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# FORECASTING SLOPE STABILITY WITH A DIGITAL TWIN: PERFORMANCE EVALUATION

Luca Piciullo[1,2]

*1 Norwegian Geotechnical Institute (NGI), Oslo, Norway. E-mail: luca.piciullo@ngi.no*

*2 Department of Built Environment, Oslo Metropolitan University (OsloMet), Olso, Norway*

Minu T. Abraham[1]

*1 Norwegian Geotechnical Institute (NGI), Oslo, Norway. E-mail: minu.treesa.abraham@ngi.no*

Ida N. Drøsdal[1]

*1 Norwegian Geotechnical Institute (NGI), Oslo, Norway. E-mail: ida.norderhaug.drosdal@ngi.no*

This study details a case from Norway, where a digital twin of a slope was developed utilizing real-time monitoring, numerical modelling, and machine learning (Piciullo et al., 2024). Moreover, a performance evaluation of the digital twin in predicting the Factor of Safety (FoS) is presented. This digital twin is deployed on a web-based platform called NGI Live, functioning as a cloud service to daily forecast the stability of the modelled slope. The FoS values are projected for the subsequent three days, using monitored hydrological variables (Heyerdahl et al., 2018) and meteorological data sourced from publicly available data-sources. NGI Live aggregates data from diverse sources, storing and displaying it in real time via online dashboards. Hydrological parameters, including volumetric moisture content (VWC) and pore water pressure (PWP), are monitored at various slope locations, and these data were used to validate the numerical model of the slope and calculate FoS for different time frames. The modelled FoS values, alongside the monitored hydrological variables and meteorological conditions, were employed to train two distinct data-driven models: one using Polynomial Regression (PR) and another utilizing Random Forest (RF). These pre-trained models serve as proxies for the numerical model within the cloud service to forecast FoS values using forecasted hydrological and meteorological variables. Meteorological forecasts are obtained from publicly accessible sources, while hydrological variables are forecasted using a Python-based package called Pastas (Collenteur et al., 2019), which utilizes the historical relationship between monitored variables and meteorological conditions. A performance evaluation has been carried out to compare the FoS forecasted with the machine learning models (PR and RF) and the GeoStudio numerical model, assessing their accuracy and reliability in predicting slope stability. This method is readily exportable and holds potential for implementation at additional sites for landslide early warning.

*Keywords*: Internet of Thing; landslide; digital twin; forecast; real-time; hydro-geotechnical modelling.

## 1. Introduction

Landslides pose significant risks to infrastructure and communities, particularly in regions like Norway, where steep slopes and variable climatic conditions increase susceptibility to slope instability. To address these challenges, this study introduces an innovative Internet of Things (IoT)-based Local Landslide Early Warning System (Lo-LEWS, Piciullo et al., 2018) for a slope in Eidsvoll, Norway, adjacent to a railway and a cultural heritage site. Leveraging the concept of digital twins, virtual models that replicate the behaviour of physical systems, this research builds on the framework proposed by Piciullo et al. (2022) and detailed in Piciullo et al. (2024). The digital twin integrates real-time hydrological monitoring, meteorological data, and numerical modelling to forecast the slope's FoS over a rolling three-day period. Deployed on the NGI Live web-based platform, it uses data-driven models, including Polynomial Regression (PR) and Random Forest (RF), trained on historical and forecasted hydrological, meteorological, and vegetation variables. A performance evaluation has been carried out to compare the FoS forecasted with the machine learning models PR and RF and the GeoStudio numerical model, assessing their accuracy and reliability in predicting slope stability.

