon and Zhang (2022), a data-centric approach is essential for the successful application of ML in geotechnics. This means that the quality, quantity, and organization of data directly impact the accuracy and reliability of ML models.

When the underlying data is sparse, inconsistent, or poorly structured, ML models tend to produce inadequate or even misleading results. This is especially critical in geotechnical contexts, where errors in predictions can lead to unsafe designs or costly project delays. For example, ML models trained on biased or incomplete data may fail to generalize correctly to new sites, resulting in unreliable soil classification, parameter estimation, or failure prediction.

Moreover, geotechnical data often originates from diverse sources such as field investigations, laboratory tests, and monitoring systems, each with varying formats, resolutions, and quality levels. Integrating these heterogeneous data types into a coherent dataset suitable for ML requires rigorous data management and preprocessing steps. This includes data cleaning, normalization, handling missing values, and ensuring standardized data formats.

Virtually everyone beginning work with ML encounters the same challenge: a substantial amount of time is often spent cleaning and structuring data. Instead of immediately engaging with the more stimulating aspects, significant effort must be devoted to preparing data for ML applications.

A few years back, Kydland et al. (2021) presented an approach using ML to interpret total soundings. Total soundings are the most used site investigation method in onshore Norway, and their methodology enabled automated interpretation of stratigraphy across all sounding points. However, the original workflow required manual retrieval and import of files, which made both execution and the ML model training process time-consuming. Today, this solution leverages the Field Manager API, resulting in a more streamlined and efficient use of the algorithm and a significant reduction in manual effort.

At NGI, we have applied elements of ML in our projects for several years, and there is no doubt that robust data management greatly facilitates ML-based workflows. This holds true for both small-scale applications, such as interpreting soundings in minor projects, and for large-scale offshore wind developments, where site investigation and seismic data are combined and used to predict synthetic CPT datasets for entire project areas using ML (NGI/SAND Geophysics, 2022).

3.10 *Digital twins*

Good data management is also a critical prerequisite for the successful implementation of digital twins in geotechnics. Digital twins rely on the continuous collection, storage, and analysis of large amounts of data from sensors, geotechnical investigations, and computational models. If data is not handled systematically, with clear structure, version control, quality assurance, and traceability, errors in the models may occur, leading to misleading analyses and decisions. Effective data management not only ensures accurate and up-to-date representations of reality but also facilitates collaboration across disciplines, long-term historical record keeping, and automatic model updates. This is essential for unlocking the full potential of digital twins as decision-support tools in complex geotechnical projects.

To make a good digital twin one is also dependent on knowing the uncertainties in both the data on which the twin is based on and the data obtained and implemented in the digital twin during the operational phase. And as explained in chapter3.5, good data management is a key for managing to assess the uncertainty.

As stated in Babanagar et al. (2025), digital twins offer promising benefits for many applications within geotechnical engineering. However, as this paper aims to emphasize, their success is fully reliant on effective data management as the first step.

At NGI, we have several ongoing initiatives related to digital twins in the geosciences. One such project involves a slope in Eidsvoll north of Oslo, published in Piciullo et. al. (2025), where a monitoring system has been installed to continuously measure groundwater levels at various locations and transmit the data to NGI Live. Based on slope geometry and the interpreted stratigraphy and soil parameters, the system continuously calculates the slope's safety factor. Using this structured dataset, we obtain a descriptive digital twin in accordance with the classification provided by DNV-GL (2023). If, in addition, external data such as weather forecasts with anticipated future precipitation in the area were incorporated, the system could be further developed into a predictive digital twin. This would enhance the value of the analysis and provide the owner of the railway line located at the top of the slope with an early indication of any reduction in the calculated stability of the slope to a critical level.

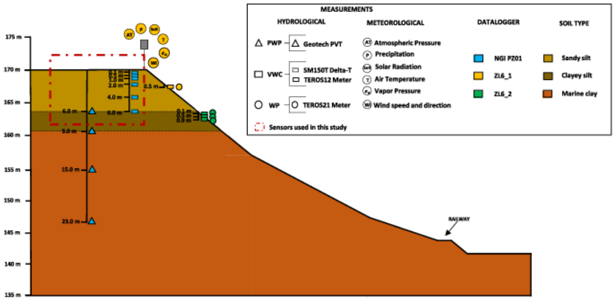

Figure 7. Schematization of the slop (Piciullo et. al. 2024)

4 CONCLUSIONS

As demonstrated through examples from the Norwegian geotechnical industry, effective data management is now enabling companies to innovate across multiple dimensions: improving operational efficiency, developing new interpretation models, enhancing traceability, and creating more accurate ground models. With the most critical datasets, field investigations, laboratory testing, and instrumentation data, starting to get well-managed, the industry is beginning to realize tangible benefits from this foundational investment.

However, the transformative potential extends far beyond current achievements. Advanced capabilities such as batch processing, machine learning applications, and sophisticated uncertainty calculations using Bayesian statistics represent the next frontier of innovation. Future integration of emerging datasets, including InSAR and geophysical data, promises to deliver even more insightful and accurate ground models that could fundamentally transform geotechnical practice.

While the immediate results from scripting and generative AI tools can be compelling, experience has shown that without robust data management foundations, development efforts quickly stagnate and the full potential of available data remains unrealized. We have observed this pattern both in NGI and across other organizations, reinforcing that data management is not merely supportive, it is foundational to sustained innovation.

5 ACKNOWLEDGEMENTS

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