## 2. Study area

The study area is located in Eidsvoll municipality, Akershus County, Norway (60° 19′ 23.376″ N, 11° 14′ 44.646″ E), characterized by a climate with moderate rainfall, low humidity, minimal wind, and significant daily and annual temperature variations. The region has experienced notable rainfall events, such as prolonged precipitation in autumn 2000, which triggered multiple landslides after nearly three months of continuous rain (Jaedicke and Kleven, 2008), and high cumulative rainfall in summer 2011, causing floods and landslides. Geologically, the area features Precambrian Granodioritic to Tonalitic gneiss bedrock overlain by Quaternary deposits, including clay, sand, and gravel, with glacifluvial and fluvial sand and gravel deposits prevalent near the Vorma River. The monitored slope, approximately 25 m high with a 45° inclination in its upper section, poses a risk to railway lines at its base and is located immediately east of a cultural heritage site, including a 12th-century church and graveyard. Due to this proximity, structural slope stabilization measures are not feasible, necessitating non-invasive monitoring. The slope, which has shown no prior deformations, is equipped with multiple sensors to track hydrological conditions. The slope is susceptible of rapid to very rapid silt slides, with the possibility of evolving into flowslide, according to the classifications by Hungr et al. (2014) and Cruden and Varnes (1996). In late spring/early summer 2016, SM150T sensors were installed to measure volumetric water content (VWC) and soil temperature at six depths (0.1 m, 0.5 m, 1 m, 2 m, 4 m, and 6 m), and GEOTECH PVT piezometers were placed at four depths (6 m, 9 m, 15 m, and 23 m) to monitor pore-water pressure (PWP). The slope's soil stratigraphy, determined through lab tests (granulometric curves, pressure plate tests, Atterberg limits) and in-situ CPTu tests, consists of a sandy silt layer (~6 m thick), a clayey silt layer (~3 m thick), and a deep marine clay layer. For this study, only data from the 2016 SM150T VWC sensors (at all six depths) and the 6 m PWP sensor were used, as soil below 7 m is saturated, rendering deeper piezometer data less relevant (Piciullo et al., 2022).

## 3. Methodology

A real-time slope stability analysis using a digital twin has been developed and implemented for an unsaturated slope adjacent to a railway in Eastern Norway (Piciullo et al., 2024). This system builds upon the comprehensive IoT-based local landslide early warning system (Lo-LEWS) framework proposed by Piciullo et al. (2022), which integrates key phases such as monitoring, modelling, forecasting, and warning. The real-time analysis incorporates hydrological monitoring, publicly accessible meteorological data, and numerical modelling to create data-driven models for forecasting slope stability for the rolling 3 days. The monitoring and modelling phases were crucial for understanding the slope's hydrological behaviour. GeoStudio SEEP software was used to back-calculate in situ monitored volumetric water content (VWC) and pore water pressure (PWP) on a daily basis. Validation through Taylor diagrams highlighted the importance of preliminary VWC calibration and the inclusion of meteorological and vegetation variables. Sensitivity analysis on hydraulic conductivity anisotropy further improved model accuracy in back-calculating hydrological parameters. The model successfully replicated monitored conditions over periods of 6 months, 1 year, and 1.25 years, although recalibration is recommended after six months. Daily slope stability analysis was performed by coupling GeoStudio SLOPE with the transient hydrological model SEEP to calculate the FoS. Data-driven models for real-time slope stability forecasting were developed based on the outputs from GeoStudio. Daily variation in hydrological, meteorological, and vegetation variables were used to train PR and RF models for forecasting daily FS values over a rolling three-day period. Accurate FS forecasting was achieved by integrating forecasted hydrological, meteorological, and vegetation variables. Hydrological inputs for the data-driven models were forecasted using Pastas (Collenteur et al., 2019), an open-source Python package for hydrogeological time series analysis, which predicted VWC and PWP using historical and projected meteorological and vegetation data. A web-based platform (WBP) was developed to automate daily operations, including data retrieval via APIs, three-day rolling forecasts, and result communication. If thresholds for FoS, VWC, or PWP are exceeded, alerts are sent via text messages and emails to system managers, facilitating prompt action.

### 3.1. *The digital twin*

In the context of slope stability, a digital twin is a virtual model that simulates, analyses, and predicts a slope's behaviour under various conditions. For the slope in Eidsvoll, Norway, this digital replica integrates geotechnical, environmental, and hydrological data from field surveys, real-time monitoring, and meteorological inputs to create a dynamic representation (Piciullo et al., 2024). The digital twin, built using the numerical model from Piciullo et al. (2022), data-driven models, and the Python-based Pastas package (Collenteur et al., 2019), enables real-time simulations of the slope's hydrological and stability conditions. Historical and forecasted meteorological data, including precipitation, air temperature (T), snow depth (SD), relative humidity (RH), wind speed (WS), solar radiation (SoR), albedo, and leaf area index (LAI), are used as inputs for Pastas to forecast volumetric water content (VWC) and pore-water pressure (PWP) over a rolling three-day period. Historical data, covering the past 365 days, are retrieved from the Norwegian Meteorological Institute's weather stations (via Frost API) and grid-based data from Open-meteo. Forecasted meteorological data are sourced from MET Norway's Locationforecast API and Weather forecast API. These inputs, combined with predefined functions for temporal variation of solar radiation, LAI, and albedo, allow Pastas to predict VWC and PWP for the next 72 hours. These forecasted hydrological variables, along with T and LAI, are then fed into the pre-trained data-driven models to predict the slope's FoS for the same 72-hour period, a timeframe chosen for early warning purposes. A flowchart (Figure 1) illustrates the explanatory variables and timeline of this forecasting process, detailing how historical and forecasted data are integrated to monitor and predict slope stability in real time, enhancing risk assessment and mitigation strategies for the Eidsvoll slope.

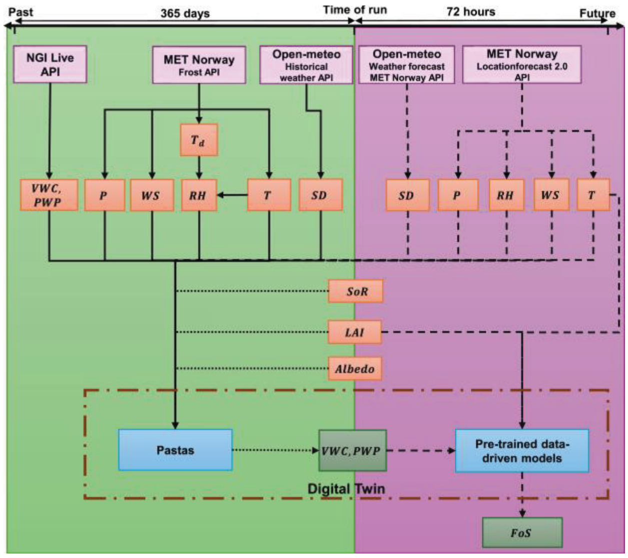


Figure 1. Flowchart showing the variables used for forecasting VWC, PWP and. The firm lines indicate inputs from past and the dashed lines indicate inputs from future. The dotted lines indicate that the variable has values from both past and future (from Piciullo et al., 2024)

## 4. Performance evaluation of the forecasted Factor of Safety for a three-month period

A three-month period (April–June 2024) has been selected for the performance evaluation of the FoS forecasted with the digital twin. This period was chosen due to the continuity and reliability of the available input data used for forecasting. To assess the robustness of the predictions, a sensitivity analysis was conducted using the software GeoStudio. The analysis considered key geotechnical parameters for the involved soil layers, as detailed in the table below.

Table 1: variable of the sensitivity analysis, with indication of the base value and rage.

| Property | Base Value | Modified Range |
|---|---|---|
| Pore Pressure | – | Variable (± 5 kPa) |
| Clayey Silt – Layer 2: Cohesion (c′) | 8 kPa | 0 – 16 kPa |
| Clayey Silt – Layer 2: Friction Angle (φ) | 32° | 24 – 40° |
| Sandy Silt – Layer 1: Cohesion (c′) | 8 kPa | 0 – 16 kPa |
| Sandy Silt – Layer 1: Friction Angle (φ) | 36° | 28 – 44° |

The sensitivity analysis shows that pore pressure is the most critical parameter influencing slope stability, with increasing pore pressure causing a significant reduction in the FoS (Figure 2). For sandy silt (layer 1), the friction angle has a stronger effect on stability compared to cohesion, while for clayey silt (layer 2), cohesion plays a slightly more decisive role than friction angle. Overall, the results highlight the importance of pore pressure indicating a strong negative correlation between pore pressure and slope stability, which is expected since higher pore pressure reduces effective stress and shear strength.

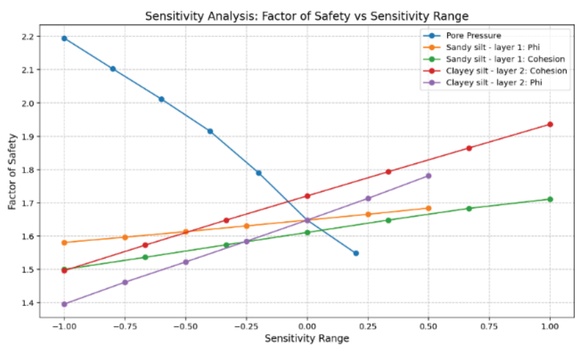


Figure 2: Result of the sensitivity analysis: Factor of safety as a function of the sensitivity range.

Figure 3 compares the forecasted FoS obtained with two machine learning approaches, PR and RF, against the reference values from GeoStudio over the selected April–June 2024 period. To complement this comparison, a probabilistic analysis was carried out using Monte Carlo simulations, where the same parameters considered in the sensitivity analysis were varied. From this distribution of FoS values, the standard deviation was calculated by focusing on the lowest FoS observed during the selected time window. The comparison between the forecasted FoS and the GeoStudio reference highlights clear differences in model performance. The Random Forest (RF) predictions show a more stable trend and generally follow the GeoStudio results, indicating a better ability to capture non-linear soil behaviour. In contrast, the PR forecasts display significant fluctuations, with frequent under- and over-estimations of FoS, reflecting sensitivity to local variations and potential overfitting. Overall, RF provides a more reliable forecast for FoS, while the deterministic GeoStudio model remains smoother and less variable, serving as a consistent benchmark.

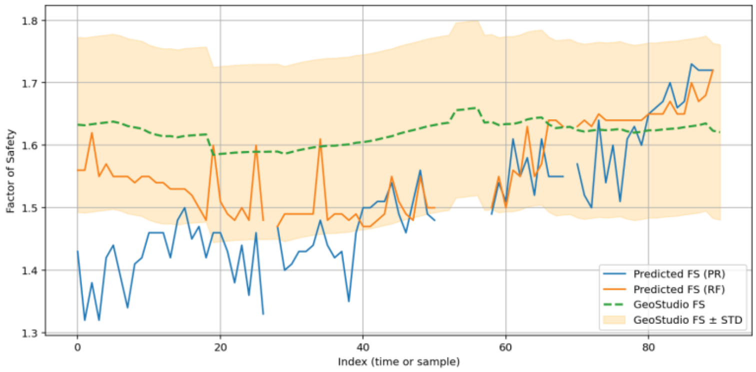


Figure 3: Forecasted FoS obtained with two machine learning approaches, Polynomial Regression (PR) and Random Forest (RF), against the reference values from GeoStudio over the selected April–June 2024 period, considering a standard deviation (STD) of 0.14.

## 5. Conclusions

The IoT-based Local Landslide Early Warning System (Lo-LEWS) developed for the Eidsvoll, Norway slope represents a groundbreaking approach to real-time slope stability forecast. The framework combines geotechnical, hydrological, and meteorological data to forecast the slope's FoS over a rolling three-day period using the Pastas package and machine learning models. This interdisciplinary approach, spanning geotechnics, hydrology, meteorology, instrumentation, and informatics, establishes a digital twin for proactive monitoring and forecasting. The sensitivity analysis reveals the critical influence of pore pressure, with FoS decreasing by 29%, highlighting its dominant role in reducing effective stress and stability. Less importance is associated with the geotechnical parameters (i.e., cohesion and friction angle) of layer 1 compared to layer 2. The comparison of the forecasted FoS from PR and RF against GeoStudio reference values over April–June 2024 show that RF predictions exhibit stability, closely tracking GeoStudio results and effectively capturing non-linear soil behaviour. In contrast, PR forecasts show significant fluctuations, with frequent under- and over-estimations, indicating sensitivity to local variations and potential overfitting. This interdisciplinary approach, combining expertise in geotechnics, hydrology, meteorology, and informatics, offers a scalable solution for proactive slope stability management. The data and scripts used for the model can be accessed at: https://github.com/norwegian-geotechnical-institute/local-slope-stability-forecast.

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